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RESEARCH ARTICLE

The conundrum in smart city governance: Interoperability and compatibility in an ever-growing ecosystem of digital twins

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Abbreviations: BIM, building information modeling; CDT, city digital twin; CEUS, Consumer Energy Usage Data in Smart City Development; CKG, Cities Knowledge Graph; DT, digital twin; GIS, geographic information system; ICT, information and communication technology; MP, meta-practice

Abstract

Today, technological developments are ever-growing yet fragmented. Alongside inconsistent digital approaches and attitudes across city administrations, such developments have made it difficult to reap the benefits of city digital twins. Bringing together experiences from five research projects, this paper discusses these digital twins based on two digital integration methodologies—systems and semantic integration. We revisit the nature of the underlying technologies, and their implications for interoperability and compatibility in the context of planning processes and smart urbanism. Semantic approaches present a new opportunity for bidirectional data flows that can inform both governance processes and technological systems to co-create, cross-pollinate, and support optimal outcomes. Building on this opportunity, we suggest that considering the technological dimension as a new addition to the trifecta of economic, environmental, and social sustainability goals that guide planning processes, can aid governments to address this conundrum of fragmentation, interoperability, and compatibility.

Policy Significance Statement

As cities across the globe aspire to become smarter, the rapid pace of siloed technological developments and their growing complexities and pitfalls have become too significant for city administrations and politicians to ignore. This is exacerbated by the novel developments of city digital twins based on a diversity of software and technologies. We scrutinize a variety of digital twins to discern opportunities to address interoperability and

compatibility. In overcoming technological lock-ins driven by business interests, we conclude that software developments need to pay greater attention to practical realities. We contend that city administrations would also have to step up to spearhead, rather than sway toward these technologies for their processes.

1. Introduction

Planning cities has always been complex as cities are dynamic living systems that evolve daily. Many city planning processes consider the development of cities along economic, environmental, and social sustainability goals. In the 21st century, the advent of faster, cheaper, and smaller electronic devices available to a mass consumer base across the globe have altered these urban dynamics. The extensive diffusion of internet users and sensor technologies deployed in the built environment has led to the accelerating velocity of data processing capabilities and production of large data streams that can be aggregated, processed, and analyzed for more efficient operations and smarter cities (Townsend, 2013; Komninos et al., 2019; Mora and Deakin, 2019). Considering the ever-growing digital ecosystem, this paper critically revisits the opportunities and challenges of smart city solutions for governance and planning processes. In order to understand urban development opportunities today, this paper suggests to add a technological dimension to the trifecta of economic, environmental, and social sustainability goals that guides city planning. It will also raise questions on the conundrum of interoperability and compatibility for a more holistic urban modeling ecosystem.

Presently, city administrators and politicians have recognized the potential of technological solutions and by extension, smart cities to address urban sustainability issues while enhancing the quality of urban life across scales (Townsend, 2013; Kitchin, 2014; Grossi and Pianezzi, 2017; Mora and Deakin, 2019). To this end, they have often initiated, advocated, and endorsed new technological endeavors in public, private, and research institutions across diverse disciplines such as Germany's third iteration of model Smart Cities projects (Bundesministerium des Innern, für Bau und Heimat, 2021) and Singapore's Smart Nation initiatives (Smart Nation Singapore, 2021). This generates a growing diversity of digital solutions ranging from interactive online dashboards for city statistics to proprietary optimization tools for city logistics, building management, and infrastructure planning (van Winden and van den Buuse, 2017; Komninos et al., 2019).

On one hand, the ever-growing diversity of smart city solutions has been successful in addressing many real-world problems. However, as a consequence of their individual funding initiatives, these solutions are not necessarily compatible or interoperable with other initiatives either in their set-up, software, or hardware (Van et al., 2015; Robert et al., 2017). Interoperability is defined as the ability of tools and systems to understand and use the functionalities of other tools, while compatibility is defined as the capacity of different tools to work together in the same environment and data format without further modifications. With Industry 4.0, the complexity and choice of tools will inevitably increase as various public, private, and research organizations remain fragmented in their research and development efforts (Lasi et al., 2014; Van et al., 2015; Mora et al., 2017; Robert et al., 2017). This has resulted in the formation of large isolated data silos amidst the current state of an ever-growing heterogeneous, distributed, and dynamic digital ecosystem. Consequently, knowledge sharing and collaboration processes are inhibited, stifling innovation for greater resource efficiency in an era confronted by resource shortages and sustainability issues (Lasi et al., 2014; Van et al., 2015; Rech et al., 2018).

Furthermore, many smart city solutions result from individually funded research or project grants that as a result often do work by themselves, but are not necessarily compatible with other initiatives either in their set-up, software or hardware. These solutions, often represented by small-scale pilot projects, require further alignment to implement place-based approaches and to avoid fading out after their trial periods. When implemented suitably, they could be expanded and replicated to establish a flourishing urban modeling ecosystem that addresses urban challenge at various scales (van Winden and van den Buuse, 2017). On the other end, large-scale smart city projects led by one big tech company, such as the now suspended Google Sidewalks project in Toronto, have raised ample data privacy and retention concerns that citizens have become wary of big technology firms in future. Weaving these perspectives, the smart urbanism of tomorrow will likely be the sum of numerous individual solutions, which magnifies the challenge of interoperability and compatibility.

The approaches to digital twin (DT) technologies may be the crucial vehicle to help address the interoperability and compatibility conundrum. According to Bolton et al. (2018), DTs are “a realistic digital representation of assets, processes, or systems in the built or natural environment” that “creates the opportunity for positive feedback into the physical twin.” There is a variety of DTs developed with different approaches and purposes across spatial and temporal scales (Bolton et al., 2018). In this paper, we critically assess the adoption of the city digital twin (CDT) for city planning and governance processes at the building, network, neighborhood, system, city, regional, or national scale. The CDT is an ecosystem of DTs that does not need to reflect all DT capabilities and features, given the difficulties associated with replicating urban complexities. For example, it is important to know the location of windows in a CDT, but it does not require all detailed window information (materials and dimensions) available in a building DT. In this regard, CDTs must be able to integrate various digital systems, formats, applications, and even other DTs. This would generate sufficient information and data for an interoperable and compatible platform that is capable of representing the entire city and its various domains into the digital sphere (Batty, 2018; Shahat et al., 2021).

To the best of our knowledge, the knowledge management approaches of CDTs can be classified into two approaches, namely, system and semantic integration. System integrated CDT directly connects various technologies into one single consolidated application for users to access. Semantic integrated CDT provides a common ontological framework that can standardize any data, from knowledge domains covered by its ontologies, into semantically rich data formats with context and meaning. This enables data to be integrated, shared, and reused across applications, systems, and even domains. Nevertheless, existing discourses on CDTs for city planning and governance are still in their infancy with little practical research (Shahat et al., 2021). There are still many open questions, including what would a DT for the city require? In its aim to critically reflect on the two common CDT approaches to address the conundrum of fragmentation, interoperability, and compatibility, the paper is guided by three research questions:

- Why is the notion of interoperability and compatibility significant to smart cities?
- What are the new opportunities that DTs present to address the conundrum of interoperability and compatibility?
- What are the learning points of existing CDT projects in view of facilitating interoperability?

