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Data-Driven Urban Digital Twins and Critical Infrastructure Under Climate Change: A Review of Frameworks and Applications

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Abstract

Urban Digital Twins (UDTs) are rapidly emerging as a transformative tool for enhancing the resilience and sustainability of critical infrastructure (CI) in smart cities, particularly in the face of climate-induced risks. They have gained significant attention in both research and real-world applications. By integrating real-time data, advanced simulations, and predictive analytics, UDTs facilitate data-driven decision-making and optimise urban systems. Given the complexity of urban environments and dynamics, addressing interdependency, interoperability, and inclusiveness is crucial for their effective implementation. This article examines the role of UDTs in managing CI, summarising key risks, technological advancements, and applications. A conceptual framework is proposed in this study to outline the resources required and the potential of UDTs in addressing climate challenges. Despite their promise, the implementation of UDTs faces multidimensional challenges: This article also explores these barriers and future directions for overcoming them through interdisciplinary collaboration, standardisation efforts, and inclusive governance frameworks. As UDTs continue to evolve, sustained innovation and equitable resource distribution will be essential to maximising their impact on the future of urban infrastructure and climate resilience.

Keywords

critical infrastructure resilience; smart cities; urban analytics; urban digital twins; urban management; urban planning

1. Introduction

Critical infrastructure (CI) refers to systems, assets, and networks that underlie the delivery of vital public services, whether they are in the private or public sector (Alkhaleel, 2024). They are fundamental to the operation of cities, as they underpin essential services such as energy, transportation, and public safety. With increasing automation and digitalisation, infrastructure systems, processes, and resources are becoming more complex, forming highly interconnected networks (Brucherseifer et al., 2021). The proper functioning of a single CI system is crucial both by itself and for the systems it supports. A failure in one CI system can trigger cascading economic, social, environmental, and political impacts. For instance, the 2021 Texas blackout halted economic activities, disrupted communication, and compromised public safety (Busby et al., 2021). In particular, the crisis disproportionately affected low-income and minority communities, who endured longer power outages and faced greater challenges in accessing essential services (Lee et al., 2022). Similarly, in May 2021, a ransomware attack led to the shutdown of the Colonial Pipeline, disrupting the supply of gasoline, diesel, and jet fuel across the southeastern United States. This resulted in a surge in fuel prices, panic buying, and consumers struggling to secure enough fuel for daily operations (Beerman et al., 2023). Meanwhile, the intensifying climate change exacerbates the multifaceted risks to CI, such as flooding, sea-level rise, storms, and heatwaves (Argyroudis et al., 2022; Kantamaneni et al., 2023; Kumar et al., 2021). These climate-induced events strain the resilience of CI, highlighting the need for adaptive strategies to mitigate their impacts. It is therefore crucial to assess the impact of climate change on CI performance and to develop comprehensive adaptation strategies that also consider social, economic, and political factors (Jin & Zhu, 2024; Kingsborough et al., 2017).

Urban Digital Twins (UDTs) have gained significant traction in both research and practical applications in recent years, particularly in the study of CI within smart cities. By integrating real-time data from ubiquitous sensing devices, such as IoT, UDTs analyse and visualise infrastructure dynamics, enabling more informed decision-making (Boccardo et al., 2024). The concept of UDTs extends the Digital Twin (DT) paradigm, which was initially developed in the industrial sector to create virtual models of physical objects for monitoring and simulation. Applied to urban environments, UDTs construct dynamic, data-driven models of cities that integrate multiple urban systems and processes. They facilitate data-driven decision-making for urban operators, offering insights into predictive maintenance, proactive interventions, and efficient resource allocation (Kanigolla et al., 2024). Beyond merely mirroring physical infrastructure, UDTs capture the interconnections between individual entities, dismantling traditional silos to enhance stakeholder collaboration. This fosters innovation in addressing complex urban challenges, ranging from resilience planning to sustainable development (Ersan et al., 2024; Joshi & Badola, 2024). Cities such as Barcelona, Singapore, Helsinki, Copenhagen, Stuttgart, and Zurich have already implemented UDTs to support diverse applications, including infrastructure health monitoring, disaster response, environmental management, traffic control, and the optimisation of energy supply, lighting, parking, and waste management (Boorsma, 2016; Dembski et al., 2019; Euklidiadas, 2024; OPSI, 2024; Schrotter & Hürzeler, 2020).

UDTs development for CI has also garnered increasing recognition from governments and professional organisations, as evidenced by the publication of various roadmaps, manifestos, and reports. In 2018, the Centre for Digital Built Britain (CDBB) launched the National Digital Twin Programme, aiming to establish an interconnected ecosystem of DTs across the built environment. This initiative was designed to improve the management and resilience of national infrastructure (CDBB, 2020). Similarly, in 2020, the Defence Science and Technology Laboratory, an affiliate of the UK Ministry of Defence, published *Future Cities: Trends and Implications*, a report examining emerging urban trends and their impact on CI. The report highlighted how rapid urbanisation and the growing concentration of human activities in cities are pushing governments to address economic, political, social, and environmental challenges. It emphasised that UDTs could provide cities with critical tools to navigate the complexities of future urban environments effectively (Bogan & Feeney, 2020). In addition, the World Economic Forum and Eurocities released comprehensive frameworks on UDTs in 2022 and 2024, respectively, outlining best practices and guiding principles for their infrastructure implementation. This framework underscored the transformative potential of UDTs in enhancing CI management (Euro Cities, 2024; World Economic Forum, 2022). Emphasising their transformative potential, both reports highlight how UDTs can enhance resilience, efficiency, and data-driven decision-making in urban planning and infrastructure development.

