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Developing Human-Centered Urban Digital Twins for Community Infrastructure Resilience: A Research Agenda

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Abstract

Urban digital twins (UDTs) have been identified as a potential technology to achieve digital transformative positive urban change through landscape architecture and urban planning. However, how this new technology will influence community resilience and adaptation planning is currently unclear. This article: (1) offers a scoping review of existing studies constructing UDTs, (2) identifies challenges and opportunities of UDT technologies for community adaptation planning, and (3) develops a conceptual framework of UDTs for community infrastructure resilience. This article highlights the need for integrating multi-agent interactions, artificial intelligence, and coupled natural–physical–social systems into a human-centered UDTs framework to improve community infrastructure resilience.

Keywords

digital twin, human-centered, infrastructure resilience, urban planning

Introduction

Global population projections forecast rapid urbanization in already vulnerable coastal areas (Neumann et al. 2015). Increasing coastal development exposes more people and infrastructure to both short-term and long-term natural disasters and climate change threats. For example, increasingly frequent extreme weather events have caused exponentially growing flood damages and other secondary hazards in flood-vulnerable communities, leading to catastrophic economic losses and infrastructural failures. Natural hazard risks and associated losses on infrastructure systems can only be understood and reduced through integrated investigations across multiple disciplines, cultures, and international boundaries (Neumann et al. 2021; Strandsbjerg Tristan Pedersen et al. 2021b).

Coastal communities can largely reduce hazard vulnerabilities and achieve long-term socially and environmentally intelligent development through science-informed adaptation planning activities (Davlasheridze et al. 2021). The development of smart cities has enabled the collection and availability of various physical, cyber, and social sensing data to support planning activities (Allam and Jones 2021; Kudva and Ye 2017). Analysis and evaluation of modern cities increasingly requires integrating these multidimensional data sources. For example, the availability of location-based services through urban sensing technology has shaped urban life as well as planning activities toward collaborative efforts between planners, the public, scientists, and the business communities (Evans-Cowley 2010). As a result, urban planning and management is changing from a reliance on managing urban growth to also understanding interactions between natural, physical, cyber, and social systems within cities. Urban digital twins (UDTs) provide a platform for supporting this transformation (Batty 2021).

The concept of UDTs originated from the digital revolution nearly two decades ago (Bostrom 2003). Although there is a lack of a consensus definition of a digital twin, it is generally believed that a UDT is a virtual representation of an integrated urban system, where the digital built environment serves as the platform to link physical, cyber, and social infrastructure systems and to provide a data-driven decision-making platform through a variety of models and methods (Rong et al. 2020; Tao and Qi 2019; Yoo 2013). In this article, we review the subset of UDTs that we believe to be most beneficial for increasingly vulnerable coastal communities, focusing on UDTs that support community resilience and adaptation planning.

UDTs benefit coastal communities by providing three-dimensional (3D) visualization, augmented reality (AR), virtual

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city model, and prediction capabilities, among others. A digital twin infrastructure platform can enable both ubiquitous networked immersion and virtual human teleportation to any location and scale of the built environment (Park et al. 2019). This will assist planners in solving the compound societal and environmental challenges and designing needs while simultaneously allowing for augmented and virtual interaction. For example, the capabilities to accurately visualize and dynamically update the conditions of community infrastructure enable local residents to create changes in their neighborhoods and assist with solving existing and future issues (Ham and Kim 2020). Simultaneously, the ability to model climate change-based scenarios and test their impacts on the built environment through quantitative measurements offers unprecedented capabilities for evaluating the hyper-local effects of projected climate change phenomena, such as sea-level rise (Han, Zhao, and Li 2020a, 2020b). In coastal regions, such capabilities associated with UDTs have tremendous possibilities for informing and improving coastal hazard preparedness and recovery. Therefore, a digital twin of the coastal infrastructure system will contribute to the development of smarter infrastructure, in which human, institutions, and environments are harmoniously and sustainably considered (Batty 2018b). As a result of synchronizing a range of planning activities, a decision-support UDT will facilitate the reduction of planning conflicts, improvement of infrastructure system performance, and more effective use of social and environmental resources (White et al. 2021).

The integration of human-centered resilience into UDT development promotes the concept of human-centered UDTs; this research is, however, still in its inception compared with the study of aggregated community resilience (Batty 2018a). Therefore, it is important to understand the progress and challenges of the digital twin. To fill this gap, this article synthesizes existing research on UDTs and develops opportunities for human-centered UDTs in infrastructure resilience modeling and hazard mitigation planning. Our objectives are: (1) to synthesize existing research on UDTs for smart city management through a scoping review of the relevant literature; (2) to identify challenges and opportunities for human-centered UDTs in community adaptation planning; and (3) develop a conceptual framework of UDTs for community resilience.

This article is organized in the following order: Scoping Review of UDT Research section presents a scoping review of UDT literature. Then, Challenges in UDT for Community Resilience Planning section highlights and discusses the challenges in developing and deploying UDTs for coastal community resilience planning. Opportunities from Human-Centered Digital Twins for Infrastructure Resilience section builds on these challenges and discusses the opportunities for applying UDTs to increase coastal community resilience; here, we also introduce the human-centered UDT as a key feature. Finally, Conclusion section concludes the article with a summary that highlights our key recommendations for future work on UDTs for community resilience.

Scoping Review of UDT Research

Because the concept of a UDT is currently ill-defined and related studies are both highly diverse and vary, a full systematic review of UDTs is not appropriate at this stage. Instead, we conduct a scoping review to help clarify the definition of a UDT and identify related research gaps.

Review Methodology

This review will inform urban resilience researchers and practitioners about the data, methods, and tools used in UDTs.

Our approach follows a four-stage analysis framework to identify and filter the current literature, including a literature search, a screening process, a selection of literature, and an analysis of selected literature (Jelokhani-Niaraki 2021; Prasara-A and Gheewala 2017). The reference source of this research was obtained from the web of science. We conducted a bibliographic analysis and review from both quantitative and qualitative perspectives. The existing publications on UDTs were retrieved from the Web of Science by keywords. We used “urban planning” or “city planning” combined with “digital twin” or “3D city model” to filter existing planning-related research in the first step. Second, a list of keywords was utilized to filter planning literature returned from step one to identify publications mentioning UDT techniques: [“urban simulation,” “augmented reality,” “virtual reality,” “artificial intelligence,” “Internet of things” (IoT), “GIS”]. Any literature mentioning at least one keyword was identified as relevant to this review. This process resulted in a total of 91 selected publications.

A co-occurrence network was used to visualize connections between keywords from the selected publications (Figure 1). Among these publications, UDTs have been defined as 3D semantic city models or digital representation of IoT for the next generation of smart city systems (Gong et al. 2017; Howell et al. 2016; Xuan 2015). Datasets used for building UDTs include 3D point clouds data, traditional geospatial data, and social sensing data (Fan, Jiang, and Mostafavi 2020). UDT models can be mainly classified into two categories: 3D city model and dynamic spatial–temporal urban analytics systems. The 3D city models are mainly built on 3D point clouds of buildings, infrastructure, and geospatial data. They are also primarily used for 3D simulation of the urban environment, collective decision making, and planning. Dynamic spatial–temporal urban analytics systems are built using real-time sensing data, two dimensional (2D) geospatial building, and infrastructure data (Bradley 2015; Zhao et al. 2021). They appear to be mainly used for real-time infrastructure management, evidence-based decision making, and planning (Forster et al. 2015; Kunze 2016; Xuan 2015). While 3D city models are often used interchangeably with UDTs, they are not the same. UDTs emphasize the simulation power of computer models, while 3D models are simply a visualization method. Although a 3D city model is a subset or can be a type of UDT, we review 3D models related to UDT development in this manuscript to showcase what has been done.

