Digital Twin for the Next Generation of Urban Land Administration and 3D Spatial Planning

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Key words: Digital Twin, Land Administration, 3D Cadastre, Spatial Data

SUMMARY

Traditional land administration and spatial planning methods are challenged by the increasing complexity of urban land management due to urbanisation. Compact city development with high-rise buildings, developing complex infrastructures above and underground, and decreasing natural resources are some examples that need urgent attention. On the other hand, the advancements in digital technologies, multi-dimensional data models and spatial data infrastructures created an opportunity for the next generation of urban land administration and 3D spatial planning. This study aims at introducing a novel system architecture and a web-based platform for spatially enabled digital twins.

A composable system architecture proposed integrating 2D, 3D, and 4D (time) data for visualisation, query, and analytics. The system provides data harmonisation, web-based data access, and 3D data conversion capabilities. The system was also developed through the customisation of open-source libraries. To understand the opportunity and challenges of such a digital platform, we examined its application in 3D cadastre visualisation, queries, assessment, and development envelope controls. The 3D cadastre was also used for further applications, including high-rise building development assessment and line of site analysis. Other potential usages of data integration for 3D spatial analysis were examined by populating the 3D development enveloped by adopting a land development framework.

A spatially enabled digital twin can potentially offer an opportunity for the next generation of land administration and 3D spatial planning. In addition, the 3D cadastre visualisation and query capabilities in the digital twin highlighted the added value and potential application of data in other disciplines, including 3D property valuation, asset management, and building compliance and maintenance. However, the technology alone is not a solution for moving toward the next generation of land administration and spatial planning. Standard, organisational, and business challenges need to be considered and addressed for a successful digital modernisation in land administration and spatial planning

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1. INTRODUCTION

The traditional land administration and spatial planning issues have been communicated in several practical and scientific reports [1], [2]. From a land administration perspective, there are two major challenges, first, as it has been highlighted by the United Nation's Committee of Experts on Global Geospatial Information Management [3], the majority of people worldwide, lack access to secure land rights for creating sustainable, resilient, and inclusive societies. Therefore the UNGGIM (2020) framework for effective land administration is developed to accelerate efforts to record, document, and recognise the land rights, responsibilities, and restrictions (RRR), as well as the people and land relationships. Second, due to the fast increasing development of complex buildings and urban infrastructures worldwide, the current two-dimensional (2D) data and processes for land and property management are challenged [4]. Therefore, land and geospatial authorities and the governments need to upgrade the existing methods of data capturing, computing, adjusting, and publishing the cadastral survey data to address both horizontal and vertical aspects of RRR in the land.

Moreover, the spatial planning practice using 2D and long-term data (e.g. 5-years period of population data collection) has also been challenged by new urban planning and design paradigms such as compact city development, water sensitive urban design, and climate-adapted urban development [1], [5], [6]. While planning support systems (PSS) have been offering robust tools for data-driven and evidence-based planning [7], the challenges of 3D data integration, responsive analytics, lack of interoperability of technologies, and technical knowledge requirements for users remained barriers to implementation and utilising such systems by governments and industries [8].

However, recent developments in spatial data infrastructures and digital twins (digital representation of the real environment) have offered opportunities to address the issues of current land administration and spatial planning [9]–[12]. Leveraging different 3D data models (CityGML, IndoorGML, BIM/IFC), several governments and industries have started developing proof of concept for digital modernisation of land administration and urban planning [13]–[17]. Moreover, the governments, academia, and professional institutions started developing strategies, principles, and roadmaps for the next generation of spatial industries, which can improve several applications, including land administration, emergency management, and spatial planning [18]–[20]. For example, in 2019, the Australia and New Zealand spatial council developed the principles for spatially enabled digital twins of the built and natural environment [20]. Moreover, the Planning Institute of Australia (PIA), developed a PlanTech national working group to develop digital planning principles [18].

There are several challenges, however, that need to be considered to avoid before adopting such technologies. First, from a technical perspective, systems interoperability and data harmonisation are crucial. Second, from an organisational point of view, the implementation of such systems across different organisations with different system preferences seems to be a challenging task. Third, from an application perspective, the technologies need to be aligned with the practitioners' task and also can be driven by a non-technical person.