Emerging from a conference panel collaboration between several research institutes, this paper approaches the research questions in an unconventional manner. It presents the experiences of five DT research and development projects from several research centers—A Cambridge-based tech company CMCL, the University of Cambridge, the Cambridge Centre for Advanced Research and Education in Singapore (CARES), the University of Groningen, and the Singapore-ETH Centre. By involving each project’s researchers and gaining access to their resources and knowledge, this paper corroborates their experiences with a broader literature review to critically reflect on the current state of CDT developments. In light of word limitations, we have provided further references to each project in the acknowledgments, while keeping a summary and reflection of each project’s capabilities and shortcomings in the analysis that follows.

The paper is organized as follows. Section 1 introduces the research background, framing the conundrum of interoperability and compatibility in the context of smart cities, while critically reflecting on the critiques toward smart urbanism. Section 2 explores the prominent interdependence between urban and technological developments and their relevance to the smart city. Section 3 introduces five CDT approaches through the technological lens of system and semantic integration. Section 4 reflects on their practices, while Section 5 concludes the paper.

2. City Planning and the Fourth Technological Dimension

2.1. Urban-technological symbiosis

Throughout human history, urban developments have always been paired with technological innovation. In the 19th century, the Industrial Revolution introduced new urban and infrastructure solutions for homes, transport, and manufacturing, signifying the start of unprecedented urban development in the decades to come (Townsend, 2013; Mora and Deakin, 2019). Today, Komninos et al. (2019) distinguishes three smart city phases that have transformed the way we live. According to Komninos et al. (2019), the first phase involves digital spaces such as webpages, forums, and chatrooms and their inclusion of simple city representations and visualizations to improve communication between experts and non-experts. The advances of cloud computing in the second phase have enabled community participation and people-driven innovation through co-creation and crowdsourcing to spur a burgeoning user-centric digital urban ecosystem, that grant greater convenience and accessibility. In the latest phase, the pervasive diffusion of cost-effective physical user interfaces like mobile phones and sensors as part of the Internet of Things has enabled the availability of continuous real-time big data. When coupled with artificial intelligence developments, urban problems are resolved just in time with real-time insights and responses in new modes of human–machine interactions (Komninos et al., 2019). In this era characterized by growing complexity and volatilities, real-time responses in city management operations and governance, enabled by cyber–physical intelligence, become critical for a more inclusive, diverse, and sustainable urban environment, unachievable by human capabilities (Townsend, 2013; Anthopoulos, 2017; Komninos et al., 2019; Kunzmann, 2020).

Considering these trends, it is unsurprising that city administrators have already acknowledged the significance of technology in enhancing urban life. They are willing to fund and support a myriad of new and ongoing smart city projects, often small start-ups and experimental projects developed by research organizations, technology and non-technology firms, and individuals (Hollands, 2015; Rabari and Storper, 2015; van Winden and van den Buuse, 2017; Rech et al., 2018; Komninos et al., 2019; Mora and Deakin, 2019). This is a stark contrast to the initial market space dominated by big software firms such as IBM, CISCO, Microsoft, and Oracle (Townsend, 2013; Kitchin, 2014; Grossi and Pianezzi, 2017). Moreover, cities deploying information and communication technology (ICT) are demarcated as smart cities (Söderström et al., 2014; Grossi and Pianezzi, 2017). Implied in its meaning, ordinary cities are perceived as better when adopting ICT solutions in their operating models to become smarter (Townsend, 2013). Thus, there is a growing popularity of the smart city agenda amongst city administrations.

Nevertheless, cities should exercise caution and prudence in their optimistic fervor for smart cities. The influence of big software firms and their corporate ambitions remain entwined with current smart city developments (Townsend, 2013; Grossi and Pianezzi, 2017). The corporatization of city governance and their services, as well as the radical dependence on technology and data have been normalized implicitly without acknowledgment of their pitfalls. In guiding our arguments, we present some common criticisms of smart cities. First, corporatization could perpetuate a technological lock-in. This could cement a corporate dependency on a monopoly that cannot be easily undone or diverted (Kitchin, 2014; Marvin et al., 2015). Second, the embedding of pervasive digital solutions in urban environments may leave cities vulnerable to viruses, glitches, crashes, and hacks, despite the potential problems solved (Townsend, 2013; Kitchin, 2014). For example, the subway network is dependent on the continuous delivery of software, in which software crashes could inhibit subway functionality (Kitchin, 2014). Third, the development of automated digital surveillance networks has raised concerns on the rights to privacy, confidentiality, and freedom of expression (Townsend, 2013; Kitchin, 2014; Ho, 2017). In particular, citizens are increasingly wary and anxious of large-scale smart city projects and their impact on their privacy (Rabari and Storper, 2015; Shimizu et al., 2021). Last, another criticism is that many smart cities have a common tendency to inaccurately associate the quantification of urban problems with the notion that they are solvable or optimizable through computational procedures (Kitchin, 2014; Marvin et al., 2015; Rabari and Storper, 2015). In reality, cities are complex living systems (Batty, 2013; Yamu, 2014) with uncontrollable, unpredictable, “wicked” problems in which introducing one solution may lead to more problems even with coordinated efforts (Rittel and Webber, 1973). In this regard, adoption of a technocratic governance diminishes their scope, which ignores wider social and environmental perspectives that shape urban life and their individual identities (Kitchin, 2014).

These criticisms are exemplified through the distinct smart city implementations across geographies. Smart city projects in Asia often feature infrastructure-oriented projects implemented by developmental states like Singapore and South Korea (Ho, 2017). But city administrations and researchers are questioning the effectiveness of these solutions for enhancing quality of life relative to their capital cost. Ho (2017) examines the energy management capabilities of smart homes in Singapore, which fail to implement lasting behavioral changes to reduce residential energy consumption. In contrast, smart city projects in Europe and North America often emphasize on their decentralized and participatory projects (Ho, 2017). One criticism of such cities is the tendency for corporations to reframe urban sustainability challenges to prioritize corporate interests by managing the symptoms over addressing their root causes, while plausibly marginalizing their citizens (Kitchin, 2014, 2015). Evans et al. (2019) broaches on the penchant of current clean energy approaches for urban populations toward smart meters and smart grids managed by a digital system. Instead, there is little discussion on developing new forms of community energy provisions or reducing resource consumption to empower citizens. Accordingly, when city governance is perceived as long-term market opportunities for vendors, smart cities foreground economic developments over their promises for social and environmental sustainability (Townsend, 2013; Kitchin, 2014, 2015; Marvin et al., 2015; Ho, 2017; Evans et al., 2019).

Embedding technologies into cities and their inhabitants’ lifestyles also holds the unique challenge of managing the different developmental phases of cities. Smart cities are often marketed with one-size-fits-all narratives that uses popular canonical examples such as Songdo or Masdar City (Kitchin, 2015). In actuality, there are various permutations of smart cities and their technologies that cannot be clearly defined or classified (Townsend, 2013; Komninos et al., 2019). Cities are unique living systems that develop at their own paces, with rarely, shared milestones, trajectories, or technologies. For example, as an existing city, Singapore often retrofits and upgrades its infrastructure with new technologies as part of its Smart Nation initiatives (Smart Nation Singapore, 2021). On the other hand, greenfield smart cities like Songdo City in South Korea embed the latest technologies directly into their city design and construction. Furthermore, cities develop at a slower pace than technology advances. By the time a city has completed their latest smart city project, the implemented technologies may be outdated, with a newer, improved version available on the market. In an era of rapid technological advances, an ever-growing digital ecosystem, and varying city development phases, interoperability and compatibility become vital requirements in ensuring that smart cities are not just able to speak to each other, but to communicate internally, today and in future.