Recognising the growing interest in UDTs for CI, several review studies have explored their development, applications, and challenges. Jafari et al. (2023) and Vieira et al. (2022) examined the role of DTs in enhancing the efficiency and resilience of CI, particularly in energy grids and transportation networks. C. Liu et al. (2023) expanded the scope by categorising urban space as a distinct CI type, primarily focused on structural health monitoring. Other reviewers, such as Argyroudis et al. (2022) and Alibrandi (2022), have discussed DTs as part of broader digital solutions for CI resilience, with the latter introducing the concept of risk-informed DT for structural integrity assessment. Callcut et al. (2021) provided a unique perspective by integrating industry insights, revealing a strong demand for DT standardisation, governance, and decentralised administration, contrasting with the fragmented approaches in academic literature. Additional studies (Lehtola et al., 2022; Mazzetto, 2024; Riaz et al., 2023) have delved into data integration, decision-making frameworks, and the socio-technical challenges of UDTs implementation. However, despite valuable insights into specific CI sectors and technological progress, few reviews explicitly prioritise climate change adaptation. This indicates the research gap, as the potential of UDTs to address climate-induced risks and enhance long-term resilience remains underexplored.

More critically, the connectivity and the collective interdependencies and synergies of an SoS, which is critical in analysing the complexity of cities, have not been sufficiently investigated. Yu and He (2022) briefly discuss interdependencies in disaster management, noting that they add layers of complexity to disaster prediction. Their proposed DT framework incorporates multi-source data fusion, feature recognition, and semantic integration; however, it does not fully capture the cascading effects of interdependent infrastructure failures. Similarly, Fan (2022) highlights the role of human mobility data in enhancing resilience and equity within DT frameworks, yet without a comprehensive approach to modelling cross-sector interdependencies, the broader systemic vulnerabilities remain unaddressed.

Another critical gap is the limited consideration of citizen participation and engagement in UDTs development. While Ye et al. (2023) advocate for a human-centred approach to UDTs for CI resilience, stressing inclusivity in planning and the integration of socio-environmental data via social sensing, such efforts are largely confined to specific case studies, i.e., coastal communities, rather than being broadly applied to urban environments. Furthermore, despite growing calls for participatory UDTs, the implementation of mechanisms for public involvement remains fragmented. Mazzetto (2024) argues for adaptive governance structures and transparent communication channels to facilitate engagement, yet practical strategies for embedding citizen feedback into UDTs-driven decision-making processes are still lacking. These gaps highlight the need for a more holistic approach that not only models interdependent infrastructure networks but also fosters meaningful civic participation to enhance resilience and equity in urban planning.

This article aims to examine how UDTs support the operation and planning of CI for climate change adaptation. Specifically, by establishing the methods of selecting the review samples for comprehensive and systematic analysis, the article begins with an outline of the methodology used to identify and select the reviewed materials. Then, we reveal the impacts of climate change on CI, highlighting the resulting vulnerabilities and the necessity of adopting a UDTs approach. We analyse and categorise the CI studied, the risks addressed, and the applications provided in the reviewed samples; based on them, the genetic framework and the enabling technologies are synthesised. Finally, we identify future directions and challenges spanning technological, social, and policy-related barriers, and provide recommendations to address these gaps and strengthen the practical implementation of UDTs.

The article concludes by summarising key findings and their implications for advancing UDTs in climate-resilient CI planning and management. This cohesive structure contributes to the ongoing dialogue on leveraging digital innovation for sustainable and adaptive urban infrastructure.

2. Review Materials

The research follows the widely used PRISMA framework to guide its methodology. This involves searching for articles using keywords within established academic databases (commonly Web of Science, Scopus, and Google Scholar) and retrieving them. Irrelevant articles are then filtered out based on predefined criteria, such as language and duplication. Subsequently, the remaining articles are characterised, analysed, and systematically mapped. However, this approach has two significant limitations.

The first limitation is that, since being recognised as a top 10 strategic technology trend by Gartner in 2017, the concept of DT has gained prominence; however, its definition remains ambiguous, with no clear consensus in the scientific community (M. Liu et al., 2021; VanDerHorn & Mahadevan, 2021). The terminology associated with DT continues to evolve, as reflected in a regularly updated glossary published by the Digital Twin Consortium (DTC, 2025). Consequently, there is no universally accepted definition or formal guidance for referencing DT in scholarly literature. This ambiguity presents two key challenges: First, the term is often overapplied; some studies describe systems as DT despite them missing essential features such as real-time synchronisation, bidirectional data exchange, or predictive capabilities. Second, many studies that are highly relevant to the DT field do not explicitly use the terms “digital twin” or “urban digital twin” in their titles, abstracts, or keywords. As a result, excluding such studies risks overlooking important contributions and would limit the scope and comprehensiveness of this review.

The second significant limitation is that, outside academia, numerous UDTs initiatives have been led by governments, private enterprises, and civil society organisations. Given the significant financial, technical, and institutional resources required to implement UDTs in real-world settings, many of the most pioneering and innovative developments have emerged from these practice-based initiatives. Unlike academic studies, the outcomes and insights from these efforts are often disseminated through alternative formats such as policy reports, industry white papers, and project documentation. These sources offer valuable insights into the practical implementation of CI planning, management, and resilience. However, such materials are typically not indexed in standard academic databases, making them less visible to researchers and more difficult to systematically include in academic reviews.

Therefore, this article adopts a comprehensive approach that combines the results from academic search engines with knowledge from the authors' research experience in the field, collaborating with government bodies, private sectors, and social organisations. To align with the primary aims of this article, greater emphasis is placed on synthesising key theoretical and technological advancements, covering both the current state and future development in the main body of this article.

The detailed method of selecting the review samples is explained in Supplementary File 1 and the scientific mapping of the bibliometric data is displayed in Supplementary File 2: Supplementary File 1 outlines the step-by-step filtering procedure applied to the initial search results. As shown in Figure SF1, this includes removal of duplicates, screening based on relevance, and the addition of critical academic and industrial contributions identified through expert knowledge. Supplementary File 2 offered further descriptive insights. Table SF1 categorises the reviewed materials by document type, including research papers, review papers, conference papers, book chapters, and reports (primarily from non-academic sources). This typological breakdown demonstrates the diversity of sources included in the review and supports a balanced understanding of both scholarly and practice-based contributions. Figure SF2 highlights the temporal distribution of publications, showing a notable increase since 2019, which has remained consistently high. Tables SF2a, SF2b, and SF2c list the five most cited works in each category: research papers, review papers, and conference proceedings, respectively. Figure SF3 presents a keyword co-occurrence map generated from the initial dataset. This visualisation validates the breadth of covered topics, identifies key thematic clusters, and reveals dominant technical approaches and application domains. The mapping exercise supports the robustness of the methodology and underpins the final selection of review materials.