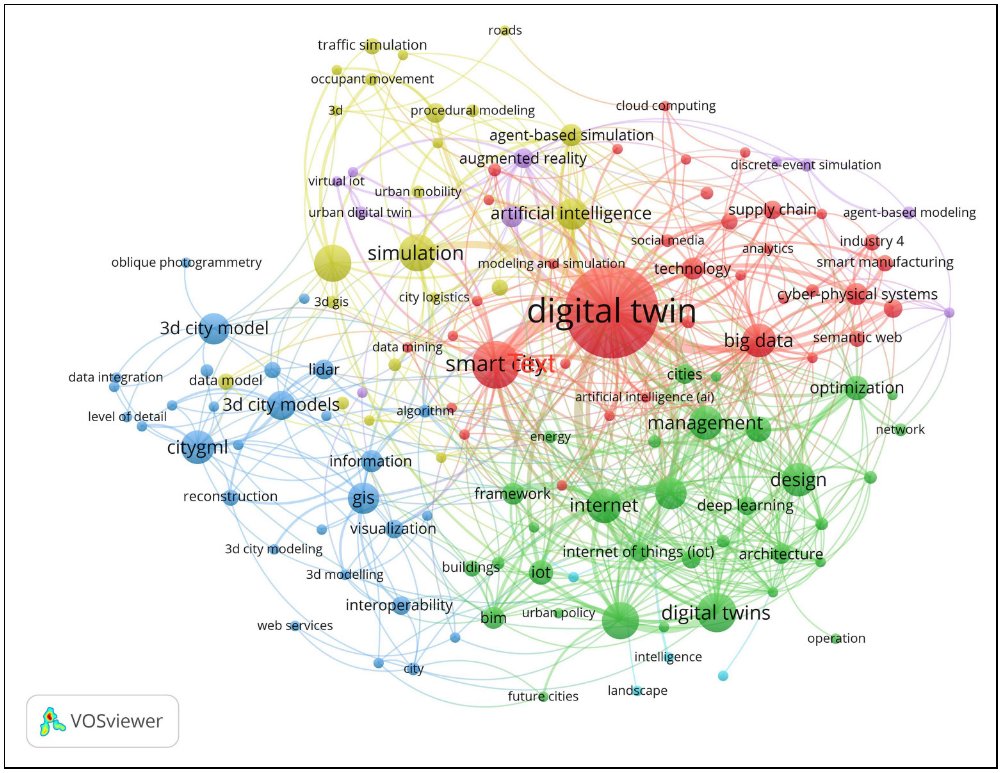

Figure 1. The co-occurrence network based on high-frequency keywords.

Defining UDT

A UDT is normally defined by considering the meanings of its three constituent terms: (1) "urban," which suggests a focus on relatively dense or built-up, city-like environments; (2) "digital," which suggests data storage and analysis in a computer-readable format; and (3) "twin," which suggests that the digital model is similar or even identical to the urban area of interest. Some definitions also designate that the digital twin interacts with the real system (e.g., the built environment) in real time (Tomko and Winter 2019).

The greatest challenge in defining UDT is determining how tightly it must be coupled with the real urban environment. Some investigations consider software for modeling urban environments as the prototype or even fully fledged UDTs. For example, White et al. (2021) describe a UDT as a model developed to characterize key features of socioeconomic systems and physical environments through the integration of interdependent social and infrastructural datasets into a unified urban modeling system (White et al. 2021). However, because such models are an abstraction or a simplification, they can hardly be the same as the real system, leading to some debates as to whether they qualify as UDTs. For the purpose of this article, we do not emphasize how far a model must be linked to the living environment to qualify as a UDT, but instead focus on recent applications of the UDT concept in the urban planning context. Specifically, we focus on those papers that are relevant to UDT and coastal resilience planning. We believe this much narrower and topic-specific scoping review of the digital twin concept has a strong potential to benefit practice in the increasingly important area of community infrastructure resilience.

In the community mitigation planning context, UDT technologies often benefit stakeholders by providing 3D modeling, VR, and urban simulation functions. The 3D city visualization models can provide planners, architects, and community participants with almost real disaster experiences for a proposed structure or site plan before it is built. The 3D city model is a long-established term on which there are a large number of publications (Ketzler et al. 2020). Similarly, VR coupled with urban simulation allows planners to interact with environments in an immersive, first-person view before designs are implemented. In the context of community adaptation planning, UDTs also provide important approaches for gaining deeper insights into community resilience through the simulation of multidimensional socioeconomic consequences of climate risk (Francisco, Mohammadi, and Taylor 2020; Ye et al. 2021). Since UDTs often facilitate and incorporate these modeling, visualization, and simulation functions, we include these terms in our scoping review to help narrow our search results for UDT literature to articles that would be most likely to contribute to community infrastructure resilience.

UDT Data

Geospatial data, such as earth observation from remote sensing, geographical information systems (GIS), building information modeling (BIM), and real-time sensing data, need to be properly managed in UDT applications to connect data acquisition, data modeling, and data visualization. Without effective management of the growing size of geospatial data, planning for complex resilience issues in coastal communities cannot be achieved, as the coastal community is a complex system where ocean and continent meet. The resulting interactions among natural, social and economic systems must be described across multiple dimensions, requiring significant resources for advanced data acquisition and management, modeling, and visualization.

UDTs aim to facilitate monitoring of infrastructure, buildings, and the landscape of the built environment (Hor, Jadidi, and Sohn 2016). Emerging sensor technologies and IoT deployments enable real-time data collection and monitoring of urban systems through UDTs. Big data and Artificial Intelligence (AI) help ensure that useful information from the enormous amount of data can be easily extracted (Rathore et al. 2021). Nevertheless, compared to the application of these techniques, the integration of multiple datasets into a UDT framework to support decision making is quite challenging. In our review, we found that UDTs mostly use 3D data to represent the surface of urban environments, with other data types mentioned much less frequently. As an important data source for BIM, point cloud data from terrestrial laser scanning is also an important data source in digital twin modeling. Additionally, remote sensing data from satellite imagery provides essential dynamic semantic information of city spaces and landscapes. Due to different formats and representations of GIS and BIM data, the fusion of these two data types is necessary for applications in UDTs (Ketzler et al. 2020). For example, City Geographically Markup Language (CityGML) and its newer formats such as JSON (CityJSON) or database (3DCityDB) are examples of 3D city model standards to describe building geometries (Ledoux et al. 2019). Those standards allow for creating a hierarchical data structure that optimizes massive 3D data for visualization purposes. These geospatial data include point clouds, imagery, and 3D buildings.

A common way to create a 3D city model beyond the 3D buildings is through combining 3D objects with 2D city maps and two-and-a-half dimensional (2.5D) geodataset (Ledoux et al. 2021); 2.5D digital terrain datasets are usually derived from 2D/3D geodatasets (e.g., see Pepe, Fregonese, and Crocetto 2019; Liang et al. 2016). However, 3D city models constructed based on 2.5D datasets may lose some valuable information from 3D point cloud data. For instance, height information from 2.5D city models is usually from interpolation rather than 3D measurements. To fill this gap, Lehner and Dorffner (2020) presented a concept to transform geodatasets in Vienna into a geodigital twin, which could serve as a geodata hub to process all relevant datasets to facilitate the construction of a city information model. To achieve this, they proposed a modified level of detail specification based on the datasets available for Vienna. Relatedly, Xue et al. (2019) created a digital twin by developing an unsupervised learning algorithm based on invariant cross-section characteristics of objects in 3D point clouds and clustering 3D LiDAR point clouds into city objects.

UDT Methods

The 3D city models are essential for visualization and situational awareness purposes in UDTs (Biljecki et al. 2015). Nevertheless, constructing a 3D city model is very time-consuming and tedious; this challenge is frequently mentioned in UDT-related articles. To facilitate this process, Ledoux et al. (2021) developed a "3dfier," which can automatically generate buildings, roads, overpasses, trees, and other objects in 3D city models. Other tools, like CityEngine, support urban design by showing changes in the planned urban environment (Aboushal 2021). Cesium is another open platform for 3D geospatial data applications, which transforms multiple types of data into 3D models. Regardless of how they are generated, the 3D models are usually combined with other techniques—including AI, big data analytics, and sensor technology—to build UDTs. For example, to integrate GIS and VR to enhance public participation in planning, Rzeszewski and Orylski (2021) uses VR to visualize and explore heterogeneous 3D datasets for urban planning.

