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USE CASES FOR DISTRICT-SCALE URBAN DIGITAL TWINS

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ABSTRACT:

Efficient usage and management of abundant data are crucial for organisations, especially in the light of a lack of in-depth IT knowledge. Digital twins (DTs) are particularly expected to assist organisational processes, as behaviours of physical components are realistically represented by them using data for individual use cases. Nevertheless, DTs are extremely reliant on their use cases, leading to an extensive DT catalogue. However, a conclusive list of use cases for this accumulation of feasible DT application areas does not exist. To address this issue, this paper documents the use cases of Urban Digital Twin (UDT) platforms and applications with a state-of-the-art review. The study focuses on district-scale UDT applications that model, manage and analyse—buildings, transportation, energy, water, utility, and infrastructures that form smart cities. In order to catalogue diverse use cases found in several sectors, theoretical reasoning is developed. Our study provides a classified inventory that can be helpful for stakeholders in companies, government agencies and academia—such as researchers, architects, facilities managers, developers, and city planners.

1. INTRODUCTION

There is an abundance of data generated in academia, government organisations, and private companies as a result of ongoing digitalisation. To make effective use of this data, data integration within a sophisticated IT infrastructure is a prerequisite. The administration and proper usage of the acquired data are crucial for an organisation; especially due to the lack of in-depth IT knowledge (Kugler et al., 2021). Digital Twin (DT) is an idea that interfaces physical and virtual entities through an information linkage that is promising in this unique situation. Various industries are developing DT technologies as part of their digital transformation and decision-making processes (van der Horn and Mahadevan, 2021).

In 1998, the ‘digital twin’ term was mentioned in ’Alan Alda meets Alan Alda 2.0’ for a digital copy of an actor’s voice (Hodgins, 1998). However, the concept of DT have been profoundly recognizable starting around 2002 and were introduced in production engineering by Micheal Grieves (Grieves and Vickers, 2017). There has been an exponential growth in the usage of the term ‘digital twin for cities’ and it has replaced ‘3D city model’ in articles published after 2015 (Ketzler et al., 2020). New industries and use cases continue to expand as the DT concept evolves. Divergent definitions have led to confusion and ineffective implementations, which threatens to dilute the technology and render it ineffective. DTs make use of data to simulate how a physical product behaves under specific use cases. In addition, they gain value by supplying relevant data to the model. Nevertheless, DTs are extremely reliant on their use cases, leading to an extensive DT catalogue (van der Valk et al., 2021). However, a conclusive list of use cases for this accumulation of feasible DT application areas does not exist (Gerlach et al., 2021; Kugler et al., 2021; Jones et al., 2020).

Simultaneously, determining the appropriate use cases for DTs could be difficult. A methodical approach can simplify the development of use cases after the definition. The use case evaluates an actor’s technical aims in order to achieve a result through contact with the system. The system provides a service to the user by delivering the result (Weilkiens, 2011).

Beyond visualization, 3D city models are increasingly used across many domains and for a broad range of purposes such as emergency response, flooding, energy demand calculation, noise propagation, urban planning, solar irradiation estimation, etc. (Biljecki et al., 2015). The interaction of buildings with their immediate environment should be considered from the perspective of the city district level (Boje et al., 2020). Lately, due to enhanced computation and storage systems, simulations and applications are being developed for both district- and city-scale models (Hietaharju et al., 2019). Nevertheless, clarification in the classification of district-scale use cases is lacking, as use cases are predominantly considered at the component or city scale (Shahat et al., 2021). In this context, our paper documents use cases of Urban Digital Twin (UDT) platforms and applications with a state-of-the-art review of district-scale DT applications as a focus.

A district is an administrative division of a country or town with fixed borders and is used for official purposes. However, the term district is used differently in different contexts and countries, generally as wards or sub-cities that are subdivisions of a municipality or ‘prefecture-level city’. In this paper, we refer to the term district as areas smaller than cities and larger than a neighbourhood (block of buildings). We include all large-scale UDTs which serve the purpose of smart city initiatives and often emerge as pilot case studies for a city-scale deployment.