This study aims at introducing a novel system architecture and a web-based platform for spatially enabled digital twins. The platform is designed to address the technical, organisational, and human aspects of digital transformation in the government and industries. The paper continues by reviewing the state-of-the-art literature and reports on the application of digital twins in spatial and planning industries. The progress, challenges, and gaps will be explained in this section. Then, in section three the paper proposes a system architecture to address identified challenges and gaps in the second section. As an example, section four describes two areas of digital twin applications within modern land administration and urban planning. The paper ends with discussing the proposed developments, their implications, potential contribution to the theory and practice, limitations, and future research agenda.

2. DIGITAL TWIN TREND IN SPATIAL AND PLANNING INDUSTRIES

Digital Twin (DT) a term that was coined in the early 2000s by Michael Grieves in Product Lifecycle Management (PLM), has changed over time and extended its applications into different disciplines [21]. Over the last two decades, the definition of DT has changed but the main concept remained quite stable. It refers to the construction of digital information of a physical system, which is embedded into the system and creates a "twin" of that physical entity through its entire lifecycle. As such, the concept of DT in PLM suggests that two virtual and real systems are connected through four phases: a) creation; b) production (manufacturing); c) operation; and d) disposal [22].

Recent advancements in the internet of things (IoT) technology and other real-time data streaming and data collection methods as well as cloud computing opportunities have created an ecosystem ready for the implementation of DT ideas in different disciplines. Nowadays, the DT is being defined in the context of infrastructure development and lifecycle [23], geospatial data infrastructures [24], building and facility management [23], [25], oil and gas industries[26], and health applications [27]. As mentioned in the previous section, several governments have already adopted the concept of DT and defined a series of principles persuading their future digital transformations[28], [29]. Demonstrating the broad spectrum of DT application domains has created a great deal of attention to digital technologies in academic, industry, and government sectors.

In 2020, the stakeholders from the abovementioned three sectors formed a Digital Twin Consortium (DTC) as a global ecosystem, in which different working groups collaborate to drive consistency in terminology, system architecture, and interoperability of digital twin technologies. One of the major contributions of this consortium is a generic definition of DT, that will be used as the basis for this paper:

"*A digital twin is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity.*

> • *Digital twin systems transform business by accelerating holistic understanding, optimal decision-making, and effective action.*
>
> • *Digital twins use real-time and historical data to represent the past and present and simulate predicted futures.*
>
> • *Digital twins are motivated by outcomes, tailored to use cases, powered by integration, built on data, guided by domain knowledge, and implemented in IT/OT systems."* [30]

While there are many DT definitions by academia and industries, the DTC definition is generic and flexible to be applied in a smart city context, which is the interest of this paper. This definition incorporates Grieves' [21] fundamental concepts in DT including virtual representation, the real world (both entities and processes), and the link between the virtual and real-world that can be synchronised.

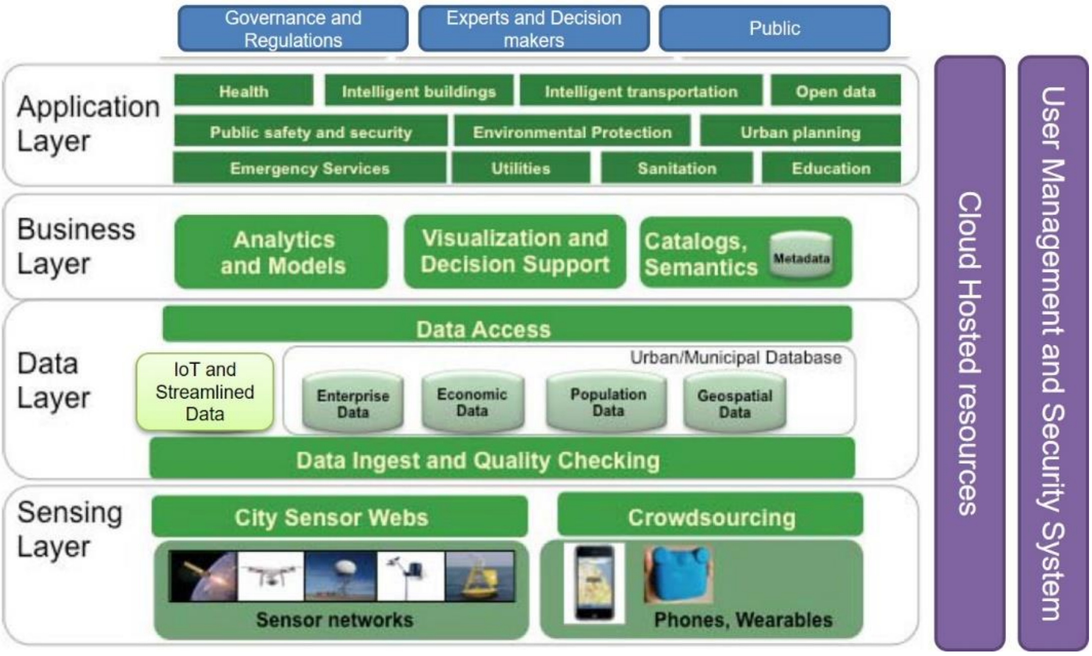


Figure 1 Enterprise Smart City, Modified and adapted from [40].

