Preprint Cambridge Centre for Computational Chemical Engineering ISSN 1473 – 4273

The Conundrum in Smart City Governance: Interoperability and Compatibility in an ever-growing digital ecosystem

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released: December 22, 2021

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Preprint No. 287

UNIVERSITY OF CAMBRIDGE

Keywords: Digital Twins, Internet of Things, Interoperability, Urban Planning, Smart Cities

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Abstract

In the ongoing pursuit for smarter cities, city administrations are confronted by a challenge to manage the rapid and fragmented technological developments. The latest developments of urban digital twins further contributes to this complexity. This paper suggests that in order to truly reap the benefits of digital twins, city administrations must consciously acknowledge these rapid technology advances and their poor interoperability and compatibility. Bringing together experiences from five research projects, this paper discusses the variety of digital twins based on two common digital integration methodologies – systems and semantic integration. We revisit the nature of the different underlying technologies, discussing the subsequent implications for interoperability and compatibility in the context of planning processes and smart city goals. 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 help governments to address this conundrum of fragmentation, interoperability and compatibility.

Contents

1 Introduction

Planning cities have 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 21^{st} 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 analysed for more efficient operations and smarter cities [30, 33, 48]. Given the growing spotlight on the potential of planning technologies such as Digital Twin (DT) for urban planning and smart city design, this paper critically revisits the challenges of employing these digital planning tools. 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 through the lens of two different technological approaches - system and semantic integration.

Today, city administrators and politicians have recognised the potential of technological solutions and by extension, smart cities to address urban sustainability issues while enhancing the quality of urban life across scales [22, 26, 33, 48]. To this end, they have often initiated, advocated, and endorsed new technological endeavours in public, private and research institutions across diverse disciplines such as Germany's third iteration of model Smart Cities projects [12] and Singapore's Smart Nation initiatives [44]. This generates a growing diversity of digital solutions ranging from interactive online dashboards for city statistics to proprietary optimisation tools for city logistics, building management and infrastructure planning [30, 50].

Although the ever-growing diversity, range and extent of compatibility between new and old technologies means that real-world problems are being solved at unprecedented speeds, these solutions have also generated an immense number of heterogeneous systems that are often not interoperable or compatible with each other [40, 49]. 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 organisations remains fragmented in their research and development efforts [32, 34, 40, 49]. In the current state of an ever-growing heterogeneous, distributed and dynamic digital ecosystem, large isolated data silos are formed and have inhibited knowledge sharing and collaboration processes, leading to the increasing importance of both interoperability and compatibility today [30, 32, 49].

Interoperability and compatibility enables collaboration and more efficient decision making processes, which leads to greater resource efficiency and innovation in an era confronted by resource shortages and sustainability issues [32, 38]. Furthermore, interoperability and compatibility are important at a time when large research grants are continuously given to support the growing uncoordinated and largely unsuccessful development of smart city solutions. If these ineffective smart city solutions, often represented by small-scale pilot projects, have stronger collaboration with each other and active communication with the stakeholders, they would not be likelier to fail and fade out after their trial periods. Instead, such solutions could be expanded and replicated to establish a flourishing urban modelling ecosystem that addresses urban challenge at various scales [50]. To raise awareness, stakeholders of smart city initiatives have to recognise the pitfalls of a disjointed dynamic digital ecosystem and follow up by formulating strategies on how the various digital systems can be integrated to become interoperable and compatible.

In the current smart city discourse on digital integration, there is a growing research interest in the DT concept as the next generation of planning support systems. Through integrating various digital systems, formats and applications into one common interface, the DT could generate sufficient information and data for an interoperable and compatible system that is capable of representing the entire city and its various domains into the digital space [5, 42]. Nevertheless, existing discourses on DTs for city planning are still in their infancy with little practical research and lack of international standards or protocols [42]. Current DT experiments are focused on replicating a visual representation of the city in the digital space, which holds great commercial value for navigation, wayfinding and stakeholder engagement. Nevertheless, they often neglect the DTs' real-time analytical and processing capabilities for the development and evaluation of scenarios which is critical to aid urban planning and governance systems address urban problems. Given the experimental status of DTs, it remains unclear how different DTs approach interoperability and compatibility between various systems and applications. Furthermore, it is unclear whether an applied-model approach is able to address both urban problems and arrive at an holistic, integrated digital ecosystem.

In its aim to critically reflect and overcome the conundrum of fragmentation, interoperability and compatibility, the paper is guided by two research questions:

- Why is the notion of interoperability and compatibility significant to smart cities?
- What are the ongoing approaches to the integration of various digital systems, formats and applications?