This paper evaluates the use cases of UDT platforms and applications based on a literature review. The contribution of the paper is to list and analyse several UDT use cases which represent the interactions between a system and its stakeholders. In Section 2, related work is discussed. In Section 3, we develop theoretical reasoning to catalogue the diverse use cases found in numerous sectors based on the services they provide

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to the stakeholders. Next, we consider a classification into six UDT use case groups, namely, District-/City-Level Forecasting, Emergency Planning, Operational Optimisation, Participatory Planning, Policy Development, and Scenario Modelling. This classification has been adopted from the recent work of Callcut et al. (2021). In Section 4, we list and describe the various use cases for DTs we considered for classification. Based on evident patterns emerging from DTs that provide similar services, we propose a conceptual architecture for developing the UDT adapted to the six UDT use case groups. In the discussion and conclusion, we discuss the findings and possibilities of future research on the topic of UDT use cases.

2. RELATED WORK

Deren et al. (2021) highlights that the construction of smart cities can be practical by establishing a city operation center which acts as a high-level design and planning office, and the corresponding implementation of policies customised to cities. They further describe five main applications based on digital twins for smart cities such as Smart grid digital twin services, Smart city operation, Smart city traffic brain, Smart city public epidemic services, and flood monitoring and flood situation services. However, their list of applications does not include various types of natural disasters or system failure risk assessment, monitoring and emergency planning required for cities. Public health services can provide a broad list of applications uniquely for the particular populations within cities or districts and may not be limited to epidemic situations periodically faced by cities. Similarly, Deng et al. (2021) propose digital twin patterns based on smart cities development and existing DT technologies. They discuss critical technologies involved in Digital Twin cities such as Building Information Modeling (BIM), 5G, Surveying and Mapping, Internet of Things (IoT), Collaborative Computing, Blockchain, and Simulation. Further in this context, our research links DT technologies and existing DT applications for smart cities through a conceptual architecture for the development of UDTs (refer Section 4.7).

Callcut et al. (2021) investigate applications and usage of DTs for civil infrastructure systems (CISs) with current definitions and concepts. According to their findings, even though DTs are essentially comparative in various sectors, their application has generally been siloed inside sectors. Based on the results of their survey, some respondents felt their work with DTs crossed a few sectors, hence generalizing about DTs being sector-specific could be incorrect. By analysing the applications in each sector, researchers set up a table of use cases. Beyond sector classification, they assign categories to use cases that can be helpful to identify trends in DT services that are targeted at certain sectors. The assigned categories are Anomaly Detection, Demand Forecasting, Predictive Maintenance, Emergency Planning, Security Resilience, Maintenance Scheduling, Operational Optimisation, Service-life Forecasting, Timetable Optimisation, Construction Process Optimisation, Route Forecasting, Scenario Modelling, Planning Optimisation, City-level Forecasting, and Policy Development. These categories serve as a baseline for our classification due to similarities in the scale.

Our study focuses on finding use cases in the smart-city sector, hence it may not necessarily apply to all infrastructure sectors. According to Callcut et al. (2021), 'smart city' is a large-scale version of a DT that uses IoT technologies to link and map a city with its digital version. They further emphasise that a smart city must have people-centered technological breakthroughs that strive to recover well-being and take a complete approach that incorporates social, economic, and environmental factors through planning solutions. They found forecasting, maintenance, optimisation and planning as the most common use cases. Additionally, their analysis shows that DT use cases essentially fall into two categories based on a temporal scale: futures assessment (long-term); and operations management (short-term). It is quite established that it will be far more valuable to obtain insights for a shorter temporal scale because the insights will be more certain (Callcut et al., 2021). Hence, this study will focus on defining the uncertainty that surrounds large-scale DTs. We try to include both short and long-term operation management that DTs offer on a district-scale.

The technologies involved in the development of DT platforms are rapidly evolving. These technologies include: maintaining a real-time DT to provide a more accurate and reliable model; an efficient data storage system using cloud or edge computing; a realistic user experience by producing a virtual environment using Augmented Reality (AR) or Virtual Reality (VR); or to analyse models using Machine learning (ML) methods or Artificial Intelligence (AI).

