From building to city level dynamic digital Twin: a review from data management perspective

J Yan[1], Q Lu[1], Z Fang[1], N Li[2], L Chen[3] and M Pitt[1]

[1] The Bartlett School of Sustainable Construction, University College London, 1-19 Torrington Place, London WC1E 6BT, UK
[2] Department of Construction Management, Tsinghua University, Beijing 100084, China
[3] School of Architecture Building and Civil Engineering, Loughborough Univ., Loughborough LE11 3TU, UK

j.yan.21@ucl.ac.uk

Abstract. The development of the digital twin (DT) has been focused greatly after the concept was brought from the manufacturing and aerospace areas. In the architectural, engineering, construction and facility management (AEC/FM) sector, DTs are capable of integrating heterogeneous metadata and cutting-edge technologies like artificial intelligence and machine learning to create a dynamic digital environment for various purposes. Although building information modelling (BIM) appears to be a significant contributor to DTs, one of the major limitations for DT development is how to construct and provide a shared data environment for all stakeholders to collaborate throughout the life cycle. Furthermore, as the stakeholders' requirements range of DTs expands from a single building to multiple buildings and regional/city levels, the information and data management gaps (e.g., BIM and GIS data integration) are more challenging and critical. To address these gaps, this paper aims to 1) review the current data management for building and city level DTs from a technical perspective; 2) summarise their major data management issues from building to city levels based on the review; 3) introduce the concept of city-level Common Data Environment (CDE) that addresses the issues identified above, and discuss the possibilities of developing a CDE for a dynamic city-level DT.

1. Introduction

The focus given on digital twin (DT) has been accumulated greatly in recent years, especially when Covid-19 is striking the world, researchers in almost all industries are exploring how the digital transformation might rock the world [1]. In AEC/FM sector, although at a relatively theoretical research stage, the number of academic works on DT soared in a recent couple of years [2]. In the reviews and other DT-related research, building information modelling (BIM) has been identified as a valuable and indispensable technology and data source for DTs [2-4]. However, the point has also been figured out that the single data source of BIM itself cannot be recognised as a well-developed DT. For instance, there were implementations like a data-driven DT framework integrating BIM and IoT and verified in a single building [5] and a BIM/GIS-based information Extract, Transform, and Load (BG-ETL) architecture that assisted building facility management [6]. As the complexity of the data sources increased, these studies indicated that one of the most critical obstacles for DTs development is the data management issue in the digital environment of heterogeneous structured and non-structured data. Moreover, as the concept of DTs has evolved, a DT is expected to be a comprehensive digital approach to manage, plan and predict the physical environment [7]. Both the application areas and data requirements of DTs extend from building/infrastructure level to regional/city level. For example, the necessity of a National Digital Twin (NDT) in the UK has been proposed to construct an ecosystem of federated DTs which could bring benefits for the public in terms of environment, economy, society, and so on. [8]. And a prototype of an urban DT for the 30,000-people town of Herrenberg in Germany was constructed [9]. The transforming trend from building to city DTs development is inevitable.

To address the abovementioned issues, this paper aims to 1) review the current data management for building and city level DTs from a technical perspective (Section 2,3 and 4); 2) conclude major data management challenges, especially for city level DTs based on the review (Section 4); and 3) introduce the concept of city-level Common Data Environment (CDE) that addresses the issues identified above and discuss the possibilities of developing a CDE for a dynamic city-level DT (Section 5).

2. Methodology

This paper reviews the current DT related studies from building and city levels. Two types of works are included in this paper. Firstly, recent works that directly indicate the DT creations have been evolved. Then, the studies that indirectly construct the digital environment for functional purposes (e.g., facility management, energy management, city governance) without acknowledging the DT creations but actually contribute to the data management areas have also been included in this study. All the reviewed works should have developed an actual digital environment for stakeholders to collaborate according to the theoretical DT frameworks. At each level, the reviewed studies are analysed from the data management perspective, i.e. data sources and data integration methods.