Grieves et al. (2017) [31] suggest that the concept of DT can be used in a complex system to mitigate unpredictable and undesirable emergent behaviour. This merely applies to many complex systems including cities. Batty (2007) [32] argued that cities are highly complex systems with uncertain and unpredictable outcomes of their entities' behaviour. As a result, ideally, the application of DT in cities is an attempt to create a virtual representation of linkage between socio-economic, functional, and physical processes [33], which aligns with the requirements of modern land administration [34] and spatial planning[35], [36]. Specifically, spatial data plays a fundamental role in creating a digital infrastructure to encourage wider applications of digital twins [37] in the lad administration and spatial planning. Recent research and technical reports considered the spatial digital twin as a vital approach to improving the feasibility of smart cities [37]. However, the literature highlighted the challenge of data integration, lack of coordination in different services, and complexity of systems in the smart cities initiatives.

According to Kim et al., (2021) [38], the smart city is a platform for technological and social innovation, which by leveraging the Information and Communication Technologies (ICT) facilitates the cities' productivity, sustainability, and liveability. The state and local governments need to manage data silos and governance different smart initiatives by various disciplines and business processes to facilitate both technological and social innovations. As an example, data generated from environmental sensors (e.g. temperature, humidity, wind) should be integrated with the sensor readings of parking availability and/or pedestrian count in a unique point of access to return value to all stakeholders. There are other potential big data such as crowdsourced and volunteered geographic information (VGI) [5], [39] that can be harvested and used for smart services in the cities. Effective management of such data and analytics can benefit different applications such as public safety and security, environmental protection, and urban planning functions as demonstrated in Figure 1. The enterprise framework for smart cities shown in Figure 1 is developed by Open Geospatial Consortium (OGC) and provides important instances from the technological, business, and application layers.

Despite understanding the importance of emerging technologies, there is a lack of design and implementation of overarching architecture to realise the benefits of multi-disciplinary data and analytics integration in the context of smart cities.

3. A SPATIALLY ENABLED DIGITAL TWIN

Designing and implementing a digital twin system is a comprehensive and complicated task. It demands multidisciplinary knowledge and experience, including software engineering, cloud infrastructure, big data management, analytics, modelling, visualisation, third-party tools and libraries integration, user management, access control, security, ecosystem planning and roadmap, etc. The system architecture of a spatially enabled digital twin system may vary across various requirements and design goals, while its backbone components should largely remain the same, as Figure 2 illustrates.

As data is the lifeblood of a DT system, a dedicated **Data Portal** is required to handle the complexity of multi-sourced and heterogeneous data management in three categories. **Spatial Data Management** tackles the traditional geospatial datasets including vector and raster data files, geodatabases, and metadata records. Spatial data can be either hosted in DT's data centres or more preferably, directly connected to and synchronised with external data servers through open standards. Open Geospatial Consortium (OGC) has created a whole family of royalty-free and publicly available standards to support interoperable solutions for enabling location-based services and mainstream IT systems. Accessing geospatial data through open standards can significantly mitigate the data silo and data island problems and help maintain a single source of truth in the entire ecosystem.