The simulation models, which traditionally have been studied extensively both in 2D and 3D space to inform policymaking, will be a core part in UDT applications for community planning supported by the increasing computing power. For example, the agent-based model (ABM), which reveals human behaviors and their interactions with the built environment, is an important approach that can be integrated in the virtual environment. The 3D environments have the potential to create a better sense of place for agents to act and interact with the advancement of 3D visualization and 3D model (Cheliotis 2021; Crooks, Hudson-Smith, and Patel 2011). Compared to 2D, 3D can better mimic real-world environments with minimal information loss and simulate the interactions between humans and space. With a growing computation power, several recent works have built 3D ABMs to simulate human activities in urban space. Cheliotis (2020) simulated human spatial behaviors in public parks, considering agents' visions empowered by a 3D ABM. Lenfers et al. (2021) integrated real-time data from IoT sensors into ABM simulation as a digital twin of its real-world counterpart to investigate how real-time data can improve predictive capabilities of ABM in studying active travel behaviors. Other microsimulation models, like micromobility simulation models, can also be applied to examine local planning policies in a more realistic model environment (Han, Zhao, and Li 2020a, 2020b). For example, Kořínek, Tázlar, and Štekerová (2021) exported 3D building information from BIM and created a simulation environment in an ABM platform, toward building a digital twin model for urban infrastructure planning. As such, the 3D ABM framework is anticipated to contribute to the field of architectural and urban design.

An UDT can provide an approach to integrate various capabilities of 2D and 3D models, such as data integration, visualization, AI, or simulation. For example, in Lenfers et al.'s (2021) application, a 2D ABM based on the Multi-Agent Research and Simulation (MARS) open-sourced software, was linked with

IoT technology to design a symbolic simulation environment based on the interactions between a simulation environment and its physical counterpart (Glake et al. 2017). UDT based on domain-specific and application-specific information extracted from multiple Machine Learning (ML)/AI tools and 3D point clouds can be used in many fields, such as environmental monitoring, disaster management, and urban planning (Döllner 2020).

UDT Applications

Digital twin applications originated in the aerospace sector and manufacturing industry. Recently, applications in urban environments have gone beyond geometry and information modeling and been applied in smart cities and society, systems engineering, healthcare, utility processes, and robotics for their advantages in improving assurance of system management (Pedersen et al. 2021a). From an urban planning perspective, UDTs have the potential to leverage understanding of cities through digital transformation and integration of various state-of-the-art technologies and open new opportunities to collective planning and decision making. It is widely agreed that UDTs is a virtual pairing of the physical world, which allows for data analysis and monitoring of urban systems (Mohammadi, Taylor, and Ieee 2017). A UDT system can detect issues in urban systems before they occur, identify possible substantial consequences in the physical world, or be used as an interactive tool to assist participatory decision making in city planning and geodesign (Li and Milburn 2016).

UDTs have been successfully applied in many cities globally. Some of the well-known UDT applications include the smart city platform of Helsinki (Ruohomäki et al. 2018), the 3D city model of ETH Zurich (Schrotter and Hürzeler 2020), and virtual Singapore (Gobeawan et al. 2018). These comprehensive UDTs all claim to help improve community infrastructure resilience by testing alternative measures to prepare for extreme events. Li, Yu, and Shao (2021) described several additional examples of how digital twins may facilitate construction of smart cities by mapping physical complexities in the real world to virtual systems. The authors presented five digital twin applications based on a smart urban GIS platform, which includes a smart city operation brain, an intelligent monitoring system, a smart traffic management system, a public epidemic control system, and a smart flood monitoring system. The UrbanSim Inc. developed their platforms for affordable housing (Waddell et al. 2020) and transportation planning (Yedavalli et al. 2021).

Other studies developed UDTs focusing more on the integration of heterogeneous datasets into multilayer systems and using ML/AI techniques to create geospatial platforms based on IoT and animation software. Lu et al. (2020) presented a multilevel UDT for building and infrastructure maintenance. White et al. (2021) designed and built a digital twin for flood evacuation planning in Dublin, Ireland. The designed UDT included layers of terrain, buildings, and infrastructure, mobility layers, as well as digital and virtual city layers. It enables multiple simulation applications, including flood simulation, and crowd simulation. These results illustrate potential strengths of UDTs to improve engagement of citizens on collective planning decision making and support natural disaster management. In addition, the virtual Singapore project provides a smart city platform to collect real-time data through IoT sensors for analyzing evacuation models, which enables city planners to optimize evacuation plans and minimize possible structural damage and loss of life in urban areas (Ford and Wolf 2020).

A UDT can facilitate human–environment interactions as well. Dembski et al. (2020) developed a prototype of UDTs for participative and collaborative planning and design processes using a mixed approach in Herrenberg, Germany. A 3D model of the built environment was built into the digital twin platform together with space syntax-based street networks, an urban mobility simulation model, and a pollution simulation model. Ahn et al. (2020) proposed a digital twin city model for effective risk-informed decision making in urban planning. In addition, a recent 3D UDT study in the Computer-Aided Virtual Environment enabled an updatable model along with interactive and immersive visualization, which aims for robust prediction of future patterns of potential risks based on physical vulnerability in urban areas (Kim, Kim, and Ham 2019). The updated UDT model allows analyzing the spatio-temporal information of physical vulnerability, which supports city decision makers to predict primary and secondary damage incurred by infrastructure failure (Ham and Kim 2020). Those UDTs analyze "what if" scenarios with the increased visibility into a given hazard event.

Challenges in UDT for Community Resilience Planning

Although UDTs show a potential to help enhance community infrastructure resilience, challenges exist in constructing UDTs for community adaptation planning. Identified challenges of digital twin development at different stages of digital twin modeling include data management, visualization, and integration of subsystems. Carvalho and da Silva (2021) evaluated the limitations of digital twin-based systems research from a sustainability perspective, and found several barriers in digital twins, including unclear understandings of the potential benefits of digital twins and needed improvements to technical implementation of digital twins in the context of data sensing and analytics, visualization, information modeling, and simulation. As such, this section details three critical challenges in complex decision making, digital twin visualization, and social–physical systems integration when developing UDT systems for promoting community resilience.

Insufficient Support for Complex Decision Making

Developing a 2D map and 3D virtual environment are two fundamental steps in the construction of digital twin modeling (Dembski et al. 2020). Further, the application of AR and VR in digital twins could improve planning design by facilitating a transition from expert driven decision making to collective decision making. However, several challenges must be resolved to achieve UDT modeling for community resilience. Most existing UDTs are ad hoc platforms for customized purposes. There is a lack of flexible UDT platforms to integrate multiple datasets from different sources for a variety of purposes. Existing tools, such as CityEngine, cannot fully provide powerful data management and real-time interactive analysis in UDT applications. This limits the application of UDTs in urban planning and related fields.

Risk-informed decision-making efforts in coastal communities involve both gathering and sense-making of information before/during/after an incident. Many local planning agencies already have systems to gather information about major critical infrastructures. Examples include vulnerability examination and monitoring systems regarding which bridges are likely flooded and which need to be closed for further inspection (Ham and Kim 2020). However, in adaptation decision making, urban planners and policymakers often involve in-depth analysis and knowledge interpretation. For example, although infrastructure damage from flooding can be estimated based on historical datasets, it is not clear how to build infrastructure to accomplish resilient flood adaptation—especially when coupled with a changing climate (Fereshtehnejad et al. 2021). Understanding the multiplier effects of natural hazards on infrastructure systems requires measuring dependencies between social and physical systems (Arrighi, Pregnolato, and Castelli 2021).