To the extent of our knowledge, integration strategies can be classified into two approaches, namely, system and semantic integration. The traditional system integration directly connects various digital tools, formats and systems through a common interface into one single consolidated application for users to access. The semantic integration provides a common ontological framework that can standardised any data into semantically-rich data formats with context and meaning, enabling data to be integrated, shared and reused across applications, systems and even domains. In this paper, the classification provides a framework to structure the five DT research experiments from several research institutes – Cambridge-based 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 experiment's researchers and gaining access to their resources and knowledge, this paper is able to present a comprehensive overview of each experiment's capabilities and shortcomings for a more critical reflection of DTs in general. Section one introduces the research background, framing the problem of interoperability and compatibility in the context of smart cities. Section two presents the prominent interdependence between urban and technological developments and their relevance within the smart city context. Section three and four present the system and semantic integration respectively. Section five reflects on current DT practices while Section six concludes the paper.

2 City Planning and the 4th 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 [33, 48]. Today, technological innovations such as the Internet of Things, Internet of Services and cyber-physical systems and their exponential growth in processing power to capture and process data at extensive scales, in better resolution and quasi-real-time have enabled cities to become smarter, optimising city operations and improving governance through greater transparency and openness [30, 48]. City administrators have already acknowledged the significance of technology in enhancing urban life, as evident in the demarcation of cities deploying Information and Communication Technology (ICT) as smart cities and the myriad of smart city projects that are in progress [22, 45, 50]. Implied in its meaning, ordinary cities are perceived as better when adopting ICT solutions in their operating models to become smarter [48].

Despite being a relatively recent paradigm, smart city developments are advancing rapidly and can already be identified in three distinct phases. [30] highlight the specific technologies and their corresponding transformation of the digital space in each phase. The first phase conceives the representation of the city in digital space through portal-type webpages, panoramic and 3D representation, augmented reality technologies and urban tagging. Ranging from simple, informative webpages, forums and chatrooms to interactive spaces with virtual agents, such digital solutions capitalise on the advantages of representation and visualisation to improve communication between experts and non-experts. Through technological advances like cloud computing, the second phase enabled citizen participation and engagement in smart city solutions such as co-creation and crowdsourcing to capitalise on the collective intelligence, social and creative capital of the population and knowledge-sharing institutions. One significant contribution of the second phase is that of a people-driven innovation based on principles of openness, realism and user empowerment in new digital solutions. The latest phase comprises the search for a more inclusive, diverse and sustainable urban environment, and the availability of real-time big data round the clock through the diffusion of pervasive real-world user interfaces capable of retrieving and transmitting data as part of the Internet of Things via mobile phones, smart devices, and sensors embedded in physical spaces. Artificial Intelligence using deep learning and natural language processing techniques has enabled the collection, aggregation and analysis of such big data streams to gain insights on the management and optimisation of urban flows, systems and domains. Problems can now be resolved just in time with real-time responses in new modes of human-machine interactions. Thus, whether cities are at different stages of smart city development or yet to adopt smart solutions, these historical trends demonstrate the significance of technological innovations in propelling urban developments and the subsequent higher quality of life, and such a symbiotic relationship will hold true as cities continue to evolve in future. These rapid technological advances also leave city administrations with the challenging task of managing the fragmented approaches to smart cities. Such approaches often leads to ineffective distributed approaches that fall short of delivering the promises of smart cities. We argue that the next phase inevitably needs to focus on overcoming this fragmentation and complexity. Centred on interoperability and compatibility, this endeavour would need to build on both technological solutions as well as consider organisational practicalities.

2.2 The Ever-growing Heterogeneous and Dynamic Digital Ecosystem

Despite the potential of a technology-enabled society, smart cities today have yet to fulfil this promise in the face of a fragmented digital ecosystem. These smart city ideals were initially heavily advocated by big software and hardware firms such as IBM, CISCO, Microsoft, Intel, Siemens, Oracle, SAP [22, 26, 48]. Possessing innovation and technological knowledge, these corporate interests advocate for more technological solutions in attempts to expand their market share and maximise their profits and economic interests [22, 24, 26, 45]. In pursuing these economic interests, these urban entrepreneurs often design their proprietary digital solutions not to be interoperable or compatible with their competitors in order to hopefully establish a technological lock-in for their offerings and monopolise the market [24, 26, 49].