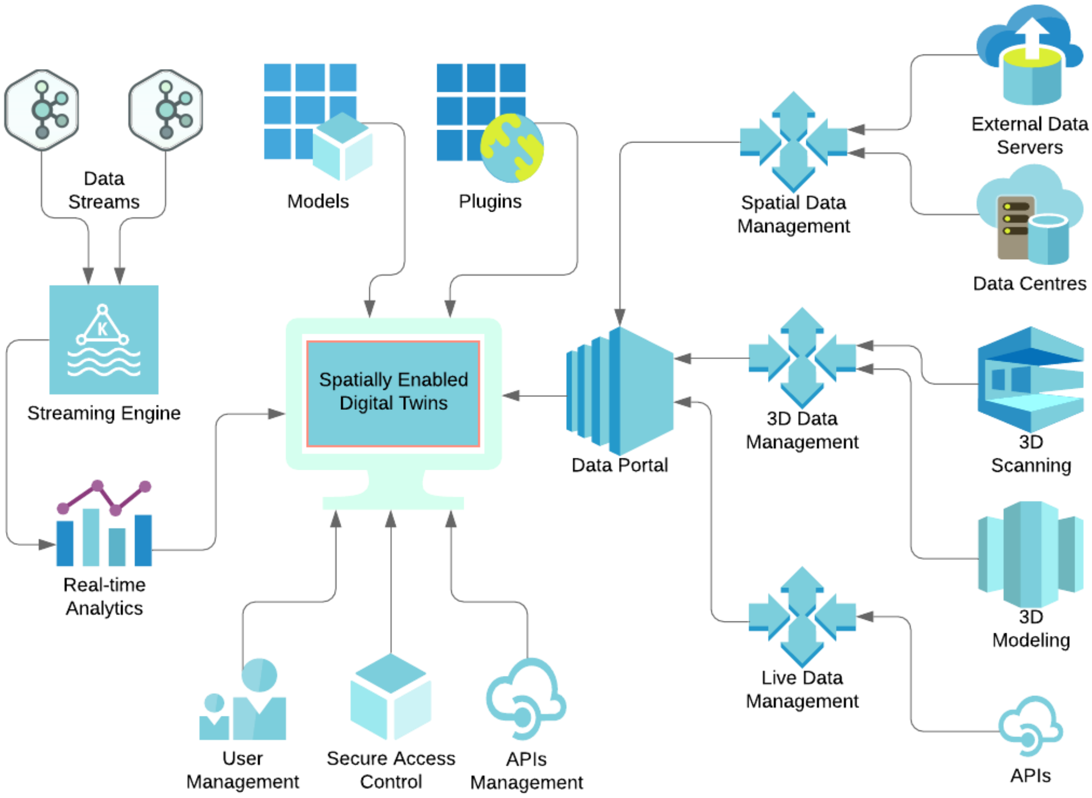


Figure 2 Conceptual system architecture for spatially enabled digital twins.

3D datasets are crucial for DT as they play a key role in visualising and representing the physical environment with enhanced realism. **3D Data Management** assures that miscellaneous 3D data formats can be converted, consolidated, and consumed by the system for visualisation, interaction, and analytics purposes. Compared with 2D data, 3D data reveals more details of the real world; while the main challenge is to create a comprehensive and lossless process to translate divergent 3D formats (both geometries and attributes) into semantically parseable data standards for 3D rendering and operations.

Live Data Management serves as an information aggregator, harvesting, harmonising and analysing diverse live feeds with heterogeneous formats. To achieve timely situational awareness, DT systems should come with abundant live information through external channels, such as live incident alerts, traffics, weather conditions, social media, VGI (volunteered geographic information) etc. A series of connectors can be created to monitor and synchronise live feeds from various sources; and advanced NLP (Natural Language Processing), NLU (Natural Language Understanding) models and GeoAI algorithms then can be applied to clean, parse and understand the textual and spatial contents of the live information for timely decision-making support.

Another special data category in DT is the **Real-time Data Stream** which typically has high-throughput and low-latency characteristics. A **Streaming Engine** is required for ingesting and processing massive real-time information from diverse channels such as IoT sensor networks, CCTV streams, real-time vehicle trajectories, business transactions etc. Besides this, DT should also be able to cache and store real-time data, so analytics models and simulation tools can be applied to learn the patterns from accumulated data and make predictions for the future.

The capabilities for analysis, simulation, prediction and decision support in DTs are achieved through its wide range of **Models** (system built-in) and **Plugins** (user-contributed). The efficacy of code and algorithms, such as artificial intelligence (AI), machine learning technologies and other advanced analytics, can process the data within the digital twins and then deliver knowledge and insights and model future scenarios(ANZLIC, 2019). Compared with plugins, built-in models are usually more sophisticated as they are specially designed and implemented in DT for certain tasks, such as urban flood simulation, bushfire propagation modelling, pedestrian movement, road network traffic simulation, etc. Built-in models are also more computation-intensive and require specific datasets to work with. Third-party tools and libraries can be elaboratively integrated into DT as models through SDKs (Software Development Toolkits) or APIs (Application Programming Interfaces), which can dramatically expand the DT capabilities. On the other hand, plugins are created and maintained by the DT community. DT users can also be treated as contributors as they are empowered to share their knowledge and expertise with the entire DT community by committing scripts (e.g., R, Python, Java etc.) and algorithms as plugins to handle common data processing and analysis problems.