3. Climate Change and Its Impact on CI

Climate change presents a growing threat to CI by intensifying extreme weather events and exacerbating environmental stressors. Even with the implementation of the most ambitious decarbonisation programs, climate change will persist, bringing more extreme weather than previously experienced (Allard, 2021). Compared with general disaster risks, such as industrial accidents or incidental infrastructure failures, which often occur as discrete, short-term events, climate-induced risks are characterised by their chronicity, systemic impact, and growing uncertainty over time (Shortridge & Camp, 2019). Rising sea levels, projected to increase by 1.3 to 1.6 meters by 2100, will heighten flood risks and accelerate coastal erosion, endangering communities and infrastructure in low-lying areas (van de Wal et al., 2022). Additionally, the Intergovernmental Panel on Climate Change (IPCC) warns that rising global temperatures will lead to heavier rainfall and more frequent flooding, even in regions previously deemed low risk (O'Neill et al., 2017). These changes pose instant short-term disruptions to CI: Flooding can submerge transportation networks and energy systems, cutting off access and halting operations; heatwaves drive up energy demand while compromising infrastructure integrity, causing track buckling and runway degradation; and extreme winds, wildfires, and storms inflict structural damage, leading to power outages and transportation disruptions. As climate hazards intensify, the resilience of CI becomes increasingly critical to maintaining urban functionality and safety. In addition, long-term climate trends will continue to disrupt and reduce the capacity and efficiency of infrastructure (Dawson et al., 2018). The unpredictability of future weather events highlights the vulnerability of even robust systems to extreme conditions (Kim et al., 2017), affecting disadvantaged groups such as those with low socioeconomic status in particular (Yang & Ho, 2017); they demand holistic, anticipatory strategies rather than reactive ones.

Addressing these complex challenges requires a comprehensive approach that accounts for system interdependencies, prioritises sustainability, and anticipates cascading risks. This means not only integrating natural and human-made systems but also fostering innovation and applying a life cycle perspective to enhance infrastructure resilience. In this context, UDTs have emerged as a promising solution for the planning, monitoring, and adaptation of CI under climate pressures. They bridge the gap between reactive and anticipatory strategies by supporting both immediate operational adjustments and long-term planning. For example, the Gemini Principles, developed by the CDBB, distinguish between two main types of DTs: Type 1 DTs are focused on dynamic, real-time models for operational control, while Type 2 DTs are oriented towards strategic planning and investment based on long-term insights (Bolton et al., 2018). Both types provide actionable feedback loops, whether through automated controls or informed capital investments, that enhance the adaptive capacity of CI systems. Next, the implementation of these UDTs solutions in the reviewed works is revealed.

4. Implementation of UDTs for CI

To examine how UDTs are being implemented in the reviewed works, we first identified the types of CI addressed, the climate-induced risks considered, and the services or applications offered in each study. Table 1 presents representative case studies across four key sectors: transportation, water, energy, and the built environment. While some studies did not present concrete applications for generating actionable insights on climate-related risks, they were included due to their foundational conceptual contributions and the transferability of their methods to broader disaster risk management contexts. Most studies focus on acute hazards such as flooding, sea-level rise, strong winds, and extreme heat. In contrast, risks associated with water scarcity, such as prolonged droughts and large-scale wildfires, remain underexplored. While some studies consider shifts in water demand, few address the broader supply–demand dynamics under drought conditions. Where drought is considered, studies tend to focus on complex predictive modelling, with limited development of actionable decision-support tools (Henriksen et al., 2022; Wu et al., 2023). A similar pattern is evident in wildfire research, which emphasises detection and modelling through data fusion (Huang et al., 2024; Hyeong-su et al., 2019; Zhong et al., 2023); however, it offers little insight into the impacts or operational planning strategies of CI.

From a life cycle assessment (LCA) perspective, Michael Grieves, widely recognised as a leading advocate of DTs, proposed three distinct DT types. These include the Digital Twin Prototype (DTP), which represents conceptual designs; the Digital Twin Instance (DTI), corresponding to a specific system in operation; and the Digital Twin Aggregate (DTA), which integrates all existing DTIs to form a comprehensive system-level representation (Grieves, 2023). These paradigms, included in Table 1, though predominantly presented as DTIs, already exhibit characteristics of DTAs. They provide insights by correlating past state changes with subsequent behavioural outcomes while leveraging collective learning from user populations.

These insights emerge from complex interactions among a variety of adaptive agents, which include not only individual entities such as citizens, vehicles, and households, but also organisational stakeholders, such as investors, CI operators, and policymakers. These agents, whether cognitive or automated, continuously interact with their environment and each other, responding to constraints, making decisions, and adjusting behaviours. This creates dynamic feedback loops that shape system performance, inform policy interventions, and influence how reality is perceived and acted upon within the urban context.

Table 1. Paradigms of climate-induced risks addressed, and key stakeholder insights provided by UDTs of CI in existing studies.

