Going beyond net zero: digital twins for achieving socio-ecological sustainability in the built environment

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Going beyond net zero: Digital twins for achieving socio-ecological sustainability in the built environment

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Abstract
Purpose – In this paper, we review and discuss the contemporary research on large-scale digital twins to identify the extent of socio-ecological and systems thinking in the context of sustainable built environment. We unpack the techno-rationalist view that relies on technology for problem-solving and argue that digital twins can facilitate a more nuanced assessment of sustainability challenges, including social equity, cultural preservation, and ecological resilience.
Design/methodology/approach – We conducted a content analysis-based review of studies drawing from Scopus and Web of Science databases using search strings to identify studies that develop complex, socio-ecologically aligned digital twins at neighborhood and city scales. We excluded studies that focused on a single building or a technology, as well as those that were situated in physical sciences, such as energy fuels, chemistry, or mathematics, to understand the extents of system complexity and interdisciplinary thinking, types of integrated data, digital twin maturity and underlying challenges for future research directions.
Findings – The findings illustrate the early stages of the digital twin development with respect to complex systems. Despite the relatively few studies reporting more mature and complex digital twin models, we illustrate how large-scale digital twin developments remain largely domain-specific, with projects yet to be seen as interventions within larger complex systems.
Originality/value – We contribute to the understanding of applying systems thinking in the development of socio-ecological urban digital twins. We identify key considerations and propose a preliminary framework for creating purpose-driven digital twins, aiming to foster more impactful questions regarding their purpose and value and to support interdisciplinary dialogue.
Paper type: Review

Keywords: digital twin, scale, socio-ecology, systems thinking, smart city, review.

1. Introduction

The alarming effects of climate change and environmental degradation have prompted various global policies that set ambitious targets for reducing carbon emissions by 2050 (Climate Change Committee, 2019; United Nations Environment Programme, 2022). The urgency of climate change as well as the recent COVID-19 pandemic have raised questions of what the future of the built environment should look like and how that future can be realized. Carbon emission targets and achieving "net zero" initiatives have thus prompted many digital transformation initiatives that mobilize technology and data science to monitor, simulate and evaluate potential solutions across sectors to meet the decarbonization goals.

In the built environment disciplines, one such initiative that has attracted much attention is the concept of digital twins that connect physical and digital assets to support data-driven decision making in complex environments. For example, in the UK, digital twin technology is seen as an opportunity to improve performance, quality and value of national infrastructure (Nochta et al. 2021). This has resulted in the development of the National Digital Twin Programme (CDBB, 2019), which offers a broad vision of connected digital twins across environmental, social and economic spheres driven by the ultimate goal of ‘enabling people and systems to flourish’. This shift has also challenged built environment practitioners to consider the long-term consequences of interventions (Whyte *et al.*, 2020) and has led to a greater focus on outcomes rather than outputs, and a broader digital context within which project data can be situated, for example in the context of ‘smart’ cities.

Yet, given that global demand for energy is ever-increasing, the pursuit of carbon emission reductions has consequently focused efforts largely on understanding and reducing energy consumption in the context of infrastructure and building performance. However, much research suggests that responding to current and future climate challenges is far more complex, a “super-wicked” problem that defies simplistic technological solutions and often prioritizes short-term goals with competing priorities (Levin *et al.*, 2012; Rabeneck, 2008). Thus, achieving sustainable built environment goals is complex and calls for approaches that transcend any single discipline and move away from project-bound methodologies to those where models span organizational and jurisdictional domains (Whyte *et al.*, 2019). As Rabeneck (2008) argued, any understanding of asset performance demands a broader perspective to articulate needs within a given context. Initiatives such as the National Digital Twin in the UK have begun to offer long-term visions of interconnected, purpose-driven and outcome-focused digital twins, grounded in systems thinking approaches. Such approaches consider economic, social and ecological layers as critical data components in digital ecosystems for understanding the built environment. Yet, these social and ecological layers will tend to remain siloed without involving allied built environment disciplines, as well as those from the realms of sociology, ecology, and anthropology in conversations about critical data situated at the intersection between human behavior and technological innovation.

The pervasiveness of digital technologies across the architecture, engineering, and construction fields has presented new ways to connect physical environments with digital ecosystems. While technological innovation has always been paired with urban development (Quek *et al.*, 2023), in recent years, the concept of technology has shifted toward the digital and the notion that reality itself is no longer analogue, but rather connects to digital representations of itself (Ewart, 2018). While the proliferation of low-cost consumer technologies paired with big data and the Internet of Things has offered a range of opportunities to improve the design, delivery, and operation of physical assets, this has also raised questions about how to interpret ever-growing raw and complex data sets to understand how we use the built environment and make informed decisions about its future (Nikolić and Whyte, 2021).

In this paper, we review recent literature on large-scale built environment digital twins (DTs) and argue that while these models tend to be promoted as potent industry-agnostic applications to support decarbonization goals, their narrative has largely been dominated by technology-focused methods. In the next section, we reviewed studies that raise questions about informing holistic approaches to developing long-term purpose-driven digital twins for sustainable environment. Specifically, we explored the socio-ecological view of cities as complex systems to understand the extent of systems thinking, system complexity and cross-sector boundaries, as well as the underpinning technology landscape and procedures for developing digital twin models. Section three introduces methods for reviewing literature. Section four presents the results from a general overview of research trends and the thematic analysis. The final two sections discuss the findings and provide directions and opportunities for future research. Here, we argue that by moving beyond energy consumption and carbon emission metrics, digital twins can facilitate a more nuanced assessment of sustainability challenges that extend to factors such as social equity, cultural preservation, and ecological resilience.

2. Background

2.1. City-scale digital twins

The use of digital twin models in built environment practice has emerged from the recognition that the delivery of physical assets has become inseparable from their digital counterparts, offering the potential for extensive data-capture processes to understand their use and improve their operation. Just as with ‘smart cities’, the term ‘digital twin’ has become a catchphrase in the sustainable urban development discourse (Colding and Barthel, 2017). With real-time asset data available, information derived from digital twins can influence future investment decisions, especially for serial clients such as government agencies, and inform considerations to alter user behaviors or optimize assets in new projects (Whyte and Nikolić, 2018).

The *digital twin* concept was first introduced in 2002 in the aerospace field as a method for product lifecycle management (Grieves, 2019) and its use remains predominant in manufacturing. The concept, which refers to bi-directional data coupling of the digital representation and its physical counterpart for the purposes of monitoring, control, operation or simulation of assets and processes, has become a core for digital transformation initiatives in the built environment disciplines. However, given that this concept originates from an engineering domain, its application in the built environment context has not been altogether straightforward. Unlike in the aerospace and manufacturing fields, digital twins for the built environment tend to span broad scales, professional domains and jurisdictional units, and inherently encompass complex systems involving heterogeneous data sources and non-linear sub-system interactions, which often limits the predictability of their performance.

Recent digital twin applications in the built environment domain, which to date have been driven by efficiency concerns, include smart cities, structural health monitoring, infrastructure planning and management (e.g., roads, power, water, transportation), agriculture, and urban planning and development. Data sources are typically collected from citizens, sensor webs, and IoT devices connected to infrastructure systems, such as transportation, water supply, utilities, schools, hospitals and other community services (Allam and Jones, 2021). Urban infrastructure and 3D city models are developed mostly by linking BIM models with data (Ferré-Bigorra *et al.*, 2022) and have prompted recent efforts to address various environmental and sustainability-related challenges, such as predicting commuting behaviors and transportation choices (Lenfers *et al.*, 2021), evaluating carbon emissions (Park and Yang, 2020), predicting energy consumption based on energy profiles of consumers (Onile *et al.*, 2021), track outdoor comfort in street settings (Liu *et al.*, 2023), and incident response and management (Wolf *et al.*, 2022). These initiatives illustrate the potential of digital twins to monitor various urban conditions and parameters and inform the responses for more efficient design solutions. Moreover, urban environments are dynamic living systems that constantly evolve (Quek et al., 2023) and any interventions in these complex systems are intricately tied to economic, environmental, and social sustainability concerns. Hence, a growing call exists to view urban areas as socio-ecological systems that require transdisciplinary approaches, tools and techniques for managing urban challenges in a meaningful way (Dembski *et al.*, 2020; Nel *et al.*, 2018; Tzachor *et al.*, 2022).

2.2. Cities as complex socio-ecological systems (of systems)

The complexity of responding to broad sustainability challenges increases proportionally with the scale and multiple dimensions of interventions (i.e. environmental, social, economic, and technological). Drawing from the biophysical world, the concept of socio-ecological systems (SES) recognizes the many ways in which human actions affect the environment (Schlüter *et al.*, 2019).

Moreover, ongoing rapid urbanization has led to calls to understand the ecological impact of the underlying processes and systems that should be prioritized for long-term social and ecological resilience (Mundoli *et al.*, 2017), and where social participation is seen to be crucial in decision-making processes (Elsawah *et al.*, 2019). For example, one socio-ecological approach to climate change adaptation identifies at least ten systems that need to be considered, including land-use, transportation, communication, economy, governance, and social structures (Bi and Little, 2022). According to the SES concept, complex biophysical networks, including cities can be represented as assemblies of coupled human and natural systems (Marcotullio and Solecki, 2013), or as a 'system of systems'.

The ever-rising carbon footprint of cities has prompted the creation of a range of urban development and assessment frameworks such as eco-cities, low-carbon cities, smart cities and urban metabolism (Bi and Little, 2022). However, most of these approaches tend to focus on carbon emission reductions (Ameen *et al.*, 2015), or favor economic and technological innovations (Hunter *et al.*, 2019). Nochta et al. (2021) extended this criticism to the discourse around city-scale digital twins that tend to hold an equally technology-centric view, primarily focused on demonstrating technical functionality.