IoT platforms and corporations offer their exclusive and segregated DT solutions with data encoded in dissimilar ways. This creates an absence of interoperability and impedes different use cases that need data trade between organisations. Platenius-Mohr et al. (2020) present a suitable solution with a list of requirements to ensure interoperability between DTs. Engineering rules can be flexibly applied to the source and target systems by using the approach they propose. A customisable mapping model is at the center of their solution; with on-demand interpretation with generation first and followed by customisation. API-based and file-based access is the preferred method to access the result. Bidirectional information exchange of comprehensive information models is thus enabled both online and offline.

In addition to archetypes derived from the literature, van der Valk et al. (2021) interviewed industry experts and extended these with figures derived from DT characteristics. This database was used to derive clusters of DTs, with every cluster possessing a specific characteristic arrangement. Specific patterns in their configurations were used to identify these characteristics. They specify preliminary mandatory characteristics that DTs should contain—a data acquisition system, a raw data input system, data governance rules, multiple data sources, retrieval and processing of data. Furthermore, from these characteristics they identified archetypes for DTs, representing a maturity model for the overall development of DTs from a more Basic Twin to an Exhaustive Twin. Despite being subjected to certain limitations, their archetypes analysis lays a significant system for the order of DTs, allowing to sort the separating streams in research on DTs. In their concept paper, Kugler et al. (2021) develop a method for use case related views of DTs. They emphasise that creating views of a DT with a methodical approach is fundamental to dealing with abundant data and decreasing the quantity of unused data without being influenced by the rising intricacy of existing IT frameworks.

In our study, we create an architecture for developing a UDT platform which is use case specific. Further, we classify all the UDTs documented in our literature review based on their use case(s) in the following section.

3. REVIEW METHODOLOGY

In this paper, the main methodology applied is literature review, documentation and classification of UDT use-cases. For the review and screening, we rely on various sources such as scientific literature, online resources and project reports that focus on the utilisation of UDTs comprehensively (refer Section 3.1). To avoid ambiguity, we define the terminology of UDTs, especially in the context of a district and a city in Section 3.2. In Section 3.3, we list the criteria that need to be fulfilled by use cases in order to be part of the catalogue. Finally, in Section 3.4, we propose our classification based on the services that are provided by the UDT use cases.

3.1 Sources for the review

As the foundation for decisions regarding future approaches to defining UDTs for smart city initiatives, an exhaustive review of DT literature for the smart city sector was undertaken. With keywords—'Smart-city', 'Urban' and 'Digital-Twin'—, searches were conducted in Google Scholar and Scopus. Peer-reviewed papers were considered for documentation of DT projects after screening for relevance. Next, grey literature such as reports, white papers, and unpublished research from research organizations and industries was accessed. Even though grey literature is not peer-reviewed and is considered potentially biased, it is still used to gather perspectives of those implementing and working with DTs. And since the term 'digital twin' has only come into extensive usage in recent years, there is a possibility that approaches that had DT methodology may have not surfaced in the keyword search. At the same time, the 'digital twin' term might be misconstrued as a 'digital shadow' or 'digital model'. Hence, a thorough filtering process is important.

3.2 Digital twin terminology

Numerous scholars emphasise the ambiguity of the DT definition regarding cities or districts (Batty, 2018; Kandt and Batty, 2021). Additionally, the representation of a city's physical assets using DTs often does not capture its social or economic function. According to Stoter et al. (2021), researchers have come to the consensus that UDTs for smart city initiatives should: (i) contain 3D city models; (ii) have semantic or geometrical information; and (iii) have sensor data in real-time; and (iv) implement the most effective design, planning, or system operation and intervention decisions through a variety of analyses and simulations. Importantly, to help those choices, all data should be presented to clients (residents, leaders, specialists) in an all-inclusive resource dashboard within a DT interface that is user-friendly. During our screening of digital twin use cases, we use this definition for filtering DT instances from those that cannot be deemed as such.