CI sector	CI	Risks	Applications	Study
Transportation	Rail	Extreme temperature/ Flood	Providing stakeholders with accurate and up-to-date information for infrastructure investments and safety measures.	Kaewunruen et al. (2022)
	Road	Flood	Improving the coordination among different actors involved in disaster response.	Fan et al. (2021)
			Pinpointing vulnerable locations across the city under various flood scenarios.	Ghaith et al. (2022a)
			Adjusting traffic control measures in response to changing conditions, enhancing resilience to disruptions.	Xu et al. (2023)
	Port	Sea-level rise	Identifying vulnerabilities in port infrastructure, supporting investments and operational adjustments.	Karatvuo et al. (2022)
	Airport	Extreme temperature/ Strong wind	Fundamental data hub envisioning resilience planning.	Agapaki (2022)
Energy	Grid	Storm	Identifying system vulnerabilities	Braik and Koliou (2023)
	Utility pole	Strong wind	Encouraging participatory sensing involves the community in monitoring and reporting infrastructure issues, fostering a collaborative approach to urban resilience.	Ham and Kim (2020)
	Gas pipe	Extreme temperature	Knowledge graph for integrating cross-domain data, enhancing collaboration among experts.	Savage et al. (2022)
Water	Reservoir	Storm	Utilising user-generated data from social media enables a more comprehensive understanding of local impacts during disasters.	Fan et al. (2020)
	Wetland	Flood	Supporting decision-making in pollution control and habitat preservation. Adjusting water flow and introducing filtration mechanisms.	Aheleroff et al. (2021)
	Drainage		Early warning systems enable mitigation implementation. Supporting land-use planning.	Ghaith et al. (2022b)
			Improving the accuracy of water level predictions, assessing the impact of different preventive measures.	Roudbari et al. (2024)
	Inland waterway	Generic	Forecasting responses to both anticipated and unforeseen events.	AlexandraMicu et al. (2025)

Table 1. (Cont.) Paradigms of climate-induced risks addressed, and key stakeholder insights provided by UDTs of CI in existing studies.

CI sector	CI	Risks	Applications	Study
Built environment	Buildings structure	Extreme temperature	Informed decisions on infrastructure design and maintenance.	Alibrandi (2022)
	Open space		Forecasting urban overheat exposure to reduce its impact.	Mavrokapnidis et al. (2021)
	Urban Morphology		Simulating cool air flows for UHI mitigation.	Schrotter and Hürzeler (2020)
		Extreme temperature/ Flood	Enabling collaboration among stakeholders, including citizens, for proactive planning.	Dembski et al. (2019)
	Heritage	Flood/ Sea-level rise	Protecting the natural and cultural heritage and the unique waterways and pedestrian roads.	Villani et al. (2025)

4.1. Synthesised UDTs Framework for CI Under Climate Change

Researchers have devoted substantial effort to developing a universal, adaptive, and replicable DT architecture, with a key characteristic being the widespread use of a layered approach to group similar components (Gürdür Broo et al., 2022). Despite variations in technical methods and naming conventions, certain core characteristics and essential components remain fundamental (Tao & Qi, 2019; Tao et al., 2018). These typically include: (a) a dynamic linkage between physical and virtual assets, (b) real-time bi-directional data exchange, (c) integration of heterogeneous data sources, (d) simulation and predictive modelling capabilities, and (e) an ability to support decision-making and stakeholder collaboration (Barresi, 2023; Bettencourt, 2024; Ferré-Bigorra et al., 2022; Gil et al., 2024; Poornima et al., 2024; Qanazi et al., 2025; Therias & Rafiee, 2023; Weil et al., 2023).

Across the literature, the layered UDTs framework structure reflects the need to integrate diverse technologies, data sources, and functionalities to provide a comprehensive and dynamic representation of urban environments. For example, Peldon et al. (2024) proposed a five-layer architecture, beginning with the physical reality and extending into digital domains encompassing data handling, modelling, integration, and service delivery. Aheleroff et al. (2021) conceptualised a three-layer structure comprising physical, digital, and cyber layers. These represent: (a) data actuation in real-world objects, (b) digital models such as computer aided design (CAD) for minimal viable representations of physical assets, and (c) a cloud-based layer for generating information, knowledge, and insights. Similarly, Ferré-Bigorra et al. (2022) outlined a four-layer UDTs architecture, including data acquisition, digital modelling, simulation, and service/actuation. While they position the physical environment prominently in their framework, they clarify that it is mirrored by the UDTs but not technically part of it. Deng et al. (2021) proposed a structure comprising three core layers: infrastructure construction, which includes sensing and transmission devices; an "urban brain" platform functioning as the intelligence hub; and application layers supporting service delivery and management. For this article, the adopted and proposed framework is based on the C2PS (Cloud-based cyber-physical systems) architecture by Alam and El Saddik (2017). It offers a reference architecture that integrates cloud computing with cyber-physical systems. It provides the capability of reconfiguration and scalability, enabling a complex SoS, making it particularly suitable for managing complex urban infrastructures.

As shown in Figure 1, a generic framework is proposed with a specific focus on contextualising UDTs for managing CI under climate-induced risks. While C2PS focuses predominantly on system-oriented cloud–cyber–physical interactions, this framework extends those principles by embedding socio-technical dynamics and governance considerations throughout the layers. Adaptive governance and citizen participation were explicitly introduced into the framework, as well as a five-layer structure—acquisition, processing, integration, intelligence, and interaction—reflecting the progression from raw data generation to actionable outcomes. We acknowledge that several existing studies define an extra forefront layer, usually named as the physical layer (Alva et al., 2022; Jiang et al., 2022; Lv et al., 2022), representing the actual physical counterpart that UDTs mirror. However, we argue that, while identifying these assets is a necessary step, it should not be considered part of the UDTs' technical framework but rather as a prerequisite.

As the foundation, the acquisition layer collects data on CI operations and climate-induced environmental impacts. They are then transmitted to ensure synchronisation with their virtual representations. This layer is also referred to as the data layer in other studies (Aheleroff et al., 2021; Gürdür Broo et al., 2022; Kaewunruen et al., 2022; Peldon et al., 2024). Beyond these, we suggest that extra data sources are required, including participatory CI usage and status data via citizen science and community sensing, and relevant government policies and strategies addressing climate change mitigation.