Presenting these contrasting perspectives on smart cities, it becomes clear that the technological influence on urban governance is complex. Even when faced with challenges like interoperability and compatibility, smart cities have demonstrated the power of technology to redefine and reconfigure the relations within and between people, their communities, governments, and the urban environment (Townsend, 2013; Anthopoulos, 2017; Evans et al., 2019). As cities continue to evolve in the face of rapid urbanization, climate change, resource scarcity, globalization, and their intensifying inter-city competition (Angelidou, 2015), neither striving for technocratic dominance nor disposing all technologies are optimal solutions (Kitchin, 2016). It is more convincing that human–cyber–physical interactions will hold value and evolve, leading to a stable symbiotic relationship between technology and cities. Hence, in order to understand the urban development opportunities of tomorrow, this paper suggests to add a technological dimension to the trifecta of economic, environmental, and social sustainability goals that guides city planning. Moreover, we will scrutinize the complexity of interoperability and compatibility within the current digital ecosystem to foster their potential to enhance urban governance.

2.2. *The emerging digital ecosystem and city digital twins*

Empowered by the decreasing entry costs, increasing government support and economic opportunities, the proliferation of various smart city solutions across scales has led to an ever-growing digital ecosystem (Angelidou, 2015; van Winden and van den Buuse, 2017; Rech et al., 2018; Komninos et al., 2019). These digital solutions often capitalize on knowledge management processes such as collecting public information to address specific issues (Angelidou, 2015). Regardless, many are not able to interoperate with other solutions, which has resulted in often unsuccessful developments (Kitchin, 2014; Hollands, 2015; Marvin et al., 2015; Van et al., 2015). This is concerning when predominant investors are city administrations, who are left with less financial resources and a challenging task of managing fragmented and ineffective approaches to smart cities. Moreover, as they are often represented by small-scale pilot projects, it is questionable if such micro-solutions are sufficient to address challenges at the city scale, especially considering the scales of urban information flows and complexities. Thus, micro-solutions regularly fail to embrace a digital ecosystem framework necessary to produce greater value to urban communities (Kitchin, 2014; Angelidou, 2015; Hollands, 2015; Van et al., 2015).

We argue that the next years inevitably need to focus on building a flourishing urban modeling ecosystem that considers organizational practicalities, resources, interoperability, and compatibility. Given the growing anxiety and wariness of large-scale digital solutions in urban landscapes (Rabari and Storper, 2015; Shimizu et al., 2021), it becomes increasingly difficult to convince citizens to support and fund bigger smart city projects. In contrast, successful examples of smart cities adopt a system of systems approach, streamline urban knowledge management processes, and balance the economic, sociocultural, spatial, and institutional perspectives of cities (Yigitcanlar et al., 2019). Considering these two perspectives, smart cities will likely converge toward individual micro-solutions to address urban challenges while protecting the interests of citizens.

In enabling interoperability and compatibility across micro-solutions, the current knowledge management approaches of CDTs should be of interest. Given the complexity of virtually replicating physical systems, CDTs generally involve the integration of multiple micro-solutions as components to form their physical, network, and computing layers (Semeraro et al., 2021; VanDerHorn and Mahadevan, 2021). This architecture is necessary to incorporate a large amount of data and models to replicate and address urban complexities. To the extent of our knowledge, CDT have two approaches, namely, system and semantic integration.

Traditional system integration approaches connect various individual digital systems, services, and tools into a single DT application through a common interface. The DT often provides the same functionalities as the underlying applications, except that it is now consolidated and convenient for users to access in a single platform. At present, such an approach is one reason for the weak interoperability and compatibility between digital solutions.

Semantic integration approaches could address the conundrum from a different direction. These approaches adopt Semantic Web technologies to provide a common framework that allows data and their relationships to be represented using ontologies, providing context to the data, and facilitating it being shared and reused across applications and systems (W3C, 2009). These technologies have already been proposed as suitable candidates to overcome many of the current challenges facing smart city developments, including data interoperability issues, poor machine readability, and the scalability of solutions to large and complex systems such as cities (W3C, 2015; Ronzhin et al., 2019). By following the principles of Linked Data (Berners-Lee, 2006; Bizer et al., 2011), the Semantic Web enables the discovery, integration, querying, and transfer of information between different domains and systems via the World Wide Web (Noy et al., 2019; Akroyd et al., 2021).

Answering the first research question, the literature highlights the trajectory of city planning and governance processes toward an ever-growing digital ecosystem of individual micro-solutions for supporting their workflows and decisions. Amidst the growing diversity of approaches and systems, interoperability and compatibility are vital enablers to ensure that such costly solutions can benefit their citizens and support city administrations. This endeavor would require a common platform to access and share data across city administration departments, thus, demanding they change their workflows to achieve their desired outcomes. In this regard, the approaches to CDTs offer new opportunities for city administrations to integrate various digital systems, formats, applications, and even other DTs into a broader ecosystem, and create a common platform (Bolton et al., 2018).

2.3. State-of-the-art city digital twins

This section introduces the CDTs through a state-of-the-art on their definitions and discussion. In this paper, CDTs are considered an ecosystem of DTs, which connects the different information flows, but may not have all DT features. Today, a growing diversity of DTs are being developed for various use cases across geographies. Although they tend to have no fixed technology or systems, DTs commonly adopt building models (from building information modeling [BIM], geographic information system [GIS] or other sources) and Internet of Things data into their approaches. Additionally, they are characterized by their capabilities, rather than technologies (Boschert et al., 2018; VanDerHorn and Mahadevan, 2021). Fundamentally, a DT provides a digital representation of the state and behavior of a real-world system, environment, and/or processes, and can bilaterally interact in real-time with their physical counterpart throughout its life cycle (Batty, 2018; Bolton et al., 2018; Kritzinger et al., 2018; Shahat et al., 2021; VanDerHorn and Mahadevan, 2021).

Given their amalgamation with various technologies, DTs are often confounded with similar technologies in their definition, capabilities, and challenges, and should be clarified to progress their developments (Kritzinger et al., 2018; Shahat et al., 2021; VanDerHorn and Mahadevan, 2021). Firstly, DTs are not 3D or BIM models. Traditional 3D models merely represent a physical object or entity at a specific time into the digital realm, but DTs are able to update their description over time (Shahat et al., 2021; VanDerHorn and Mahadevan, 2021). BIM models incorporate their physical information into the digital representation to enable comprehensive intelligent urban management (Semeraro et al., 2021; Shahat et al., 2021). The difference between DTs and BIM belies their cyber–physical interactions. BIM models require manual data insertions, which is achieved autonomously for DTs in real-time (Semeraro et al., 2021; Shahat et al., 2021). Secondly, DTs are not simulation models. Simulation models predict future states of a physical system based on a fixed set of assumptions that is abstracted from reality (VanDerHorn and Mahadevan, 2021). Although DTs may incorporate simulation models, they are also able to update the parameters to the actual physical states in real time (VanDerHorn and Mahadevan, 2021). Lastly, DTs are not surrogate, Machine Learning, or Artificial Intelligence models. Such models are computationally cost-effective approximate models that adopt a set of training data to mimic the behavior of the original simulation model (VanDerHorn and Mahadevan, 2021). Instead, DTs virtually represents the real-time states of a physical system, rather than being a mimicry of a model of reality (VanDerHorn and Mahadevan, 2021).