3.3 Criteria for the inclusion

3.3.1 Urban digital twins for smart city initiatives: As per the definitions found in literature about smart city initiatives, UDTs must be able to provide planning and decision support to cities in terms of their administration, infrastructure, economical development, and citizen engagement.

3.3.2 Scale of the model: We exclude DTs at the component scale and, instead, document DTs at the district and city scale. Part of this decision is based on the concept of districts being basic administrative units in cities, yet, there is a lack of emphasis on documentation of DT use cases for district scale.

3.3.3 Limitations: Although DTs at smaller scales, such as building- and component-scale, that are developed as a smart city initiative, may have an impact on a larger scale, to avoid any ambiguity, we have not included any DTs with models smaller than district-scale. While this is an obvious limitation, we believe that this segregation sets a clear boundary between urban DTs and the rest.

3.4 Classification

UDT Project	Use case					
	(a)	(b)	(c)	(d)	(e)	(f)
Rinascimento [1]	-	-	Yes	-	-	Yes
Port of Anzio [2]	-	-	Yes	-	-	Yes
NUS-FRS [3]	Yes	-	Yes	-	-	Yes
Urban Strategy [7]	Yes	-	Yes	-	-	Yes
SAVe project [8]	-	Yes	-	-	-	Yes
Turin [10]	-	-	-	Yes	Yes	-
CAVE [12][13]	-	-	-	Yes	-	Yes
Victoria [16]	Yes	Yes	Yes	Yes	-	-
Sofia city [17]	Yes	-	Yes	Yes	-	Yes
TEDA [18]	Yes	Yes	Yes	-	-	Yes
CReDo [21]	Yes	Yes	-	-	-	Yes
Kelowna [24]	-	-	Yes	Yes	-	Yes
Kalasatama [30]	-	-	Yes	Yes	-	-
Yeouido [32]	-	-	Yes	-	-	Yes
Cambridge [33]	Yes	-	Yes	-	-	Yes
CitySnap [36]	-	-	Yes	Yes	-	-
NRF-VS [38]	-	Yes	Yes	-	-	-
DestinE [39]	Yes	Yes	-	-	-	-
NSW [40]	Yes	Yes	Yes	Yes	-	-
QLD spatial [45]	Yes	Yes	Yes	Yes	-	-
DUET [46]	Yes	-	Yes	Yes	-	Yes
City of Zurich [47]	Yes	-	Yes	-	-	Yes
GeoVCM [50]	-	-	Yes	Yes	-	-
ROCK project [52]	-	-	Yes	Yes	Yes	-
Vcity [56]	-	-	Yes	-	-	-
Dadaocheng [57]	-	-	-	Yes	-	-
Georgia Tech [59]	-	-	Yes	Yes	-	-

Table 1. Overview of the documented use cases for Urban Digital Twins classified into six groups: (a) District-/City-Level Forecasting (b) Emergency Planning (c) Operational Optimisation (d) Participatory Planning (e) Policy Development (f) Scenario Modelling. The use case columns are indicated as "Yes" if the UDT project provides the respective service.

Following the review, an overview of the documented use cases for Digital Twins is summarised in Table 1. The use cases are classified into six groups—District-/City-Level Forecasting, Emergency Planning, Operational Optimisation, Participatory Planning, Policy Development, and Scenario Modelling. This classification is largely adopted from Callcut et al. (2021) and further based on the criteria and definition mentioned in the previous sections. DTs for smart cities may have more than one service provided at the same time that addresses citizen engagement or administration. Therefore, the inventory shows instances of Digital Twin projects falling into multiple groups.

4. LIST AND DESCRIPTION OF USE CASES FOR DIGITAL TWINS

4.1 Use case: District-/City-Level Forecasting

DTs can be a tool for urban areas to manage the difficulties of fast urbanization, achieving objectives of urban resilience and sustainability, including the assignment and utilization of assets, preparation and upkeeping of water supply, and recycling infrastructures (Mohammadi and Taylor, 2017). A city is an intricate arrangement of numerous different actors, with a large number of jobs, connections and communications. In order to document this, the DT of a city can best be built as a biological system of single twin elements (Johannsen et al., 2021).