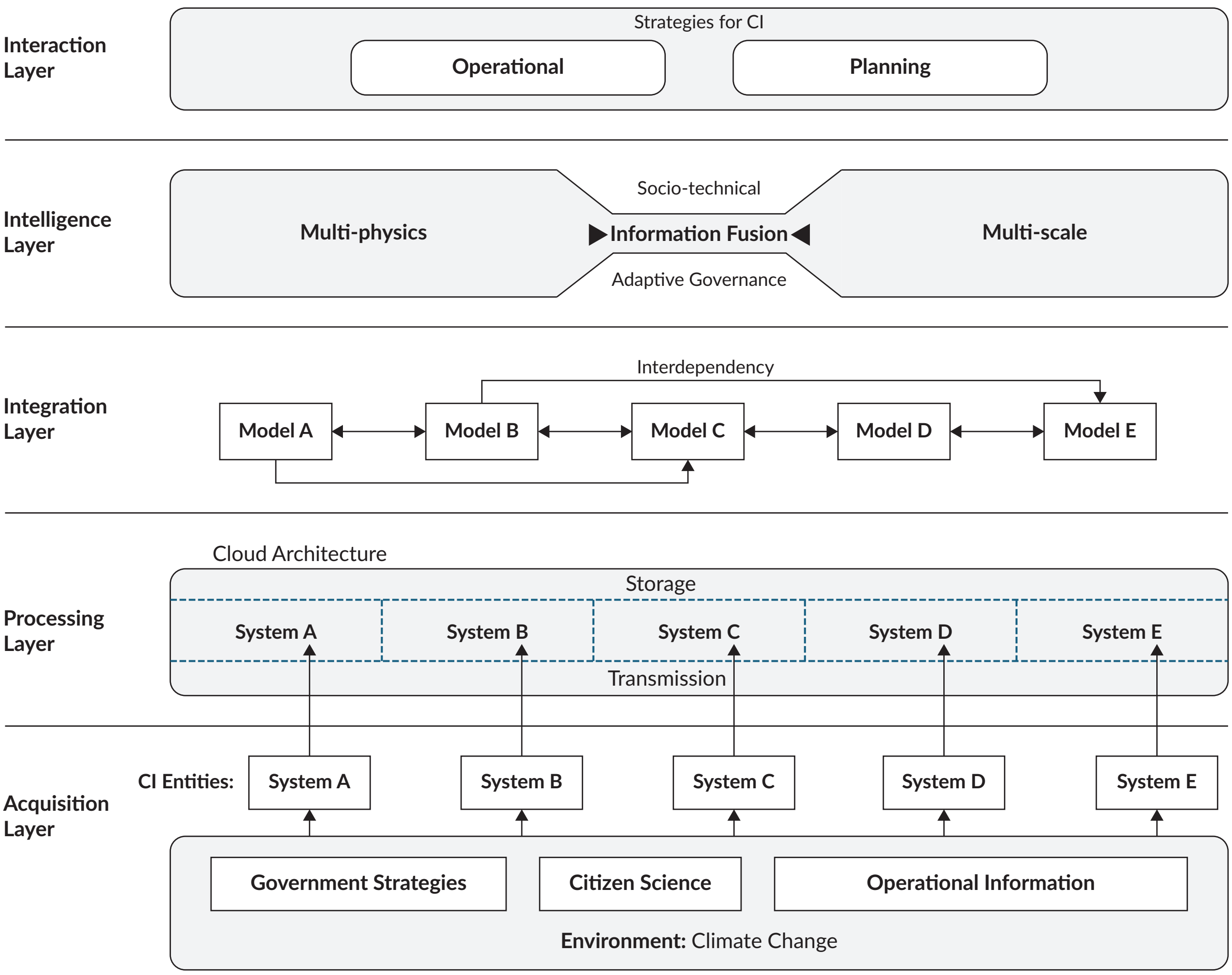

Figure 1. Generic framework of UDTs for managing climate-induced risks to CI.

Building on this, the processing layer handles the transmission, storage, and exchange of the collected data, facilitating the creation of the digital counterpart. High-speed, low-latency communication technologies, including 5G, Wi-Fi, Bluetooth, and LoRa, are vital for real-time data synchronisation (Durão et al., 2018; Liang et al., 2020; Mashaly, 2021). Additionally, scalable cloud-based storage solutions, such as data lakes, are increasingly adopted for advanced data mining and analysis (Neugebauer et al., 2024).

The integration layer incorporates knowledge-based and data-driven modelling approaches to simulate real-world behaviours at varying levels of abstraction (Jeong et al., 2022). Given the complexity of CI, a modular approach is frequently employed to ensure scalability and flexibility. System design tools such as SysML (systems modelling language) and AADL (architecture analysis and design language) are useful to define the structure and address interdependencies across components (Madni et al., 2019; Whyte et al., 2019). However, as UDTs are increasingly applied to SoS, identifying and managing hidden interdependencies remains a significant challenge. Effective detection and evaluation mechanisms are therefore essential for comprehensive integration.

Beyond integration, the intelligence layer enables the fusion of multi-physics and multi-scale simulation outputs, generating cross-domain intelligence by federating individual models. A common approach involves partitioning data into solution domains and implementing a hierarchical system that prioritises objectives accordingly (Jeong et al., 2022; Tuegel et al., 2011). In addition to technical analytics, this layer has been expanded in our framework to incorporate knowledge from socio-technical approaches and adaptive governance. These extensions aim to ensure that intelligence outputs are not only technically sound but also socially legitimate and contextually grounded.

At the top of the framework, the interaction layer serves as the interface between the UDTs and its end users. It supports a range of operational and planning applications, including scenario modelling, deliberative tools, and participatory planning, allowing users to explore system performance and co-develop informed strategies. Outputs generated in the digital space are fed back into the physical system, activating the twinning mechanism: Virtual simulations guide real-world interventions, while real-time changes in the physical environment continuously update and refine the digital counterpart.

Together, these layers constitute a structured yet flexible framework supporting UDTs applications for climate resilience in CI. This layered architecture enables end-to-end digital continuity from capturing real-time physical data to translating it into actionable insights, thereby supporting predictive and adaptive responses to climate-related stressors. Through this cohesive digital infrastructure, UDTs enhance the resilience of CI systems by making them more responsive, robust, and resource-efficient in the face of escalating environmental challenges.