In the context of smart cities, CDTs are expected to replicate the complexity of cities in real-time. This augments the monitoring and steering of city processes and services across domains such as transport, energy, and health, while supporting decision-making processes to analyze, plan, and govern the built environment (Batty, 2018; Semeraro et al., 2021; Shahat et al., 2021; VanDerHorn and Mahadevan, 2021). Moreover, CDTs are anticipated to enable an unprecedented scope for stakeholder engagement in public participation and collaboration between the experts as well as non-human actors and machines (Dembski et al., 2020; Shahat et al., 2021). Furthermore, CDTs are potentially place-based solutions. At the city level, a one-size-fit-all computational procedure and algorithm is insufficient to replicate and address their unique combination of contexts, complexities, and problems. As DTs are able to update their assumptions based on real-time feedback loops, they could generate place-based insights and solutions, tailored to the nuances of localities like their unique characteristics, lifestyles, history, and policies.

Nevertheless, due to their ongoing experimental status, current adoption of CDTs in smart cities remain limited. A recent review by Shahat et al. (2021) highlights three key research challenges that contributes to the incomplete status of current CDTs. First, attempts to include non-physical systems such as social behaviors and economic systems often encounter significant challenges (Batty, 2018; Shahat et al., 2021).

Second, despite demonstrating the capacity to update the virtual representation, current CDTs have yet to achieve mutual cyber–physical integration (Shahat et al., 2021). Notably, there is a common misconception that the virtual-to-physical connection of DTs must reflect a physical state change. However, this connection is often intended to generate feedback serving an outcome, which need not be a physical state change (VanDerHorn and Mahadevan, 2021). For example, when the outcome is to optimize inspection campaigns of large infrastructures, identification of the highest risk areas for targeted inspections are sufficient to meet the DT's notion of virtual-to-physical connection, without any change to the physical infrastructure (VanDerHorn and Mahadevan, 2021). Last, the knowledge management potential of CDTs is not fully realized. Knowledge management processes create, share, and utilize knowledge to drive collaboration and innovation, bolstering organizational learning, efficiency, and performances (Angelidou, 2015; Israilidis et al., 2021). Underpinning these processes are the availability of the complex, extensive, and heterogenous city data. Although we acknowledge that data is not neutral nor apolitical, it remains important to describe the information flows of a city, which is impossible to accomplish through human capabilities alone (Kitchin, 2014; Evans et al., 2019). Currently, the size and complexity of city data, alongside the lack of standardization, have inhibited the level of data quality and accuracy across various sources (Shahat et al., 2021). Hence, interoperability and compatibility between these different data sources and their technologies becomes a key bottleneck for present and future city administrations toward making headway on CDT and smart city applications.

The remainder of this paper will introduce and evaluate five CDT research and development projects at various development stages, through a critical reflection on their approaches and relevance for practitioners. The paper will also highlight how current knowledge management approaches, undertaken by CDTs, have the capacity to address interoperability and compatibility concerns. As smart cities move toward real-time cyber–physical bilateral interactions, it is vital to acknowledge the significant knowledge gap in the growing complexity of urban systems. As urban systems and their interactions continue to evolve, their growing complexity hinders the capacity to represent the behavior and operation of urban systems in digital formats, if it is even possible (Batty, 2007; West, 2017). Recognizing the broader urban dynamics, this reflection will be structured based on the four meta-practice (MP) identified in planning processes by von Richthofen et al. (2022). Representational MP is the act of representing entire or parts of urban systems, often in a visual manner. Evaluative MP is the act of assessing properties of an urban environment to determine if they satisfy particular requirements or accomplish goals via single or multi-criteria monitoring and modeling. Projective MP is the act of creating specifications of new urban systems or their parts, based on an envisioned or desired (future) urban system or its properties at many scales. Synthetical MP is the act of managing, gathering, using, creating, and synthesizing the inherent data and knowledge flows to plan urban systems. Thus, this reflection provides a foundation to pave the way toward adopting the CDTs in practice and ultimately, delivering smart city promises and addressing urban problems.

3. City Digital Twins Implementation

Although the existing literature body has rightfully pointed out the difficulties of coordinating research efforts arising from the varying perspectives and definitions in building CDTs, we believe that being more open to various projects that may not strictly classify as a CDT, but have relevant DT features, would contribute greater value to the ongoing applications and discussions. As a budding field and costly endeavor, these ongoing CDT projects may not have been initiated as a DT application. Often, they originated from other technologies and perspectives, before evolving into a DT application over time. These experiments also develop at their own pace alongside their unique combination of underlying technologies and data sources. In this context, each project would have unique experiences with interoperability and compatibility. Moreover, as their concept is still unfolding dynamically, instilling a strict classification on CDTs could dismiss valuable experiences with interoperability and compatibility. Accordingly, this paper has taken a broader definition to scrutinize and cross-examine five CDT projects across geographies, which offer a real-time digital representation of the real world.

3.1. The system integration approach

This section presents two DT applications based on the traditional system integration process.

3.1.1. Herrenberg digital twin

The town of Herrenberg in Germany has been the subject of one CDT application as a collaboration between High-Performance Computing Center Stuttgart (HLRS), the Fraunhofer Institute, the University of Stuttgart, the University of Groningen and the local authorities. The DT is intended to guide the town's future mobility developments and address the significant pollution arising in the form of emissions and noise from heavy car traffic. The innovative experiment also explores how DTs could assimilate virtual and augmented reality technology for more collaborative and participatory processes in urban planning and urban design. As described in Dembski et al. (2020), the Herrenberg DT comprises seven digital tools, datasets and analytical models: (a) A hybrid 3D city model based on geographic data and information. (b) A mathematical street network model using space syntax. (c) Urban mobility simulation using an open-source traffic simulation software—Simulation of Urban Mobility (SUMO). (d) Air-flow simulation using an open-source computational fluid dynamics application—OpenFOAM. (e) Sensor network data describing particulate matter, temperature, and humidity. (f) Empirical quantitative data describing pedestrian and cyclist routes. (g) Empirical qualitative data describing the perception of urban spaces through feedback, ratings and photographic impressions. The urban DT was incorporated in the collaborative visualization and simulation environment (COVISE) allowing for data and digital technologies to be integrated seamlessly. COVISE is an extendable open-source distributed software environment. It enables the Herrenberg DT to be visualized across scales in an immersive virtual reality environment.

3.1.2. Cambridge city-level digital twin

The Cambridge city-level DT project, hosted at the Cambridge Centre for Smart Infrastructure and Construction (CSIC) and developed in collaboration with local authorities, explores how data describing the built environment can help improve city planning, management and the delivery of public services. The Cambridge CDT is a tool that facilitates city-level integration by coordinating and connecting various other digital tools and datasets. The project has completed two phases to date, one focusing on the broader city region and one zooming into the specifics of a local strategic development site. Simulating future journeys to work using existing and open data sources on land use, transport and commuting patterns such as the UK Census, Business Register and Employment Survey, and Labour Force Survey through the modeling framework in Figure 1, the initial digital model prototype generated two digital transformation scenarios regarding remote working and electric vehicles, to demonstrate the DT's potential policy use to address interdependence across the policy domains of land-use planning, transport, energy, and air quality, and support scenario development and analysis (Nochta et al., 2021b).

The second phase aims to understand how combining conventional data with emerging sensor-based "big data sets" could improve the model's quality and the analytical outputs' policy relevance. Using a large transport monitoring dataset via Automatic Number Plate Recognition, the CDT model has been extended to explore travel patterns to, from and around the Cambridge Biomedical Campus—one of the designated strategic development sites in the city region, with the potential to provide thousands of new jobs and homes over the course of a decade. The extended model features a new algorithm for inferring the purpose of a trip and the potential socio-economic characteristics of car users according to anonymized vehicle trajectories, to understand traffic patterns and their policy implications (Wan et al., 2021).

