GOING BEYOND ENERGY CONSUMPTION: DIGITAL TWINS FOR ACHIEVING SOCIO-ECOLOGICAL SUSTAINABILITY IN THE BUILT ENVIRONMENT

Dragana Nikolić & Ian J. Ewart
University of Reading, UK

ABSTRACT: *Digital twins have attracted much of the attention from the researchers and policy makers as a potent industry-agnostic concept to support ambitious decarbonization goals. Consequently, much of the latest research has focused on computational methods for building and connecting digital twins to monitor and measure energy consumption and resulting emissions from buildings. At the same time, it has been recognized that achieving a truly sustainable built environment goes beyond environmental sustainability and is much more complex, calling for approaches that transcend any single discipline. Initiatives such as the National Digital Twin in the UK and globally, begin to offer a long-term vision of interconnected, purpose-driven and outcome-focused digital twins, grounded in systems thinking. Such approaches recognize the economic, social and ecological layers as critical data components in these digital ecosystems for understanding the built environment as a whole. Yet, social and ecological sustainability will remain difficult to address without involving allied disciplines and those from the realms of sociology, ecology, or anthropology in a conversation about the critical data sitting at the intersections between human behavior and technological innovation. In this paper, we review and discuss the state of the art research on digital twins to identify the disciplines dominating the narrative in the context of a sustainable built environment. We unpack a techno-rationalist view that emphasizes the sole reliance on technology for problem-solving and argue that by going beyond energy consumption and carbon emissions, digital twins can facilitate a more nuanced assessment of sustainability challenges, encompassing social equity, cultural preservation, and ecological resilience.*

KEYWORDS: *Digital twin, socio-ecology, sustainability, smart city, review.*

1. INTRODUCTION

The alarming effects of climate change and environmental degradation have prompted various global policies to set ambitious targets for reducing carbon emission by 2050 (Climate Change Committee, 2019; United Nations Environment Programme, 2022). The urgency of climate change as well as the recent pandemic have raised many questions of what the future of the built environment should look like and how that future can be envisioned and accomplished. Carbon emission targets or achieving "net zero" have thus prompted many digital transformation initiatives as a way to mobilize technology and data science to monitor, simulate and evaluate possible solutions across sectors to meet the decarbonization goals and improve overall performance. In the built environment disciplines and construction specifically, one such initiative that has attracted much attention is the concept of digital twins as a way to connect physical and digital assets to support data-driven decision making in complex environments. In the UK for example, the National Digital Twin Programme (CDBB, 2019), offers a broad vision of connected digital twins across environmental, social and economic spheres driven by an ultimate goal of enabling people and systems to flourish. This shift has also challenged built environment practitioners to consider the long-term consequences of any 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 the global demands for energy are increasing, the pursuit of carbon emissions reduction has consequently focused efforts on understanding and reducing energy consumption in the contexts of infrastructure and building performance. However, research points out that responding to the climate challenge is far more complex, or a "super-wicked" problem that defies simplistic technological solutions and often prioritizes short-term goals with competing priorities (Levin et al., 2012; Rabeneck, 2008). Achieving a truly sustainable built environment is much more complex, calling for approaches that transcend any single discipline and move away from project-bound methodologies to those where developed models span organizational and jurisdictional units (Whyte et al., 2019). As Rabeneck (2008) argues, any understanding of asset performance demands a systems perspective to better articulate needs within a given context. Initiatives such as the National Digital Twin in the UK and globally, begin to offer a long-term vision of interconnected, purpose-driven and outcome-focused digital twins, grounded in systems thinking. Such approaches recognize the economic, social and ecological layers as critical data components in these digital ecosystems for understanding the built environment as a whole. Yet, social and ecological sustainability will remain difficult to address without involving allied disciplines and those from

Referee List (DOI: 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Dragana Nikolic, Ian Ewart, *Going Beyond Energy Consumption: Digital Twins for Achieving Socio-Ecological Sustainability in the Built Environment*, pp. 1061-1071, © 2023 Author(s), CC BY NC 4.0, DOI 10.36253/979-12-215-0289-3.106

the realms of sociology, ecology, or anthropology in a conversation about the critical data sitting at the intersections between human behavior and technological innovation.

In this exploratory paper, we review recent research around large-scale digital twins for the built environment and argue that while promoted as a potent industry-agnostic concept to support ambitious decarbonization goals, the narrative has been dominated by technology-focused methods to meet such goals. We identify literature that raises critical considerations for informing the holistic approaches to developing long-term purpose-driven digital twins for a sustainable environment. We review the relevant literature to unpack a techno-rationalist view that emphasizes the sole reliance on technology for problem-solving and argue that by going beyond energy consumption and carbon emissions, digital twins can facilitate a more nuanced assessment of sustainability challenges, encompassing social equity, cultural preservation, and ecological resilience. We explore a set of underlying assumptions and considerations such as the authority of the data, system complexity and cross-sector boundaries, and the technology landscape and procedures to enable constructive questioning. This approach allows us to understand how digital twin applications are subject to dominating business cases driving their development, which can consequently affect the design and operation of built environment projects. Moreover, we take the view that it is becoming increasingly difficult to sustain the traditional compartmentalized practices, but 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 consequences for how digital technologies are used, demanding new and different kinds of data and processes, providing new challenges to the construction informatics research community and to practitioners.