4.2. Data Portfolios

The datasets underpinning UDTs contain data on CI entities, the change of surrounding environments due to climate change, and agents such as vehicles, cargo, and people, as categorised in Table 2. Remote sensing data and engineering models, including CAD, form the geometric foundation of UDTs data. The integration of GIS, BIM, and CityGML enriches these models by adding semantic information beyond spatial dimensions (Kasprzyk et al., 2024; Shi et al., 2023). As BIM data evolves towards multi-dimensional representations, it serves as a crucial source for cost analysis, sustainability assessments, and life cycle management (Charef, 2022). Real-time environmental and agent-based data are primarily collected through sensing technologies such as IoT devices, CCTV, and GPS tracking. Additionally, crowd-sourced participatory data from social media, mobile applications, and public events is emerging as a key source, providing up-to-date information on disruptions while enhancing inclusivity (Argota Sánchez-Vaquerizo, 2025; Ham & Kim, 2020).

Table 2. Data structures and sources applied in the existing UDTs of CI for climate change.

Entity	Studies
Remote sensing (LiDAR point cloud, DEM, 3D Buildings, Satellite image)	Agapaki (2022); Alibrandi (2022); Dembski et al. (2019); Fan et al. (2021); Ghaith et al. (2022a, 2022b); Ham and Kim (2020); Mavrokapnidis et al. (2021); Roudbari et al. (2024); Schrotter and Hürzeler (2020)
Engineering model (CAD, CAE, BIM, CityGML)	Aheleroff et al. (2021); Ham and Kim (2020); Kaewunruen et al. (2022); Karatvuo et al. (2022); Mavrokapnidis et al. (2021)
Geospatial (Energy grid, Pipeline, Geo-tagged photo)	Agapaki (2022); Ghaith et al. (2022a); Ham and Kim (2020); Savage et al. (2022); Villani et al. (2025); Xu et al. (2023)
Sensor/IoT (Electric meters, Gas meters, Water meters, Sensors for structural health monitoring)	Alibrandi (2022); Ghaith et al. (2022b); Mavrokapnidis et al. (2021); Pesantez et al. (2022)
Stakeholder database	Braik and Koliou (2023); Roudbari et al. (2024); Villani et al. (2025)
Environment	
Sensor/IoT (temperature sensors, wind speed sensors, air quality monitor, flow gauge)	Agapaki (2022); Aheleroff et al. (2021); Ghaith et al. (2022a); Kaewunruen et al. (2022); Karatvuo et al. (2022); Mavrokapnidis et al. (2021); Villani et al. (2025); Xu et al. (2023)
Participatory (Disruption location, People perception, Newly built/proposed structure)	Dembski et al. (2019); Fan et al. (2020, 2021); Ham and Kim (2020); Schrotter and Hürzeler (2020)
Agents	
Sensor/IoT (flight data, traffic sensor)	Agapaki (2022); Xu et al. (2023)
CCTV (vehicle detection, pedestrian detection)	Mavrokapnidis et al. (2021); Xu et al. (2023)
GPS tracking (vessel location)	Villani et al. (2025)

4.3. Data Processing and Analytics

As shown in Table 3, to address the challenges posed by the heterogeneous and dynamic nature of urban data, UDTs commonly employ cloud-based architectures to facilitate data integration and interoperability. This approach enables seamless data sharing, enhances decision-making processes, and improves cross-sector collaboration. By harmonising diverse data standards from IoT, BIM, and GIS, UDTs ensures semantic-level interoperability across different industries, fostering a more cohesive digital ecosystem (Shi et al., 2023).

However, the seamless sharing and processing of data also raise critical concerns regarding data privacy, ownership, and security. Key issues such as consent management, data provenance, and the right to access and control data must be carefully considered, particularly when dealing with personally identifiable information or sensitive urban datasets. Legal and governance frameworks may impose restrictions on how

Table 3. Data processing and analytic methods in the existing UDTs of CI for climate change.

Modelling	Studies
Data mining/filtering	Fan et al. (2020); Ham and Kim (2020); Kaewunruen et al. (2022); Roudbari et al. (2024)
Multi-source fusion/integration	Aheleroff et al. (2021); Alibrandi (2022); Braik and Koliou (2023); Dembski et al. (2019); Fan et al. (2021); Ghaith et al. (2022a, 2022b); Ham and Kim (2020); Mavrokapnidis et al. (2021); Savage et al. (2022); Schrotter and Hürzeler (2020); Villani et al. (2025); Xu et al. (2023)
Cloud architecture	Aheleroff et al. (2021); Xu et al. (2023)
Ontology development	AlexandraMicu et al. (2025); Savage et al. (2022)
Analytic	
Knowledge graph	AlexandraMicu et al. (2025); Fan et al. (2020, 2021); Pesantez et al. (2022); Savage et al. (2022)
Simulation (hydraulic simulation, traffic simulation, energy simulation)	Alibrandi (2022); Dembski et al. (2019); Ghaith et al. (2022a, 2022b); Karatvuo et al. (2022); Schrotter and Hürzeler (2020); Xu et al. (2023)
ML (image ranking, neural network)	Aheleroff et al. (2021); Alibrandi (2022); Fan et al. (2020); Ghaith et al. (2022b); Mavrokapnidis et al. (2021); Roudbari et al. (2024)
Bayesian network	AlexandraMicu et al. (2025); Alibrandi (2022); Braik and Koliou (2023); Ham and Kim (2020)
Game theory	Alibrandi (2022); Fan et al. (2021)
Geospatial analytics (KDE, localisation)	Dembski et al. (2019); Fan et al. (2020); Ham and Kim (2020); Savage et al. (2022); Villani et al. (2025)
Statistical/Mathematical model)	Agapaki (2022); Braik and Koliou (2023); Kaewunruen et al. (2022); Villani et al. (2025)

data can be collected, stored, and shared, which may vary significantly across jurisdictions. Therefore, UDTs development can incorporate technologies such as blockchain for secure data provenance tracking and immutable audit trails, and employ privacy-preserving computation techniques (e.g., federated learning or differential privacy) to enable data analysis without exposing sensitive information. Automated consent management systems embedded in the UDTs architecture can also support users in maintaining control over their data. In parallel, robust data governance frameworks guided by principles of transparency, accountability, and regulatory compliance (e.g., GDPR) can be implemented to clearly define roles, responsibilities, and access protocols across stakeholders.