Over time, big technology firms ceased to be the sole proprietors of new digital solutions as the barriers to technological development fell, in lieu of greater governmental support and funding, and the surge in technological expertise amongst the general population. Aiming to include citizens and promote public participation in their cities, various stakeholders in research organisations, non-technology firms and even individuals have begun developing their own smart city solutions [24, 30, 33, 38]. Often, these technological developments such as mobile phone applications remain disjointed from other digital systems and applications, mostly addressing a specific issue where public information is collected to offer a solution for the community. However, these micro-solutions fail to embrace a digital ecosystem framework to produce greater value to the communities.

As smart cities gain prominence, such troubling trends have persisted in spite of the concerns raised on poor interoperability and compatibility [30, 38, 40, 49]. In other words, as smart city developments progress, the current digital ecosystem of heterogeneous and dynamic digital tools will continuously grow. Moreover, cities are complex living systems [4, 56] with uncontrollable, unpredictable, “wicked” problems in which introducing one solution may lead to more problems even with coordinated efforts [39]. Hence, the poor interoperability and compatibility within such an ecosystem are detrimental to achieve the promises of smart cities in addressing urban sustainability issues and could waste resources when duplicating technological solutions to address the same issues.

2.3 Smart City Planning Technologies

In discerning these issues, this paper looks at the smart city's ever-growing digital ecosystem and its various developments and disciplines, such as 3D city models, Digital Twins, Urban Analytics and Informatics, and Geographic Information System (GIS), as a broader and complex concept known as City Information Modelling (CIM) [19, 47]. In clarifying the previously ill-defined and fragmented concept, [19] conducted a literature review and establish that CIM-related research has generally been applied for the integration of urban design and analysis, sustainability assessment methods concentrating on building energy performance, urban simulation and visualisation, and management of urban assets like heritage infrastructure and disaster prevention. Although CIM initially emerged as an extension of Building Information Modelling (BIM) to the city level, it has evolved over time to include more perspectives and functions, with greater emphasis on generating more semantically rich 3D city models and enabling BIM-GIS and CAD-GIS integration for geospatial capabilities [19]. With the multitude of perspectives and rapidly developing disciplines, CIM becomes dependent on more collaborative developments across various digital tools, rather than a singular technology or platform in order to deliver the promises of the smart city [19]. Thus, [19] defines CIM in a broader sense as:

> "...the practice of using interactive digital technologies in the process of urban planning, by all actors and stakeholders, to collaboratively deliver the vision of a Smart City: a sustainable, inclusive, healthy, prosperous and participative city. CIM consists of an ecosystem of interoperable (open source) tools from different knowledge domains, for data processing, urban analysis, design, modelling, simulation and visualisation. These tools are connected via shared ontologies to a semantically rich CIM, based on open standards, in a multi-scale and multi-temporal database, that integrates a wide range of (big) open data sources representing the full range of urban features, systems and processes." (p. 512)

At present, although CIM tools aim to support the planning and governance processes, they are yet to be fully adopted in practice largely due to their lack of user-centric design. Often from design backgrounds like architecture, urban planning and design, users favour the physical form and their experiential qualities, incorporating ideas such as human scale, place-making, social life and the community, into their work tasks and requirements [19, 47]. This contrasts the technocratic perspectives of researchers and developers involved in software development, who are focused on optimisation and efficiency. Moreover, these CIM-related data are often not as convenient to access due to poor interoperability and compatibility issues, bureaucratic red tape and privacy concerns [19]. Accordingly, it is unsurprising that practitioners are reluctant to adopt the cold methodological technocratic CIM tools into their practice.

Given the all-encompassing nature of CIM, the paper narrows the focus and scrutinises the rapidly developing urban DTs to bring greater clarity while reflecting on digital planning tools as a whole, in anticipation of their capacity to represent and manage the complexities of cities and their challenges. As simulation models, DTs provide a digital representation of the state and behaviour of a real-world system and can bilaterally interact in real-time with the physical counterpart throughout its life cycle [5, 10, 31, 42]. Past successes of DTs in the manufacturing processes – production planning and control, maintenance, and product life – have demonstrated their capability in simulating and optimising systems to increase competitiveness, productivity and efficiency [31]. In the context of city planning, urban DTs are expected to simulate the complexity of cities in real-time, in order to monitor and optimise city processes such as transport, energy and health, and support decision-making processes to analyse, plan and govern the built environment [5, 42]. Moreover, DTs are also expected to enable an unprecedented scope for stakeholder engagement in public participation and collaboration between the experts as well as non-human actors and machines [14, 42].