2. THE SOCIO-TECHNICAL LANDSCAPE IN THE BUILT ENVIRONMENT

The pervasiveness of digital technologies across architecture, engineering, and construction practices as seen through a convergence of material science, robotics, 3D printing, sensors, artificial intelligence, and other technologies, presents new digital capabilities that connect physical environments with digital ecosystems. Technological innovation has always been paired with urban development (Quek et al., 2023), although in recent years, the concept of technology has shifted inexorably towards the digital and the view that the world, and reality itself is no longer analogue, but is made up of a digital representation of itself (Ewart, 2018). While the proliferation of low-cost consumer-market technologies paired with big data and Internet of Things has offered an enticing world of opportunities to improve the design, delivery, and operations of physical assets, it has also raised questions about how to make sense of the ever-growing raw and complex data sets to understand how we use the built environment and make informed decisions about its future (Nikolić & Whyte, 2021).

The concept of digital twins in the built environment practice has grown out of the recognition that the delivery of physical assets has become inseparable from the delivery of its digital counterpart and with a potential for an extensive data-capture to understand its use and improve its operation. With real-time asset data enabled, information received can influence future investment decisions, especially for serial clients such as governments, and aim to either change user behaviors or assets in new project interventions (Whyte & Nikolić, 2018). The digital twin idea was first introduced in 2002 in aerospace as a concept for Product Lifecycle Management (Grieves, 2019) and its use remains predominantly in manufacturing. Recent applications in the built environment include smart city initiatives, structural health monitoring, infrastructure planning and management (e.g. power, water, transportation), agriculture, and urban planning and development. In construction, the development of digital twins gained traction only in the last five years (Opoku et al., 2021), though not without challenges (Opoku et al., 2023). Urban infrastructure and 3D city models moving beyond geometry and information have started to become developed around the same time although mostly by linking BIM models with data (Ferré-Bigorra et al., 2022).

Unlike in the aerospace and manufacturing domains, digital twins for the built environment can span greater scales, professional domains and jurisdictional units, with an increasing complexity due to the heterogeneous data sources and sub-system interactions, leading to the difficulty of reliably predicting the system performance. For example, urban planning and management increasingly relies on understanding interactions between natural, cyber-physical and social systems in the form of urban digital twins (UDT) to foster human-centered resilience (Ye et al., 2023). Digital twins at city and urban scales can offer insight into how we use the built environment and inform the decisions for future interventions, yet their development is much more complex compared to DTs at building and component scales. Urban environments and cities are dynamic living systems that constantly evolve (Quek et al., 2023) and any interventions in this complex system will be intricately tied to economic and social sustainability goals as much as environmental. 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".

There is a tension between the grand challenge of setting broad sustainability goals and the practical challenge of a system-of-systems approach necessary for addressing them. For sustainable development, some of the recent reviews of digital twin applications and research (e.g. Papadonikolaki & Anumba, 2022) reveal that while holding a promise of a method to mitigate and adapt to environmental changes, the focus has been mostly on the decarbonization efforts in the energy sector and reducing energy consumption across the domains, including buildings. The research on design and delivery of buildings has encapsulated such efforts through increasing energy performance and reducing waste, although under the changing terminology of green, smart, high performance, carbon-neutral or net-zero buildings (Bonci et al., 2019; Gultekin et al., 2013; Korkmaz et al., 2010). A general survey of digital twin applications in design and construction domains, however, reflects rather an engineering approach to meeting decarbonization goals through improved sensing, monitoring, material, and data science, or predicting and simulating occupant behavior; and approach challenged by the view that the building performance is realized over time, rather than predetermined (Green & Sergeeva, 2020). The difficulty of such compartmentalized approaches and domain-specific definition of local carbon targets is that the outcomes may be insufficient to recognize the impact in a larger context and the system within which such interventions operate. 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).

The dominating narrative around net-zero carbon has prompted predominantly technology-oriented approaches to decarbonization, whether they refer to extending renewable energy technologies or improving the energy performance of buildings and infrastructure. 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). However, Waring & Richerson (2011) argued that such environmental challenges are in fact, socio-ecological in nature and therefore, designing effective responses will depend on a deeper understanding of the human-environmental interactions. Socio-ecological perspective emphasizes societal activities that impact the use of resources, rather than on environmental quality indicators with an aim to aid in planning and decision-making processes at various administrative levels (Azar et al., 1996). Ince (2023) further suggests that adopting a socio-ecological approach and systems thinking with a multidisciplinary perspective can offer new models for creating systemic and long-term solutions to sustainability problems. In practice, this would mean thinking and modeling that involves all stakeholders, performing economic and biological analyses of the environment and 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 scales and considers a set of critical resources such as natural, social, economic and cultural, all located at the intersection of interdisciplinary collaboration, moving away from short-term narrowly focused technological fixes. In this context, there is somewhat of a paradox of technological optimism where technical fixes are viewed as solutions to all problems, even those that are non-technical in nature, while social and economic factors are viewed as obstacles, rather than essential to designing solutions (Rudolph, 2023). This is further exacerbated by the plethora of isolated pilot studies and the dominance of industry-backed funded research which is unlikely to lead to truly transformative socio-ecological thinking of transdisciplinary work (Rudolph, 2023).