The recent COVID-19 pandemic, especially seen within the context of a climate emergency, has highlighted the complexities of socio-ecological systems for scenarios in which given challenges are themselves poorly defined, and consequent decisions are based on incomplete information. Building on previous work that predicted the growing difficulty of managing increasingly complex city systems (Nel *et al.*, 2018), Landman (2021) described how these challenges gave rise to simultaneous health, social, and economic crises and exposed the ability of decision makers to manage and maintain functioning systems. As a result, instead of viewing cities as manufactured or mechanical objects (Du Plessis, 2013), the proposed way forward was to consider cities as 'socio-ecological systems' whereby urban areas are viewed as "an ever-changing socio-spatial-temporal meta-process, comprising innumerable interacting and nested processes resulting from self-organization and adaptation, and resulting in the emergence of unpredictable patterns and events" (Du Plessis, 2013, p.55). This underscores the point that by concentrating on technologies to address urban challenges, research into smart cities has largely neglected many social factors resulting in a growing disparity between urban regions and policy (Nochta *et al.*, 2021; Yossef Ravid and Aharon-Gutman, 2023). Similarly, because economic activity often tends to be prioritized over social considerations, this affects decisions about where and when scarce public resources should be applied, even when the environmental factors are central to a given study. For example, Brandl and Zielinska (2020) explored the connection between environmental phenomena and working lives using the Smart City Vienna Framework and saw technological innovations through economic growth as a potential strategy to address poverty.

2.3 Socio-ecological approach: The imbalance between urban and natural systems

Contrary to those models that focus primarily on energy use as a proxy for economic and environmental sustainability, much research on SES approaches rejects this narrow definition. Likening large-scale urban environments to living systems means that there is an emergent and evolutionary quality to the morphology, networks, information, social norms and built environment fabric at various scales and dimensions (Caldarelli *et al.*, 2023; Facchini *et al.*, 2021). Such an approach requires moving away from the physicality of many digital twins and their associated data sources to prioritize interactions between layers that are not necessarily quantitative, providing an opportunity to view these models as relevant to the people and other species within a given system. Such interactions, and the networks they create, include both physical and their cyber-equivalent elements, such as transport infrastructure and its associated risks of accidents and pollution (e.g., Iacopini *et al.*, 2020), or the economics driving a given urban environment (Caldarelli *et al.,* 2023). However, these also require development to accommodate more nuanced and difficult-to-represent layers of qualitative information. For example, Colding and Barthel (2017) critiqued the 'Smart City' model for its overdependence on technical perspectives, and instead explicitly brought people into the model, suggesting that uncertainty and surprise are fundamental to any system that adapts and changes according to the response of its inhabitants to major fluctuations.

Yet, while much research that has incorporated SES frameworks generally recognizes the interactions between layers of internally complex systems, researchers often struggle to draw meaningful conclusions. For instance, studies have demonstrated causal interactions between ecosystems and well-being in cities (Tzoulas *et al.*, 2007) and qualitatively identified synergies and trade-offs between biodiversity and mental health based on green infrastructure indicators (Felappi *et al.*, 2020). However, these studies largely identify connections between only two components, whereas the potential to integrate such lessons into far-reaching policy and design approaches has fallen short. This offers opportunities to ask different kinds of questions when it comes to the design of social and critical infrastructure. For example, innovations in healthcare infrastructure could mean not only building more efficient hospitals but also creating healthier living environments in which residents have access to clean air, vegetation, social spaces and active travel options. As Bi and Little (2022) pointed out, ignoring human behavior in these digital models is bound to result in challenges for effective interventions. Some recent reviews of digital twin applications and research (e.g., Papadonikolaki and Anumba, 2022) show that while holding a promise to address environmental changes, their focus has been mostly on the decarbonization efforts in the energy sector and reducing energy consumption across domains. Finally, Waring and Richerson (2011) argued that because many environmental challenges are in fact socio-ecological in nature, designing effective responses will depend on a deeper understanding of the human-environment interactions. In practice, this means models involving all stakeholders; performing economic and biological analyses of an environment and its resources at micro- and macro scales, and participatory approaches to environmental policy design (Ince, 2023). Such perspectives invite dynamic systems thinking approaches that span spatial, temporal and organizational boundaries and consider a set of critical resources such as natural, social, economic and cultural, all located at the intersection of interdisciplinary collaboration.

3. Method

To explore the contemporary narratives in research associated with socio-ecological and systems thinking in the domain of large-scale digital twins, we conducted a content analysis-based review (Hajek *et al.*, 2022). The search was done in November 2024 using two major databases: Scopus and Web of Science. To understand system complexity and research directions, we first identified bibliographical sources using titles, abstracts and keywords that focus on digital twins at neighborhood, urban and city scales and any references to socio-ecological factors. Given that the literature on large-scale digital twins intersects with that of smart cities and 3D city modeling, a basic keyword search yielded an overwhelming number of outputs, which tracked similar challenges documented in other reviews on urban digital twins (e.g., Ketzler *et al.*, 2020; Masoumi *et al.*, 2023). To retrieve more relevant publications, in addition to applying the search terms "city", "urban" and "digital twins", we searched an additional string of keywords in both databases to identify publications that also mention "social", "ecological" or "sustainable" factors (Table 1). Ultimately, we were interested in studies that concerned complex, socio-ecologically aligned digital twin models; their data, and the disciplines involved in their development.

Table 1: Number of publication records based on databases search strings (Source: Authors' own work)

Database	Search String	Outputs
Scopus	TITLE-ABS-KEY ("city" OR "urban" OR "built environment" OR "smart city" AND "digital twin") AND TITLE-ABS-KEY ("social" OR "ecolog*" OR "sustainab*" OR "net-zero")	184
Web of Science	TS= ("digital twin" AND (city OR "smart cit*" OR "urban" OR "built environment") AND ("socio-ecolog*" OR "sustainab*" OR "net-zero"))	113
Total		297
Selected	After removing duplicates and further reviewing articles for domain relevance	166

The search was limited to available articles and conference proceedings published in English while publications from physical science domains, such as mathematics, physics, energy fuels, chemistry, or medicine were excluded (Figure 1). Duplicate articles between the two databases were removed, and in cases where authors published studies as both a conference paper and a journal article, the conference paper was excluded. A further review of abstracts revealed a wide range of approaches and definitions of digital twins, leading to an additional number of publications being omitted from further review. For example, titles that mentioned city or digital twins but focused on individual buildings were deemed irrelevant and out of scope. This process resulted in a total of 166 papers selected for further review and analysis. Out of 166 publications, the total of 137 journal articles and 29 conference papers were all published between 2014 – 2024 and with a tendency to grow annually (Figure 2).

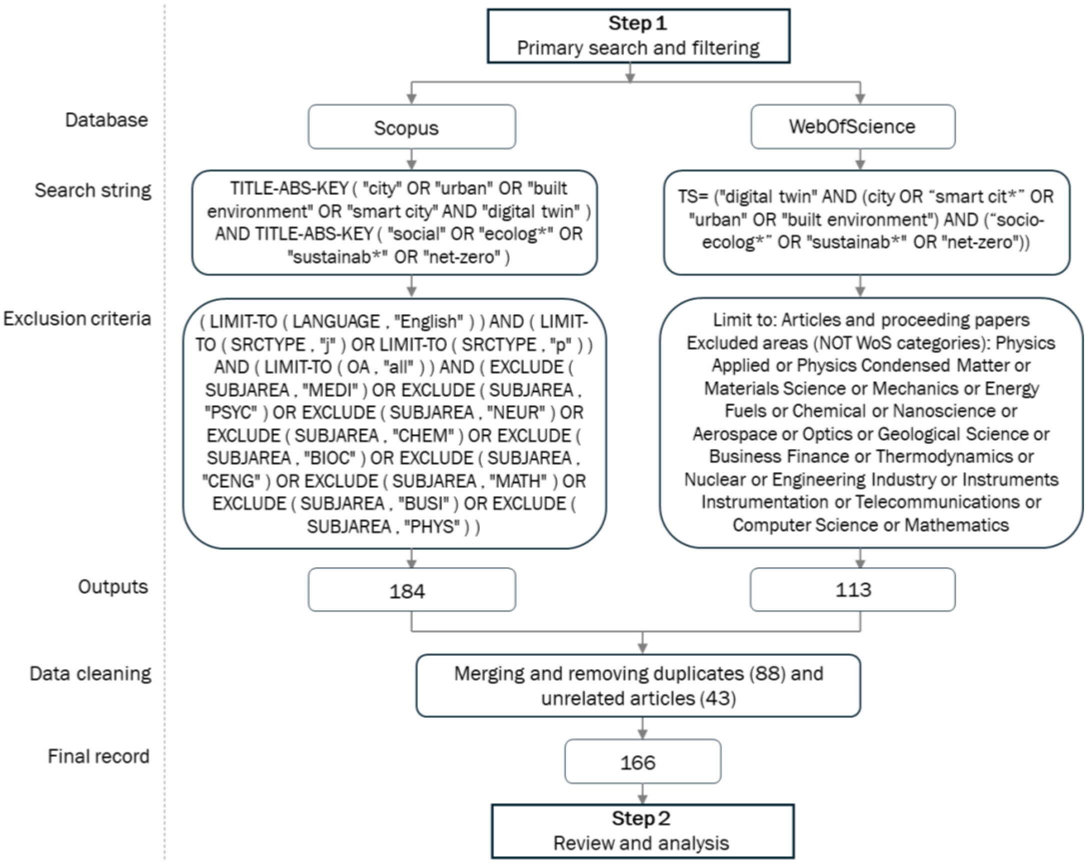

Figure 1: The flowchart of the publication search and selection process (Source: Authors' own work)

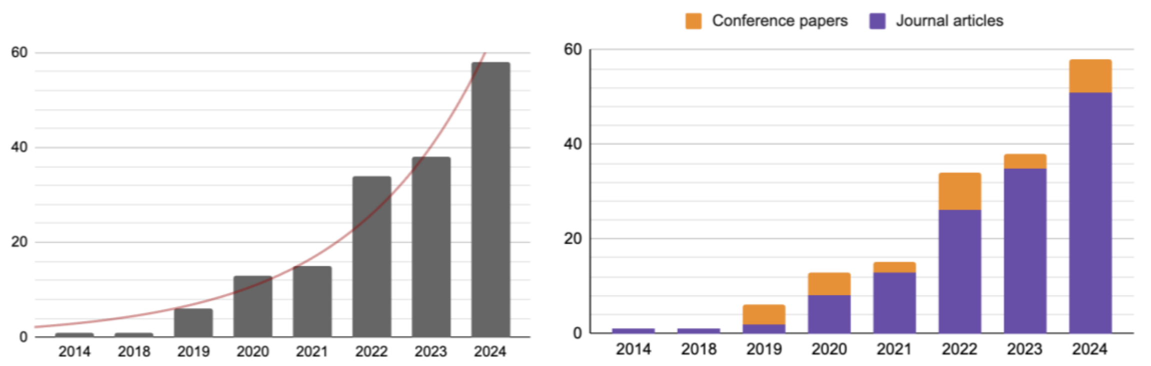

Figure 2: Frequency of publications on city digital twins per year (left) and by type of publications (right) (Source: Authors' own work)

4. Findings

As the body of large-scale urban digital twin research is relatively nascent and has grown rapidly in recent years, we did not exclude any publications *a priori* based on their research approach. After examining their focus and research design, we identified three types of publications: applied research, review (e.g., systematic, general) and conceptual (e.g., theoretical, critique, scoping, perspective). Studies that focused on any aspect of digital twin development (e.g., workflow, algorithm, modeling) and employed quantitative, qualitative or mixed methods, including case studies and pilot projects were characterized as applied research. Conversely, publications that concerned developing or advancing theoretical understanding, conceptualization or critical examination of urban-scale digital twins were categorized as conceptual research. Such papers were largely seen as foundational in nature, aiming to set the stage for further research on and implementation of these concepts for real-world digital twin initiatives. The categorization of the studies revealed that the majority (65%) represented applied research (Figure 3).