3.2. The semantic integration approach

This section presents the World Avatar—a DT that employs a semantic integration approach in conjunction with a dynamic knowledge graph (Akroyd et al., 2021). In the initial phase of development, the research focused on using the knowledge graph to overcome interoperability and compatibility issues in the decarbonization of the chemical industry in Singapore. The project has since broadened its scope to

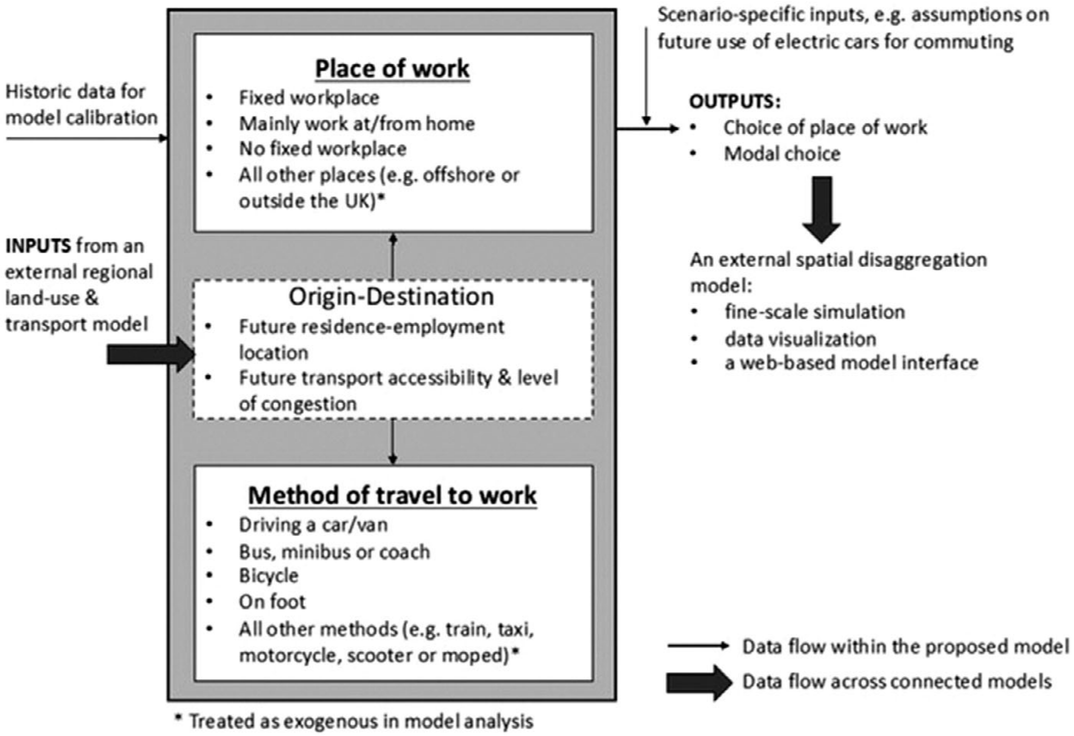

Figure 1. *Modeling framework for the Cambridge CDT prototype for journeys to work. Reprinted with permission from Nochta et al. (2021b). The original figure was published under the terms of Creative Commons Attribution License 4.0.*

include a range of applications such as air quality assessment, consumer energy, and city planning. Although we acknowledge the World Avatar DT as a largely experimental CDT, practical applications for it could be developed in the long term.

3.2.1. The dynamic knowledge graph

Although knowledge graphs are not a new technology, they remain relatively unknown to the general public despite their ubiquitous role behind many day-to-day activities, from searching the internet to browsing social media (Noy et al., 2019). They offer a structured, unambiguously and extensible machine-friendly way to represent relationships between concepts and data. In technical terms, a knowledge graph is an ontology that provides formal semantics combined with a network of instances that represent an interlinked description of entities—objects, events, or concepts (Janev et al., 2020). The data in a knowledge graph can be expressed as a directed graph, in which the nodes of the graph are concepts (e.g., a person) or their instances, and the edges are links between related concepts or instances. The set of concepts and their possible instances and relationships are defined using ontologies.

Simplifying these terms, knowledge graphs have the capacity to describe and represent objects and relationships of interest (Noy et al., 2019; Akroyd et al., 2021). In addition to their representational capability, knowledge graphs may be employed as knowledge management systems, allowing the addition and retrieval of data while deriving new knowledge based on existing information (Janev et al., 2020). Moreover, knowledge graphs can support application services to generate insights and recommendations, for example, via DTs to support city planning (Janev et al., 2020).

Unlike a traditional database, the World Avatar DT employs a dynamic knowledge graph that can be updated and restructured by autonomous computational agents (Akroyd et al., 2021). Eibeck et al. (2019)

describe the ability of agents to fulfill specific objectives, including (a) input and output, (b) updating the knowledge graph with calculated data, (c) restructuring the knowledge graph by adding instances (Devanand et al., 2019), concepts and relationships, and (d) providing services that facilitate the discovery and creation of agents (Zhou et al., 2019).

3.2.2. The World Avatar digital twin applications

The World Avatar project aims to connect data and computational agents in real-time to generate a living digital "avatar" of the real world, that remains up to date and any analysis outputs are self-consistent (Akroyd et al., 2021). The name "World Avatar" seeks to convey the possibility of representing every aspect of the real world and extend the idea of DTs to consider the possibility of representing abstract concepts and processes. Effectively, the World Avatar is an all-encompassing DT comprising every conceivable domain. Three applications of the World Avatar knowledge graph are presented, demonstrating its cross-domain capability at the national level.

3.2.2.1. Cross-Domain Air Quality Assessment. The first application relates to the assessment of the impact of shipping on air quality in Singapore. Singapore has both a high population density and hosts one of the world's busiest ports. It is therefore natural to ask how hard-to-abate sectors like shipping influence factors such as air quality in different regions of Singapore (Farazi et al., 2020). In what follows, we elaborate on the interaction between the computational agents that contribute to the air quality calculation.

The interactions between the agents are illustrated in Figure 2. Input agents update the knowledge graph with real-time information about the weather, location, and speed of ships so that it remains current in time. An emissions agent uses information about each ship to estimate its emissions. An atmospheric dispersion agent is able to use the information about the built environment, weather, and the emissions