DTs at the district or city-level are sensible computerized portrayals of urban communities (counting their resources, cycles, and frameworks) that help independent direction pointed toward conveying district or city-level results (urban management, planning, and related services) and give informed decision-making capabilities (Nochta et al., 2021). DTs at the district or city-level are a part of new urban modelling tools that aim to support city management and planning.

Johannsen et al. (2021) propose a framework that incorporates DTs of the occupants of the city, who can effectively look at and intentionally modify their digital twin through their way of behaving. They suggest that—assuming it is utilized as citizen empowerment—a DT can be used for public participation processes, not just mirroring the activities of every resident in the citywide setting yet envisioning them, permitting the clients to essentially test the impacts of their activities and conduct changes. DTs for forecasting can assist with diminishing unforeseen unfortunate results by assisting actors with better system understanding and their circumstances while the system is as of now in full activity and cannot be halted for test (Grieves and Vickers, 2017).

4.2 Use case: Emergency Planning

DTs for Emergency Planning aim to serve towards designing and preparing immediate responses or exit strategies for catastrophic incidents. The incidents that may involve natural disasters, healthcare threats, security hazards, or such dangerous situations for communities. Several attempts have been made to establish smart city DTs through the use of precise BIM and big data (Dembski et al., 2020). The smart city DT paradigm has been examined for various purposes over the past few years, including urban planning and development, disaster management, housing, manufacturing, and healthcare. Despite being useful in several domains such as urban planning and built environment, these current investigations have shown an absence of consideration regarding catastrophe or emergency related viewpoints concerning the components referenced previously (Shaharuddin et al., 2022). Shaharuddin et al. (2022) reason this is because researchers lack emphasis on details of emergencies or disasters.

4.3 Use case: Operational Optimisation

The development of operational optimisation techniques for district-scale heating systems started in the 1990s and the methods evolved as storage and computational technologies have improved (van der Zwan and Pothof, 2020). DTs for Operational Optimisation has advanced towards performance management of operations which is both practical and efficient for various urban systems and resources such as urban mobility, energy, environment, communication, building, and infrastructure.

Ni et al. (2021) offer a digitalization framework for historic structures that incorporate IoT, cloud computing, and AI. Their research uses DTs to preserve, anticipate, and optimize specified aspects using real-time and historical data analytics. Sensors or other data sources are used in historic buildings to capture heterogeneous data such as energy usage metering, indoor environment and outside temperature. The data is then periodically uploaded and kept in the cloud platform's database. These data are used to train AI models for monitoring historic buildings, estimating energy usage, and autonomously regulating energy-consuming equipment in order to achieve human comfort, building conservation, and energy efficiency balance.

4.4 Use case: Participatory Planning

Urban planners and administrators are leveraging a variety of digital platforms as tools for storing, retrieving, comparing, and processing different types of data, as well as distributed decision-making through participatory processes. Increasingly, the physical world and the digital world overlap through various digital platforms such as IoT, VR, AR, machine learning, and natural language processing. This has prompted designers to conceptualise the need to integrate dashboards and platforms from multiple smart city platforms into one system. Only through the creation of a shared ontology of the city can this task be accomplished, making it possible for the different data systems to communicate with each other. DTs, however, also need to consider aspects such as inclusivity and citizen participation when extending the concept into complex cultural and social entities like cities (Turillazzi et al., 2021).

Dembski et al. (2019a,b) present the development of a DT in VR for civic engagement in urban planning of the town Herrenberg in Germany with a population of 30,000. As a socio-spatial approach of computational analysis using space syntax, they include a mixed method for modelling, mapping and simulating with 3D models. Citizen participation within the DT is seamlessly achieved by the collaborative visualisation and simulation environment COVISE. COVISE is designed for collaborative working, allowing users to collaborate through Computer-Supported Cooperative Work (CSCW) during the analysis of the DT. For the town of Herrenberg, Germany, they carried out a pilot application with 1,000 citizens as participants using stationary and mobile VR environments. They believe that DTs for towns will offer urban planners and designers insight into changes that are intended for cities while giving citizens an opportunity to influence public decisions. It may be possible to reach a consensus by utilizing such a democratic process. However, seeking public participation and acquiring opinions on digital platforms requires motivation.