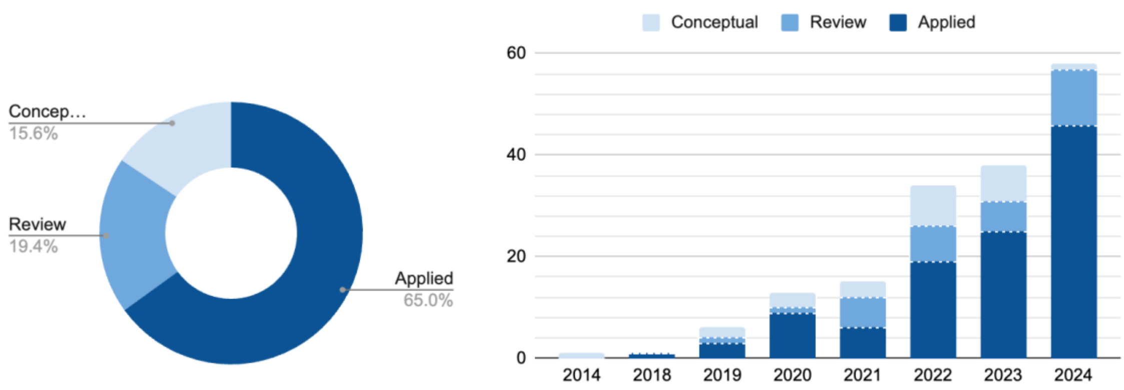

Figure 3: Publications by type of research and by year (Source: Authors' own work)

Given that prior reviews revealed a tendency for studies to focus on technical and methodological challenges or on one dimension of urban systems (Masoumi *et al.*, 2023), we were interested in the extent to which the selected studies considered large-scale digital twins through the lens of socio-ecological systems. To review our dataset, we employed Microsoft Edge' AI chat tool, Copilot, as a 'second reviewer', which offers a level of accuracy comparable to the manual process (Hill *et al.*, 2024). We reviewed a sample of ten studies both manually and with the support of Copilot following the steps outlined in the study by Hill *et al.* (2024). While the reviews agreed, our data extraction request was basic (e.g., "*what is the aim of the study?*"; "*what methodology does the study employ?*", "*to what extent does the study address socio-ecological factors?*") and we did not verify the level of accuracy for the whole dataset. However, to check the consistency of the generated outputs, we repeated the queries on an additional sample of ten random publications. Therefore, the following observations should be interpreted as general trends.

After reviewing the publications, we identified three broad ways socio-ecological factors were considered in studies, which:

1) Did not address any socio-ecological factors, either explicitly or implicitly. Such studies primarily focused on the technological and operational benefits of digital twins, data analytics, interoperability frameworks, IT solutions or primarily improving energy or transportation efficiency (e.g., Arsiwala *et al.*, 2023; Kumar *et al.*, 2018; Li *et al.*, 2022).
2) Explicitly addressed socio-ecological factors and acknowledged the complex dynamics connected to economic, ecological, and demographic changes in cities, emphasizing the need for approaches that consider urban complexity and allow for participatory processes. For example, some studies highlighted the role of citizen science and participation in response to environmental challenges and identified links between pollution, health and wellbeing, socioeconomic displacement, and municipal policies, among others (e.g., Peldon *et al.*, 2024; Spiridonov and Shabiev, 2020; Ye *et al.*, 2023).
3) Implied socio-ecological factors through the consideration of related themes, such as civic engagement, sustainable urbanization, and environmental data. Although these studies did not explicitly discuss socio-ecological phenomena, they indirectly acknowledged the interaction between humans and their environment. Such studies tended to use agent-based modeling approaches to simulate human decisions and processes in different environmental conditions (e.g., Allam and Jones, 2021; Cruz *et al.*, 2023; Lenfers *et al.*, 2021).

Reviewing the selected studies yielded an overall distribution between those that have considered socio-ecological factors (either explicitly or implicitly) and those that did not (Figure 4). Concerning the study type, applied research studies have specifically seen an increased consideration of socio-ecological factors, particularly in the last two years.

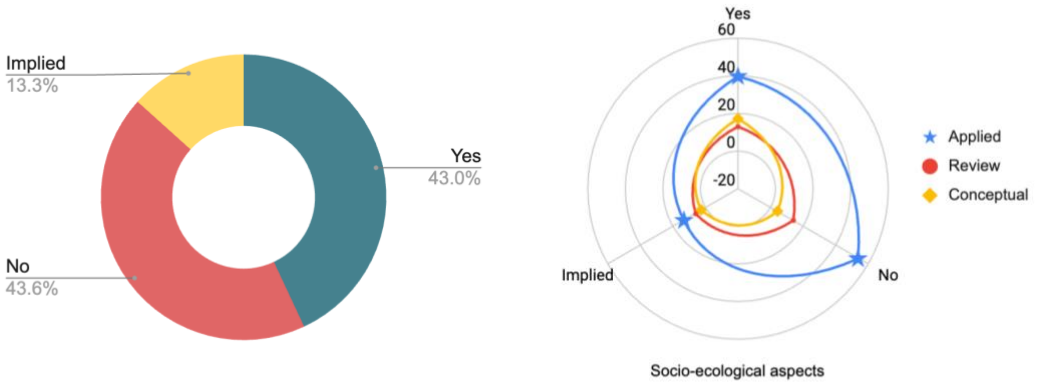

Figure 4: Proportion of reviewed studies that considered socio-ecological factors (left) and a spider graph showing the consideration of socio-ecological factors by study type (right) (Source: Authors' own work)

The studies that considered socio-ecological factors revealed that digital twin development is predominantly in the early experimental or prototyping stages. Often, these studies did not clarify any extent of functional bi-directional data exchange, and while some dynamic data handling may have been suggested by the proposed frameworks, the developed models primarily focused on integrating data, such as 3D models of the built environment, street networks, urban mobility simulations, or environmental simulations (Dembski *et al.*, 2020; Jiang *et al.*, 2022). Fewer studies included more advanced and sophisticated digital twins that integrated real-world data with a varying extent of automated real-time data flows and synchronization that enabled dynamic and complex scenario management and optimization, which are essential features of mature digital twin models (Table 2).

To understand broader trends in how large-scale digital twins are conceptualized, the following section presents a thematic analysis of the publications that included socio-ecological factors and identifies the types of data that constituted such models. Thematic analysis was deemed to be a flexible method to identify dominant concepts, approaches, and challenges for developing complex socio-ecologically driven digital twins. Given that this a growing field of research, both theoretical and applied research studies were considered relevant.

5. Emerging themes

Overall, the review suggests that research on complex, multidimensional large scale digital twins remains in the early development stages and is primarily focused on the digitalization of urban and social data and their integration with 3D urban models. From the selected publications, we identified application areas along with indicators of systems thinking that extend environmental performance. In doing so, our goal was to establish the extent of socio-ecological and transdisciplinary thinking present in this literature to inform and frame the development of large-scale digital twin models and identify potential obstacles for their implementation.

5.1 Socio-ecological digital twin conceptualization and application

The discussion of large-scale urban digital twins remains tightly coupled with smart city narratives in which the discourse is predominantly technology-driven. Here, the focus lies largely on modeling specific infrastructure needs that include flood forecasting and prevention, increasing power grid efficiency, and understanding commuting patterns for transportation needs. Despite considering socio-ecological factors, these studies do not always seem to fully exploit the concept of digital twins, as their development prioritizes technical and infrastructure factors, such as for “smart mobility” (Zaballos *et al.*, 2020), data-driven urban planning and environmental sustainability (Zhao *et al.*, 2022), and those in which the terminology shifts towards 3D (city) models as a precursor to urban digital twins (Cureton and Hartley, 2023).

Studies that considered socio-ecological factors invariably explored the societal effects of various environmental factors and interventions that influence urban planning and infrastructure management strategies. To discern a more comprehensive and holistic approach to digital twin development that integrates social dynamics and human behaviors, some researchers proposed city digital twins (CDTs) (Nochta *et al.*, 2021), urban digital twins (UDTs) (Cureton and Hartley, 2023), or social urban digital twins (SUDTs) (Yossef Ravid and Aharon-Gutman, 2023). Specifically, such studies investigated how infrastructure interventions can affect socio-economic factors, such as walkability (Kumalasari *et al.*, 2023), access to healthcare (Allen *et al.*, 2022; Nijkamp *et al.*, 2023), urban growth, aging populations and other demographic and socio-economic groups (Sadowski and Bendor, 2019; Zhou *et al.*, 2023). Furthermore, such studies tend to illustrate the importance of citizen involvement in decision-making processes, as seen in the case study of Rotterdam, where support for the local energy policy was secured through a collective review of its effects on well-being and quality of life (Nijkamp *et al.*, 2023).