Nevertheless, the current deployment of DTs in city planning and construction remains limited as an ongoing experiment by researchers and has yet to be fully adopted in practice. Despite being coined as a term within the manufacturing context in 2002 [20], this technology remains unfamiliar to most and is often confounded with similar technologies – 3D models or BIM – which fails to distinguish their definition, capabilities and challenges and may impede the technology's development [31, 42]. Moreover, given that urban DTs are an amalgamation of various technologies integrated together, they tend to have no fixed technology or systems, but are characterised instead by their capabilities [10]. Accordingly, there are different integration strategies for various urban DTs, which can be classified as either system or semantic integration. The different strategies will be introduced and evaluated through five research experiments implemented by researchers at various development stages. The next two sections introduce the technical components and goals of the five DT experiments. The reflection will then discuss their capabilities and capacity to address interoperability and compatibility issues and their relevance for practitioners, to pave the way towards adopting the DTs in practice and ultimately, delivering smart city promises and addressing urban problems.

3 The System Integration Approach

This section presents two DT applications based on the traditional system integration process. In this approach, individual digital systems, services and tools are connected 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.

3.1 Herrenberg Digital Twin

The town of Herrenberg in Germany has been the subject of one DT experiment 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 [14], the Herrenberg DT comprises seven digital tools, datasets and analytical models: (1) A hybrid 3D city model based on geographic data and information. (2) A mathematical street network model using space syntax. (3) Urban mobility simulation using an open-source traffic simulation software – Simulation of Urban Mobility (SUMO). (4) Air-flow simulation using an open-source computational fluid dynamics application – OpenFOAM. (5) Sensor network data describing particulate matter, temperature, and humidity. (6) Empirical quantitative data describing pedestrian and cyclist routes. (7) Empirical qualitative data describing the perception of urban spaces through feedback, ratings and photographic impressions. The urban DT was incorporated in the collaborative visualisation 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 visualised across scales in an immersive virtual reality environment.

3.2 Cambridge City-level Digital Twin

The Cambridge City-level Digital Twin (CDT) 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 CDT 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 modelling framework in Fig. 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 [36].

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 anonymised vehicle trajectories, to understand traffic patterns and their policy implications [54].

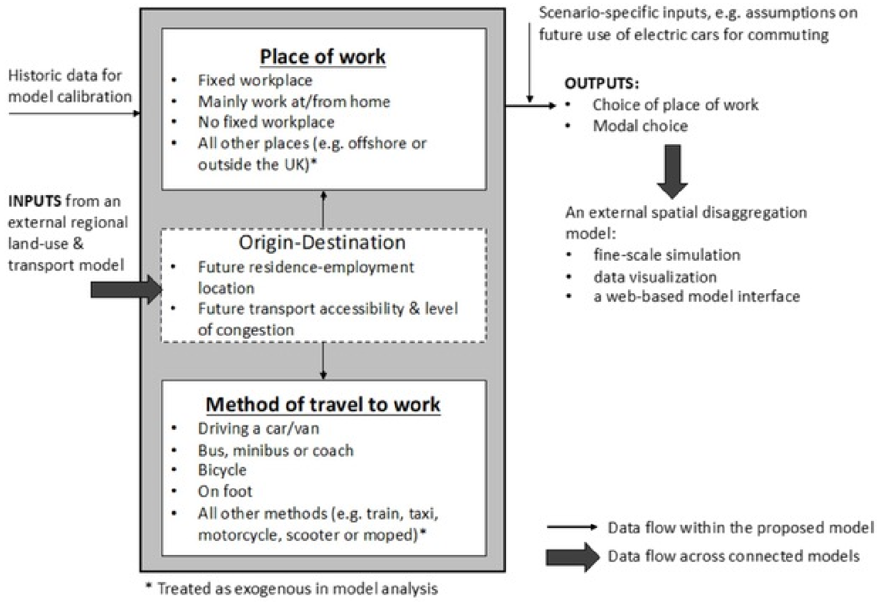

Figure 1: *Modeling framework for the Cambridge CDT prototype for journeys to work. Reprinted with permission from [36]. The original figure was published under the terms of Creative Commons Attribution License 4.0*

4 The Semantic Integration Approach

Semantic Web technologies have 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 [41, 53]. The Semantic Web provides a common framework that allows data and the relationships between data to be represented using ontologies, providing context to the data and enabling it to be shared and reused across applications and systems [52]. By following the principles of Linked Data [7, 9], the Semantic Web enables the discovery, integration, query and transfer of information between different domains and systems via the World Wide Web [1, 37].