Gamification motivates cooperation creativity, and thinking about spatial development and could also serve Smart Cities as a crowdsourcing strategy to enrich datasets. Matthys et al. (2021) demonstrate the importance of gamification of DTs for public participation with the help of the "3D city game Ghent" project, launched by the city of Ghent (Belgium) in 2016. Reconstruction of disappeared urban environments is the main focus of the project. Ghent inhabitants were co-creators in modeling in an open-source 3D software with the help of Transmedia storytelling and gamification through an animated 4D web environment and VR, AR or XR (Mixed reality) applications. Matthys et al. (2021) further offer a framework to create a parallel virtual universe of the past using DTs to help other municipalities and cities by analysing an economical and interdisciplinary 3D co-creative process.

In this context, Xu et al. (2019) developed a 3D immersive VR-driven eco feedback system that allows facility managers and occupants to interact with real-time data about energy consumption. With an implemented test case of Georgia Tech's campus, a detailed back-end and front-end design and development of the VR-integrated eco-feedback system is presented. They refer to their system as a "community-scale" test case, however, this scale does align with our study area definition of a district. They claim their research approach, if implemented widely in cities, may promote energy-conscious behaviours among its residents and facilitate timely interventions to achieve energy savings.

4.5 Use case: Policy Development

In addition to reducing pollution and congestion, poor logistics efficiency will have a detrimental effect on the city's liveability caused by low load factors due to high demand fragmentation (Marcucci et al., 2020). Considering upcoming technological, business model, and spatial-temporal changes that innovations will bring, policymakers should be prepared with tools suitable to execute dependable, timely analyses, and comprehensive scenarios of urban logistics. Marcucci et al. (2020) explain the DT concept, outlining its potential for urban freight transport policy-making and planning and clarifying how it should be conceptualized. They emphasise that without a sound theory and knowledge of how context and behaviour interact, it is impossible to understand what happens in reality. Hence, they recommend that DTs in a Living Lab approach could be characterized using both behavioural and simulation models at the same time. This helps to stimulate planning processes that are well-informed, effective, and participatory, and, consequently, to predict behaviour and reaction both to structural changes and policy measures implementations.

Papyshev and Yarime (2021) explore the DT technology potential for simulating policy interventions. New tools are required to imagine the future along with planning and quick reaction through policy responses to modern challenges. They further break down the historical backdrop of the advancement of the idea of DTs and the way things are presently being embraced on a city-scale. In the DT models, simulations of the activities of individuals in urban environments are often based on historical data, which means they cannot predict things based on data that is not available and may present certain privacy concerns. Therefore, acquisition and utilisation of detailed behavioural information for governmental simulation is complex. They believe that an expected solution to these difficulties is synthetic data. They widen the concept of data creation towards synthetically human-generated artificial data which imitates the actual data replacing the machine-generated data. Based on this notion, data is generated for urban mobility with the help of a Task-Based Approach. This approach aims to use games with the purpose based on urban data and data labelling game practices. Due to the fact that no real individual in society will be represented by the data generated through this method, it will not cause legal or privacy concerns. Accordingly, a synthetic population can be created for the DT to illustrate realistic behavioural responses to hypothetical policy interventions.

Jouan and Hallot (2020) advocate the application of DT principles, as a digital replica using Heritage BIM models for preventive conservation of heritage places. Based on extensive literature review, they propose a framework which combines the management planning process and DT for built heritage conservation. They emphasise a value assessment process for conservation based on the identification of tangible features of significance, threats and the corresponding mitigation strategies. An information structure on preventive conservation strategies is the result of the data model. In the context of policy development, this framework demonstrates the need for a DT approach and sets a foundation for future implementation.