Table 2: Applied research studies that considered socio-ecological factors in large-scale digital twin development (Source: Authors' own work)

	Reference	Data included	DT maturity
1	(Zaballos *et al.*, 2020)	*Environmental*: Weather, temperature humidity air quality, lighting, noise. *Users*: Occupancy, movement patterns, emotion detection. *Energy*: Energy consumption, energy efficiency. *Building Information*: Building layout, IoT device locations, usage schedules.	Mature bi-directional flow
2	(Castelli *et al.*, 2022)	*Environmental*: Air quality, temperature, noise, water quality, living plants' health. *User Data*: From citizens and tourists interacting with the city. *Infrastructure*: Information from cellular base stations, roadside units, traffic levels *Participatory*: Mapping and geo-referenced surveys of values, feelings, and behaviors. *Actuator Data*: To implement solutions and close the feedback loop.	Advanced (real-time data enriched)
3	(Hofmeister *et al.*, 2024)	*Geospatial*: Building footprints, heights, and elevations. *Economic*: Historical property sales transactions and property values. *Environmental*: River levels, weather, and flood warnings. *Energy performance*: Energy certificates, property types, usage categories, and energy ratings. *Demographic*: Population density data	Mature bi-directional flow
4	(Wang and Wang, 2024)	*Energy Infrastructure*: Capacity, ramp-up, and ramp-down rates of renewable energy sources. *Environmental*: Carbon emissions and environmental impact coefficients. *Economic*: Total cost and cost efficiency comparisons for various optimization techniques. *Performance Monitoring*: Load demand forecasting *Aesthetic Impact*: Aesthetic scores for the visual impact of energy infrastructure.	Advanced (real-time data enriched)
5	(Chen *et al.*, 2024)	*(Non)Structural*: Lifecycle management of buildings and infrastructure systems. *Environmental*: Energy harvesting efficiency, flood zone susceptibility, green space. *Sensors*: Real-time data from infrared/hyperspectral cameras, LiDAR, magnetometers. *Asset Management*: Building envelopes, and damage/cost scenarios in earthquake events. *Security*: Security protocols, including visibility analysis and magnetic field mapping.	Mature bi-directional flow
6	(Liu and Zoh, 2024)	*Energy infrastructure*: Renewable energy sources, energy storage facilities. *Energy Flow Algorithms*: Specialized algorithms for managing energy flow within the grid. *Economic*: Data to optimize performance and reduce operational costs. *Environmental*: Landscape considerations to promote ecological preservation.	Advanced (real-time data enriched)
7	(Coors and Padsala, 2024)	*3D Building Models*: Geometry and semantic data of buildings. *Energy*: Energy demand, load profiles, and energy potential at the building scale. *Socio-Demographic*: Age, income, household size, to readiness for energy transitions. *Techno-Economic*: Technical and economic feasibility of energy strategies. *Dynamic Urban Processes*: Traffic movement, energy storage options, incl. electric vehicles. *Simulation*: Energy simulations and visualizations of energy flexibility scenarios.	Mature bi-directional flow
8	(Ascari *et al.*, 2024)	*Traffic*: Real-time and near-time from traffic counters, IoT sensors and cloud services. *Citizens' Perceptions*: Posts and comments related to noise complaints from citizens. *Institutional* Datasets: Legacy and open noise-related and traffic-related datasets.	Advanced (real-time data enriched)
9	(Shulajkovska *et al.*, 2024)	*Geospatial*: City geometry and street maps. *Traffic*: Real-time traffic conditions and historical traffic patterns, commuting flows. *Demographic*: Population data statistics on income and living conditions. *Environmental*: Emissions data, noise data to estimate environmental impact.	Advanced (real-time data enriched)
10	(Luleci *et al.*, 2024)	*Topographic*: Terrain elevations, water bodies, and vegetation specific to the region. *Infrastructure*: Roads, bridges, power plants, electrical substations, water treatment plants, healthcare facilities, emergency services, law enforcement units, educational institutions, parks, recreational facilities, government buildings, and waste facilities. *Economic*: Zoning, tax rates for different zones and simplified economic mechanisms *Natural Disaster Data*: Probabilities for storms, tornadoes, and wildfires, disaster amplitudes. *Traffic*: Rules, speed limits, number of lanes, traffic signal locations, public transit	Advanced (real-time data enriched)
11	(Villanueva-Merino *et al.*, 2024)	*Geospatial:* City Information Model (CIM) of buildings, green areas, mobility infrastructure. *Social*: Age-Friendly Neighbourhood Index (AFNI) framework evaluating age-friendliness of outdoor spaces and buildings, transport and mobility, housing, and social participation. *Solutions Catalogue*: A repository of urban interventions aimed at improving age-friendliness. *Simulation module*: AI to evaluate and optimize the age-friendliness of urban areas *Multicriteria Analysis*: A decision-support tool to prioritize urban interventions.	Advanced (real-time data enriched)

Given the complexity of the undertaking, most studies reported on developed workflows, methodologies, or multidimensional frameworks for sourcing and integrating socio-economic, ecological, governance and other data (e.g., Yigitcanlar *et al.*, 2019). The few studies that developed functional or mature digital twins investigated the integration of social dimensions into traditionally technological frameworks to support socially and environmentally inclusive urban interventions (Shulajkovska *et al.*, 2024); co-creation of age-friendly neighborhoods (Villanueva-Merino *et al.*, 2024); assistance for policy makers in addressing the effects of noise and air pollution from traffic on citizens health and wellbeing (Ascari *et al.*, 2024); and assessing the resilience of socio-economically vulnerable communities during disasters (Luleci *et al.*, 2024).

5.2 The extent of systems thinking present in digital twin development studies

Studies that developed digital twin models integrated at least three or more urban systems (e.g., energy, economy, transportation, water, land use, social structures, waste management, governance) by using both structured and unstructured data sets (Table 3). This approach allowed for modelling interactions between different systems, such as the impact of policy on urban management (Castelli *et al*. 2022), and tensions between specific dimensions, such as economic development and environmental sustainability (Zhao *et al.*, 2022), or energy efficiency and occupant comfort (Zaballos *et al.*, 2020).

Table 3: Data types used in the development of urban digital twins from the applied research studies that addressed socio-ecological factors (Source: Authors' own work)

	Type of data	Examples
Structured	Physical and Geospatial	3D and BIM models of city buildings, hydrodynamic modes, infrastructure, topographic maps, surface models and maps, spatial locations, and terrain
	Environmental Data	Weather patterns, temperature, lighting, air quality, water quality, wind flow, noise, heating efficiency, flood sensors, solar panel data, vegetation index, green spaces, and other ecological factors
	Social and Demographic	Population demographics (including age, disability and socioeconomic status), social vulnerability.
	Economic Data	Real estate values, land use, commercial zones, and industrial areas, economic activities, food waste system, social services, and cultural settings.
	Mobility Data	Traffic flows, congestion patterns, public transportation usage, walkability, driving habits and pedestrian movement patterns.
	Human Behavior Data	Patterns and trends in human activities and behaviors within the city (e.g. commuting patterns, walkability preferences)
	Health and Wellbeing	Health-related information, emotion detection system for acoustic, visual and thermal comfort, quality of life metrics, access to recreational amenities.
	Policy and Governance	Urban planning regulations, zoning laws, and policy frameworks. Decision-making processes, governance structures, and stakeholder engagement
Unstructured	Citizens' perceptions	Textual information (such as social media posts), visual data (images, videos), and audio data (e.g. noise levels) for comprehensive situational awareness

The involvement of various stakeholders and communities was therefore seen as a of critical determinant of the extent of systems thinking approaches. For example, the case study of Herrenberg (Dembski *et al.*, 2020) discussed a digital twin development that incorporated both structured (e.g., 3D city and BIM models, street networks, environmental data, and time series data) and unstructured data (e.g., photos, recordings of street noise, citizens' comments as text notes) to visualize and simulate 'what if' scenarios to enable public participation in decision-making processes. Moreover, to promote social inclusion and more effective governance, this study included youth and other demographic groups that are typically sidelined in urban planning processes (Dembski *et al.* 2020). Engaging stakeholders by sourcing citizen data allows for local knowledge, concerns and perspectives to be incorporated, which is important in ensuring that socio-ecological factors are considered in decision-making processes. Yet, while crucial, studies highlight the inherent difficulty in ensuring meaningful and representative citizen participation and the need for trust in local governments (Kumalasari *et al.*, 2023; Nijkamp *et al.*, 2023)

While most of the reviewed digital twin models remain in the pilot phase, several studies included digital twins with bidirectional data capabilities that allow for real-time optimization of physical assets (e.g., Chen *et al.*, 2024; Coors and Padsala, 2024) that could be considered more mature models (Masoumi *et al.*, 2023). These studies illustrate the growing level of systems thinking in linking technological applications with social data, policy instruments and stakeholder engagement efforts.

5.3 Practical challenges for realizing socio-ecological digital twin models

Our review also revealed many technological and strategic challenges faced by the development of large-scale digital twins in addressing socio-ecological and environmental goals. These challenges were categorized into three broad categories (Table 4).

As data sits at the foundation of all digital twin models, sourcing and processing of the relevant data surfaced as critical considerations. Kumalasari *et al.* (2023) illustrate how gathering accurate and comprehensive data on citizens' walking preferences is both difficult and time-consuming. Zaballos *et al.* (2020) illustrate the challenge of handling of the vast IoT-generated data, which requires robust data storage, processing and visualization systems to ensure real-time monitoring and support decision-making processes. There was a consensus across the literature that analysis of the vast production of data from projects, sensors, and users, increasingly relies on machine learning and artificial intelligence methods. Moreover, the use of social data can raise ethical and legal questions (Lupton, 2015). Further, the expansion of automated data collection and processing has brought another set of related challenges, including privacy, ethics, discrimination, bias, calibration, and overfitting (Helbing *et al.*, 2021). Simply put, as datasets grow larger, their filtering generally becomes less efficient (Caldarelli *et al.*, 2023). This unfettered production of data also signals a separation between the digital and the human whereby one of the purported benefits of the digital revolution—the production of 'big data'—can becomes dangerous without recognizing our limited ability to make use of it (Ewart, 2018).

Model-related challenges are closely related to those of data integration due to the known challenges in achieving interoperability necessary for interdisciplinary collaboration. Creating digital twin models with a socio-ecological focus requires inputs not only from the allied built environment disciplines, but also from the fields of sociology, anthropology, ecology, and planning. For example, Savage et al. (2022) found that in the UK, changes in energy consumption patterns resulting from a combination of measures in carbon tax, technology adoption and land use data would affect social inequality. However, coordinating diverse disciplines alone is challenging (Zaballos *et al.*, 2020). Furthermore, each discipline uses domain-specific tools and methodologies, potentially perpetuating a 'silo' mentality (Nikolić and Whyte, 2021).