3. METHOD

To explore the current narratives in research associated with socio-ecological systems thinking in the domain of digital twins, we conducted an initial level of a systematic review where we first identified bibliographical sources that focus on urban or city digital twins as we were interested in the broader scale digital twins to understand the system complexity. In the search, we excluded studies that were in the physical science areas, such as mathematics, physics, chemistry or medicine. We conducted a search of the Scopus database to sample articles and studies using the following sampling string:

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") AND

(LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp")) AND (LIMIT-TO (LANGUAGE , "english")) AND (EXCLUDE (SUBJAREA , "phys") OR EXCLUDE (SUBJAREA , "math") OR EXCLUDE (SUBJAREA , "medi") OR EXCLUDE (SUBJAREA , "ceng") OR EXCLUDE (SUBJAREA , "neur") OR EXCLUDE (SUBJAREA , "chem"))

The search yielded 153 publications including journal articles (92) and conference papers (61), all published between 2018-2023 (Fig. 1). Publications in the area of social science are among top five, flanked by those in the areas of engineering, computer and environmental sciences, and energy (Fig. 2). Lastly, it was interesting to observe that the significant funding in this area comes from the European funding schemes, followed by the national science funding programs in the U.S. and China (Fig. 3).

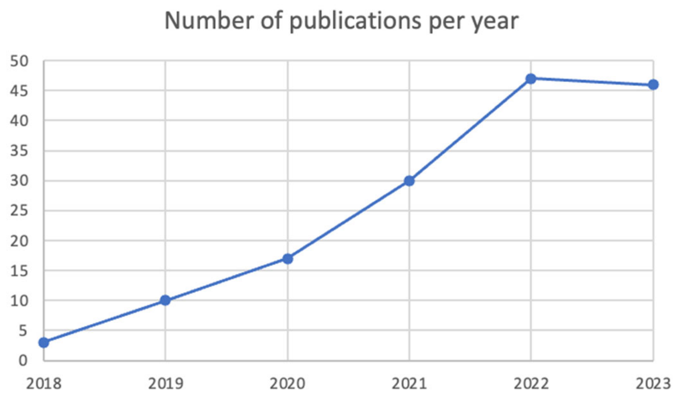

Fig. 1: Number of publications on urban and city digital twins per year

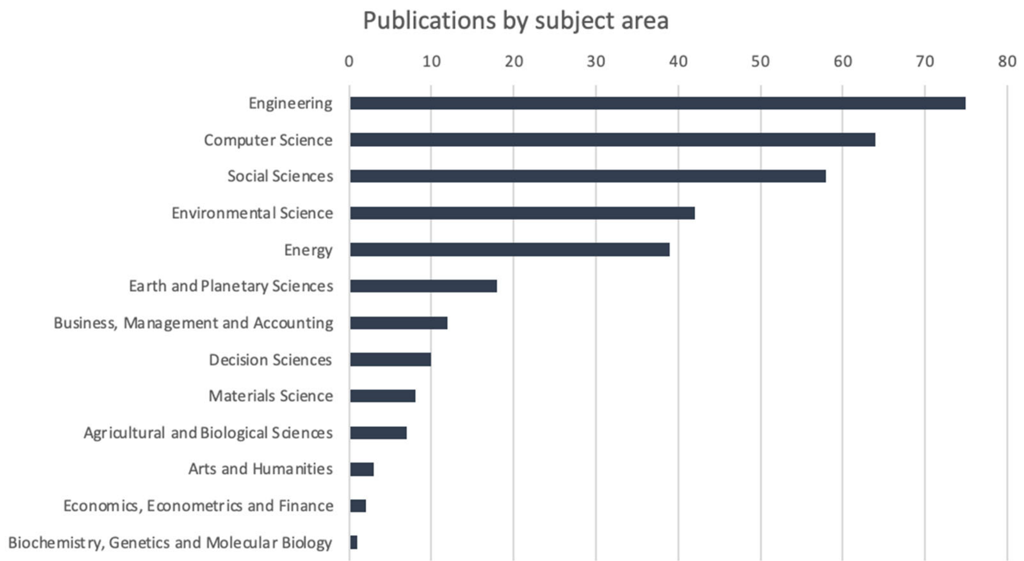

Fig. 2: Number of publications on urban and city digital twins per year

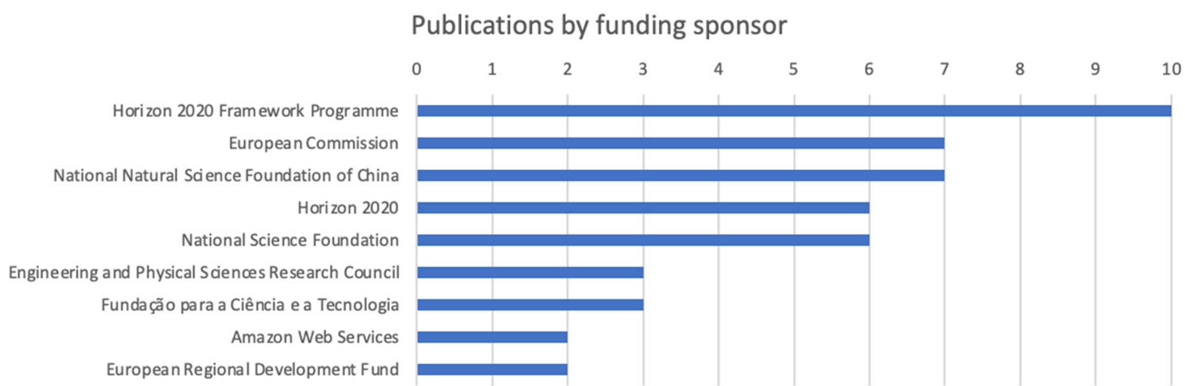

Fig. 3: Publications by funding sponsor

However, the review of abstracts revealed a wide range of approaches and methods with a high degree of varying conceptualization of problems and definition of digital twins, leading to a considerable number of papers being omitted from further review. For example, papers that approached digital twin models from an engineering perspective or conceptualized them as a single system with no links made to either social or ecological issues were out of scope (e.g. water system focusing on flood risks). Similarly, papers focusing only on economic, technological or social aspects were omitted as well. Lastly, papers that only focused on digital models that did not interact with their physical counterpart were not considered to be digital twins as defined. This has led to a list of 25 publications that were selected for further review to identify themes, considerations, developments and challenges for developing complex socio-ecologically driven digital twins (Table 1).

Table 1: Select publications with key data.

No	Reference	Title	Type	Focus
1	Yigitcanlar T. et al. (2019)	The making of smart cities: Are Songdo, Masdar, Amsterdam, San Francisco and Brisbane the best we could build?	Article	Multidimensional framework
2	Sadowski J. and Bendor R. (2019)	Selling Smartness: Corporate Narratives and the Smart City as a Sociotechnical Imaginary	Article	Counter-narrative of technology salvation
3	Dembski F., et al. (2020)	Urban digital twins for smart cities and citizens: The case study of Herrenberg, Germany	Article	Practical use of UDT and part. engagement
4	Goel R.K., et al. (2021)	Self-sustainable smart cities: Socio-spatial society using participative bottom-up and cognitive top-down approach	Article	behavioral intellig., trans-disc knowledge