4.6 Use case: Scenario Modelling

DTs for Scenario Modelling explore design options and analysis through realistic modeling of a real-world problem for virtual testing. For instance, the prospective quantitative assessment of automated traffic functions can be accomplished using realistic simulation techniques supported by virtual testing (field tests and virtual experiments) (Brunner et al., 2019). Comprehensive datasets and statistical leverage required to analyse scenario space for high-dimensional traffic, particularly safety assessment and "stress testing" of automated driving functions, can be created by virtual trials or scenario modelling. According to Brunner et al. (2019), several facets of a realistic scenarios are (i) stochastic and probabilistic nature of processes, (ii) human factors, (iii) edge cases and outliers, and (iv) technology limitations. They highlight that in the modeling process the hardest challenge is not to construct models but to demonstrate their usefulness and a realistic model may not satisfy stakeholders. A Digital Twin generation with its digital representation of reality is a key step toward realistic modeling for virtual testing to simulate. The goal of their research project "Functional and Traffic Safety in Automated and Networked Driving" (SAVe) is to create a DT which will cover a substantial segment of the Ingolstadt (Germany) road network. To demonstrate validity, numerous individual observations and statistical data are compared to observations made at the urban proving ground.

4.7 Conceptual architecture for developing an Urban Digital Twin

During our literature review, we found that use cases that provide similar services to their stakeholders have evident patterns of technologies being used for their DT implementation. For instance, District-/City-Level Forecasting DTs require large scale simulation capability and corresponding decision-making support within their DT development. With this prerequisite, District-/City-Level Forecasting DTs rely on cloud computing technologies to serve their high computational requirements. Emergency Planning DTs need to monitor physical systems in real-time and have a response strategy to the disruption, hence its DT implementation requires a protocol to be embedded for a response to an emergency or case of disruption. Operational Optimisation DTs need to monitor physical systems in real-time and simulate for optimisation. Therefore, an IoT system and an efficiency protocol to improve physical systems through feedback are important as part of their implementation. Gamification techniques and AR/VR help to create immersive user experiences and are commonly seen in Participatory Planning DTs. Policy Development DTs need an impact assessment for hypothetical policy inputs and to help users generate scenarios of behavioural responses for future policy implementation. Scenario Modelling DTs require iterative modelling and comparison of scenarios to support decision-making. Based on these evident patterns emerging from similar DT use cases, we propose a conceptual architecture for developing a UDT adapted to the six DT use case groups and link it to respective DT technologies involved in UDT development (see Figure 1).

Our conceptual architecture illustrates the data-flow in the physical and digital systems using three structured layers—Physical,