Table 4: Overview of select hindrances to the development of large-scale digital twins (Source: Authors' own work)

Category	Issues	Description
Data	Volume/Quality	Overproduction of unusable data vs. co-production of socially relevant information; data quality; data errors
	Bias	Selection bias or misrepresentation of marginalized communities in the design and deployment of digital twins
	Availability/Ethics	Private, proprietary or other sensitive data, especially social data; security, legal and commercial boundaries
	Heterogeneity	Domain-specific data types and formats; qualitative vs. quantitative; static vs. dynamic; spatio-temporal, coding and structuring approaches
	Reusability	Lessons learned recorded in a machine-readable form; cross-pollination or knowledge between projects and domains
	Ownership	Enable individuals and communities to envisage and understand data on a human scale; calibration of citizens data
Model	Complexity	Physical, social, ecological datasets; dynamic spatial-temporal and socio-ecological changes
	Abstraction	Abstraction in content, scale, detail and time, to limit the computation and load time of spatial and other types of analysis.
	Optimization	Model assumptions are clear; data are transparent; trade-offs and contradictions between different targets and outcomes
Integration	Siloed development	Within the design, social, and engineering sciences; between research and practice; techno-rationalism and corporatization of technology
	Interoperability	Integrating multiple GIS, BIM, CIM, 2D and 3D data models; individual technology solutions
	Scalability	Difficulty to apply model structures to other contexts; required upgrades to existing assets, resource allocation, user adaptation, security
	Digital divide	DT development and integration bound to the available investments and resources at district, region or country levels

With respect to models, the difficulty of simulating complex 'systems of systems', such as urban environments has long been debated, and some have questioned the prioritization of digital twins over less complex monitoring systems (Ferré-Bigorra *et al.*, 2022). Moreover, the general abstraction levels of digital twin models, while necessary to reduce computation time of analyses, suggest that the 'mirror concept' of reality cannot work for these applications (Stoter *et al.*, 2021). And while it might be naïve to expect digital twins to fully represent a complex reality, the decisions about what to include or exclude remain critical. Stoter et al. (2021) further investigated the inherent uncertainty of complex systems that is often missing from digital twin models and suggested that simulations should not be confused with predictions of reality. This is also true of the types of interactions that are modelled, as they often synergistic, probabilistic, and variable across spatial and temporal scales (Caldarelli et al. 2023). In turn, these processes may result in recommendations that favor a specific criterion at a single point in time. Further, Caldareli et al. (2023) argued that digital twins are often focused on shorter-term dynamics rather than changes over years or decades. Moreover, complexity theory has surfaced as a framework for designing smart cities (e.g., Yossef Ravid & Aharon-Gutman, 2023) to address issues of uncertainty, diversity and emergence and inform policymakers on how to address unpredictable behavior of urban systems (Caldarelli *et al.*, 2023).

As the challenges above illustrate, the integration of data, models and approaches across domains and scales remains the overarching obstacle in the development of urban digital twins as the integration of diverse datasets, models and methods that can better assess human behavior remain underexplored (Delmelle, 2021). Despite notable developments in multi-dimensional urban digital twins, the domain remains nascent and faces challenges and trade-offs, prompting some to critique these developments as too 'physicalist' while massively oversimplifying human interactions (Caldarelli *et al.*, 2023), and for their heavy reliance on technology as a means to address urban and environmental challenges (Nochta *et al.*, 2019; Yossef Ravid and Aharon-Gutman, 2023). For example, advanced smart city initiatives, such as those for Singapore[1] and Beijing[2], increasingly embed new technologies into urban design and infrastructure retrofits, which presents challenges for the city's phased developments and the pace of technological development. As Quek et al. (2023) illustrated, cities develop at a much slower pace than technologies, and by the time urban projects are completed, technological solutions will be outdated. This further exacerbates the challenges of integration, interoperability, and compatibility, perpetuating the cycle of pursuing technological solutions to technology-created problems.

6. Discussion

Recent developments in urban digital twins testify to the complexity of replicating complex and evolving systems, which is perhaps one of the reasons for the prevalent adoption of technocratic approaches that prioritize single systems that tend to ignore wider social and environmental factors (Kitchin, 2014; Semeraro *et al.*, 2021). As Bi and Little (2022) illustrated, major societal challenges (e.g., climate adaptation, sustainable energy, healthy environments) that share multiple systems (e.g., land-use, agriculture, watershed, energy, transportation, social systems, etc.) would all need to be integrated into models that connect across building and urban scales to truly understand their interactions. This inevitably presents challenges for developing large-scale digital twins to accurately represent the dynamics of such complex systems. Moreover, even advanced developments of socio-ecological digital twins struggle to capture these multi-dimensional interactions as they often reveal tensions between the two primary areas of interest.

From the perspective of addressing grand challenges, this suggests that large-scale urban digital twin models will always remain partial representations of reality, as some systems and data inputs will inevitably be prioritized over others. In fact, Batty (2018b) doubted that the development of comprehensive urban digital twin models will be ever possible, while others frame this as simply a matter of maturation (Masoumi *et al.*, 2023). Nochta *et al.* (2021) illustrated this by describing the difficulty in defining socio-political data for modelers of digital cities, resulting in models that often ignore such complexities in favour of more easily represented technical data. As a result, this pragmatic oversimplification of models can perpetuate the use of existing strategies that focus on discreet, single-issue interventions, ultimately falling short of meeting sustainable built environment goals (Omrany and Al-Obaidi, 2024).

Put simply, because the predictability of complex systems is inherently limited, so too are digital twins as their model representations. For this reason, the phrase itself has invited criticism of its applicability or appropriateness. Batty (2018b) calls the 'digital twin' a cliché as he argues that a digital representation of the real system is still too abstract to be considered its mirror-like replica. Tomko and Winter (2019) similarly argue that the 'twin' metaphor is axiomatically ill-conceived and should be replaced with a cyber-physical-social system because the coupling of the physical with the digital is more akin to an organism 'with a brain' rather than a mechanism.

Furthermore, the overarching technological influence on urban governance in which social perspectives have largely been absent presents academics, professionals, and policy makers with the challenge of facilitating outcome-based and value-driven decision making processes that

[1] https://www.smartnation.gov.sg

[2] https://www.beijingcitylab.com/projects-1/43-smart-cities-review/

support more comprehensive social, environmental and economic values. A general survey of digital twin applications in design and construction reflects rather an engineering approach to meeting decarbonization goals through increasing energy performance and reducing waste, although under the changing terminology of green, smart, high performance, carbon-neutral or net-zero buildings. Consequently, the global quest for smart products, buildings, cities and systems has been met with an ever-growing and more diversified digital ecosystem of software and siloed technological developments, a situation that has prompted calls for the technological dimension to be included in the sustainability trifecta of economic, environmental and social goals guiding the urban planning and development (Quek *et al.*, 2023). A paradox of the technological optimism is that the technical fixes are viewed as solutions to all problems, including those that are non-technical in nature, while social and economic factors are viewed as obstacles, rather than essential to designing solutions (Rudolph, 2023). As a result, most indicators developed so far have been primarily describing the state of the environment, rather than the relationship between society and ecosystems (Azar *et al.*, 1996).

There is a tension between the aspirational view of connected digital twins in achieving sustainable built environment goals and their practical development, which is largely driven by efficiency measures in infrastructure operations. However, this presents an opportunity to ask broader, more impactful questions about our objectives, and move beyond a narrow, physicalist view of social, transportation or health infrastructures—an approach that often perpetuates single-issue interventions. By shifting this perspective, we can start viewing roads and bridges, for example, not just as components of transportation networks, but also as public spaces that foster social interaction and community engagement, blurring the distinction between economic and social infrastructure. For example, exploring how digital twins can help us understand and investigate options for a healthy urban environment opens new avenues for identifying the interconnected factors that shape cities across multiple dimensions. In the case of healthy urban environments, this might include quantitative epidemiological data, policy-driven data on healthcare services, environmental surveys of biodiversity, as well as qualitative socio-ecological data on green spaces, emotional wellbeing, cultural significance and so on. Hence, it is becoming imperative to promote conversations between the allied built environment and social disciplines to avoid single-issue dominance that could lead to unintended consequences, furthered by partially informed policies (Whyte *et al.*, 2020). This has implications for how digital twins are developed and implemented, demanding new processes and guidelines driven by strategic and purposeful questions. Ultimately, as Grieves (2019) argues, the success of digital twins will need to create value for the users of the systems, generally defined through value propositions or “use cases”.

To support purposeful questioning and assess the viability of developing complex socio-ecological digital twins, we discerned three broad areas of consideration (Table 5). We begin with a strategic value proposition that informs the subsequent technological and governance approaches to their development, implementation and life cycle operation. The strategy begins with a value proposition in the form of specific and well-defined practical questions that a given digital twin should help answer. Apart from data accessibility and associated ethical concerns, the lack of viable value propositions further hampers collaboration across sectors (Nochta *et al.*, 2021; Tomko and Winter, 2019). This involves identifying the needs of both primary users (such as engineers, operators, and decision-makers) and affected users (such as citizens) who are also often sources of information and knowledge. Given that digital twin models are dynamic, this process is of course iterative and needs to account for new information and questions over time. It has been widely recognized that future urban digital twins will require scalable solutions whereby multiple professional domains contribute data and inform relevant analyses (Savage *et al.*, 2022). Researchers that develop complex digital twins employ knowledge from at least three or more disciplines, such as urban planning, environmental science, computer science (Dembski *et al.*, 2020), energy and transportation, cognitive science, urban planning, data science and AI (Castelli *et al.*, 2022). This further involves defining appropriate spatial and temporal boundaries with functionality to determine the technology considerations.