Given these capabilities, this section presents the World Avatar – a DT that employs a semantic integration approach in conjunction with a dynamic knowledge graph [1]. 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 include a range of applications such as air quality assessment, consumer energy and city planning.

4.1 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 [37]. 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 [25]. 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 [1, 37]. 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 [25]. Moreover, knowledge graphs can support application services to generate insights and recommendations, for example, via DTs to support city planning [25].

Unlike a traditional database, the World Avatar DT employs a dynamic knowledge graph that can be updated and restructured by autonomous computational agents [1]. [16] describe the ability of agents to fulfil specific objectives, including (i) input and output, (ii) updating the knowledge graph with calculated data, (iii) restructuring the knowledge graph by adding instances [15], concepts and relationships, and (iv) providing services that facilitate the discovery and creation of agents [57].

4.2 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 [1]. 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.

4.2.1 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 [18]. 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 Fig. 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 informa-

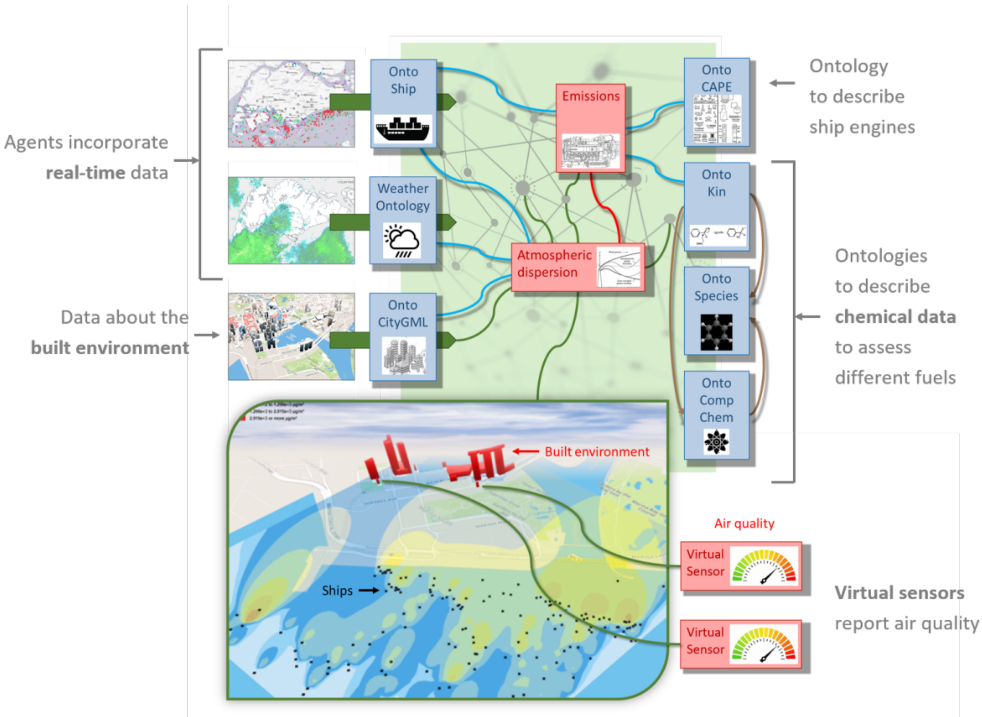

Figure 2: *Real-time cross-domain estimation of the impact of emissions from shipping to air quality. Adapted with permission from [18]. Copyright © 2020 American Chemical Society*

tion about the built environment, weather, and the emissions 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, grey 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 [17]. 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 behaviour 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.

4.2.2 Consumer Energy Usage Data in Smart City Development

The second application concerns the consumer energy market in Singapore. The recent liberalisation 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 decarbonised, resilient and affordable electricity. An overview of the CEUS project is illustrated in Fig. 3.

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 standardised format. Common Information Model is a well-established open standard for information modelling in the power systems domain that provides standard unambiguous definitions and representations of various energy related concepts [6, 11]. A Common Information Model grammar has to be developed to cater for the idiosyncrasies of Singapore's consumer energy market arising from its recent liberalisation. 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 standardised 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 test-bed 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 CIM, the information provided by the CEUS platform paves the way towards a consumer DT [2].