DT systems should come up with a comprehensive **User Management** component and natively support a multi-user environment for collaborations. Users from various organisations can securely manage their resources such as datasets, models, and plugins within the DT infrastructure. A robust and flexible Role-Based Access Control (RBAC) mechanism should be placed as the foundation for DT resources management. Users can grant CRUD (create, read, update and delete) permissions to other users or groups for accessing their resources in DT.

Although it serves as critical digital infrastructure, DT should never be treated as a closed system. On the contrary, a DT platform can only unleash its full power can potential when being elaborately designed and developed as an open ecosystem. A sophisticated **API Management** component is required to meet this purpose. It will assure secure and efficient data exchange and computation resources balance between DT and peripheral services, applications and systems. This is key for achieving scalability and extensibility for DT systems.

In the next section, two sample applications of such a spatially enabled digital twin will be discussed to demonstrate its usability in land administration and urban planning.

4. MODERN LAND ADMINISTRATION AND SPATIAL PLANNING APPLICATIONS

4.1 3D Cadastre Interactive Visualisation, Query and Manipulation

The modern land development processes today require access to 3D spatial information as some functions mainly depend on 3D data existence. As a 3D digital cadastral system needs to provide an integrated 3D view of legal boundaries and rights, restrictions and responsibilities (RRR) in multi-storey properties, the 3D data integration and visualisation capabilities of DT suit this requirement well. In this work, the BIM/IFC is selected as the 3D cadastral data model. In particular, the “IfcSpace” type is used to define the legal boundaries (volumes) in 3D and related RRR information is stored as attributes for each property. For a multi-storey complex building, the initialisation of 3D cadastre information can be achieved in BIM/IFC editor applications such as Autodesk Revit.

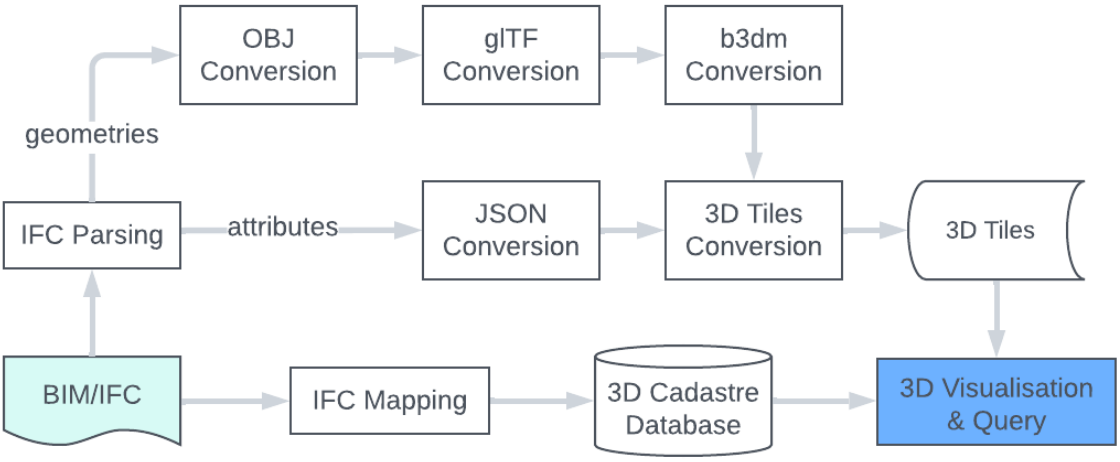
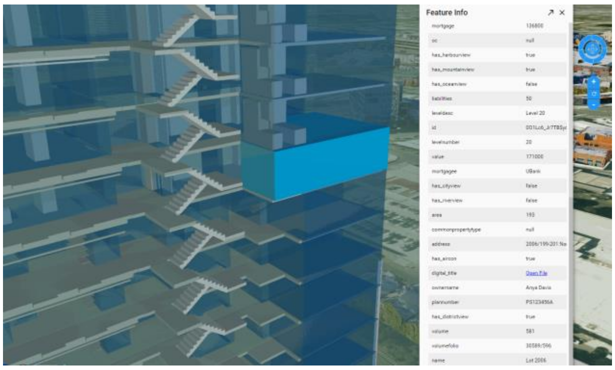