5	Shahat E. et al. (2021)	City Digital Twin Potentials: A Review and Research Agenda	Article	incl. of socio-econ. components
6	Yossef B. & Aharon-Gutman M. (2022)	The Social Digital Twin: The Social Turn in the Field of Smart Cities	Article	Complexity theory
7	Benedetti A.C., et al. (2022)	The Process of Digitalization of the Urban Environment for the Development of Sustainable and Circular Cities: A Case Study of Bologna, Italy	Article	Predictive tool for urban planning
8	Tzachor A., et al. (2022)	Potential and limitations of digital twins to achieve the Sustainable Development Goals	Article	modeling socio-technical and socio-ecological systems
9	Corrado C.R. et al. (2022)	Combining Green Metrics and Digital Twins for Sustainability Planning and Governance of Smart Buildings and Cities	Article	metric-driven framework for sustainability planning of a sociotechnical system
10	Charitonidou M. (2022)	Urban scale digital twins in data-driven society: Challenging digital universalism in urban planning decision-making	Article	socio-tech. perspective of smart cities
11	Ferré-Bigorra J. et al. (2022)	The adoption of urban digital twins	Article	limitations of city digital twins
12	Bozeman J.F. et al. (2023)	Three research priorities for just and sustainable urban systems: Now is the time to refocus	Article	social equity and justice, circularity, and DTs
13	Ye X. et al. (2023)	Developing Human-Centered Urban Digital Twins for Community Infrastructure Resilience: A Research Agenda	Article	human-centered UDTs framework
14	Peters, D. and Schindler, S. (2023)	FAIR for digital twins	Article	sustainable data landscape
15	Kumalasari D. et al. (2023)	Planning Walkable Cities: Generative Design Approach towards Digital Twin Implementation	Article	human perspective in scenario development
16	Al-Sehrawy R. et al. (2023)	The pluralism of digital twins for urban management: Bridging theory and practice	Article	DT inconsistencies and poorly measured priorities
17	Masoumi H. et al. (2023)	City Digital Twins: their maturity level and differentiation from 3D city models	Article	going beyond 3D viz. an, monitoring
18	Quek H.Y. et al. (2023)	The conundrum in smart city governance: Interoperability and compatibility in an ever-growing ecosystem of digital twins	Article	systems and semantic integration
19	Dembski F. et al. (2019)	The Digital Twin Tackling Urban Challenges with Models, Spatial Analysis and Numerical Simulations in Immersive Virtual Environments	Conf paper	civic engagement in urban planning
20	Wan L. et al. (2019)	Developing a city-level digital twin - Propositions and a case study	Conf paper	theory and policy experimentation
21	Mohammadi N., et al. (2020)	Knowledge discovery in smart city digital twins	Conf paper	spatiotemporal knowledge discovery framework
22	Yue A. et al. (2022)	Smart Governance of Urban Ecological Environment Driven by Digital Twin Technology: A Case Study on the Ecological Restoration and Management in S island of Chongqing	Conf paper	Urban restoration
23	Zou S. et al. (2022)	A Preliminary Study on the Development and Application of Digital Twin Landscape Architectures in the Context of Smart City	Conf paper	digital twin landscape architecture
24	Akimov L. et al. (2023)	The Environmentally-Efficient Canal District Design Respecting Urban Context	Conf paper	landscape restoration
25	Cruz P. et al. (2023)	Towards e-Cities: An Atlas to Enhance the Public Realm Through Interactive Urban Cyber-Physical Devices	Conf paper	heterogeneous urban cyber-physical projects case studies