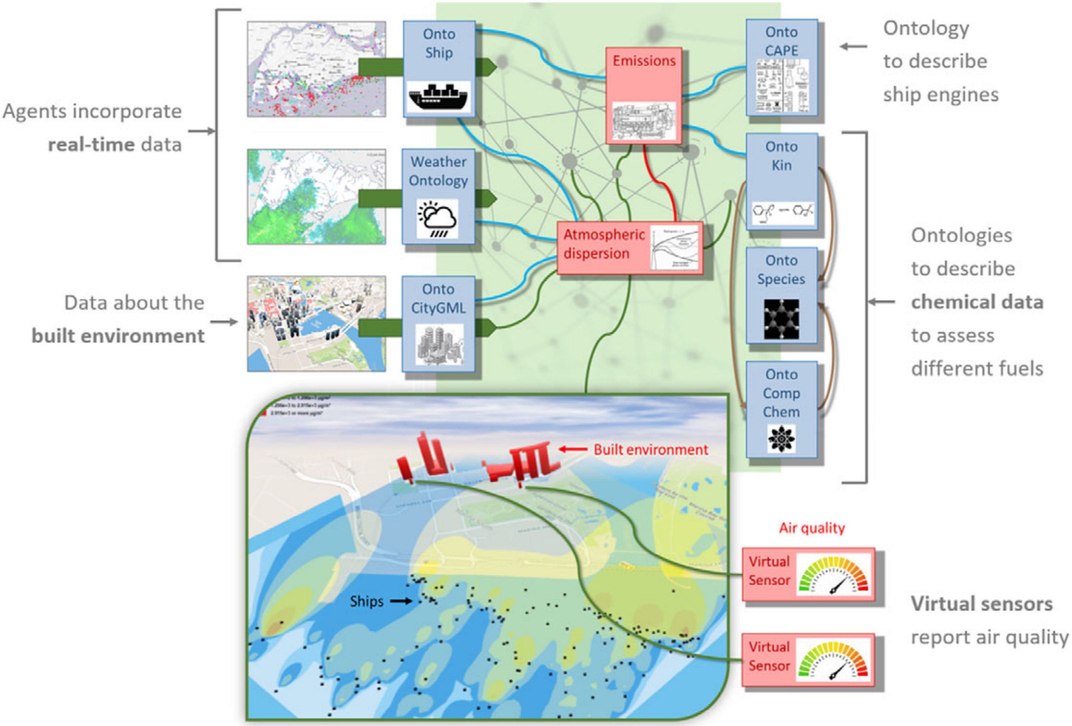

Figure 2. *Real-time cross-domain estimation of the impact of emissions from shipping to air quality. Adapted with permission from Farazi et al. (2020). Copyright © 2020 American Chemical Society.*

from each ship to simulate the dispersion of the emissions. Virtual sensor agents monitor the resulting air quality estimates at different locations.

The calculations performed by agents can take any form, including physics-based models with a theoretical structure, gray box models that combine some theoretical structure with data-driven components, and pure data-driven models. The agents are able to wrap around existing software, including both open-source and commercial software. Furthermore, agents modify the dynamic knowledge graph based on changing context and data availability (Eibeck et al., 2020). Through the integration of models and data from different domains, agents acting on the dynamic knowledge graph are able to perform tasks within and across domains to simulate the behavior of systems and the consequences of current activities. As a proof-of-concept, it highlights how the data and model integration capabilities of the dynamic knowledge graph are general and can be applied to any domain of interest inclusive of urban systems.

3.2.2.2. Consumer Energy Usage Data in Smart City Development. The second application concerns the consumer energy market in Singapore. The recent liberalization of Singapore's electricity market in 2018 has given consumers more choice and flexibility in selecting suitable electricity retailers and pricing plans to meet their needs. In light of this, the Consumer Energy Usage Data in Smart City Development (CEUS) project aims to develop a knowledge-enabled, data-driven common platform to provide real-time information about consumer energy usage to enable individual consumers and local government to make more informed decisions and promote more active participation in the energy market. This would empower consumers, foster innovation for a consumer-oriented energy grid, and promote the provision of more decarbonized, resilient and affordable electricity. An overview of the CEUS project is illustrated in Figure 3.

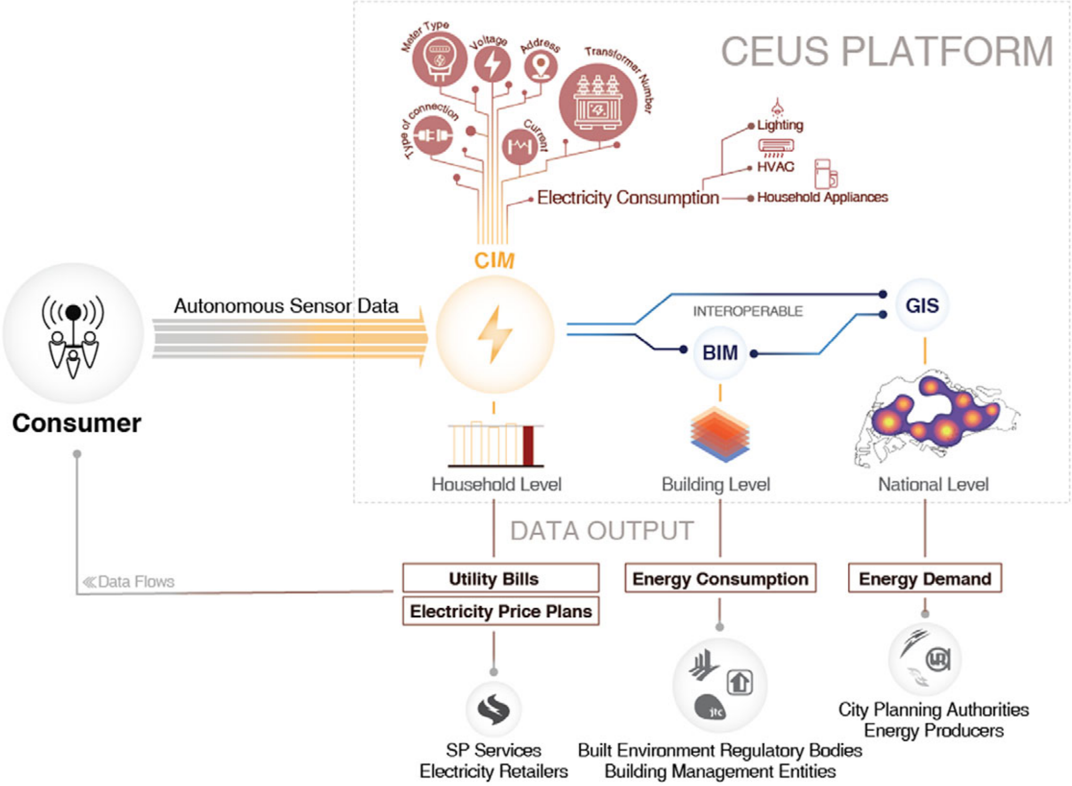

Figure 3. *Overview of the CEUS project.*

The CEUS project has three key components. First, a Singapore-specific Common Information Model grammar was developed to represent consumer energy usage information in a standardized format. Common Information Model is a well-established open standard for information modeling in the power systems domain that provides standard unambiguous definitions and representations of various energy related concepts (Britton and deVos, 2005; Becker and Saxton, 2008). A Common Information Model grammar has to be developed to cater for the idiosyncrasies of Singapore's consumer energy market arising from its recent liberalization. Second, the standards will be developed to adopt a consumer semantic format to enhance its interoperability and compatibility with other data formats and systems. Establishing the grammar in the form of standardized consumer semantics extends the expressivity of its formal definitions, enabling it to encode the necessary contextual information to support complex tasks such as automation and reasoning. The resulting Common Information Model will be integrated with an autonomous agent framework based on a dynamic knowledge graph to enable seamless and effective consumer energy usage data exchange with third party services such as electricity retailers and regulatory bodies. Third, the CEUS project reviewed existing smart city policies to identify and suggest implementation solutions that add value for policy makers. CEUS acts as a testbed for greater interoperability and compatibility between diverse technological systems to overcome existing data silos and share data with more stakeholders while respecting consumer privacy. In particular, CEUS tests how consumer energy data can be made interoperable and allow seamless integration between key planning software such as GIS and BIM. By laying a foundation for the integration of real-time energy consumption data into planning technologies, the information provided by the CEUS platform paves the way toward a consumer DT (Balijepalli et al., 2021).