Infrastructure systems (such as transportation, communication, sewage and water, and electricity systems) play vital roles in the security, economy, and public health/safety of a society. The interdependence between critical infrastructure systems creates a unified urban system. Due to the interdependence between infrastructure systems, decisions regarding infrastructure resilience require a more thorough understanding of system-wide urban resilience. Existing data-driven models using AI could improve prediction accuracy given historical records. Nevertheless, future cities cannot be predicted (Batty 2018b). The current 3D models designed for visualization are insufficient to support complex decision making within the urban nexus of human and natural systems for situations with rapid socioeconomic and environmental changes. Global climate change would result in rapid deterioration of the local environment, which may cause more unprecedented natural disasters (Strandsbjerg Tristan Pedersen et al. 2021a). Technology evolution, such as the adoption of autonomous vehicles, also produces disparate socioeconomic changes in urban infrastructure systems (Zhang and Guhathakurta 2021). It is challenging to make long-term infrastructure investment decisions under high uncertainties of the coupled natural and social systems.

Lack of Engagement and Unclear Goals for Participatory Urban Planning

Coastal communities usually have diverse populations, demanding consideration of environmental justice and other complex needs. A participatory planning approach is now considered fundamental to all community planning efforts, especially in highly demographically diverse communities. It is essential that these participatory planning efforts are also inclusive. The concept of UDTs for participatory planning relies on the integration of dynamic data and information in decision making coordinated by IoT systems. Nevertheless, most existing datasets for UDT development do not reflect dynamic features in urban systems. Timely and accurately capturing socioenvironmental changes in cities through social sensing in UDT for planning practice needs to be further explored. Second, although 3D city models could enhance visualization of the urban spatial–temporal information, current UDT is not convenient to use 3D city models to simulate urban system changes. It can be challenging to integrate data from various sources and efficiently visualize different formats of data within a single platform in terms of both computational power and software integration. Therefore, more flexible UDT applications for a variety of planning purposes are urgently needed. Third, current UDT platforms focus more on the development of 3D urban environments. However, few studies have demonstrated how to integrate existing 2D planning models into UDT platforms. These 2D models, such as land-use change and transportation demand models, are essential tools for planners to study future urban landscape and transportation planning. Traditionally, these models are calibrated and tested using expert knowledge or local travel survey data. It is not currently clear how UDTs could utilize social sensing data to improve existing planning models through multidimensional visualization.

Research Gaps in Integrating Social–Physical–Natural Systems to Tackle Climate Change Impacts

To tackle challenges in coastal resilience from natural disasters, it is crucial to incorporate resilience models to answer "what if" questions for community design and planning purposes. Microsimulation models with socioenvironment interactions on the individual level can play a role in simulating human behaviors under social and environmental changes and examining alternative urban designs or land-use plans to improve community infrastructure resilience in sustainable development. Existing research on UDTs focuses more on the software side of creating virtual digital models of the physical environment, rather than on human-centered behavior analysis for participatory urban planning and policymaking. Given the highly diverse and heterogeneous information in resilience studies, new studies need to fill the gaps between 3D city model and participatory urban planning, including exploring how integrating geodesign and agent-based simulations within digital twins may meet this need. Specifically, in addition to simulating how disasters and climate changes can threaten physical urban systems, UDTs should enable decision makers to foresee the cascading impacts of climate hazards on social resilience. For instance, based on the simulated or observed building/road damages caused by a flood event, UDT models can infer the potential impacts of damaged buildings/roads on the accessibility to local business, social capital, public health, and education systems.

Opportunities from Human-Centered Digital Twins for Infrastructure Resilience

Integrating Multisourced Data Analytics for Infrastructure Data Science

UDTs can facilitate data-driven decision making for infrastructure management by connecting different datasets and applications (Arrighi, Pregnolato, and Castelli 2021). In this context, UDTs' abilities to inform infrastructure-related policy decisions could provide a timely and viable approach to enhancing the resilience capabilities of coastal people and communities. Particularly, human-centered and social-centered resilience studies built on infrastructure data from crowdsourcing, remote sensing, and social sensing could strengthen the science and practice of infrastructure resilience through community-driven capacity-building activities. These activities account for the social, cultural, environmental, and health factors of people and infrastructure in vulnerable areas that influence communities' ability to thrive (Cai et al. 2018; Zou et al. 2018).

Urban infrastructure systems, including physical, cyber, and social infrastructure, are fundamental to undergird urban economies and play an essential role in maintaining the proper functionality of cities (Nochta et al. 2021). As Simpson (2001) mentioned, the ability to analyze multisource information is one of the challenges in urban planning. Data-driven modeling and analysis via UDTs can help identify people and places that are most physically and socially vulnerable and thus minimize environmental and economic disruption to people and communities (Ham and Kim 2020). Given that the size of available physical, cyber, and social infrastructure data relevant to disaster resilience has been growing at an exponential rate, there is an imminent need for leveraging infrastructure resilience through more effective data management and applications (Zhou et al. 2019). Although sophisticated models have been applied individually to assess the vulnerability of a single place (e.g., Galveston, Texas; see Fereshtehnejad et al. 2021), such models are not easily extensible to other places and datasets. Research on how to integrate heterogeneous data, algorithms, and models efficiently for complex urban policymaking and resilience decision making is needed to fill this gap.

Data management is the core component of UDT modeling. Although many robust, reliable, free, and easy-to-use data management systems exist (including PostgreSQL, Oracle, and SQLite), the development of UDTs requires utilizing data from heterogeneous sources (Fan, Jiang, and Mostafavi 2020), including real-time sensors, geospatial datasets, and BIM systems for urban terrain, land use, and infrastructure data (among others). Conducting read/write operations on these datasets can be time or resource consuming. As a major technique to achieve infrastructure resilience in smart city construction, the development of UDTs needs to efficiently support multisource data fusion, state-of-the-art algorithms and models for data analytics and provide a multidimensional reference for urban studies and planning.

Recent technological developments provide opportunities for UDTs to more efficiently meet the needs for data management and modeling. Cloud-based systems with distributed data management and high-performance computing power can facilitate UDT data fusion and analysis (Zhang and Guhathakurta 2021). The availability of distributed, local, up-to-date, and free social sensing data, such as Geo-tagged Twitter and Foursquare, together with infrastructure and spatiotemporal data from ubiquitous sensors and social sensing will significantly help meet the data needs to build human-centered UDT. In addition to cloud-based solutions, redundancy processing or downscaling may also be needed in study areas based on large datasets, since it can be challenging to conduct a model-based simulation of the entire city in a short time and within a 3D environment, especially if considering future uncertainties from climate change and policy interventions. A multilayered data management system within UDT models is necessary to achieve this (Tao and Kang 2021). The recent development of ready-to-use AI tools also provides cutting-edge techniques and models to tackle challenges in urban infrastructure systems (Homainejad 2015). These tools and models often require data fusion of large, heterogeneous datasets (including from ubiquitous urban sensors and public data sources, such as socioeconomic data from census surveys) to calibrate and validate the model structure and fine-tune model parameters. So UDTs would provide a platform for automating AI and big data analysis for infrastructure resilience (Anejionu et al. 2019; Kudo, Akitomi, and Moriwaki 2015).

Finally, because the top-level design of UDT systems plays a fundamental role in data management and sharing objectives, knowledge graphs may also be useful in UDT development. The development of digital twin data and application system architecture needs to consider the role of each subsystem and engagement between different subsystems. To make smart city systems more interoperable and explainable, knowledge graphs with semantically linked information on urban infrastructure systems, communities, and the built environment, could be used to create a linked framework for sharing data and support various purposes of infrastructure resilience. A knowledge graph of a digital twin for coastal resilience could aid in understanding infrastructure/subsystem dependencies and improving knowledge from datasets and subdiscipline domains (such as landscape, transportation, buildings, and ecology) for planning and purposes. For example, Akroyd et al. (2021) developed a digital twin based on the knowledge graph to support intelligent design without affecting the physical world.