Table 5: Areas of consideration for developing, implementing and updating large scale digital twins (Source: Authors' own work)

DT	Plan / Design / Build / Operate / Upgrade		Potential challenges
Strategy	Value proposition	What question(s) should the DT help answer? Who will benefit from the DT? (Who is the primary user? Who are affected users?)	▪ Purpose and/or goal underspecified ▪ Product-driven rather than a value-driven process
	Type	Product; Process; System; System of Systems (SoS)	▪ Scope and information requirements unclear
	Purpose	Emulate; Simulate	▪ Function ambiguous (monitoring, control, prognostic, optimization, simulation, etc.)
	Spatial scale	Building, neighbourhood, city, region	▪ Scope, content, information requirements not clear
	Temporal scale	Pragmatic (short term), progressive (mid-term), transformational (long term)	▪ Data and information update cycles not specified ▪ Deterministic approach to DT development (no evolution in data and questions)
	Knowledge sourcing	Public participation; Expert collaboration Data interpolation and extrapolation	
Technology	Data	Collection (source, type, format) Processing (filtering, analysis, synthesis)	▪ Data availability, interoperability ▪ Conflicting spatial/time scales of data and information
	Modeling	Stochastic vs. deterministic System dynamics; agent based modeling	▪ System/process complexity, uncertainty and variability ▪ Tension between deterministic and stochastic approaches
	Visualization	Static, dynamic, dashboards, interfaces.	▪ Misrepresentation, not closing the feedback loop
	Metrics	Environmental; Social; Economic; Ecological, etc	▪ Unclear performance metrics or lack of quantifiable metrics
	Temporal integration	Real time; Batch processing	▪ Human control vs automation
Governance	Data governance	Quality and integrity Security and privacy Data sharing and interoperability standards Data ownership and access control	▪ DT solutions developed independently ▪ Costs of technology solutions and resources ▪ Coordination between government agencies, private companies, and the public
	Regulatory policies	Ethical guidelines Environmental regulations Public engagement and transparency Liability and accountability	▪ Technology development outpacing the policies

Developing relevant metrics is also essential for monitoring performance and outcomes and can be achieved through advanced analytics and machine learning algorithms. Moreover, technology integration is key and can often be facilitated through cloud computing, edge computing, and advanced simulation software. Recognizing the diverse range of potential users—many of whom are knowledgeable laypeople rather than technical experts—requires developing accessible and relevant modes of data presentation and visualization tools. Lastly, effective governance is vital in the implementation of digital twins to ensure data quality, security, and privacy, and guidelines on data ownership, access control, ethical implications, and regulatory compliance are necessary to protect sensitive data and maintain trust. However, to date the proliferation of many public and private research and development efforts have further diversified the digital ecosystem at the expense of knowledge sharing and cross-domain collaboration, leaving the development of urban digital twins in perpetual infancy (Shahat *et al.*, 2021).

This approach aims to foster conversations among professionals, much like the way that BIM standards and codes of practice have structured conversations around the information management process among project team members. While many challenges remain, this guideline would also promote transparency in defining priorities, identifying potential risks and limitations across all stages of development, implementation and operation.

7. Conclusions and recommendations for future research

The urgencies of climate change and sustainable development have propelled explorations of large-scale urban digital twins as a data-centric, cross-disciplinary platform that could promote better decisions through mutual learning, public participation, and stakeholder engagement. We reviewed publications on urban digital twins to identify the extent of socio-ecological and systems thinking in the context of sustainable built environment. Our analysis illustrated that this is a fast-growing area of research, although urban digital twin conceptualization, development, and implementation remain in an early stage, based on narratives intersecting with those of smart cities. The complexity of urban environments—shaped by spatial, social, environmental, and economic factors—has proven challenging for digital 'twinning'. This has left most digital twin developments falling well short of effective modeling or inclusion of socio-ecological and socio-technical factors.

Although a socio-ecological perspective expands the sustainability framework by promoting systems thinking and introduces new theories that necessitate multidisciplinary approaches, our analysis illustrated that current urban digital twins tend to focus on a limited number of datasets and do not consider practical interventions within larger, complex systems. However, some recent studies have begun to explore ways to develop complex digital twins that align with socio-ecological thinking, where urbanization, biodiversity, socio-economic development and environmental management intersect. These studies often emphasize how certain critical requirements for socio-ecological digital twin developments, such as public participation and interdisciplinary collaboration remain the most difficult to manage. Furthermore, efforts to address technological bottlenecks, such as data interoperability, federation, integration, scalability and futureproofing, continue to challenge the development of digital twins, often at the expense of socio-ecological dimensions that could shape intervention scenarios.

These conclusions led us to recognize that, to foster more impactful questioning of the purpose and value of digital twin development and to support interdisciplinary conversations, we needed to propose an initial set of key considerations and associated risks that make assumptions and priorities more transparent. Our contribution to this debate is a preliminary framework that emphasizes an interactive cycle of purpose-driven digital twin development, where strategic questions about goals, data, systems boundaries, and interdisciplinary and citizen engagement inform technology- and governance-related considerations. Future research needs to expand this framework into a more comprehensive set of guidelines or potentially a code of practice, challenging the existing preoccupation with technological aspects and purported solutions. Furthermore, since our analysis is limited to publications in English, dominated primarily by western industrialised contexts, future research should also address this limitation by expanding into broader cultural and international perspectives that go beyond the net zero agenda, making use of socio-ecological digital twins.

With this work, we have contributed to the body of knowledge on applying systems thinking to the development of socio-ecological urban digital twins. We build on prior reviews that focused on developing technical and socio-technical frameworks, offering a novel approach to the purpose-driven development of complex digital twins. When well-designed, urban digital twins—like other technologies—should support human agency, improve society and democratize decision-making, while leveraging interdisciplinary expertise without relinquishing responsibility and authority. However, integrating diverse datasets and disciplines requires not only overcoming technical challenges, but also crafting new narratives around salient spatial, social, and ecological features in the urban environment. Perhaps, reframing these challenges as beneficial socio-ecological opportunities rather than obstacles could shift our collective academic focus beyond the technology itself toward a more nuanced and productive engagement with the world.

References

Allam, Z. and Jones, D.S. (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*, Vol. 101, p. 105201, doi: 10.1016/j.landusepol.2020.105201.

Allen, T.R., McLeod, G., Richter, H. and Nielsen, A. (2022), "Digitally Twinning Coastal Resilience Via Multsensor Imagery, in Situ Sensors, and Geospatial Analysis", *IGARSS 2022 - 2022 IEEE International Geoscience and Remote Sensing Symposium*, pp. 4739–4742, doi: 10.1109/IGARSS46834.2022.9883133.

Ameen, R.F.M., Mourshed, M. and Li, H. (2015), "A critical review of environmental assessment tools for sustainable urban design", *Environmental Impact Assessment Review*, Vol. 55, pp. 110–125, doi: 10.1016/j.eiar.2015.07.006.

Arsiwala, A., Elghaish, F. and Zoher, M. (2023), "Digital twin with Machine learning for predictive monitoring of CO2 equivalent from existing buildings", *Energy and Buildings*, Vol. 284, p. 112851, doi: 10.1016/j.enbuild.2023.112851.

Ascari, E., Cerchiai, M., Gorrasi, P., Longo, A., Mencagli, G., Miccoli, F. and Zappatore, M. (2024), "OUTFIT: Crowdsourced Data Feeding Noise Maps in Digital Twins", *Proceedings of the 4th Workshop on Flexible Resource and Application Management on the Edge*, Association for Computing Machinery, New York, NY, USA, pp. 39–46, doi: 10.1145/3659994.3660312.

Azar, C., Holmberg, J. and Lindgren, K. (1996), "Socio-ecological indicators for sustainability", *Ecological Economics*, Vol. 18 No. 2, pp. 89–112, doi: 10.1016/0921-8009(96)00028-6.

Batty, M. (2018a), "Artificial intelligence and smart cities", *Environment and Planning B: Urban Analytics and City Science*, SAGE Publications Ltd STM, Vol. 45 No. 1, pp. 3–6, doi: 10.1177/2399808317751169.

Batty, M. (2018b), "Digital twins", *Environment and Planning B: Urban Analytics and City Science*, Vol. 45 No. 5, pp. 817–820, doi: 10.1177/2399808318796416.

Bi, C. and Little, J.C. (2022), "Integrated assessment across building and urban scales: A review and proposal for a more holistic, multi-scale, system-of-systems approach", *Sustainable Cities and Society*, Vol. 82, p. 103915, doi: 10.1016/j.scs.2022.103915.

Brandl, J. and Zielinska, I. (2020), "Reviewing the Smart City Vienna Framework Strategy's Potential as an Eco-Social Policy in the Context of Quality of Work and Socio-Ecological Transformation", *Sustainability*, Vol. 12 No. 3, p. 859, doi: 10.3390/su12030859.

Caldarelli, G., Arcaute, E., Barthelemy, M., Batty, M., Gershenson, C., Helbing, D., Mancuso, S., *et al.* (2023), "The role of complexity for digital twins of cities", *Nature Computational Science*, Vol. 3 No. 5, pp. 374–381, doi: 10.1038/s43588-023-00431-4.

Castelli, G., Cesta, A., Ciampi, M., De Benedictis, R., De Pietro, G., Diez, M., Felici, G., *et al.* (2022), "Urban Intelligence: Toward the Digital Twin of Matera and Catania", *2022 Workshop on Blockchain for Renewables Integration (BLORIN)*, pp. 132–137, doi: 10.1109/BLORIN54731.2022.10028437.

CDBB. (2019), “National Digital Twin Programme”, available at: https://www.cdbb.cam.ac.uk/what-we-did/national-digital-twin-programme (accessed 31 July 2023).

Chen, G., Alomari, I., Taffese, W.Z., Shi, Z., Afsharmovahed, M.H., Mondal, T.G. and Nguyen, S. (2024), “Multifunctional Models in Digital and Physical Twinning of the Built Environment—A University Campus Case Study”, *Smart Cities*, Vol. 7 No. 2, pp. 836–858, doi: 10.3390/smartcities7020035.

Climate Change Committee. (2019), “Net Zero - The UK’s contribution to stopping global warming”, *Climate Change Committee*, available at: https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/ (accessed 31 July 2023).

Colding, J. and Barthel, S. (2017), “An urban ecology critique on the ‘Smart City’ model”, *Journal of Cleaner Production*, Vol. 164, pp. 95–101, doi: 10.1016/j.jclepro.2017.06.191.

Coors, V. and Padsala, R. (2024), “Urban Digital Twins Empowering Energy Transition: Citizen-Driven Sustainable Urban Transformation towards Positive Energy Districts”, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XLVIII-4-W10-2024, pp. 51–56, doi: 10.5194/isprs-archives-XLVIII-4-W10-2024-51-2024.

Cruz, P., Oliveira, I., Figueiredo, B., Lopes, J. and Freitas, P. (2023), “Towards e-Cities: An Atlas to Enhance the Public Realm Through Interactive Urban Cyber-Physical Devices”:, *Proceedings of the 12th International Conference on Smart Cities and Green ICT Systems*, Prague, Czech Republic, pp. 58–69, doi: 10.5220/0011975500003491.