4. EMERGING THEMES AND THE DISCUSSION

The select list of publications demonstrates that the research focusing on large scale digital twins is still in early stages and some of the relevant discussions and debates remain largely embedded within the "smart city" literature. From the select list of publications, we sought to identify the application areas, as well as the indicators of the systems thinking that extend the environmental performance. In doing so, our goal was to establish the extent of socio-ecological and transdisciplinary thinking informing the development of large-scale digital twins and the potential obstacles for their implementation.

4.1 Urban digital twins and smart cities

Digital twins at urban scales have been tightly coupled with the smart city narratives where the focus has been largely on modeling specific infrastructure needs that include forecasting and preventing of floods, increasing the efficiency of power grids, understanding of commuting patterns for transportation, as well as modeling and prevention of epidemics in the public health domain. From the literature, such digital twins have been variably termed city digital twins (CDT), urban digital twins (UDT), or social urban digital twins (SUDT). The greatest challenge, however, is determining how closely the digital twin should be coupled with the real urban environment and whether the abstraction and simplification of social or economic datasets could even qualify such models as digital twins (Ye et al., 2023). While the promise and the potential for city digital twins to not only mirror and interact with the physical counterpart, but also account for social and economic aspects (Wan et al., 2019), fewer studies elaborate on the complexity of developing such models or describe the interactions and dependencies between the heterogeneous data sets spanning spatial and temporal description of environmental, social, and economic factors (Savage et al., 2022). Although digital twins of cities have been developed, it is difficult to discern with consistency what systems have been modeled in each implementation and to what extent, further confusing the understanding of urban or city digital twins (Ferré-Bigorra et al., 2022).

What has also become apparent from the review is that the discussion of city, or urban digital twins is tightly coupled with the smart city narratives. The relationship between city digital twins and smart cities is not yet clear, although the smart city conceptualization as technology-assisted and connected infrastructure and communities through sensors and automation closely resembles that of a digital twin. In that context, both digital twins and smart cities that are deemed to be successful are those that adopt a system of systems approach and balance the sociocultural, geospatial, and institutional perspectives of cities beyond the means of technology solutions (Quek et al., 2023; Yigitcanlar et al., 2019). Yigitcanlar et al. (2019) offer a multidimensional conceptual framework that centers on urban policy to inform urban planning and development where innovation economy, socioeconomic equality, ecological sustainability and (smart) governance, each equipped with their own performance indicators, are all critical for building smart cities.

Some studies expand the use of urban digital twins with sociological approaches by focusing on social issues such as urban aging and gentrification, poverty, or other social disparities, termed as social urban digital twins (SUDT) (Sadowski & Bendor, 2019; Yossef Ravid & Aharon-Gutman, 2023). Such studies exemplify attempts to integrate social fabric with the built urban space, although not without raising ethical and legal questions behind the need to collect social data, currently the focus of the field of Digital Sociology (Lupton, 2015). At the same time, the criticism of such developments is based on observations that corporations tend to reframe urban sustainability challenges that favor narrow economic gains at the expense of socio-ecological sustainability, especially in the context of energy consumption and smart grids (Evans et al., 2019; Quek et al., 2023). Nevertheless, all the city digital twin developments testify to the complexity of replicating such complex and evolving systems, even at the physical levels, which is perhaps one of the reasons for the adoption of technocratic approaches that ignore wider social and environmental factors (Kitchin, 2014; Semeraro et al., 2021).