3. Data management in building level

3.1. Data sources

A DT refers to a digital representation of physical assets, processes, and systems [7]. Jiang et al. differentiated BIM from DT by indicating that the BIM model lacks the connections and twin relationships between the virtual and physical parts [3]. Therefore, a DT cannot be a singular 3D model or an individual source of data. In the current DT-related studies at the building level, primary data sources have been summarised in Table 1. The data sources can be divided into geometric representations and non-geometric representations.

- Geometric representations: although many data formats are capable of 3D geometry storage like 3D Studio Max (.3dx), SketchUp (.skp) and Collada (.dae) [10], BIM model from popular software like Revit and ArchiCAD is the most common data source. It provides Industry Foundation Classes (IFC) data format, the primary open data schema used for information exchange within the AEC/FM sector, including geometric and semantic information at the data level [10]. As for the data status, researchers may argue the geometric representation should be dynamic because the actual physical building may be renovated in the whole building life cycle [11], some may think the updating time difference is long to consider as dynamic data.
- Non-geometric representation: this category of data sources constructs the connections between the virtual and physical worlds. For example, RFID or QR code bridge the gap between existing building facilities and their virtual counterparts. Multiple building systems like BMS and BAS in the operation and maintenance (O&M) phase collect data through sophisticated sensors and devices [12] and the systems usually deal with low-volume low-velocity data [13]. In addition, data from IoT devices collect real-time data from the built environment with features of high-volume, high-velocity. And IoT devices generate a mix of data formats, including structured, semi-structured, and unstructured data. This data might include analog signals, discrete sensor readings, device health metadata, or large files for images or videos [14].

Table 1. Summary of data sources for building-level DTs

Data source	Data format	Data content	Status

BIM	IFC	provide 3D Geometry and semantic information for the whole built environment	Static/Dynamic
RFID/QR Code	multiple	asset or equipment identification	Static
O&M management systems (e.g., BMS, BAS, AMS, EMS, SMS, CMMS)	varied based on different vendors	control, monitor and collect data of building equipment and systems like power, HVAC, energy and daily services records like work orders	Dynamic
IoT	multiple	collect real-time data of built environment (e.g., CO2, humidity, sound, lighting)	Dynamic

Note: RFID-Radio-frequency identification, BMS-building management system, BAS-building automation system, AMS-asset management system, EMS-energy management system, SMS-security management system, CMMS- Computerized maintenance management system

3.2. Data integration methods

Because of the fact that a DT is supposed to be composed of different data sources, a shared data environment that can integrate heterogeneous data is very important. Table 2 summarises the recent studies of shared and integrated data environments for building-level DTs. Among the reviewed studies, BIM in IFC data format was the one and only choice for geometric representation of the physical world, however, a data interpreter of IFC data might be needed for the integration purpose in some situations [15]. A couple of studies mentioned 3D model integration with GIS [6, 16] to increase the data richness of a building DT, which might be adopted for the further city-level data integration purpose. There were also studies proposing DT architectures for both building and city levels, which have been included in the following section of this paper. Besides, based on the summarised data sources, creating a shared data environment with BIM and IoT was the most addressed issue [5, 13, 15, 17]. And since the traditional building management systems indicated in Table 1 provided thorough building facility data, the integration of these data with BIM and IoT tends to be a necessity.

Furthermore, a dominant trend of the summarised DT studies is that the shared data environments have been designed as web-based platforms or systems [13, 15, 16, 18]. They intended to solve the web-based data integration problems like data sources mapping, interpretation etc. The web-based services and cloud storage capability could benefit stakeholders by accessing and collaborating central projects data. And some of the web-based platforms or systems studies were developed to be the DT "engine" that can derive more applications. Commercially, there are Forge from Autodesk and Descartes from Bentley that could be the "engine" that can integrate different data sources. Some academic studies have adopted them as pilot implementations [7, 18], where they were considered as the shared data integration environment.