Integrating Multi-Agent Interactions for Coastal Risk Communication

Integrating scientific knowledge related to social and physical interactions will facilitate coastal risk communications in hazard mitigation. Although the human capacity to understand and manage climate risk is increasing over time, the path to integrating scientific knowledge and social learning into risk management has been relatively slow. For example, recent studies found that, although many communities across the United States have a much higher flood risk under sea-level rise than the Federal Emergency Management Agency has estimated, many residents in these communities lack understanding of these risks and oppose updating flood risk maps due to possibly higher insurance rates (Flavelle et al. 2021). Similarly, long-term decision making on urban development and infrastructure investment can be challenging without a comprehensive understanding of and preparedness for climate change and sociotechnical evolution. Infrastructure resilience and efficient risk management need to respond fast to potential risks within complex socioenvironmental systems. Up-to-date scientific knowledge needs to be timely delivered to public and private stakeholders through virtual simulation and scenario planning to enhance disaster response and collective decision making. UDT platforms that facilitate awareness and understanding of complex and emergent risks are, therefore, needed to enhance coastal risk management through more resilient decision making.

Through customizable geospatial tools, a UDT platform could represent an integrated social and human-centered infrastructure system for infrastructure resilience. Urban micromobility simulation models have been widely used to examine the vulnerability of transportation systems under disasters and adverse climate conditions (Han et al. 2021). The vulnerability of urban infrastructure systems has also been widely examined under climate change impacts (Neumann et al. 2021). However, applications of these research outcomes to support planning discussions and decision making are still rare.

The integration of up-to-date social and physical infrastructure data, vulnerability, and resilience assessment models with scientific information into the digital twin framework will substantially facilitate coastal risk communications in infrastructure management. Up-to-date science-informed climate adaptation scenarios and their potential effects on infrastructure resilience need to be analyzed and visualized in an ad hoc digital environment tailored to meet stakeholders' needs. In one such effort, a research team studied how flood models may be combined with economic loss models to create interactive tools exploring scenarios for local to national economic impacts of a hurricane storm surge in Galveston Bay (Yildirim and Demir 2019). Results showed that the complexity and design of tools used to visualize the scenarios should be adaptable to the varying needs, expertise, and abilities of different user groups (Retchless et al. 2021).

To better engage stakeholders, UDT platforms should be similarly adaptable in their design—including through the use of multiple presentation formats, such as interactive maps and AR/VR techniques. This diversity of presentation formats will encourage collective decision making through public participation and improve social learning on infrastructure risk and community vulnerability. Such tools and platforms need to help users place hazards events and exposure levels in a more local and meaningful context, thereby increasing user engagement (Bolton et al. 2018). The ability to personalize and contextualize hazards may be particularly important when studying infrastructure risk under complex hazards (i.e., those with long-time scales, multiple scenarios, lagged responses, and multivariate human–environment interactions) that create wicked problems for risk communication for infrastructure.

Integrating Coupled Natural–Physical–Social Systems for Landscape Architecture

Landscape architecture is the field that deals with the design, planning, and management of natural and built environments (Li and Milburn 2016). Traditionally, changes in local climate conditions and social and human elements in infrastructure systems have been rarely considered in landscape dynamics. Advancements in location-aware, communication, and mobile technologies during the past two decades, as well as improved understanding of natural environmental change processes, have transformed the focus and use cases of landscape architecture, shifting it from mostly site-scaled static assessments to community-scale or regional-scale assessments of spatial, temporal, and dynamic relationships that integrate human behaviors across multiple environments.

Although advances in studying community vulnerability to hazards over the past few decades have enabled improved landscape planning for community resilience, given the difficulty of integrating multiple GIS, BIM, and CIM (Civil/City/Construction Information Modeling) into a single UDT platform, most existing studies focus on building a digital twin environment through digital maps rather than applying landscape or urban planning approaches. Existing urban simulation models create an opportunity to extend UDT platforms beyond current digital maps-based approaches to support analyses that include interactions between land use, transportation, the economy, and the environment (Han and Peng 2019).

Further, silos within the design, social, and engineering sciences as well as yawning gaps between research and practice have made sustainable and equitable development difficult (Ye et al. 2021). Coastal risk communications require decision makers to better identify the potential risk of diverse stakeholders, connect with stakeholders using up-to-date information, and inspire stakeholders to make risk-wise decisions under adverse conditions. Microsimulation modeling results could indicate adaptation benefits under different public–private adaptation scenarios and future climate change projections on multiple spatial–temporal scales (Han and Peng 2019). Digital twin platforms need to integrate urban simulation models in evaluating adaptation plans and visualizing results. The digital twin's integration of these models should emphasize facilitating decision makers' understanding and interpretation of scenario simulation results under the compounding effects of urban development and climate change (Small and Xian 2018).

Critical to risk-informed decision making in coastal communities before/during/after an incident is the gathering and sensemaking of information. By enabling coupled socioenvironment interactions in the virtual system, human-centered UDT

Table 1. Challenges and Opportunities for Urban Digital Twins.

Challenges	Opportunities
Insufficient support for complex decision making	Integrating multisourced data analytics for infrastructure data science
Lack of engagement and unclear goals for participatory urban planning	Integrating multi-agent interactions for coastal risk communication
Research gaps in integrating social–physical–natural systems to tackle climate change impacts	Integrating coupled natural–physical–social systems for landscape architecture

platforms could function as an interactive laboratory for future cities by incorporating landscape architecture design into infrastructure systems based on justified "what if" assumptions. Various physical, socioeconomic and natural climate factors could be considered in the design and planning of the built environment and provide collaborative forms of design through multiple techniques and models. The advancement of built environment science through the integration of digital and social elements within the UDT will create diverse simulated built environment scenarios (Liu et al. 2017). The linkage of these processes to human-centered infrastructure resilience through community engagement will also provide necessary, localized information to feed into the model.

Since there exists no readily available digital twin model and source of information for up-to-date "local data related to vulnerability and associated potential cascading risk assessment, a readily available UDT for infrastructure resilience will allow us to better understand the current state of communities by quickly identifying up-to-date potential risks for effective risk-informed decision making while avoiding potential damage to the real urban systems (Akroyd et al. 2021). Researchers still need to fill this gap in UDT modeling to understand the high-resolution, contextualized spatiotemporal information of local vulnerability, including its relationship to physical, cyber, and social infrastructure widely distributed within coastal communities affected by hazards. Challenges in UDT for Community Resilience Planning section, and Opportunities from Human-Centered Digital Twins for Infrastructure Resilience sections are summarized in Table 1.

Conclusion

This article presents a review of the research on UDTs, identifies crucial challenges in building UDTs, and proposes a research framework for UDTs for infrastructure resilience. Given the range of adaptation planning goals and constraints, coupled with uncertainty as to when the actual planned activity will take place, the development of a standard operating procedure that complies with local needs through engagement poses another challenge. Further, modeling the interactions and dynamics between and within natural and social systems at high spatial–temporal resolutions can be difficult due to a lack of accurate data, unknown mechanisms, dynamic changes in the built environment, and intensive computation costs. More informed decisions and better affordances for interagency coordination may lower the costs of maintaining and using the coastal infrastructure system, which can contribute novel understanding and provide innovation in addressing infrastructure challenges. The UDT platform will allow residents, planners, and decision makers to communicate, monitor, project, and track the impacts of multiple infrastructure management scenarios and activities and assess potential social and economic impacts of various construction, maintenance, and alternatives (both current and planned).

In order to fully benefit from the UDT, this study suggests that future UDT for coastal infrastructure resilience needs to integrate multisourced data analytics, human-centered infrastructure risk assessment, 3D urban visualization, and AI into the same framework. The benefit of developing 3D UDT based on IoT and web technologies will provide flexible and ready-to-use platforms for decision makers and planners for resilience planning. The use of emerging ML and AI technologies could effectively develop data-driven tools for situational risk awareness. The human-centered digital twin framework enables multiple infrastructure resilience services, including emergency responses, risk identification, and adaptation planning and decision making. UDTs facilitate interdependencies between infrastructural systems, which will leverage infrastructure risk management under climate uncertainties. The human-centered UDT model integrates data-driven analytics with theory-driven models to present a multisensory learning environment for collective planning and evidence-based decision making, which will enhance decision outcomes in community resilience planning and infrastructure risk management.