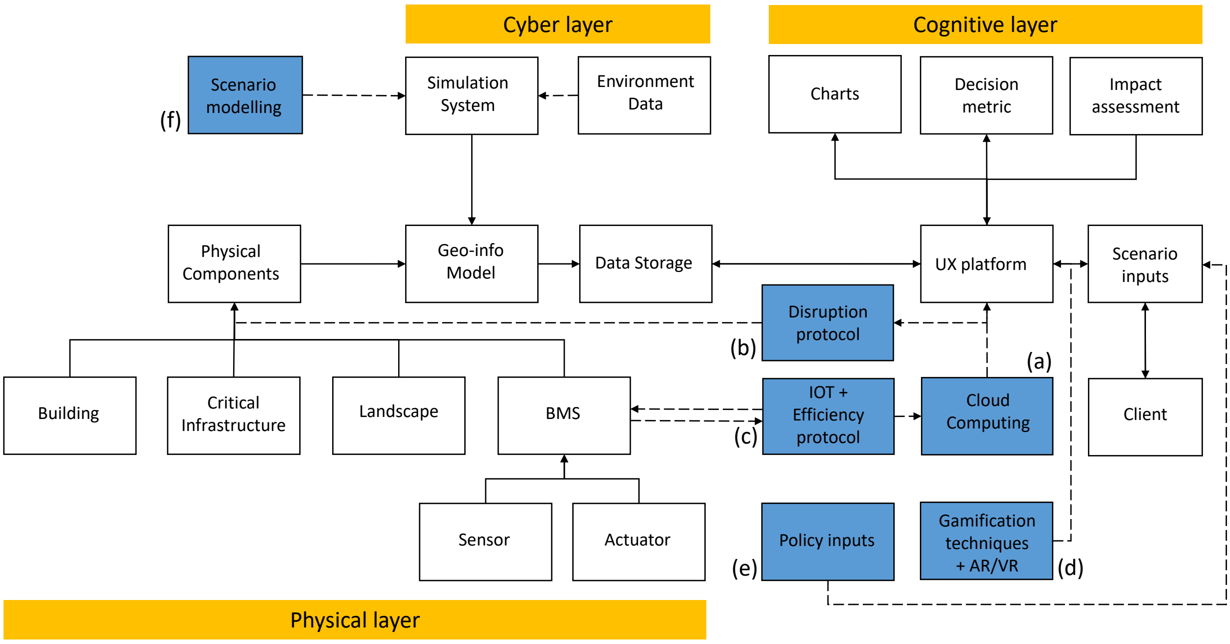

Figure 1. Conceptual architecture for developing an Urban Digital Twin. Note: BMS–Building Management System, IOT–Internet of things, VR–Virtual Reality, AR–Augmented Reality. Blue colored boxes indicate technologies specific to six UDT use case groups as listed in Table 1.

Cyber and Cognitive. The Physical layer contains physical components that form smart cities such as a Building, Critical infrastructure, Landscape and Building Management System (BMS)—both Sensors and Actuators. The information from this layer is transferred to the Cyber layer, where it is represented by Geo-Information Models with coordinates and meta data. This is supported by a Simulation System and additional Environmental Data, which helps in analysing the data from the physical layer based on the services required by the UDT. A Data Storage system is used to generate a UX (user-experience) Platform to communicate the processed data to a Client or Stakeholder. The UX platform and its interactive system, designed to support decision-making for its user, form the cognitive layer of our proposed architecture. We highlight the add-on technologies that emerged from the evident patterns in similar UDT use cases in Figure 1.

5. DISCUSSION

In our literature review, we found numerous classifications of use cases for UDTs based on the sectors, levels of detail provided on the UDT platform, and scale of the platform. However, few of these classified use cases based on the interactions between stakeholders and the system. On the other hand, evident patterns do emerge from similar UDT services. Based on these use case patterns, we propose a conceptual architecture for developing an Urban Digital Twin adapted to six use case groups and link it to respective DT technologies involved in UDT development.

Furthermore, we classify use cases of UDT based on the services they provide to the stakeholders—District-/City-Level Forecasting, Emergency Planning, Operational Optimisation, Participatory Planning, Policy Development, and Scenario Modelling. However, this classification is limited to the smart-city sector and might not apply to all other sectors of Civil Infrastructure Systems. Hence, there is a need to create such a specific classification of UDT use cases in other sectors based on the services they provide to the stakeholders. Nevertheless, we believe that this classification may lead to new insights into the use case related definitions for DTs, which at the moment are quite generalised.

One major issue we encountered in the classification process of DT use cases is segregating district-scale DTs from other lower-scale DTs. DTs at a building- and component-scale that are developed as a smart city initiative may have an impact on a larger scale. To avoid any ambiguity, we have not included DTs with models smaller than district-scale, however, comparing the two will be an interesting next step in our research.

6. CONCLUSION

With a state-of-the-art review, this paper documented the use cases of UDT platforms and applications. The contribution of the paper is a list and analysis of several UDT use cases which represent the interactions between a system and its stakeholders. The study further focused on district-scale UDT applications that model, manage and analyse buildings, transportation, energy, water, utility, and infrastructures that form a city. We developed theoretical reasoning to catalogue the diverse large-scale use cases found in the smart-city sector based on the services they provide to stakeholders. The UDT use cases documented in our review process are classified into six groups—District-/City-Level Forecasting, Emergency Planning, Operational Optimisation, Participatory Planning, Policy Development, and Scenario Modelling. In our research, we found that the two groups—Emergency Planning and Policy development have the least amount of UDT use cases developed and leads to future research work on UDTs for Emergency Planning and Resilience. We believe that our study provides a classified inventory and conceptual architecture for developing UDTs that can be helpful for stakeholders in companies, government agencies and academia—such as researchers, architects, facilities managers, developers, and city planners.

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