4.2.3 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 synthesise 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 digitalisation 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 categorised ongoing research efforts related to Semantic Web technologies and city planning around four meta-practices in the planning process [51]. It was identi-

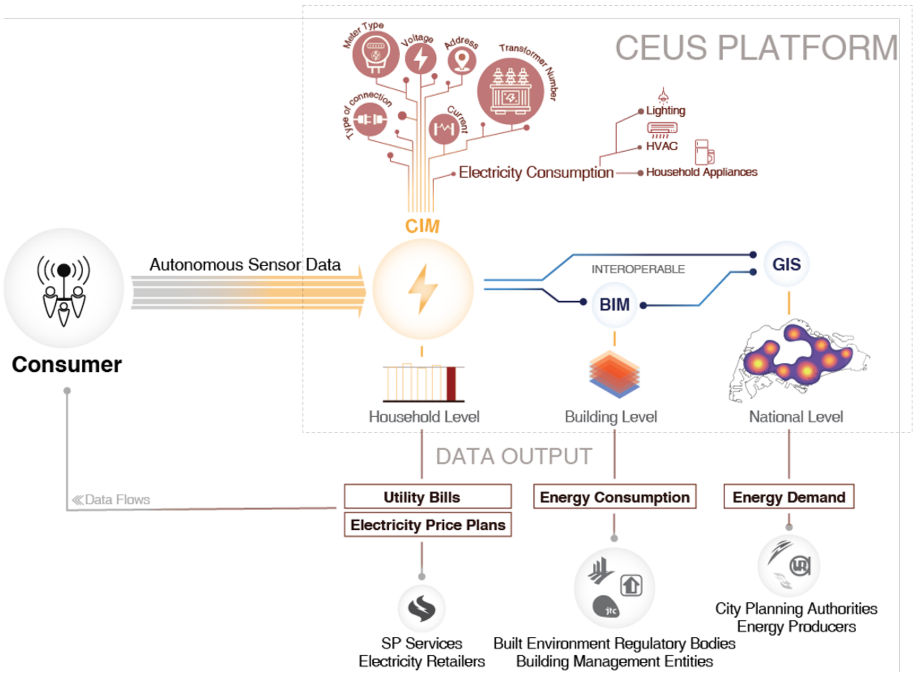

Figure 3: *Overview of the CEUS Project*

fied that although current systems present data, they provide little capabilities to synthesise 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 [51]. Firstly, the CKG automates aspects of data gathering and processing in order to generate useful information and knowledge about cities. Secondly, tools, concepts and targets from different city planning departments and distinct knowledge domains are integrated to formulate more comprehensive complex definite planning questions. Thirdly, the CKG conducts advanced scenario planning, supporting planners to analyse different variants of their proposals.

Currently, the CKG researchers have established a Semantic 3D City Database in the form of an urban knowledge graph, that can load and link 3D city data through a OntoCityGML ontology [13]. The ontology builds on the work of Kolbe and co-workers to develop semantic city representations [23, 27–29, 46]. The design of the knowledge graph provides 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 [21]. Another application is to determine the urban energy performance of different land use allocations in Singapore [43]. 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.

5 Reflecting on Current Digital Twin Practices

5.1 Lessons from existing practices

Although urban DTs are still in development, each of the five DT experiments and their different goals highlights the potential for DT to aid urban planning and governance processes in multiple ways. The Herrenberg DT and Cambridge CDT showcase the potential and relevance of adopting participatory planning processes to integrate urban governance insights into data and modelling results. Current DT discourses are largely confined to a techno-centric perspective with emphasis on demonstrating technical functionality [36]. However, cities are complex living systems with various intangible influences (policy, human behaviour, commercial interests) that are difficult, if not impossible, to capture through data and digital technologies [8, 39, 55]. Without a thorough understanding of urban governance issues, 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 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 [35].

To do so, 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 [14]. 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 [14]. Through the use of spatial and visual representation as a translation aid, the resulting reduction in complexity allows the results of simulations 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 of people 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 [36]. 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, DTs have the potential to tackle urban complexity by visualising 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.

The three World Avatar applications highlights the DTs' potential to overcome the existing professional silos in practice, for instance only targeting traffic congestion without coordinating or considering other policy domains. Adding an innovative technological perspective, the World Avatar examples have demonstrated the capability 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 standardised and structured semantic framework that can be wrapped around new and existing digital tools, applications and systems. This allows the knowledge graph to overcome the prevalent interoperability and compatibility issues of DT, even in an ever-growing heterogeneous, distributed and dynamic digital ecosystem. Furthermore, by overcoming the significant institutional and technical difficulties in data sharing and management leading to the silos, the DTs enable the optimisation of entire urban systems across policy domains. Ultimately, through augmenting data management and digital technology adoption across various sectors and actors, these experiments and their diverse applications highlights that DT 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 in practice and delivering smart city ideals.