4.2 Technological optimism and implementation reality

The development of large-scale city digital twins generally involves the integration of 2D and 3D information and data models, such as BIM or GIS, and data sources, such as sensors, Internet of Things, and other solutions that form the physical, network and computing layers (Quek et al., 2023; Semeraro et al., 2021). Research on large scale city and urban digital twins remains more focused on the software side of modeling the physical environment, rather than on participatory planning and policymaking informed by human-centered behavior analysis, an approach that would enable planners and policy makers to understand the knock-on effects of environmental changes on social resilience (Ye et al., 2023). As the complexity of urban systems that need to be modeled and integrated is increasing, so has increased the rate of various siloed technological developments, posing new challenges for the city administrations and governance. It has been widely recognized that city digital twins will require a transition from single institutions to scalable solutions where multiple professional domains contribute the data and inform the relevant analyses (Savage et al., 2022). The technical complexity of integrating various data formats, applications, systems and other sub-system DTs has consequently drawn much more attention to the technological considerations for resolving such issues. The proliferation of various public and private technological research and development efforts have further diversified the digital ecosystem at the expense of knowledge sharing and cross-domain collaboration, leaving the development of city digital twins in their infancy (Shahat et al., 2021).

Though technological challenges remain important to be resolved, the field of smart city and digital twin developments have become progressively critiqued for their heavy reliance on technologies as means to manage urban and environmental crises (e.g. Nochta et al., 2019; Yossef Ravid & Aharon-Gutman, 2023). Advanced smart city initiatives, such as Singapore[1] or Beijing[2] for example, increasingly embed new technologies into city design, retrofitting or upgrading their infrastructure, which presents challenges for the city's phased developments and the pace of technological developments. As Quek et al. (2023) illustrate, cities develop at a much slower pace than technologies, whereby the time projects are completed, the technology solutions may well become outdated. This further exacerbates the existing challenges of integration, interoperability, and compatibility, perpetuating the cycle of pursuing technological solutions to technology-created problems. Some studies have pointed out the challenge of profit-driven corporate interests seeping into the social realm by appropriating and dominating the narrative of urban challenges and technological fixes (Sadowski & Bendor, 2019; Yossef Ravid & Aharon-Gutman, 2023). This complex technological influence on urban governance where social perspective has been largely absent, presents academics, professionals and policy makers with a real challenge of working together to enable outcome-based and value-driven decision making that drives more comprehensive social, environmental and economic values. The ever-growing digital ecosystem of various digital twin technology solutions has consequently raised several practical challenges that extend those of interoperability alone.

4.3 Practical challenges for socio-ecological and systems thinking

The review of studies revealed a number of both technological and strategic challenges facing the development of large scale complex digital twins for addressing socio-ecological and environmental goals. These have been broadly categorized into three categories (Table 2) and described further below.

Table 2: Overview of select hindrances to the development of large-scale digital twins.

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; 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
	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
	Digital divide	DT development and integration bound to the available investments and resources at district, region or country levels

Data is the basis of all digital twins and generating, accessing, filtering, analyzing and using relevant data presents an array of different challenges for the development and usability of digital twins. There is a general consensus across the literature that the overproduction of data, either from the projects or sensors and users, is a problem, prompting an increasing reliance on machine learning and artificial intelligence to process and make sense of the ever growing volumes of raw data. This vast and unfettered production of data also signals the separation between the digital and the human where the suggestion that one of the benefits of the digital revolution is the production of 'big data', becomes dangerous without recognizing our limited ability to make use of it (Ewart, 2018). On the other hand, the needed data may not be easily available due to privacy or proprietary issues.

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

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

Most instances of urban digital twins developments are based in 3D models, while the integration of 2D information and non-graphical data is far more sporadic. Ye et al. (2023) in their review demonstrate how multidimensional visualization of integrated social sensing data, land-use change and demand models for example, while essential for planning of future urban landscape, is largely missing. Furthermore, data use is driven by the purpose of their primary users reflecting an inherent bias, even when data are quantitative (Nikolić & Whyte, 2021). In addition, different coding schemes used across the professional domains for describing and structuring the data complicates efforts to automate the querying of data (Peters & Schindler, 2023). Still, planning and design approaches, especially at broad urban, social, and environmental scales, involve consideration of a range of factors, uncertainties, and conflicting goals, all largely part of a decision-making process of which automation is not yet capable (Allam & Dhunny, 2019).

The difficulty of simulating complex systems of systems, such as urban environments has long been debated where some have questioned the value of digital twins in the face of simpler monitoring systems (Ferré-Bigorra et al., 2022). Complexity theory has surfaced as a conceptual framework for studying and designing smart cities (e.g. (Yossef Ravid & Aharon-Gutman, 2023) to help deal with issues of uncertainty, diversity and emergence and inform policies on ways to cope with unpredictable behavior of urban systems. Creating digital twins with a socio-ecological focus necessitates inputs not only from the allied built environment disciplines, but also from the fields of sociology, anthropology, ecology and planning, which still remains short in supply. The importance of such approaches informing policies is illustrated by Savage et al. (2022) where the changes in energy consumption patterns resulting from a combination of measures in carbon tax, technology adoption and land use data would affect social inequality in the UK.

Resulting from the challenges above, the integration of data, models and approaches across domains and scales perhaps remains the over compassing challenge to the development of complex and connected digital twins. Integration of diverse datasets, models and methods that better account for differences in human behaviors further remain underexplored (Delmelle, 2021). It is clear that future tools will have to incorporate different types of data from a variety of domains. This however, does not even account for the computational resources needed to process such large and complex datasets. The remaining controversy is the viability of urban digital twins and whether they can ever truly represent the intra- and inter-social complexity of socio-technical and socio-ecological systems, especially those that incorporate societal elements (Batty, 2018).