To assess the impact of climate change, UDTs leverage simulation techniques and machine learning models to predict system behaviour and evaluate potential risks (Ferré-Bigorra et al., 2022). These models integrate historical data and real-time inputs from urban sensors to produce high-resolution forecasts, enabling early-warning systems and scenario testing for extreme weather, flooding, or heat events. Advanced methods such as knowledge graphs and Bayesian networks further enhance predictive capabilities by providing structured knowledge representations, principled data assimilation, optimal control, and uncertainty quantification (Lei et al., 2023; Mandal & O'Connor, 2024). Additionally, for decision-making optimisation, game theory is applied to simulate competitive and cooperative interactions among stakeholders. By modelling strategic behaviours and trade-offs, this approach enables policymakers to test various intervention strategies and identify incentive structures that mitigate potential challenges and promote collaboration in urban planning and infrastructure management (Cai, 2024).

4.4. Services and Interfaces

As outlined in Table 4, current UDTs applications typically provide two main types of services: short-term operational services and long-term strategic services. Short-term services focus on real-time situational awareness, including monitoring dynamic demands, detecting emerging hazards, and assessing CI performance. These insights support immediate decision-making, enabling real-time control measures and adaptive resource allocation to mitigate the impact of unfolding events. In parallel, long-term services support broader strategic objectives. These include predictive maintenance of infrastructure systems, scenario-based urban planning, investment prioritisation, and enhanced public engagement in long-term policy processes. They are delivered through a variety of user interfaces, such as dashboards, APIs, and immersive visualisation tools, ensuring the accessibility of insights for diverse stakeholder groups, from technical operators to policymakers and the public. They align with the two types of DT categorised in the aforementioned Gemini Principle (see also Bolton et al., 2018).

Studies offer holistic approaches covering both types. For instance, Aheleroff et al. (2021) present a DT that features a live dashboard for real-time monitoring and control of pumps and valves in a wetland system to mitigate flooding. At the same time, it leverages historical data to support predictive maintenance. This architecture allows for immediate response to anomalies and, simultaneously, informed long-term decision-making.

Table 4. Actionable information provided and user interfaces in the existing UDTs of CI for climate change.

Service	Studies
Situation awareness	Aheleroff et al. (2021); Fan et al. (2020, 2021); Ghaith et al. (2022a, 2022b); Ham and Kim (2020); Mavrokapnidis et al. (2021); Pesantez et al. (2022); Roudbari et al. (2024); Villani et al. (2025); Xu et al. (2023)
Resource distribution	Agapaki (2022); Braik and Koliou (2023); Fan et al. (2021); Ghaith et al. (2022a, 2022b); Roudbari et al. (2024); Savage et al. (2022)
Predictive maintenance	Aheleroff et al. (2021); Alibrandi (2022); Ham and Kim (2020); Kaewunruen et al. (2022); Karatvuo et al. (2022)
Investment/Planning strategy	Dembski et al. (2019); Kaewunruen et al. (2022); Karatvuo et al. (2022); Schrotter and Hürzeler (2020); Villani et al. (2025)
Public engagement	Dembski et al. (2019); Ham and Kim (2020); Schrotter and Hürzeler (2020)
Real-time control	Aheleroff et al. (2021); Fan et al. (2020); Xu et al. (2023)
Interface	
Live dashboard	Aheleroff et al. (2021); Ghaith et al. (2022b); Karatvuo et al. (2022); Savage et al. (2022); Xu et al. (2023)
API	Aheleroff et al. (2021); Xu et al. (2023)
VR/AR	Aheleroff et al. (2021); Dembski et al. (2019); Ham and Kim (2020); Mavrokapnidis et al. (2021)
3D visual/interaction	Ghaith et al. (2022a); Roudbari et al. (2024); Schrotter and Hürzeler (2020)

5. Challenges and Future Directions

Despite growing commitment and attention to UDTs, their effective implementation in supporting CI under climate-induced risks faces multi-dimensional challenges. They are critical for improving the practicality of UDTs, ranging across technical, institutional, and social dimensions.

5.1. Technical Challenges

The primary technical challenges in implementing UDTs in CI, particularly in addressing climate change-induced risks, revolve around integrating multi-domain knowledge and identifying emergent properties within complex urban systems. Addressing these challenges requires a comprehensive approach that combines technological innovation, strategic planning, and cross-sector collaboration.

As previously discussed in Section 4.1, UDTs must integrate diverse data sources from multiple sectors, each with different levels of abstraction, as well as varying volumes, velocities, and formats of raw data (Iglesias et al., 2020). This often results in data heterogeneity and fragmentation, complicating the effective operation and maintenance of infrastructure systems. The fusion of various models and simulations requires interdisciplinary expertise and cooperation (Deng et al., 2021). Integrating segmented DTIs of existing infrastructure into DTAs is particularly challenging due to the lack of standardised frameworks and a shared understanding of DT architectures. Second, the implementation of UDTs is often hindered by high costs, driven by inefficient business models and the significant investment required for advanced technologies and infrastructure development (Wicaksono et al., 2023). Third, beyond technical complexity and cost barriers, ensuring data privacy and cybersecurity for CI is a critical challenge. As UDTs collect and process vast quantities of sensitive data, centralised architectures are particularly vulnerable to cyber threats and data breaches.

To address these challenges, the adoption of technical protocols and frameworks can facilitate smoother model integration and interoperability. Developing more efficient business models and leveraging cost-effective technologies, such as remote sensing, cloud computing, and AI-driven analytics, can help reduce financial constraints. Additionally, shifting towards decentralised architectures can enhance system resilience and security, mitigating risks associated with cyberattacks and data vulnerabilities.

5.2. Institutional Challenges

A major institutional challenge in UDTs implementation is the absence of widely accepted standards, which significantly impairs efforts to enhance infrastructure resilience. The lack of standardisation leads to inefficient data exchange, biased analyses, and inconsistencies in information interpretation. Consequently, this hampers deployment efforts, causes misalignment among stakeholders, and reduces willingness to participate in UDTs initiatives.