Nevertheless, digital planning tools including DTs have yet to be adopted in practice as existing DT practices fail to consider their users' needs and requirements. City planning often requires inputs such as expectations, concerns and constraints from diverse stakeholders and domains. Given the inherent social risks such as privacy breaches and marginalisation when collecting these inputs, the availability of data may be locked behind organisational silos with poor data sharing frameworks. Moreover, there is a significant knowledge gap in the understanding of the growing complexity of urban systems. As urban systems continue to evolve and the interactions between different domains become more complex, this lack of understanding hinders the capacity to represent behaviour and operation of urban systems in digital formats, if it is even possible [3, 55]. In structuring the knowledge gap, we reference the four meta-practices (MP) identified in planning processes by [51]. 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 modelling. 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 synthesising the inherent data, information, and knowledge flows to plan urban systems.

5.2 System vs. Semantic Digital Twin

In comparing their capacity to resolve interoperability and compatibility issues in the synthetical MP, the semantic DT is more suitable with its dynamic ontological approach. The two system-integrated DTs are still reliant on static manual data input and configurations to build the application and its components for a specific use case. Despite their success, these urban DTs are also yet another digital tool that is often incompatible and not interoperable with other DTs in terms of their systems, formats and protocols. The growing complexity of the digital ecosystem and the associated large data streams, along with existing organisational 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 DT could immediately integrate more data for new use cases without complex data transformation if there is an existing ontology.

However, as ongoing research experiments, DTs' 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 modelling 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 DT to support Representational, Evaluative and Projective MP through its dynamic agent framework. Notably, while semantic DT are arguably more developed to handle more planning-related tasks and MP, it remains unclear which approach is better as all DTs has yet to be adopted in practice or evaluated. It is impractical to make a comparison and evaluation between the two integration strategies based solely on development speeds. Given that planning processes revolves around making more informed decisions and proposals [47], an appropriate evaluation criteria should instead, be the data processing and analytical capabilities and their planning outcomes. Moreover, it can be argued that DTs are not yet designed to support the technical deliverables of urban planning and governance practice. Similar to the four MPs, design professionals are required to identify issues through various information sources, evaluate existing proposals, suggest new strategies, and communicate their ideas through visual mediums [47]. However, existing DT applications are limited to specific use cases in primarily urban mobility, which does not comprehensively cover the entire urban planning or governance systems and may overlook certain intangible aspects that cannot be translated into digital format. Although current DTs have primarily sped up information flows and enable easier interpretation of existing data through data visualisation methods, they have also yet to generate new strategies, suggestions or insights for design professionals to perform their tasks. Thus, there remains a lack of evidence with practical planning outcomes that can evaluate and validate the DTs' potential to improve urban planning or governance processes.

6 Conclusions

At present, existing trends have demonstrated that technology has and will continue developing at breakneck pace alongside urban developments. City administrators, private businesses and citizens have recognised the potential of ICT and smart cities in addressing urban sustainability issues. Such motivations alongside the low barrier to entry have spurred public agencies, private entities, research organisations and even individuals to partake in the development of digital solutions to address specific urban problems, but often without any collaboration or wider coordination. It is anticipated that these technological developments will have profound consequences for jobs and decision-making, which introduces a new conundrum for city administrations. The ever-growing heterogeneous, distributed and dynamic digital ecosystem fails to embrace a digital ecosystem framework that produces greater value to communities and is potentially resource inefficient, which runs contrary to smart city goals. In recognition of the ever-growing role of ICT solutions in smart cities, we propose that the next phase of smart city developments should be more conscious of implementing planning support systems through explicitly adding a new technological dimension to the trifecta of sustainability goals in city planning processes. By adding this dimension explicitly, it provides syntax to describe and give meaning to the aggravating interoperability and compatibility issues, and how to overcome this conundrum in the smart city context.