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References

Aboushal, E. A. 2021. "Regenerative Design of a Defined Urban Space Using CityGML Model." *Journal of Urban Planning and Development* 147 (3): 15. https://doi.org/10.1061/(asce)up.1943-5444.0000723.

Ahn, C., Y. Ham, J. Kim, and J. Kim. 2020. A Digital Twin City Model for Age-Friendly Communities: Capturing Environmental Distress from Multimodal Sensory Data. Paper presented at the Proceedings of the 53rd Hawaii International Conference on System Sciences.

Akroyd, J., S. Mosbach, A. Bhave, and M. Kraft. 2021. "Universal Digital Twin—A Dynamic Knowledge Graph." *Data-Centric Engineering* 2: e14. https://doi.org/10.1017/dce.2021.10.

Allam, Z., and D. S. Jones. 2021. "Future (Post-COVID) Digital, Smart and Sustainable Cities in the Wake of 6G: Digital Twins, Immersive Realities and New Urban Economies." *Land Use Policy* 101: 13. https://doi.org/10.1016/j.landusepol.2020.105201.

Anejionu, O. C. D., P. Thakuriah, A. McHugh, Y. Sun, D. McArthur, P. Mason, and R. Walpole. 2019. "Spatial Urban Data System: A Cloud-Enabled Big Data Infrastructure for Social and Economic Urban Analytics." *Future Generation Computer Systems* 98: 456–73. https://doi.org/https://doi.org/10.1016/j.future.2019.03.052.

Arrighi, C., M. Pregnolato, and F. Castelli. 2021. "Indirect Flood Impacts and Cascade Risk Across Interdependent Linear Infrastructures." *Natural Hazards and Earth System Sciences* 21 (6): 1955–69. https://doi.org/10.5194/nhess-21-1955-2021.

Batty, M. 2018a. *Digital Twins* 45 (5): 817–20. https://doi.org/10.1177/2399808318796416.

Batty, M. 2021. "The Digital Transformation of Planning." *Environment and Planning B: Urban Analytics and City Science* 48 (4): 593–7. https://doi.org/10.1177/23998083211016122.

Batty, M. 2018b. *Inventing Future Cities*. Cambridge, MA, USA: MIT press.

Biljecki, F., J. Stoter, H. Ledoux, S. Zlatanova, and A. Çöltekin. 2015. "Applications of 3D City Models: State of the Art Review." *International Journal of Geo-Information* 4 (4): 2842–89. https://doi.org/10.3390/ijgi4042842.

Bolton, A., L. Butler, I. Dabson, M. Enzer, M. Evans, T. Fenemore, F. Harradence, E., et al. 2018. Gemini Principles (Report). CDBB.

Bostrom, N. 2003. "Are You Living in a Computer Simulation?" *The Philosophical Quarterly* 53 (211): 243–55. https://doi.org/10.1111/1467-9213.00309%J. The Philosophical Quarterly.

Bradley, P. E. 2015, Apr 20-23. Supporting Data Analytics for Smart Cities: An Overview of Data Models and Topology. Paper presented at the 3rd International Symposium on Statistical Learning and Data Sciences (SLDS), Royal Holloway Univ London, Egham, England.

Cai, H., N. S. N. Lam, L. Zou, and Y. Qiang. 2018. "Modeling the Dynamics of Community Resilience to Coastal Hazards Using a Bayesian Network." *Annals of the American Association of Geographers* 108 (5): 1260–79. https://doi.org/10.1080/24694452.2017.1421896.

Carvalho, R., and A. R. da Silva. 2021. "Sustainability Requirements of Digital Twin-Based Systems: A Meta Systematic Literature Review." *Applied Sciences* 11 (12): 5519. https://doi.org/10.3390/app11125519.

Cheliotis, K. 2020. "An Agent-Based Model of Public Space use." *Computers, Environment and Urban Systems* 81: 101476. https://doi.org/10.1016/j.compenvurbsys.2020.101476.

Cheliotis, K. 2021. ABMU: An Agent-Based Modelling Framework for Unity3D. SoftwareX, 15, 100771.

Crooks, A. T., A. Hudson-Smith, and A. Patel. 2011. Advances and Techniques for Building 3D Agent-Based Models for Urban Systems. no, 1, 49–65.

Davlasheridze, M., Q. Fan, W. Highfield, and J. Liang. 2021. "Economic Impacts of Storm Surge Events: Examining State and National Ripple Effects." *Climatic Change* 166 (1): 11. https://doi.org/10.1007/s10584-021-03106-z.

Dembski, F., U. Wossner, M. Letzgus, M. Ruddat, and C. Yamu. 2020. "Urban Digital Twins for Smart Cities and Citizens: The Case Study of Herrenberg." *Germany Sustainability* 12 (6): 17. https://doi.org/10.3390/su12062307.

Döllner, J. 2020. "Geospatial Artificial Intelligence: Potentials of Machine Learning for 3D Point Clouds and Geospatial Digital Twins." *PFG – Journal of Photogrammetry, Remote Sensing and Geoinformation Science* 88 (1): 15–24. https://doi.org/10.1007/s41064-020-00102-3.

Evans-Cowley, J. 2010. "Planning in the Real-Time City: The Future of Mobile Technology." *Journal of Planning Literature* 25 (2): 136–49. https://doi.org/10.1177/0885412210394100.

Fan, C., Y. C. Jiang, and A. Mostafavi. 2020. "Social Sensing in Disaster City Digital Twin: Integrated Textual-Visual-Geo Framework for Situational Awareness During Built Environment Disruptions." *Journal of Management in Engineering* 36 (3): 13. https://doi.org/10.1061/(asce)me.1943-5479.0000745.

Fereshtehnejad, E., I. Gidaris, N. Rosenheim, T. Tomiczek, J. E. Padgett, D. T. Cox, and W. G. Peacock. 2021. "Probabilistic Risk Assessment of Coupled Natural-Physical-Social Systems: Cascading Impact of Hurricane-Induced Damages to Civil Infrastructure in Galveston." *Texas Natural Hazards Review* 22 (3): 04021013. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000459.

Flavelle, C., D. Lu, V. Penney, N. Popovich, and J. Schwartz. 2021. New Data Reveals Hidden Flood Risk Across America. New York Times.

Ford, D. N., and C. M. Wolf. 2020. "Smart Cities with Digital Twin Systems for Disaster Management." *Journal of Management in Engineering* 36 (4): 10. https://doi.org/10.1061/(asce)me.1943-5479.0000779.

Forster, J., S. Fritz, J. Schleicher, and N. Rab. 2015, Sep 16-18. Developer Tools for Smart Approaches to Responsible-Minded Planning Strategies Energy and Space as Resources. Paper presented at the 33rd International Conference on Education and

Research in Computer Aided Architectural Design in Europe (eCAADe), TU Wien, Vienna, AUSTRIA.

Francisco, A., N. Mohammadi, and J. E. Taylor. 2020. “Smart City Digital Twin-Enabled Energy Management: Toward Real-Time Urban Building Energy Benchmarking.” *Journal of Management in Engineering* 36 (2): 11. https://doi.org/10.1061/(asce)me.1943-5479.0000741.

Glake, D., J. Weyl, C. Dohmen, C. Hüning, and T. Clemen. 2017. Modeling through model transformation with MARS 2.0. Paper presented at the Proceedings of the Agent-Directed Simulation Symposium, Virginia Beach, Virginia.

Gobeawan, L., E. S. Lin, A. Tandon, A. T. K. Yee, V. H. S. Khoo, S. N. Teo, and M. T. Poto. 2018. “Modeling Trees for Virtual Singapore: From Data Acquisition to CityGML Models.” *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XLII-4/W10: 55–62. https://doi.org/10.5194/isprs-archives-XLII-4-W10-55-2018.