Cureton, P. and Hartley, E. (2023), “City Information Models (CIMs) as precursors for Urban Digital Twins (UDTs): A case study of Lancaster”, *Frontiers in Built Environment*, Vol. 9, doi: 10.3389/fbuil.2023.1048510.

Delmelle, E.C. (2021), “Toward a More Socially Impactful Geographical Analysis”, *Geographical Analysis*, Vol. 53 No. 1, pp. 148–156, doi: 10.1111/gean.12213.

Dembski, F., Wössner, U., Letzgus, M., Ruddat, M. and Yamu, C. (2020), “Urban Digital Twins for Smart Cities and Citizens: The Case Study of Herrenberg, Germany”, *Sustainability*, Vol. 12 No. 6, p. 2307, doi: 10.3390/su12062307.

Du Plessis, C. (2013), “Chaos and Resilience: The Johannesburg Experience”, In L. Pearson, P. Newton, & P. Roberts (Eds.), *Resilient sustainable cities: A future* (pp. 161–179). Routledge. https://doi.org/10.4324/9781315881232

Elsawah, S., Filatova, T., Jakeman, A.J., Kettner, A.J., Zellner, M.L., Athanasiadis, I.N., Hamilton, S.H., *et al.* (2019), “Eight grand challenges in socio-environmental systems modeling”, *Socio-Environmental Systems Modelling*, Vol. 2, doi: 10.18174/sesmo.2020a16226.

Ewart, I.J. (2018), “Humanising the Digital: A Cautionary View of the Future”, In Dixon, T., Connaughton, J. and Green, S. (Eds.), *Sustainable Futures in the Built Environment to 2050*, John Wiley & Sons, Ltd, pp. 325–335, doi: 10.1002/9781119063834.ch16.

Facchini, A., Mele, R. and Caldarelli, G. (2021), “The Urban Metabolism of Lima: Perspectives and Policy Indications for GHG Emission Reductions”, *Frontiers in Sustainable Cities*, Frontiers, Vol. 2, doi: 10.3389/frsc.2020.00040.

Felappi, J.F., Sommer, J.H., Falkenberg, T., Terlau, W. and Kötter, T. (2020), “Green infrastructure through the lens of ‘One Health’: A systematic review and integrative framework uncovering synergies and trade-offs between mental health and wildlife support in cities”, *Science of The Total Environment*, Vol. 748, p. 141589, doi: 10.1016/j.scitotenv.2020.141589.

Ferré-Bigorra, J., Casals, M. and Gangolells, M. (2022), “The adoption of urban digital twins”, *Cities*, Vol. 131, p. 103905, doi: 10.1016/j.cities.2022.103905.

Grieves, M.W. (2019), "Virtually intelligent product systems: digital and physical twins", In S. Flumerfelt, D. Schwartz, L. J. Hoverstadt, S. M. Bowers, & G. N. Rzevski (Eds.), *Complex systems engineering: Theory and practice* (pp. 175–200). American Institute of Aeronautics and Astronautics. doi: 10.2514/5.9781624105654.0175.0200

Hajek, P., Youssef, A. and Hajkova, V. (2022), "Recent developments in smart city assessment: A bibliometric and content analysis-based literature review", *Cities*, Vol. 126, p. 103709, doi: 10.1016/j.cities.2022.103709.

Helbing, D., Fanitabasi, F., Giannotti, F., Hänggli, R., Hausladen, C.I., van den Hoven, J., Mahajan, S., *et al.* (2021), "Ethics of Smart Cities: Towards Value-Sensitive Design and Co-Evolving City Life", *Sustainability*, Vol. 13 No. 20, p. 11162, doi: 10.3390/su132011162.

Hill, J.E., Harris, C. and Clegg, A. (2024), "Methods for using Bing's AI-powered search engine for data extraction for a systematic review", *Research Synthesis Methods*, Vol. 15 No. 2, pp. 347–353, doi: 10.1002/jrsm.1689.

Hofmeister, M., Brownbridge, G., Hillman, M., Mosbach, S., Akroyd, J., Lee, K.F. and Kraft, M. (2024), "Cross-domain flood risk assessment for smart cities using dynamic knowledge graphs", *Sustainable Cities and Society*, Vol. 101, p. 105113, doi: 10.1016/j.scs.2023.105113.

Hunter, G.W., Sagoe, G., Vettorato, D. and Jiayu, D. (2019), "Sustainability of Low Carbon City Initiatives in China: A Comprehensive Literature Review", *Sustainability*, Vol. 11 No. 16, p. 4342, doi: 10.3390/su11164342.

Iacopini, I., Schäfer, B., Arcaute, E., Beck, C. and Latora, V. (2020), "Multilayer modeling of adoption dynamics in energy demand management", *Chaos: An Interdisciplinary Journal of Nonlinear Science*, Vol. 30 No. 1, p. 013153, doi: 10.1063/1.5122313.

Jiang, F., Ma, L., Broyd, T., Chen, W. and Luo, H. (2022), "Digital twin enabled sustainable urban road planning", *Sustainable Cities and Society*, Vol. 78, p. 103645, doi: 10.1016/j.scs.2021.103645.

Ketzler, B., Naserentin, V., Latino, F., Zangelidis, C., Thuvander, L. and Logg, A. (2020), "Digital twins for cities: A state of the art review", *Built Environment*, Vol. 46 No. 4, pp. 547–573, doi: 10.2148/benv.46.4.547

Kitchin, R. (2014), "The real-time city? Big data and smart urbanism", *GeoJournal*, Vol. 79 No. 1, pp. 1–14, doi: 10.1007/s10708-013-9516-8.

Kumalasari, D., Koeva, M., Vahdatikhaki, F., Petrova Antonova, D. and Kuffer, M. (2023), "Planning Walkable Cities: Generative Design Approach towards Digital Twin Implementation", *Remote Sensing*, Vol. 15 No. 4, p. 1088, doi: 10.3390/rs15041088.

Kumar, S.A.P., Madhumathi, R., Chelliah, P.R., Tao, L. and Wang, S. (2018), "A novel digital twin-centric approach for driver intention prediction and traffic congestion avoidance", *Journal of Reliable Intelligent Environments*, Vol. 4 No. 4, pp. 199–209, doi: 10.1007/s40860-018-0069-y.

Landman, K. (2021), "Rapidly Changing Cities: Working with Socio-Ecological Systems to Facilitate Transformation", *Urban Planning*, Vol. 6 No. 2, pp. 139–142, doi: 10.17645/up.v6i2.4472.

Lenfers, U.A., Ahmady-Moghaddam, N., Glake, D., Ocker, F., Osterholz, D., Ströbele, J. and Clemen, T. (2021), "Improving Model Predictions—Integration of Real-Time Sensor Data into a Running Simulation of an Agent-Based Model", *Sustainability*, Vol. 13 No. 13, p. 7000, doi: 10.3390/su13137000.

Levin, K., Cashore, B., Bernstein, S. and Auld, G. (2012), "Overcoming the tragedy of super wicked problems: constraining our future selves to ameliorate global climate change", *Policy Sciences*, Vol. 45 No. 2, pp. 123–152, doi: 10.1007/s11077-012-9151-0.

Li, X., Luo, J., Li, Y., Wang, W., Hong, W., Liu, M., Li, X., *et al.* (2022), "Application of effective water-energy management based on digital twins technology in sustainable cities construction", *Sustainable Cities and Society*, Vol. 87, p. 104241, doi: 10.1016/j.scs.2022.104241.

Liu, H. and Zoh, K. (2024), "Smart landscaping design for sustainable net-zero energy smart cities: Modeling energy hub in digital twin", *Sustainable Energy Technologies and Assessments*, Vol. 65, p. 103769, doi: 10.1016/j.seta.2024.103769.

Liu, P., Zhao, T., Luo, J., Lei, B., Frei, M., Miller, C. and Biljecki, F. (2023), "Towards Human-centric Digital Twins: Leveraging Computer Vision and Graph Models to Predict Outdoor Comfort", *Sustainable Cities and Society*, Vol. 93, p. 104480, doi: 10.1016/j.scs.2023.104480.

Luleci, F., Sevim, A., Ozguven, E.E. and Catbas, F.N. (2024), "Community Twin Ecosystem for Disaster Resilient Communities", *Smart Cities*, Vol. 7 No. 6, pp. 3511–3546, doi: 10.3390/smartcities7060137.

Lupton, D. (2015), *Digital Sociology*, Routledge, London, doi: 10.4324/9781315776880.

Marcotullio, P.J. and Solecki, W. (2013), "What Is a City? An Essential Definition for Sustainability", in Boone, C.G. and Fragkias, M. (Eds.), *Urbanization and Sustainability: Linking Urban Ecology, Environmental Justice and Global Environmental Change*, Springer Netherlands, Dordrecht, pp. 11–25, doi: 10.1007/978-94-007-5666-3_2.

Masoumi, H., Shirowzhan, S., Eskandarpour, P. and Pettit, C.J. (2023), "City Digital Twins: their maturity level and differentiation from 3D city models", *Big Earth Data*, Taylor & Francis, Vol. 7 No. 1, pp. 1–36, doi: 10.1080/20964471.2022.2160156.

Mundoli, S., Unnikrishnan, H. and Nagendra, H. (2017), "The 'Sustainable' in smart cities: ignoring the importance of urban ecosystems", *DECISION*, Vol. 44 No. 2, pp. 103–120, doi: 10.1007/s40622-017-0152-x.

Nel, D., du Plessis, C. and Landman, K. (2018), "Planning for dynamic cities: introducing a framework to understand urban change from a complex adaptive systems approach", *International Planning Studies*, Routledge, Vol. 23 No. 3, pp. 250–263, doi: 10.1080/13563475.2018.1439370.

Nijkamp, P., Kourtit, K., Scholten, H. and Willemsen, E. (2023), "Citizen Participation and Knowledge Support in Urban Public Energy Transition—A Quadruple Helix Perspective", *Land*, Vol. 12 No. 2, p. 395, doi: 10.3390/land12020395.

Nikolić, D. and Whyte, J. (2021), "Visualizing a New Sustainable World: Toward the Next Generation of Virtual Reality in the Built Environment", *Buildings*, Vol. 11 No. 11, p. 546, doi: 10.3390/buildings11110546.