For solutions, developing robust regulatory frameworks and well-defined organisational structures is essential for guiding both the adoption and implementation. Regulatory frameworks will help to establish necessary guidelines and standards, ensuring consistency and interoperability, while organisational structures can further shape the strategic and operational integration of UDTs within institutions. Several standardisation initiatives have emerged, like DIN SPEC 91357 “Reference Architecture Model Open Urban Platform” and the more recent DIN SPEC 91607 “Digital Twin for Cities and Municipalities,” provide nationally recognised specifications that align with existing standards. This type of standard ensures that the proposed specifications are compatible with existing standards and are officially published at the national level (Connected Urban Twins, 2025). Likewise, the GAIA-X initiative, organised in Brussels, promotes federated data infrastructure, emphasising transparency, interoperability, and sovereignty (Otto, 2022). These principles are crucial for UDTs ecosystems.

Platforms like Fiware, an open-source platform with growing adoption, offer modular components that support data standardisation and interoperability across domains (Bauer, 2022). Additionally, the DTC glossary plays a pivotal role in enhancing the interoperability of industrial systems by providing a standardised framework and common language for DT technologies. This glossary aids in creating a universal understanding and facilitates the integration of DT across various domains, thereby improving efficiency in industrial operations (DTC, 2025). These emerging standards and platforms present valuable foundations upon which UDTs development can build.

Moreover, valuable lessons can be drawn from sectors like manufacturing, healthcare, and maritime logistics. These fields have advanced in standardisation by focusing on key aspects such as interoperability, data exchange, safety, and reliability (Khan et al., 2023). Organisations like ISO, IEEE, and the Industrial Internet Consortium have introduced standards covering general frameworks, technical requirements, and best practices for manufacturing DT (Khan et al., 2023; Sun et al., 2022). UDTs development can build upon these examples to establish a more structured and coordinated approach to standardisation, facilitating broader adoption and impact.

5.3. Social Challenges

UDTs encounter significant social challenges, particularly in the uneven distribution of infrastructure data. Some areas experience excessive or redundant data collection, while others suffer from under-instrumentation and data poverty. For instance, newly developed or renovated communities may have access to high-resolution energy consumption data via smart meters, whereas older buildings still rely on manual data collection, which can compromise the accuracy and reliability of analytical outcomes.

This imbalance not only affects the quality of data but also exacerbates social divides, reinforces existing inequalities, and undermines public trust in governments and organisations. Data poverty is often correlated with broader technological and social deprivation (Serajuddin et al., 2015), and when a UDTs is built on incomplete or non-inclusive datasets, it risks producing less inclusive insights, potentially misleading decision-makers, and excluding vulnerable populations (Riaz et al., 2023). Most UDTs initiatives for CI are concentrated in economically developed cities with substantial funding. However, as climate change presents global challenges, many regions lack the necessary investment, limiting the widespread adoption and advancement of it.

In sectors like manufacturing, where DTs have advanced further, operations are typically governed by strict regulations, enabling structured implementation. In contrast, urban environments are more dynamic and less predictable, requiring UDTs to operate within both formal regulations and informal human behaviours. This makes stakeholder engagement and public trust essential. Gaining public confidence requires transparent, evidence-based insights that reflect diverse perspectives. Once trust is established, UDTs can support meaningful participation by integrating community feedback into planning and decision-making tailored to local spatial and social contexts (Jin & Zhu, 2025).

Interactive platforms and user-friendly interfaces will allow citizens to co-create solutions, contribute local knowledge, and develop a sense of ownership over resilience strategies. This is especially valuable in the context of climate-induced disasters, where community insights can enhance understanding of how urban systems interact with environmental stressors and improve preparedness. UDTs also strengthen resilience by managing interdependencies across infrastructure systems. By simulating interactions among transport, energy, and water networks, they help identify critical failure points and support more effective planning and real-time response during extreme events (Jin & Zhu, 2024; Wang et al., 2024). A SoS approach allows decision-makers to anticipate cascading failures and vulnerabilities, strengthening urban resilience.

For future development, active collaboration with communities and stakeholders during the planning and implementation of UDTs is crucial. Clear communication of benefits and proactive efforts to address privacy and security concerns can enhance public confidence and encourage participation. Policymakers should also prioritise equitable access to UDTs technologies by supporting skills development and capacity building. Finally, establishing transparent governance frameworks for data management and ensuring ethical, responsible use of data will be vital for maintaining public trust and promoting widespread adoption.

6. Conclusion

The advancement of UDTs signifies a transformative shift from conceptual development to real-world implementation, offering unprecedented opportunities to enhance urban resilience, efficiency, and sustainability. This review examines how UDTs are emerging as a powerful tool for managing CI and mitigating climate-induced risks, enabled by progress in IoT, data modelling, simulation, and advanced analytics.

Our focus on CI as an interconnected SoS underscores the necessity of understanding and managing cross-domain interdependencies. Through the layered framework proposed in Figure 1, we illustrate how digital models can account for cross-sectoral data fusion, system-level simulation, and coordinated policy intervention. We also foreground the growing role of citizen participation in the UDTs lifecycle. The proposed framework incorporates participatory sensing, community-sourced data, and the use of deliberative tools and interaction platforms, facilitating two-way engagement between digital models and real-world users.

The review also highlights persistent technical, institutional, and social challenges in implementing UDTs. As its adoption grows, there is a pressing need for strengthened collaboration to manage interdependencies, ensure interoperability, and foster inclusiveness. Addressing these barriers demands coordinated action across disciplines, sectors, and governance levels. By integrating insights from both academic and practice-based sources, this study offers a holistic foundation for advancing UDTs approaches that are technically robust and socially responsive, bringing the field closer to resilient, inclusive, and anticipatory urban systems.

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Conflict of Interests

The authors declare no conflict of interests.

Supplementary Material

Supplementary material for this article is available online in the format provided by the authors (unedited).

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