Gong, J., C. Feeley, H. Tang, G. Olmschenk, V. Nair, Z. X. Zhou, and Z. G. Zhu. 2017, Jun 25-27. Building Smart Transportation Hubs with Internet of Things to Improve Services to People with Disabilities. Paper presented at the ASCE International Workshop on Computing in Civil Engineering (IWCCE), University of Washington, Seattle, WA.

Ham, Y., and J. Kim. 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. https://doi.org/https://doi.org/10.1061/(ASCE)ME.1943-5479.0000748.

Han, Y., K. Ash, L. Mao, and Z.-R. Peng. 2020b. “An Agent-Based Model for Community Flood Adaptation Under Uncertain Sea-Level Rise.” *Climatic Change* 162 (4): 2257–76. https://doi.org/10.1007/s10584-020-02802-6.

Han, Y., C. Chen, Z.-R. Peng, and P. Mozumder. 2021. Evaluating Impacts of Coastal Flooding on the Transportation System Using an Activity-Based Travel Demand Model: A Case Study in Miami-Dade County, FL. Transportation. https://doi.org/10.1007/s11116-021-10172-w.

Han, Y., and Z.-r Peng. 2019. “The Integration of Local Government, Residents, and Insurance in Coastal Adaptation: An Agent-Based Modeling Approach.” *Computers, Environment and Urban Systems* 76: 69–79. https://doi.org/10.1016/j.compenvurbsys.2019.04.001.

Han, T. R., J. M. Zhao, and W. Q. Li. 2020a. “Smart-Guided Pedestrian Emergency Evacuation in Slender-Shape Infrastructure with Digital Twin Simulations.” *Sustainability* 12 (22): 18. https://doi.org/10.3390/su12229701.

Homainejad, A. S. 2015, May 11–15. With Geospatial in the Path of Smart City. Paper presented at the 36th International Symposium on Remote Sensing of the Environment (ISRSE), Berlin, Germany.

Hor, A., A. Jadidi, and G. Sohn. 2016. “BIM-GIS Integrated Geospatial Information Model Using Semantic Web and RDF Graphs.” *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 3 (4): 73–9. https://doi.org/10.5194/isprs-annals-III-4-73-2016.

Howell, S., J. L. Hippolyte, B. Jayan, J. Reynolds, Y. Rezgui, and IEEE. 2016, Sep 12-15. *Web-Based 3D Urban Decision Support Through Intelligent and Interoperable Services*. Paper presented at the 2nd IEEE International Smart Cities Conference (ISC2), Trento, Italy.

Jelokhani-Niaraki, M. 2021. “Collaborative Spatial Multicriteria Evaluation: A Review and Directions for Future Research.” *International Journal of Geographical Information Science* 35 (1): 9–42. https://doi.org/10.1080/13658816.2020.1776870.

Ketzler, B., V. Naserentin, F. Latino, C. Zangelidis, L. Thuvander, and A. Logg. 2020. “Digital Twins for Cities: A State of the Art Review.” *Built Environment.* 46: 547–73. https://doi.org/10.2148/benv.46.4.547.

Kim, J., H. Kim, and Y. Ham. 2019. Mapping Local Vulnerabilities into a 3D City Model Through Social Sensing and the CAVE System Toward Digital Twin City. In Computing in Civil Engineering 2019 (pp. 451–458).

Kořínek, M., O. Tázlar, and K. Štekerová. 2021. Digital Twin Models: BIM Meets NetLogo. https://doi.org/10.36689/uhk/hed/2021-01-040.

Kudo, F., T. Akitomi, and N. Moriwaki. 2015, 13-16 July 2015. An Artificial Intelligence Computer System for Analysis of Social-Infrastructure Data. Paper presented at the 2015 IEEE 17th Conference on Business Informatics.

Kudva, S., and X. Ye. 2017. Smart Cities, Big Data and Sustainability Union. Big Data and Cognitive Computing. https://doi.org/10.3390/bdcc1010004.

Kunze, A. 2016. “Urban Planning, Management and Decision-Making in the Cloud.” *Gim International-The Worldwide Magazine for Geomatics* 30 (1): 34–5.

Ledoux, H., K. Arroyo Ohori, K. Kumar, B. Dukai, A. Labetski, and S. Vitalis. 2019. “CityJSON: A Compact and Easy-to-Use Encoding of the CityGML Data Model. Open Geospatial Data.” *Software and Standards* 4 (1): 1–12. https://doi.org/10.1186/s40965-019-0064-0.

Ledoux, H., F. Biljecki, B. Dukai, K. Kumar, R. Peters, J. Stoter, and T. Commandeur. 2021. “3dfier: Automatic Reconstruction of 3D City Models.” *Journal of Open Source Software* 6 (57): 2866. https://doi.org/10.21105/joss.02866.

Lehner, H., and L. Dorffner. 2020. “Digital geoTwin Vienna: Towards a Digital Twin City as Geodata Hub. *PFG – Journal of Photogrammetry*.” *Remote Sensing and Geoinformation Science* 88 (1): 63–75. https://doi.org/10.1007/s41064-020-00101-4.

Lenfers, U. A., N. Ahmady-Moghaddam, D. Glake, F. Ocker, D. Osterholz, J. Ströbele, and T. Clemen. 2021. “Improving Model Predictions—Integration of Real-Time Sensor Data into a Running Simulation of an Agent-Based Model.” *Sustainability* 13 (13): 7000. https://doi.org/10.3390/su13137000.

Li, W., and L.-A. Milburn. 2016. “The Evolution of Geodesign as a Design and Planning Tool.” *Landscape and Urban Planning* 156: 5–8. https://doi.org/10.1016/j.landurbplan.2016.09.009.

Li, D., W. Yu, and Z. Shao. 2021. “Smart City Based on Digital Twins.” *Computational Urban Science* 1 (1): 4. https://doi.org/10.1007/s43762-021-00005-y.

Liang, J., J. Gong, J. Liu, Y. Zou, J. Zhang, J. Sun, and S. Chen. 2016. “Generating Orthorectified Multi-Perspective 2.5D Maps to Facilitate Web GIS-Based Visualization and Exploitation of Massive 3D City Models.” *ISPRS International Journal of Geo-Information* 5 (11): 212. https://doi.org/10.3390/ijgi5110212.

Liu, X., X. Liang, X. Li, X. Xu, J. Ou, Y. Chen, and F. Pei. 2017. "A Future Land use Simulation Model (FLUS) for Simulating Multiple Land Use Scenarios by Coupling Human and Natural Effects." *Landscape and Urban Planning* 168: 94–116. https://doi.org/10.1016/j.landurbplan.2017.09.019.

Lu, Q., A. K. Parlikad, P. Woodall, G. D. Ranasinghe, X. Xie, Z. Liang, and J. Schooling. 2020. "Developing a Digital Twin at Building and City Levels: Case Study of West Cambridge Campus." *Journal of Management in Engineering* 36 (3): 05020004. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000763.

Mohammadi, N., J. Taylor, and IEEE. 2017, Nov 27-Dec 01. Smart City Digital Twins. Paper presented at the IEEE Symposium Series on Computational Intelligence (IEEE SSCI), Honolulu, HI.

Neumann, J. E., P. Chinowsky, J. Helman, M. Black, C. Fant, K. Strzepek, and J. Martinich. 2021. "Climate Effects on US Infrastructure: The Economics of Adaptation for Rail, Roads, and Coastal Development." *Climatic Change* 167 (3): 44. https://doi.org/10.1007/s10584-021-03179-w.

Neumann, B., A. T. Vafeidis, J. Zimmermann, and R. J. Nicholls. 2015. "Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding—A Global Assessment." *PLoS One* 10 (3): e0118571. https://doi.org/10.1371/journal.pone.0118571.

Nochta, T., L. Wan, J. M. Schooling, and A. K. Parlikad. 2021. "A Socio-Technical Perspective on Urban Analytics: The Case of City-Scale Digital Twins." *Journal of Urban Technology* 28 (1-2): 263–87. https://doi.org/10.1080/10630732.2020.1798177.