Figure 3 The workflow for bringing BIM/IFC 3D cadastre data model into DT

To bring such a 3D cadastre model (exported as .ifc format) into DT, an elaborate workflow is developed to parse and convert the cadastre geometries and attributes to enable 3D visualisation and query in DT. The geometry data conversion consists of several steps from the original IFC format to OBJ, to glTF, then to b3dm format. The attribute (non-geometry) data is exported to JSON format which will be combined with b3dm files to create the final 3D Tiles for DT visualisation. In the meanwhile, the original IFC file also needs to be mapped into a 3D cadastre database (e.g., PostgreSQL or Oracle) so complex 3D spatial queries and analysis can be supported natively. The implementation of the mapping process is also flexible, which can be achieved by either using third-party tools such as FME or any specially designed mapping logic based on project requirements. As each element defined in 3D Tiles shares the same unique identifier stored in the 3D cadastre database, the query results generated from 3D spatial analysis in the cadastre database can be visualised and controlled in the DT frontend.

Once the 3D cadastre data is imported into DT, the user can load it in the DT web-based frontend powered by CesiumJS, an open-sourced 3D geospatial platform, for interactive visualisation, query and manipulation. Represented in 3D Tiles, the cadastre data can be visualised in along with all supported geospatial data formats in CesiumJS such as photomesh, raster, and vector layers as shown in Figure 4 (a). As BIM/IFC data model is used for storing cadastre information, besides the "IfcSpace" type, other IFC types such as "IfcSlab", "IfcWindow", "IfcDoor", "IfcWall", "IfcRoof", "IfcStair" etc., can also be visualised to give more contextual details of the cadastre and increase the realism of visualisation. Figure 4 (b) illustrates a close-up of a property lot in a 40-storey building defined by the 3D cadastre model. Building components (e.g., slabs, walls, stairs etc.) are rendered together with the property's legal boundary which is represented in the "IfcSpace" (highlighted in blue). The cadastre attributes like plan number, volume folio, title are directly displayed in the system.

Figure 4(a) 3D cadastre in DT



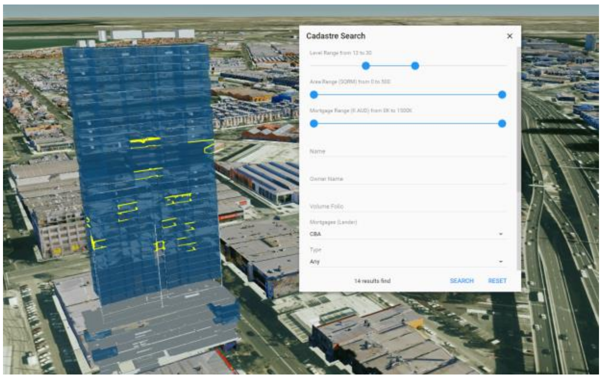
Feature Info

mortgage	136800
oc	null
has_harbourview	true
has_mountainview	true
has_oceanview	false
liabilities	50
leveldesc	Level 20
id	0D1Lc6_Jr7T8Sy
levelnumber	20
value	171000
mortgagee	UBank
has_cityview	false
has_riverview	false
area	193
commonpropertytype	null
address	2006/199-201 Na
has_aircon	true
digital_title	Open File
ownername	Anya Davis
plannumber	PS123456A
has_districtview	true
volume	581
volumefolio	30589/596
name	Lot 2006

Figure 4(b) A close-up of a property lot

3D cadastre information of multiple buildings can be visualised together, as Figure 5(a) illustrates. This is particularly useful for comparing and searching properties across buildings, such as finding all the properties owned by the same owner within a precinct; or searching for properties among various buildings with complex query criteria (e.g., with both city-view and ocean-view, between level 13 and 30 above, etc.). Search results are highlighted (in yellow) in the 3D view and details can be further queried from the cadastre record of each property, see Figure 5(b).