The endeavour has already started following the growing interest in digital integration solutions. In this paper, we present the urban DTs, a rapidly growing research field within the current smart city discourse on digital integration that has gained significant interest in recent years. DTs are expected to be able to represent and simulate the complexities of cities with a near-identical virtual representation in real-time. This allows DTs to monitor and optimise the various city processes while enabling unprecedented stakeholder engagement in public participation and collaboration between more stakeholders. The integration strategies of existing DTs can be classified into two approaches, namely, system and semantic integration. The traditional system integration approach directly connects the various digital tools, formats and systems through a common interface into one single consolidated application for users to access. On the other hand, semantic integration provides a common framework based on the use of ontologies to semantically annotate tools and data. By providing context and meaning to the data and their relationships, the ontological approach enables data to be integrated, shared and reused across applications, systems and even domains. This paper has presented five DT applications for Herrenberg (Germany), Cambridge (UK) and Singapore. The examples from Herrenberg and Cambridge adopt a system integration approach, which remains reliant on static manual user interactions to configure and set up the data transformation and sharing framework. In contrast, the World Avatar DT examples from Singapore adopts a semantic integration approach based on a dynamic knowledge graph, and demonstrates the potential of an ontological integration framework to overcome the prevailing interoperability and compatibility issues both across domains and at a city level. Although still in their infancy, all five examples have demonstrated the promise of DTs as the next generation of urban models in city planning. When designed in the right way, the DTs are able to cut across data silos to enable cross-disciplinary, inter-sectoral collaborative processes that can potentially promote public participation and stakeholder engagement. It is also hoped that DTs will support greater human agency and democracy in urban governance models to make informed decisions with clear data evidence. However, there are still many open questions and it remains unclear exactly how DTs will impact the planning process and practitioners, especially in smart cities.

The city planning process often involves the identification, evaluation and proposal of planning issues and their solutions, which are generally communicated through visual mediums. Although engaging with stakeholders and citizens has acknowledged the significance of data not as an absolute solution, but as a supplementary tool to support more informed policy decisions, it is insufficient for smart cities to shift from a technocratic model towards one that also considers the humanistic perspective of cities. Such digital tools must also consider the entire planning process. Current urban DTs are only successful in identifying key planning issues and have yet to be able to make recommendations or proposals. This is troubling as such an action of proposing solutions is a key deliverable of planning processes, which arguably is more important than identifying planning issues. Moreover, existing integration approaches employed have transformed immense noisy raw data streams that are not human-readable into visual communication tools such as dashboards, simulation models and augmented reality technologies that can be easily interpreted by any user. Such visual outcomes are often only a more efficient and swifter method to represent existing data and have yet to generate additional information or insights beyond the given dataset. In addition, models are always merely an abstraction of reality. Even if the data are updated and analysed in real-time, the proposed solutions by urban DTs should only be considered as guidelines into the future. These DTs must also be continuously updated and adapt to an ever changing, complex reality with "wicked" urban problems, where addressing one problem may create another problem that cannot be predicted by even the best experts.

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 with DTs, this paper has differentiated between semantic and system integrated DT and discern the opportunities to overcome the conundrum of interoperability and compatibility for smarter cities. When applying DTs in smart city design and planning, developers must be mindful of the limits of technology and the reality of planning processes. Hence, technology must be deliberately included and discussed as an explicit new dimension with the three urban sustainability goals to facilitate urban DTs for urban design, planning and governance purposes, which will enable a smarter, more sustainable and inclusive city.

Research data

Data availability is not applicable to this article as no new data were created or analyzed in this study.

Acknowledgements

This joint paper is a follow-up to the panel session "Towards smart city planning – digital twins and parallel world scenarios to support better public policies?" at the Data for Policy Conference 2021. We wish to thank the Data for Policy organizers for facilitating the conference and giving us the opportunity to present in the conference.

The Cities Knowledge Graph project, the CEUS project, and the World Avatar project were supported by the National Research Foundation, Prime Minister's Office, Singapore under its Campus for Research Excellence and Technological Enterprise (CREATE) programme. They were conducted at the Cambridge CARES Centre Singapora and the Singapore-ETH Centre. Markus Kraft gratefully acknowledges the support of the Alexander von Humboldt foundation. Funding for the Cambridge CDT study has been provided by the Centre for Digital Built Britain, under InnovateUK. It is also part of the Digital Cities for Change Programme funded by The Ove Arup Foundation, and supported by the Cambridge Centre for Smart Infrastructure and Construction funded by Innovate UK and EPSRC. Reallabor Stadt:quartiere 4.0—Fruhzeitige gestaltende Burgerbeteiligung fur eine nachhaltige Entwicklung Baden-Wurttembergs ("Living Lab: City Districts 4.0") is funded by the Ministerium fur Wissenschaft, Forschung und Kunst Baden-Wurttemberg.

Acronyms

BIM Building Information Modelling

CDT City-level Digital Twin

CEUS Consumer Energy Usage Data in Smart City Development

CIM City Information Modelling

CKG Cities Knowledge Graph

DT Digital Twin

GIS Geographic Information System

ICT Information and Communication Technology

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