3.2.2.3. Cities Knowledge Graph. The third application is the Cities Knowledge Graph (CKG), which explores the idea of using a dynamic knowledge graph as a knowledge management system to support city planning processes. City planners, guided by policy standards and targets, produce planning documents and proposals that synthesize information and goals from various cross-domain and multidisciplinary stakeholder dialogue. Implicitly, city planning processes rely on information flows such as gathering site information, requesting data from specialists, retrieving past proposals and decisions, building data repositories, and communicating with stakeholders. However, ongoing digitalization efforts for smart cities have yet to achieve the systematic and automatic discovery, preparation, interpretation, and delivery of relevant city planning data to support policy development.

To chart the emerging territory of semantic city planning systems, the CKG project has surveyed and categorized ongoing research efforts related to Semantic Web technologies and city planning around four meta-practices in the planning process (von Richthofen et al., 2022). It was identified that although current systems present data, they provide little capabilities to synthesize knowledge. The CKG aims to provide a Semantic City Planning System that supports the urban development process (city planning and urban governance) in three ways (von Richthofen et al., 2022). First, the CKG automates aspects of data gathering and processing in order to generate useful information and knowledge about cities. Second, tools, concepts and targets from different city planning departments and distinct knowledge domains are integrated to formulate more comprehensive complex definite planning questions. Third, the CKG will conduct advanced scenario planning, supporting planners to analyze different variants of their proposals.

Currently, the CKG researchers have established a Semantic 3D City Database in the form of an urban knowledge graph. To support representational MP, it can load and link 3D city data through a OntoCityGML ontology (Chadzynski et al., 2021), automatically load, update, and evaluate city data (Chadzynski et al., 2022b), as well as create visualizations and interfaces dynamically (Chadzynski et al., 2022a). An ontology of Singapore's land use planning regulations was added to the database (Silvennoinen et al., 2022), enabling the search for plots with particular land use or program combinations, while filtering results by other domain criteria (e.g., distance to parks). This ontology was extended with a classification of mixed-use archetypes occurring in Singapore, using Google Maps data (Shi et al., 2022). The design of the knowledge graph aims to provide management functions that enable users to perform queries and infer knowledge about the system so that they can review development states at various scales, formulate relevant policy themes, and enable dialogue within policy networks. The CKG has been applied to create cross-domain multi-scale urban planning indicators that can assess the on-site solar energy harvesting potential of different land plots in Singapore (Grisiute et al., 2022). Another application is to determine the urban energy performance of different land use allocations in Singapore (Shi et al., 2021). Existing urban-scale simulation tools are also being integrated, for example, the agent-based mobility simulation framework MATSim (Grisiute et al., 2022). One of the future steps is to automatically gather, conceptually represent, and structure governance instruments such as policy standards, principles, and targets in order to automatically infer new knowledge and semantic relationships between these instruments and the concepts they build on, evaluate specific targets and their coverage or level of representation, and use these insights to inform planning synthesis processes.

4. Reflecting on Current Digital Twin Practices

4.1. Opportunities for interoperability and compatibility

Each of the five CDT projects and their different goals corroborate with the literature findings on the CDT's potential to aid urban planning and governance processes. The Herrenberg DT and Cambridge CDT showcase the potential and relevance of adopting participatory planning processes as another source of knowledge to integrate urban governance insights into data and modeling results. Current DT discourses are largely confined to a techno-centric perspective with emphasis on demonstrating technical functionality (Nochta et al., 2021b). These examples illustrate a tendency for city administrations across distinct localities to follow and be influenced by technological developments, with a focus on interoperability and data sharing. However, cities are complex living systems with various intangible influences (policy, human behavior, and commercial interests) that are difficult, if not impossible, to capture through data and digital technologies (Rittel and Webber, 1973; Bettencourt et al., 2007; West, 2017). These solutions should extend beyond technical requirements, and be more sensitive to governance processes and their requirements such as privacy concerns. Consequently, city administrations should be involved in co-creating these digital solutions for their needs. Without their involvement, it remains unclear how the benefits proposed by current technology-driven approaches will be delivered and sustained. Thus, there is a need for interdisciplinary insights and deliberative participatory processes to become interoperable and compatible with technical data, involving prospective users ranging from the professionals who are responsible for planning and managing cities to the inhabitants of the cities, in addition to researchers and technology suppliers (Nochta et al., 2021a).

To accomplish this, the Herrenberg DT facilitated stakeholder engagement, even in the data collection stage, by involving citizens as part of a citizen science project to collect environment data from sensors and conducting public consultation through the developed mobile application "Reallabor Tracker" to gain data on the pedestrian and cyclists routes and their perceptions (Dembski et al., 2020). Moreover, the incorporation of virtual reality to enhance real-life perception can significantly support communication and decision making between stakeholders inclusive of politicians, administrative staff, experts from diverse disciplines, and citizens (Dembski et al., 2020). Using spatial and visual representation as a translation aid, the resulting reduction in complexity allows simulation results to be presented in an easier to understand manner than conventional methods and avoids the need for specialist language. Consequently, citizen participation in urban planning and design processes becomes easier and more attractive, while including groups previously excluded by conventional methods, such as children, teenagers, residents with a low level of education, migration background, or language barriers. For the Cambridge CDT, further engagement with stakeholders and residents in the area were conducted to include their perspectives and requirements when framing the problem (Nochta et al., 2021b). Following a socio-technical framework, such insights enable the participation of interested/affected parties, improving the transparency in decision-making processes while establishing responsibilities and accountability for a more meaningful policy implementation that coordinate and mediate diverse interests and goals. Thus, when interoperability and compatibility of different types of knowledge are realized, CDTs have the potential to tackle urban complexity by visualizing complex processes and dependencies in urban systems, simulating possible outcomes and impacts, while also considering its citizens' idiosyncratic needs and requirements through enabling participatory and collaborative planning.

On the semantic front, knowledge graphs are an opportunity to address the prevailing interoperability and compatibility issues in the ever-growing digital ecosystem. The three World Avatar applications highlight the knowledge graph's potential to overcome the existing professional silos in practice, for instance only targeting traffic congestion without coordinating or considering other policy domains. The World Avatar examples demonstrate the capabilities of dynamic knowledge graphs as a knowledge representation and management tool that can integrate data sources and computational models from different domains. The ontological approach provides a standardized and structured semantic framework that can be wrapped around new and existing digital tools, applications, and systems. Furthermore, by overcoming the significant institutional and technical difficulties in data sharing and management, the CDTs enable the optimization of entire urban systems across policy domains. Ultimately, through augmenting data management and technological adoption across various sectors and actors, these projects and their diverse applications highlight that CDTs are expected to enhance rather than replace human agency and democracy in urban governance models to become more data-driven and evidence-based in addressing existing urban challenges and delivering smart city ideals.