Figure 5(a) 3D cadastre for multiple buildings



Cadastre Search

Level Range from 13 to 30

Area Range (SQRM) from 0 to 500

Mortgage Range (K AUD) from 0K to 1500K

Name

Owner Name

Volume Folio

Mortgagee (Lender): CBA

Type: Any

14 results find

Figure 5(b) Cadastre query in DT

Besides the cadastre visualisation and query capabilities, DT also offers three advanced views for manipulating the 3D cadastre model, including slide view, explosion view and clipping view as Figure 6 depicts. In the slide view shown in Figure 6(a), the user can choose a storey of the building to slide out and can also control the slide-out distance. This view offers a unique and clear viewpoint for observing the property's legal boundary details. The explosion view, see Figure 6(b), applies to all 3D building elements by pushing them outwards along the 3D axes. As each element visually detaches from each other in this view, their connection relationships are unfolded to the user. The clipping view, as demonstrated in Figure 6(c), provides the user with a clipping plane (a transparent rectangle with white edges) which can clip (or cross-section) the 3D building model along either the X, Y or Z axis at any given position. It is particularly useful to reveal building details inside.

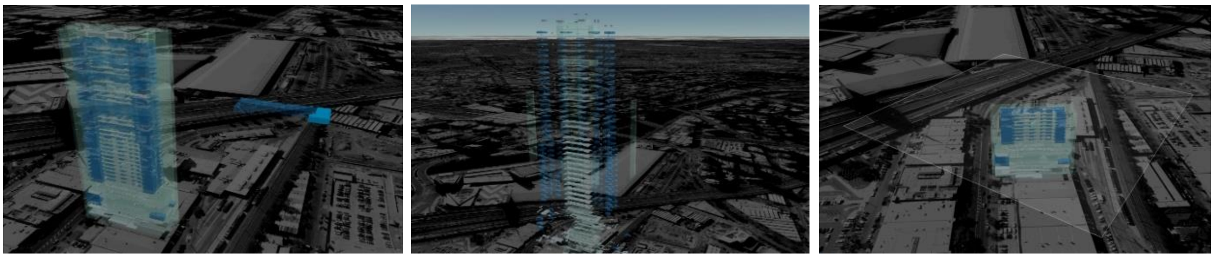


Figure 6(a) Slide View Figure 6(b) Explosion View Figure 6(c) Clipping View

4.2 3D Development Envelop Control for Urban Design

One of the urban planning challenges is when the design aspects and requirements should be implemented into policy and guidelines. There are two major issues in such a process of developing urban design guidelines and policies. First, in the current practice, the examination of urban design guidelines is limited to the pure graphical representation of the environment or proprietary GIS tools, which cannot be customised based on a particular context and design requirements. For example, practitioners use graphical 3D modelling tools to design the building envelope and use visual or numerical analysis to investigate their shadow impact on other urban features. Most of these analyses are 2D and there is a limitation in measuring the 3D spatial impacts. The results of these analytics are not accurate and debatable. Second, the representation of analysis in policy documents is in 2D diagrams, plans, written descriptions, or a combination of both, which are hard to understand and interpret. The interpretation of such a diagram for non-technical users might be difficult. Furthermore, the physical and environmental impacts of these rules could be better examined if 3D visualisation and analytics of potential buildings are conducted in the case area.

To address the abovementioned issues, a Development Envelope Control (DEC) tool was designed and implemented on the digital twin. The tool incorporates a rule-based parametric design and a 3D spatial data model and analysis method. The methodology is designed to populate the 3D buildings based on the design rules in an urban block area. This justifies the name “Development Envelope” instead of “Building Envelope”. After populating the 3D developments, users can modify the buildings’ height and setbacks (as key urban design parameters) at three levels: envelope, edge, and vertex (Figure 7). After modification, the tool can update the planning tool indicators, including floor area ratio, gross floor area, and building/development yield (maximum and optimum building capacity) automatically.

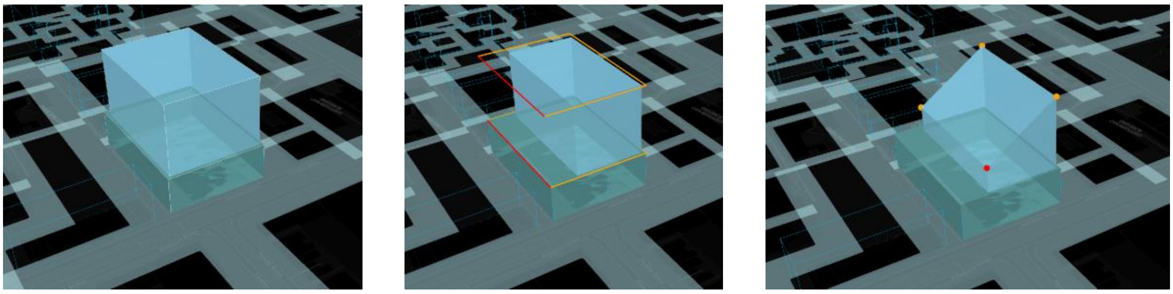

(a) (b) (c)

Figure 7 Rule-based generated 3D development envelopes, with the capability of modifying rules at (a) envelope (b) edge (c) vertex levels and the visualisation and calculation will update in real-time.