Table 2. Summary of shared and integrated data environments for building-level DTs

DT data environment /theoretical framework	Data source	Key contribution	Reference
Adaptive City Platform (ACP)	BIM, BMS, IoT	developed a data architecture for BIM and sensor data integration, spatio-temporal data and the lack of real-time response are addressed	[13]
A reference architecture for Smart Building DT	BIM, IoT	developed an architecture that used mediator i.e., TripleStore for RDF (Resource Description Framework) data	[15]

Intelligent green building rating (iGBR) framework	BIM, SWRL data for score calculation, data from social media	developed a framework supported by a semantic and social approach to realise real-time rating in green building design	[18]
Integrated digital twin and blockchain framework	BIM, IoT	developed the framework to update the BIM model with IoT data almost in real-time and recorded on the blockchain with time stamps	[17]
Architecture of the DT for a BIM-enabled construction project	BIM, IoT	developed a data-driven framework integrating BIM and IoT data and using data mining methods to optimise the physical construction operations	[5]
BG-ETL architecture	BIM, GIS, CMMS	developed an architecture that mapped BIM and GIS data and integrated it with FM systems data	[6]
Architecture of equipment maintenance and repair management	BIM, GIS, RFID/QR code	developed the automatic algorithm of the logic chain for MEP systems and an equipment grouping and labelling scheme that integrated BIM and GIS models	[16]

4. Data management in city level

4.1. Data sources

For city-level DTs, the synergy is much more complex than DTs for a single building due to considerations of the data environment, collaboration, functions, target users/stakeholders, and so on. From the data management level, the data sources are more diverse than building DTs. But we can still address the issue by dividing the sources into geometric representation and non-geometric representation. Table 1 concludes major data sources for city-level DTs in this review.

- Geometric representation: BIM data in IFC format is still the inevitable choice to represent detailed building information. By integrating BIM and GIS data, a prototype of a city-level DT model can be created [10, 19]. However, in the city context, BIM and GIS files are not always available. Therefore, the techniques (regarded as data sources in this paper) like LiDAR and aerial photogrammetry to acquire existing environment data are quite important. Although the data produced by LiDAR or photogrammetry can be more realistic in terms of materials or shapes, more steps are required to process these raw data. The added steps mean that the middle data formats (i.e., mediators) are needed from the raw data to the integration-ready data. In addition, there were also discussions about whether a detailed city model was needed considering functional aspects. Therefore, simplified grey boxes representing city assets like the geometric data from OpenStreetMap might also be a choice [20]
- Non-geometric representation: one of the primary data sources are from IoT devices and building management systems like building DTs [7, 21]. Nevertheless, the city DTs bring more potential like urban planning, city governance, transportation optimisation, environmental issue etc [22]. Thus, the data sources vary greatly due to the functional needs, which is one of the major drivers for the shared city data environment.

Table 3. Summary of data sources for city-level DTs

Data source	**Data format**	**Mediator**	**Data content**	**Status**

BIM	IFC	Mediator data formats might be required e.g., 3D Tiles, glTF	provide 3D Geometry and semantic information for the whole built environment	Static/dynamic
GIS	CityGML, CityJSON, shapefile, GeoJSON		provide 3D Geometry and semantic information for the geographic environment	Static/dynamic
Existing physical environment scanning techniques e.g., LiDAR, photogrammetry	multiple		provide high quality realistic 3D meshes of existing buildings and areas	Static/dynamic
Other 3D model sources e.g., 3DsMax, OpenStreetMap	multiple		provide 3D geometry with different level of details e.g., grey boxes or realistic models	Static/dynamic
IoT	multiple	Mediator data formats required e.g., XML, JSON	collect real-time data of existing area environment	Dynamic
O&M management systems (e.g., BMS, BAS, AMS, EMS, SMS, CMMS)	varied based on different vendors		control, monitor and collect data of multiple buildings' equipment and systems	Dynamic
Other data based on requirements	multiple		e.g., urban design, landscape governmental operation data, census data etc.	Static/dynamic

4.2. Data integration methods

In the studies that have been reviewed in this paper, there are mainly two directions of the city-level DT studies. One direction is to develop a shared data environment among different geometric representation data. For example, the efficient mapping between BIM and GIS was a critical issue that has been addressed by [10, 23-25]. Another direction is to create the shared data environment or data integration between geometric representation data and other non-geometric representation data sources regarding a building or a city's operational purposes. Examples were the studies on the link between BIM/GIS and IoT/building management system data/open governmental data/energy data [7, 9, 21, 26, 27]. Ideally, the data integration issue needs to be solved in both directions.