5. CONCLUSIONS

The twin urgency 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. The concept of urban digital twins and the value of data sharing across sector boundaries has been recognized in the UK through a National Digital Twin program (CDBB, 2019). Research, however, demonstrates that the urban digital twin conceptualization, development, and implementation are still very much in their infancy, while the narratives intersect with those of smart cities. Urban environments with a complex interplay of spatial, social, environmental, and economic factors have proven challenging for the digital "twinning", leaving most digital twin developments stopping short of modeling socio-ecological and socio-technical systems. When designed well, city digital twins, as other technologies, should support human agency and democratize the decision-making process, shifting the balance of authority away from the experts alone. Yet, despite their great potential and promise they hold, the vast technological bottlenecks exemplified in the issues of data, interoperability, federation, integration, scalability or futureproofing of technological solutions have all focused much attention on resolving such issues and at the expense of exploring and including the socio-ecological dimensions that may impact the planning and development of scenarios.

While sustainability encompasses environmental, social and economic aspects, the literature review demonstrates a predominant focus on the potential of digital twins to achieve decarbonization goals through carbon and energy consumption metrics. In this paper, we began by mapping the latest research on large-scale DT applications across domains to describe the elements of the dominant narratives for informing future changes in the built environment and addressing the challenges of sustainable development and social resilience. Although socio-ecological perspective extends the sustainability trifecta by promoting systems thinking and offering new theory necessitating multidisciplinary management approaches, we illustrated how the urban and city digital twin developments remain largely domain-specific where projects are yet to be seen as interventions within larger complex systems.

Finally, while digital twins offer powerful and novel ways to engage diverse disciplines in shared conversations, fragmented practices are maintained not only within traditional and institutionalized modes of working, but also discipline-specific tools and technologies designed to handle data at different scales and data needs. Integrating such diverse data sets not only requires overcoming issues of interoperability, but also crafting new narratives around salient spatial, social, and ecological features aimed at the users most likely to have a say in decisions with longer term consequences.

REFERENCES:

Allam, Z., & Dhunny, Z. A. (2019). On big data, artificial intelligence and smart cities. *Cities*, *89*, 80–91.

Azar, C., Holmberg, J., & Lindgren, K. (1996). Socio-ecological indicators for sustainability. *Ecological Economics*, *18*(2), 89–112.

Batty, M. (2018). Artificial intelligence and smart cities. *Environment and Planning B: Urban Analytics and City Science*, *45*(1), 3–6.

Bonci, A., Carbonari, A., Cucchiarelli, A., Messi, L., Pirani, M., & Vaccarini, M. (2019). A cyber-physical system approach for building efficiency monitoring. *Automation in Construction*, *102*, 68–85.

CDBB. (2019). *National Digital Twin Programme*. https://www.cdbb.cam.ac.uk/what-we-did/national-digital-twin-programme

Climate Change Committee. (2019). *Net Zero—The UK's contribution to stopping global warming*. Climate Change Committee. https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

Delmelle, E. C. (2021). Toward a More Socially Impactful Geographical Analysis. *Geographical Analysis*, *53*(1), 148–156.

Evans, J., Karvonen, A., Luque-Ayala, A., Martin, C., McCormick, K., Raven, R., & Palgan, Y. V. (2019). Smart and sustainable cities? Pipedreams, practicalities and possibilities. *Local Environment*, *24*(7), 557–564.

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

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

Green, S. D., & Sergeeva, N. (2020). The contested privileging of zero carbon: Plausibility, persuasiveness and professionalism. *Buildings and Cities*, *1*(1), Article 1.

Grieves, M. W. (2019). Virtually intelligent product systems: Digital and physical twins. *Complex Systems Engineering: Theory and Practice*, 175–200.

Gultekin, P., Mollaoglu-Korkmaz, S., Riley, D. R., & Leicht, R. M. (2013). Process Indicators to Track Effectiveness of High-Performance Green Building Projects. *Journal of Construction Engineering and Management*, *139*(12), A4013005.

Ince, F. (2023). Socio-Ecological Sustainability Within the Scope of Industry 5.0. In *Implications of Industry 5.0 on Environmental Sustainability* (pp. 25–50). IGI Global.

Kitchin, R. (2014). The real-time city? Big data and smart urbanism. *GeoJournal*, *79*(1), 1–14.

Korkmaz, S., Riley, D., & Horman, M. (2010). Piloting Evaluation Metrics for Sustainable High-Performance Building Project Delivery. *Journal of Construction Engineering and Management*, *136*(8), 877–885.

Levin, K., Cashore, B., Bernstein, S., & Auld, G. (2012). Overcoming the tragedy of super wicked problems: Constraining our future selves to ameliorate global climate change. *Policy Sciences*, *45*(2), 123–152.

Lupton, D. (2015). *Digital Sociology*. Routledge.