Nochta, T., Badstuber, N. and Wahby, N. (2019), *On the Governance of City Digital Twins - Insights from the Cambridge Case Study*, Working Paper, CDBB, doi: 10.17863/CAM.41083.

Nochta, T., Wan, L., Schooling, J.M. and Parlikad, A.K. (2021), "A Socio-Technical Perspective on Urban Analytics: The Case of City-Scale Digital Twins", *Journal of Urban Technology*, Routledge, Vol. 28 No. 1–2, pp. 263–287, doi: 10.1080/10630732.2020.1798177.

Omrany, H. and Al-Obaidi, K.M. (2024), "Application of digital twin technology for Urban Heat Island mitigation: review and conceptual framework", *Smart and Sustainable Built Environment*, Emerald Publishing Limited, Vol. ahead-of-print No. ahead-of-print, doi: 10.1108/SASBE-05-2024-0189.

Onile, A.E., Machlev, R., Petlenkov, E., Levron, Y. and Belikov, J. (2021), "Uses of the digital twins concept for energy services, intelligent recommendation systems, and demand side management: A review", *Energy Reports*, Vol. 7, pp. 997–1015, doi: 10.1016/j.egyr.2021.01.090.

Papadonikolaki, E. and Anumba, C. (2022), “How can Digital Twins support the Net Zero vision?”, In: Skatulla, S., Beushausen, H. (eds) *Advances in Information Technology in Civil and Building Engineering*. ICCCBE 2022. Lecture Notes in Civil Engineering, vol 358. Springer, Cham, doi: 10.1007/978-3-031-32515-1_7

Park, J. and Yang, B. (2020), “GIS-enabled digital twin system for sustainable evaluation of carbon emissions: A case study of Jeonju city, south Korea”, *Sustainability*, Vol. 12 No. 21, p. 9186, doi: 10.3390/su12219186

Peldon, D., Banihashemi, S., LeNguyen, K. and Derrible, S. (2024), “Navigating urban complexity: The transformative role of digital twins in smart city development”, *Sustainable Cities and Society*, Vol. 111, p. 105583, doi: 10.1016/j.scs.2024.105583.

Quek, H.Y., Sielker, F., Akroyd, J., Bhave, A.N., Richthofen, A. von, Herthogs, P., Yamu, C. van der L., *et al.* (2023), “The conundrum in smart city governance: Interoperability and compatibility in an ever-growing ecosystem of digital twins”, *Data & Policy*, Vol. 5, p. e6, doi: 10.1017/dap.2023.1.

Rabeneck, A. (2008), “A sketch-plan for construction of built environment theory”, *Building Research & Information*, Routledge, Vol. 36 No. 3, pp. 269–279, doi: 10.1080/09613210801928115.

Rudolph, D. (2023), “The question of ‘sustainable’ technology: From socio-ecological fixes to transformations”, *Human Geography*, Vol. 16 No. 1, pp. 81–86, doi: 10.1177/19427786221119401.

Sadowski, J. and Bendor, R. (2019), “Selling Smartness: Corporate Narratives and the Smart City as a Sociotechnical Imaginary”, *Science, Technology, & Human Values*, Vol. 44 No. 3, pp. 540–563, doi: 10.1177/0162243918806061.

Savage, T., Akroyd, J., Mosbach, S., Krdzavac, N., Hillman, M. and Kraft, M. (2022), “Universal Digital Twin: Integration of national-scale energy systems and climate data”, *Data-Centric Engineering*, Vol. 3, p. e23, doi: 10.1017/dce.2022.22.

Schlüter, M., Müller, B. and Frank, K. (2019), “The potential of models and modeling for social-ecological systems research: the reference frame ModSES”, *Ecology and Society*, Vol. 24 No. 1, doi: 10.5751/ES-10716-240131

Semeraro, C., Lezoche, M., Panetto, H. and Dassisti, M. (2021), “Digital twin paradigm: A systematic literature review”, *Computers in Industry*, Vol. 130, p. 103469, doi: 10.1016/j.compind.2021.103469.

Shahat, E., Hyun, C.T. and Yeom, C. (2021), “City Digital Twin Potentials: A Review and Research Agenda”, *Sustainability*, Vol. 13 No. 6, p. 3386, doi: 10.3390/su13063386.

Shulajkovska, M., Smerkol, M., Noveski, G. and Gams, M. (2024), “Enhancing Urban Sustainability: Developing an Open-Source AI Framework for Smart Cities”, *Smart Cities*, Vol. 7 No. 5, pp. 2670–2701, doi: 10.3390/smartcities7050104.

Spiridonov, V.Y. and Shabiev, S.G. (2020), “The urban planning information platform: progressive methods of planning and managing the sustainable development of territories”, *IOP Conference Series: Materials Science and Engineering*, IOP Publishing, Vol. 962 No. 3, p. 032035, doi: 10.1088/1757-899X/962/3/032035.

Stoter, J., Ohori, K.A. and Noardo, F. (2021), “Digital twins: A comprehensive solution or hopeful vision?”, *GIM International: The Worldwide Magazine for Geomatics*, available at: https://pure.tudelft.nl/ws/portalfiles/portal/103735235/GIM_International.pdf (accessed 21 April 2024)

Tomko, M. and Winter, S. (2019), “Beyond digital twins – A commentary”, *Environment and Planning B: Urban Analytics and City Science*, Vol. 46 No. 2, pp. 395–399, doi: 10.1177/2399808318816992.

Tzachor, A., Sabri, S., Richards, C.E., Rajabifard, A. and Acuto, M. (2022), “Potential and limitations of digital twins to achieve the Sustainable Development Goals”, *Nature Sustainability*, Vol. 5 No. 10, pp. 822–829, doi: 10.1038/s41893-022-00923-7.

Tzoulas, K., Korpela, K., Venn, S., Yli-Pelkonen, V., Kaźmierczak, A., Niemela, J. and James, P. (2007), “Promoting ecosystem and human health in urban areas using Green Infrastructure: A literature review”, *Landscape and Urban Planning*, Vol. 81 No. 3, pp. 167–178, doi: 10.1016/j.landurbplan.2007.02.001.

United Nations Environment Programme. (2022), *Emissions Gap Report 2022: The Closing Window — Climate Crisis Calls for Rapid Transformation of Societies*, Nairobi, available at: https://www.unep.org/emissions-gap-report-2022 (accessed 12 September 2023)

Villanueva-Merino, A., Urra-Uriarte, S., Izkara, J.L., Campos-Cordobes, S., Aranguren, A. and Molina-Costa, P. (2024), “Leveraging Local Digital Twins for planning age-friendly urban environments”, *Cities*, Vol. 155, p. 105458, doi: 10.1016/j.cities.2024.105458.

Wang, H. and Wang, Y. (2024), “Smart Cities Net Zero Planning considering renewable energy landscape design in Digital Twin”, *Sustainable Energy Technologies and Assessments*, Vol. 63, p. 103629, doi: 10.1016/j.seta.2024.103629.

Waring, T.M. and Richerson, P.J. (2011), “Towards Unification of the Socio-Ecological Sciences: The Value of Coupled Models”, *Geografiska Annaler. Series B, Human Geography*, Wiley, Vol. 93 No. 4, pp. 301–314, doi: 10.1111/j.1468-0467.2011.00384.x

Whyte, J., Fitzgerald, J., Mayfield, M., Coca, D., Pierce, K. and Shah, N. (2019), “Projects as Interventions in Infrastructure Systems-of-Systems”, *INCOSE International Symposium*, Vol. 29, Wiley Online Library, pp. 542–542, doi: 10.1002/j.2334-5837.2019.00618.x

Whyte, J., Mijic, A., Myers, R.J., Angeloudis, P., Cardin, M.-A., Stettler, M.E. and Ochieng, W. (2020), “A research agenda on systems approaches to infrastructure”, *Civil Engineering and Environmental Systems*, Vol. 37 No. 4, pp. 214–233, doi: 10.1080/10286608.2020.1827396

Whyte, J. and Nikolić, D. (2018), *Virtual Reality and the Built Environment*, 2 edition., Routledge, Milton Park, Abingdon, Oxon; New York, NY, doi: 10.1201/9781315618500

Wolf, K., Dawson, R.J., Mills, J.P., Blythe, P. and Morley, J. (2022), “Towards a digital twin for supporting multi-agency incident management in a smart city”, *Scientific Reports*, Vol. 12 No. 1, p. 16221, doi: 10.1038/s41598-022-20178-8.

Ye, X., Du, J., Han, Y., Newman, G., Retchless, D., Zou, L., Ham, Y., *et al.* (2023), “Developing Human-Centered Urban Digital Twins for Community Infrastructure Resilience: A Research Agenda”, *Journal of Planning Literature*, Vol. 38 No. 2, pp. 187–199, doi: 10.1177/08854122221137861.

Yigitcanlar, T., Han, H., Kamruzzaman, Md., Ioppolo, G. and Sabatini-Marques, J. (2019), “The making of smart cities: Are Songdo, Masdar, Amsterdam, San Francisco and Brisbane the best we could build?”, *Land Use Policy*, Vol. 88, p. 104187, doi: 10.1016/j.landusepol.2019.104187.

Yossef Ravid, B. and Aharon-Gutman, M. (2023), “The Social Digital Twin: The Social Turn in the Field of Smart Cities”, *Environment and Planning B: Urban Analytics and City Science*, Vol. 50 No. 6, pp. 1455–1470, doi: 10.1177/23998083221137079.

Zaballos, A., Briones, A., Massa, A., Centelles, P. and Caballero, V. (2020), “A Smart Campus’ Digital Twin for Sustainable Comfort Monitoring”, *Sustainability*, Vol. 12 No. 21, p. 9196, doi: 10.3390/su12219196.

Zhao, D., Li, X., Wang, X., Shen, X. and Gao, W. (2022), “Applying Digital Twins to Research the Relationship Between Urban Expansion and Vegetation Coverage: A Case Study of Natural Preserve”, *Frontiers in Plant Science*, Vol. 13, doi: 10.3389/fpls.2022.840471.

Zhou, Y., Lei, H., Zhang, X., Wang, S., Xu, Y., Li, C. and Zhang, J. (2023), “Using the Dual Concept of Evolutionary Game and Reinforcement Learning in Support of Decision-Making Process of Community Regeneration—Case Study in Shanghai”, *Buildings*, Vol. 13 No. 1, p. 175, doi: 10.3390/buildings13010175.