Park, S., S. Lee, S. Park, and S. Park. 2019. "AI-Based Physical and Virtual Platform with 5-Layered Architecture for Sustainable Smart Energy City Development." *Sustainability* 11 (16): 30. https://doi.org/10.3390/su11164479.

Pedersen, A. N., M. Borup, A. Brink-Kjær, L. E. Christiansen, and P. S. Mikkelsen. 2021a. "Living and Prototyping Digital Twins for Urban Water Systems: Towards Multi-Purpose Value Creation Using Models and Sensors." *Water* 13 (5): 592. https://doi.org/10.3390/w13050592.

Pepe, M., L. Fregonese, and N. Crocetto. 2019. "Use of SfM-MVS Approach to Nadir and Oblique Images Generated Throught Aerial Cameras to Build 2.5D Map and 3D Models in Urban Areas." *Geocarto International*, 37 (1): 1–22. https://doi.org/10.1080/10106049.2019.1700558.

Prasara-A, J., and S. H. Gheewala. 2017. "Sustainable Utilization of Rice Husk ash from Power Plants: A Review." *Journal of Cleaner Production* 167: 1020–8. https://doi.org/10.1016/j.jclepro.2016.11.042.

Rathore, M. M., S. A. Shah, D. Shukla, E. Bentafat, and S. Bakiras. 2021. "The Role of AI, Machine Learning, and Big Data in Digital Twinning: A Systematic Literature Review, Challenges, and Opportunities." *IEEE Access* 9: 32030–52. https://doi.org/10.1109/ACCESS.2021.3060863.

Retchless, D., W. Mobley, M. Davlasheridze, K. Atoba, A. D. Ross, and W. Highfield. 2021. "Mapping Cross-Scale Economic Impacts of Storm Surge Events: Considerations for Design and User Testing." *Journal of Maps*, 17: 1–13. https://doi.org/10.1080/17445647.2021.1940325.

Rong, Y., T. Zhang, Y. Zheng, C. Hu, L. Peng, and P. Feng. 2020. "Three-Dimensional Urban Flood Inundation Simulation Based on Digital Aerial Photogrammetry." *Journal of Hydrology* 584: 124308. https://doi.org/10.1016/j.jhydrol.2019.124308.

Ruohomäki, T., E. Airaksinen, P. Huuska, O. Kesäniemi, M. Martikka, and J. Suomisto. 2018, 25-27 Sept. 2018. Smart City Platform Enabling Digital Twin. Paper presented at the 2018 International Conference on Intelligent Systems (IS).

Rzeszewski, M., and M. Orylski. 2021. "Usability of WebXR Visualizations in Urban Planning." *ISPRS International Journal of Geo-Information* 10 (11): 721. https://doi.org/10.3390/ijgi10110721.

Schrotter, G., and C. Hürzeler. 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. https://doi.org/10.1007/s41064-020-00092-2.

Simpson, D. M. 2001. "Virtual Reality and Urban Simulation in Planning: A Literature Review and Topical Bibliography." *Journal of Planning Literature* 15 (3): 359–76. https://doi.org/10.1177/08854120122093078.

Small, M. J., and S. Xian. 2018. "A Human-Environmental Network Model for Assessing Coastal Mitigation Decisions Informed by Imperfect Climate Studies." *Global Environmental Change* 53: 137–45. https://doi.org/10.1016/j.gloenvcha.2018.09.006.

Strandsbjerg Tristan Pedersen, J., F. Duarte Santos, D. van Vuuren, J. Gupta, R. Encarnação Coelho, B. A. Aparício, and R. Swart. 2021b. "An Assessment of the Performance of Scenarios Against Historical Global Emissions for IPCC Reports." *Global Environmental Change* 66: 102199. https://doi.org/10.1016/j.gloenvcha.2020.102199.

Tao, J., and N. Kang. 2021. Texas A&M Engineering Experiment Station: V-RELLIS. Retrieved from https://sites.google.com/tamu.edu/rellisvirtualmap.

Tao, F., and Q. Qi. 2019. *Make More Digital Twins. Nature. 573: 490–491.*

Tomko, M., and S. Winter. 2019. "Beyond Digital Twins—A Commentary." *Environment and Planning B: Urban Analytics and City Science* 46 (2): 395–9. https://doi.org/10.1177/2399808318816992.

Waddell, P., C. Whitcomb, F. Figari, F. Fernandez, and J. Martinez. 2020. "Penciler: A Web-Based Affordable Housing Development Feasibility Analysis Tool." In *Handbook of Planning Support Science*, 486–505. Cheltenham, United Kingdom: Edward Elgar Publishing.

White, G., A. Zink, L. Codeca, and S. Clarke. 2021. "A Digital Twin Smart City for Citizen Feedback." *Cities (London, England)* 110: 11. https://doi.org/10.1016/j.cities.2020.103064.

Xuan, S. 2015, Mar 27-28. Semantic 3D Building Model Construction for Smart Urban Management. Paper presented at the International Conference on Industrial Technology and Management Science (ITMS), Tianjin, Peoples Republic of China.

Xue, F., W. Lu, T. Tan, and K. Chen. 2019, Oct 25-27. Semantic Enrichment of City Information Models with LiDAR-Based Rooftop Albedo. Paper presented at the 2nd International Conference in Sustainable Buildings & Structures (ICSBS), Xian Jiaotong Liverpool University, Suzhou, Peoples Republic of China.

Yao, Z., C. Nagel, F. Kunde, G. Hudra, P. Willkomm, A. Donaubauer, and T. H. Kolbe. 2018. "3DCityDB—A 3D Geodatabase Solution for the Management, Analysis, and Visualization of Semantic 3D City Models Based on CityGML." *Open Geospatial Data, Software and Standards* 3 (1): 5. https://doi.org/10.1186/s40965-018-0046-7.

Ye, X., S. Wang, Z. Lu, Y. Song, and S. Yu. 2021. "Towards an AI-Driven Framework for Multi-Scale Urban Flood Resilience Planning and Design." *Computational Urban Science*, https://doi.org/10.1007/s43762-021-00011-0.

Yedavalli, P., E. Burak Onat, X. Peng, R. Sengupta, P. Waddell, V. Bulusu, and M. Xue. 2021. SimUAM: A Comprehensive Microsimulation Toolchain to Evaluate the Impact of Urban Air Mobility in Metropolitan Areas.

Yildirim, E., and I. Demir. 2019. "An Integrated Web Framework for HAZUS-MH Flood Loss Estimation Analysis." *Natural Hazards* 99 (1): 275–86. https://doi.org/10.1007/s11069-019-03738-6.

Yoo, B. 2013. "Rapid Three-Dimensional Urban Model Production Using Bilayered Displacement Mapping." *International Journal of Geographical Information Science* 27 (1): 24–46. https://doi.org/10.1080/13658816.2012.661055.

Zhang, W., and S. Guhathakurta. 2021. "Residential Location Choice in the Era of Shared Autonomous Vehicles." 41 (2): 135–48. https://doi.org/10.1177/0739456x18776062.

Zhao, Y. X., K. L. Man, J. Smith, and S. U. Guan. 2021. "A Novel Two-Stream Structure for Video Anomaly Detection in Smart City Management." *Journal of Supercomputing* 15, https://doi.org/10.1007/s11227-021-04007-9.

Zhou, C. Y., Z. C. Du, L. Gao, W. H. Ming, J. W. Ouyang, X. D. Wang, and Z. Liu. 2019. "Key Technologies of a Large-Scale Urban Geological Information Management System Based on a Browser/Server Structure." *IEEE Access* 7: 135582–94. https://doi.org/10.1109/access.2019.2941348.

Zou, L., N. S. N. Lam, H. Cai, and Y. Qiang. 2018. "Mining Twitter Data for Improved Understanding of Disaster Resilience." *Annals of the American Association of Geographers* 108 (5): 1422–41. https://doi.org/10.1080/24694452.2017.1421897.

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