Nikolić, D., & Whyte, J. (2021). Visualizing a New Sustainable World: Toward the Next Generation of Virtual Reality in the Built Environment. *Buildings*, *11*(11), Article 11.

Nochta, T., Badstuber, N., & Wahby, N. (2019). *On the Governance of City Digital Twins—Insights from the Cambridge Case Study* [Working Paper]. CDBB.

Opoku, D.-G. J., Perera, S., Osei-Kyei, R., & Rashidi, M. (2021). Digital twin application in the construction industry: A literature review. *Journal of Building Engineering*, *40*, 102726.

Opoku, D.-G. J., Perera, S., Osei-Kyei, R., Rashidi, M., Bamdad, K., & Famakinwa, T. (2023). Barriers to the Adoption of Digital Twin in the Construction Industry: A Literature Review. *Informatics*, *10*(1), 14.

Papadonikolaki, E., & Anumba, C. (2022, October 26). *How can Digital Twins support the Net Zero vision?* [Proceedings paper]. 19th International Conference on Computing in Civil& Building Engineering (ICCCBE),. In: (Proceedings) 19th International Conference on Computing in Civil& Building Engineering (ICCCBE),. ICCCBE 2022: Cape Town, South Africa. (2022); ICCCBE 2022.

Peters, D., & Schindler, S. (2023). FAIR for digital twins. *CEAS Space Journal*.

Quek, H. Y., Sielker, F., Akroyd, J., Bhave, A. N., Richthofen, A. von, Herthogs, P., Yamu, C. van der L., Wan, L., Nochta, T., Burgess, G., Lim, M. Q., Mosbach, S., & Kraft, M. (2023). The conundrum in smart city governance: Interoperability and compatibility in an ever-growing ecosystem of digital twins. *Data & Policy*, *5*, e6.

Rabeneck, A. (2008). A sketch-plan for construction of built environment theory. *Building Research & Information*, *36*(3), 269–279.

Rudolph, D. (2023). The question of 'sustainable' technology: From socio-ecological fixes to transformations. *Human Geography*, *16*(1), 81–86.

Sadowski, J., & Bendor, R. (2019). Selling Smartness: Corporate Narratives and the Smart City as a Sociotechnical Imaginary. *Science, Technology, & Human Values*, *44*(3), 540–563.

Savage, T., Akroyd, J., Mosbach, S., Krdzavac, N., Hillman, M., & Kraft, M. (2022). Universal Digital Twin: Integration of national-scale energy systems and climate data. *Data-Centric Engineering*, *3*, e23.

Semeraro, C., Lezoche, M., Panetto, H., & Dassisti, M. (2021). Digital twin paradigm: A systematic literature review. *Computers in Industry*, *130*, 103469.

Shahat, E., Hyun, C. T., & Yeom, C. (2021). City Digital Twin Potentials: A Review and Research Agenda. *Sustainability*, *13*(6), Article 6.

Tzachor, A., Sabri, S., Richards, C. E., Rajabifard, A., & Acuto, M. (2022). Potential and limitations of digital twins to achieve the Sustainable Development Goals. *Nature Sustainability*, *5*(10), Article 10.

United Nations Environment Programme. (2022). *Emissions Gap Report 2022: The Closing Window—Climate crisis calls for rapid transformation of societies*. http://www.unep.org/resources/emissions-gap-report-2022

Wan, L., Nochta, T., & Schooling, J. M. (2019). Developing a City-Level Digital Twin: Propositions and a Case Study. *International Conference on Smart Infrastructure and Construction 2019 (ICSIC)*, 187–194.

Waring, T. M., & Richerson, P. J. (2011). Towards Unification of the Socio-Ecological Sciences: The Value of Coupled Models. *Geografiska Annaler. Series B, Human Geography*, *93*(4), 301–314.

Whyte, J., Fitzgerald, J., Mayfield, M., Coca, D., Pierce, K., & Shah, N. (2019). Projects as Interventions in Infrastructure Systems-of-Systems. *INCOSE International Symposium*, *29*(1), 542–542.

Whyte, J., Mijic, A., Myers, R. J., Angeloudis, P., Cardin, M.-A., Stettler, M. E., & Ochieng, W. (2020). A research agenda on systems approaches to infrastructure. *Civil Engineering and Environmental Systems*, *37*(4), 214–233.

Whyte, J., & Nikolić, D. (2018). *Virtual Reality and the Built Environment* (2 edition). Routledge.

Ye, X., Du, J., Han, Y., Newman, G., Retchless, D., Zou, L., Ham, Y., & Cai, Z. (2023). Developing Human-Centered Urban Digital Twins for Community Infrastructure Resilience: A Research Agenda. *Journal of Planning Literature*, *38*(2), 187–199.

Yigitcanlar, T., Han, H., Kamruzzaman, Md., Ioppolo, G., & 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*, *88*, 104187.

Yossef Ravid, B., & Aharon-Gutman, M. (2023). The Social Digital Twin:The Social Turn in the Field of Smart Cities. *Environment and Planning B: Urban Analytics and City Science*, *50*(6), 1455–1470.