Furthermore, the tool enables urban designers to examine the shadow impact on the surrounding areas. The area and volume of shadows can be measured in each time step (Figure 8).

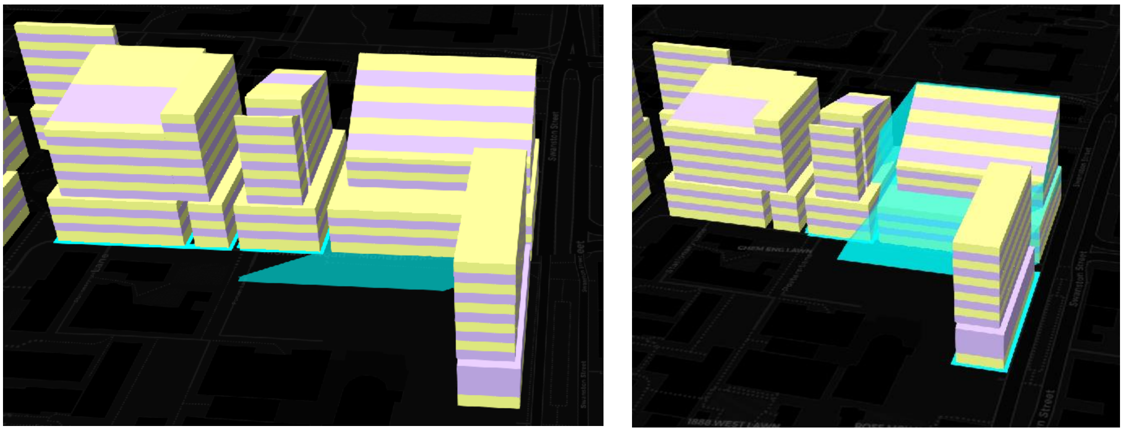


Figure 8 Time-series shadow analysis and visualisation 2D (left) and 3D (right)

5. DISCUSSION & CONCLUSION

This paper set to address the traditional land administration and spatial planning challenges by introducing a novel system architecture and technical tool development in a digital twin environment. The proposed architecture addressed challenges of inter-organisational collaboration, using geospatial standards and flexibility to integrate different analytical tools and data. This capability aligns with the OGC enterprise smart city framework [40]. Furthermore, the digital twin platform provided an opportunity to integrate the BIM with geospatial data as a proof of concept to address the challenges of 2D land administration and moving toward 3D digital Cadastre [16]. From the planning perspective, the proposed DEC tool created a capability for non-technical users to examine different scenarios for urban design rules. Furthermore, the tool enables the decision-makers to understand the environmental and physical impacts of design and planning rules on neighbouring properties and urban areas. In addition, real-time 3D analysis capability improves the interpretation of urban planning and design rules, which addresses the challenge of the current planning practice.

This study contributed to three theoretical areas. First, by providing a novel system architecture, the study improved the theory of information systems integration and interoperability. In addition, the proposed system architecture can improve studies related to inter-organisational data and tool exchange and collaboration. Second, the study provided an example of using a 3D digital cadastre with the possibility of further applications in valuation, dispute resolution, and emergency management. As such, the study contributes to the scholarship in the modernisation of land administration. Third, the study provided a proof of concept for 3D spatial planning using a user-defined rule-based parametric development envelope. This tool demonstrated how a user-centric planning tool in a digital environment can enable non-technical users. The DEC tool provides a context for further investigation of the planning support science (PSS) framework developed by [7].

It is important to validate the generated capabilities in different jurisdictions and rulesets. A potential research agenda for proposed system architecture and next generation of tools is to evaluate their scalability in different context settings. Further investigation is necessary to evaluate the role of emerging technologies, including Artificial Intelligence (AI) and Machine Learning (ML) the new generated data and capabilities to address future challenges. Furthermore, it is believed that the highly granular data generated for 3D digital cadastre and DEC, could improve our understanding of the building and city energy performances. This line of research is important to address the city and state strategies for net-zero carbon emission and climate adaptation.

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