4.2. System versus semantic digital twin

The reflection on the knowledge management approaches of CDTs is structured through the lens of the four planning MP identified in Section 2.4. Applying this framework, we aimed to center the discussion on the CDT's potential to meet the needs and requirements of city administrations and planners. In comparing their capacity to enable interoperability and compatibility in the synthetical MP, the semantic CDT is more suitable with its dynamic ontological approach. System-integrated CDTs, as shown by the Herrenberg and Cambridge CDT, are still reliant on static manual data inputs and configurations to build the application and its components for a specific use case. Despite their success, these CDTs are also yet another digital tool that is often incompatible and not interoperable with other DTs in terms of their systems, formats, and protocols. In this sense, CDTs are both an ecosystem of micro-solutions, as well as a DT agent of a larger ecosystem of CDTs. Consequently, the growing complexity of the digital ecosystem and the associated large data streams, along with existing organizational silos and data management approaches will continue to challenge system integration adopters when they attempt to balance the connection of more recent tools and systems without disrupting existing established systems. In contrast, semantic CDTs such as the World Avatar DT could immediately integrate more data for new use cases without complex data transformation, as long as there is an existing ontology covering their domain. If no ontologies exist, an ontology needs to be developed or derived from other ontologies, which introduces a barrier to entry. Thus, answering the second research question, the semantic approach implemented in CDTs is a new opportunity to address the interoperability and compatibility conundrum. Future opportunities does not stop at connecting the data flows of individual DTs across domains to a CDT, but also enable feedback from the CDT toward the individual DTs.

However, as ongoing research and development projects, CDTs' capacity to support the entire planning process remains inconclusive. The Herrenberg DT supports representational MP as a communication tool to present planning proposals to the public for feedback. Nevertheless, the proposals are often based on the practitioners' assumptions with few impacts on the evaluative or projective MP beyond encouraging participatory processes. The Cambridge CDT moves beyond representational MP to evaluative MP by conducting scenario analysis in the first phase and modeling existing traffic patterns in the second, in order to make more informed policy decisions. But they have yet to support projective MP and generate automated predictions or planning proposals to address these issues identified. In contrast, the semantic approach has enabled the World Avatar CDT to support representational, evaluative, and projective MP through its dynamic agent framework.

Although the semantic CDT are arguably more developed to handle more planning-related tasks and MP, it remains unclear which approach is better as all CDTs have yet to be adopted in practice or evaluated. It is impractical to make a comparison and evaluation between the two approaches based solely on feature lists. Given that planning processes revolve around making more informed decisions and proposals (Stojanovski et al., 2020), an appropriate evaluation criterion should instead be the data processing and analytical capabilities alongside their planning outcomes. Moreover, it can be argued that CDTs are not yet designed to support the technical deliverables of urban planning and governance processes. Design professionals are required to identify issues through various information sources, evaluate existing proposals, suggest new strategies, and communicate their ideas through visual mediums (Stojanovski et al., 2020). In this aspect, existing CDT applications have yet to generate new strategies, suggestions, or insights for design professionals to perform their tasks. They are limited to specific use cases in primarily urban mobility, which does not comprehensively cover the entire urban planning or governance systems. This may overlook certain intangible aspects that cannot be translated into digital format. Thus, as a result of their current experimental nature, there remains a lack of evidence with practical planning outcomes that can evaluate and validate the CDTs' potential to improve urban planning or governance processes.

5. Conclusions

In the ongoing pursuit for smarter cities, the rapid pace of isolated siloed technological developments and their growing complexities and pitfalls have become too significant to ignore. As a starting point for a more conscious engagement of practitioners with CDTs, this paper has analyzed the differences between semantic and system integrated CDTs, and discussed their opportunities to address the conundrum of interoperability and compatibility for smarter cities. In terms of what we can learn from existing CDT projects about facilitating interoperability, our analysis is as follows.

Firstly, the five CDT research and development projects presented in this paper support the claims of the promise of CDTs as the next generation of urban models in city planning and governance. When designed in the right way, CDTs can cut across data silos to enable cross-disciplinary, inter-sectoral collaborative processes that can potentially promote public participation and stakeholder engagement. Examples such as the Herrenburg CDT supports greater human agency and democracy in urban governance models to make informed decisions with clear data evidence.

Secondly, in technical terms, the key bottleneck of CDTs today lies in the interoperability and compatibility between the various approaches, digital solutions, and DTs. Existing trajectories of city planning and governance processes are moving toward an ever-growing digital ecosystem of individual micro-solutions for transforming their workflows. It is anticipated that these technological developments will have profound consequences for jobs and decision making. Nevertheless, much of their ongoing developments remain fragmented, perpetuating an ever-growing heterogeneous, distributed, and dynamic digital ecosystem. At the urban scale involving multiple domains and spatial scales, the weak interoperability and compatibility between digital solutions, and consequently, CDTs, hinders the capacity to develop virtual representations that can replicate the immense complexity of urban systems to support city administrations. Moreover, the bottleneck prevents the adoption of a digital ecosystem framework that produces greater value to communities and is potentially resource inefficient, which runs contrary to smart city goals and the synthetical MP that is central to the consensus-driven city planning process.

Lastly, CDTs have a long way to go beyond technical interoperability, and tackle the sociocultural and environmental dimensions of cities. Most ongoing CDT research and developments are concentrated on addressing the current technical bottleneck. They have yet to make progress on addressing many significant issues.

- The first issue is how we incorporate and interpret data in a challenging socio-political landscape bridled with privacy and security concerns. Although they may not explicitly impact their technical functionality, economic, sociocultural, and environment concerns, such as data silos, legal considerations, privacy, and political agendas, have yet to be fully engaged by the design of various digital solutions and CDTs. This push for interoperability and compatibility to share data across entities may also, counterintuitively, exacerbate the anxiety and wariness of citizens, as their data are now accessible and available to entities they have never interacted with or intended. As argued by Kitchin (2016), deliberately averting digital solutions nor pursuing smart city design at all costs are not viable approaches. Rather, cities must adopt a multi-pronged approach that weaves all aspects of a city, inclusive of data privacy, protection, and security. The semantic approach may be an interesting choice. It could explicitly incorporate technical stipulations to augment their data sharing frameworks and prevent oversharing, especially for non-critical data. However, more practical research needs to be conducted to understand and support these claims.

- The second issue is whether CDTs can produce actionable deliverables for urban governance and planning. Currently, they are only successful in identifying key planning issues and visualizing existing data more efficiently. But they have yet to generate additional insights, recommendations, or proposals, which are key deliverables of the governance and planning process. In addition, models are always an abstraction of an ever-changing and complex reality. Confronted by “wicked” urban problems, where addressing one problem may create another problem that cannot be predicted by even the best experts, the deliverables produced by CDTs will unlikely be enough to resolve the problems on their own. Instead they should be treated as guidelines to support policy decisions.
- The final issue arising from this analysis is that it is unclear whether an applied-model approach is able to arrive at a holistic, integrated digital ecosystem that allows the exploration of urban problems. Despite the capacity to integrate numerous micro-solutions, CDTs are heterogeneous place-based solutions. Each project has its own requirements and ecosystem of digital solutions that are dependent on factors, such as the level of digital literacy, ambition and budget of city administrations. This signifies that they are much more individualistic than initially thought. Moreover, current developments are still resolving the bottleneck of interoperability and compatibility that plagues today’s fragmented digital ecosystem. There is yet to be a complete CDT application that has been integrated into practice. Thus, it remains unclear exactly how CDTs will impact the governance or planning process.

Today, technological narratives have insisted on an one-size-fit-all approach, which is not applicable, at least, in the urban planning and governance context. This have led to their strong technocratic influence that often dictate the city administrations’ digital approaches and actions. Simultaneously, some administrations are pushing against these external influences, and championing their own digital solutions for their local processes and needs. Although it is unclear which trend occurred first, overcoming this “chicken and egg” situation for a smarter, more sustainable, and inclusive city will require major work. Thus, when adopting digital solutions for their processes, city administrations must be more mindful of their technical capabilities and limits while being more proactive, flexible, and selective in co-creating technologies sensitive to their processes.

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Ethical Standards. The research meets all ethical guidelines, including adherence to the legal requirements of the study country.

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