Among the city-level DTs data environments in Table 4, web-based platforms or systems are the major trends, which is the same as building DTs. The web-based studies can be categorised into two types. Firstly, the web-based platforms or data environments were built up as the "engine" that offers APIs for developers to create complete DT systems with various services [10, 23, 28]. Secondly, another type was a fully developed web-based DT platform or system that can be used by stakeholders [7, 9, 25, 26]. Moreover, for the first type of web-based platform, there are commercial providers such as Dassault, Cesium, 3D city DB that offer similar capabilities [25, 29]. For instance, the Virtual Singapore project was completed as a smart city pilot early in 2016 [30]. Other game engines like Unreal Engine and Unity also contribute to this area.

Table 4. Summary of shared and integrated data environments for city-level DTs

DT data environment /theoretical framework	Data source	Key contribution	Reference

A multitier System architecture of DT development at a city and building level	BIM, GIS, IoT, AMS, BMS, SMS and other data from sub-DTs based on services requirement	delivered a thorough framework with a pilot case study of how building and city-level DTs could be built and implemented	[7]
BIM+GIS	BIM, GIS	Provided updated BIM and GIS integration environment for smart city	[10, 31]
IoT-based data acquisition framework	BIM, IoT	developed a framework in using IoT devices and networks to establish a data acquisition system for buildings (and potentially community or city)	[21]
HDF-based BIM and GIS integration approach	BIM, GIS	an approach that created a city DT with enhanced storage efficiency	[23]
Online digital twin interaction diagram for smart city	BIM, IoT	indicated different layers of information in the city and, platform was built for urban planning for the public	[26]
An urban digital twin 3D model	BIM, LiDAR, GIS, wind simulation data etc	3D model of the city was developed for citizen participatory and environmental simulation	[9]
A Digital geoTwin for City Information Modelling (CIM)	BIM, GIS, other data e.g., census, economic, energy in the future	provided a strategy to create the geoTwin integrating BIM/GIS data as the basis of CIM	[24]
A system of DTs for the City of Zurich	BIM, GIS, Open Government Data	developed an urban digital twin environment for multiple city purposes	[32]
A web-based environment of realistic BIM and GIS information	BIM, GIS, aerial photogrammetry	provided the integrated data environment for cadastral management	[25]
A smart city digital twin architecture	Semantic information of city management e.g., urban planning, land use, energy, emergency	supported knowledge representation and reasoning with machine learning and tested with energy use analysis	[27]
Virtual Singapore platform	multiple	A dynamic 3D digital model of the city and connect all stakeholders in a secure, controlled environment powered by 3DEXPERIENCity from Dassault	[30]
A web 3D platform of digital city	multiple	developed a web-based data environment that can display over 20 data formats	[28]
3D city model (3DCM)	BIM, OSM	a data environment for urban planning	[20]

4.3. Transforming data management from building to city levels

Due to the essence of a city's diversity and complexity, a DT of a city is expected to be more dynamic and sophisticated. But there are obvious gaps based on the review of this paper. Firstly, from the data source aspect, the selection of data sources for city-level DTs should be more deliberate. Unlike the fact that BIM in IFC format tends to be the singular choice for building DTs, considerations like reality environment existence, level of details (LOD), data format interpreter, functional purpose etc. should be largely taken into account to determine the data sources for both geometric and non-geometric representations. Secondly, current city-level DT frameworks were at a pilot stage, there were limited tests of a very large size with high LOD (i.e., a real city replica) of integrated data via a web service. Thirdly, the issues of data sources and data integration are not the whole parts of data management. Other aspects like data security, visualisation, application and dynamic data maintenance are all critical issues in the realm. Generally speaking, the research on city-level DT (even including building-level DT) is at a relatively theoretical phase, where more matured frameworks and experimental studies are urgently required.

5. Discussion of CDE generation for city level DTs

5.1. Challenges of data requirements from building to city level DTs

Moving from the building to city level DTs, challenges could be categorised into the following aspects [33]:

- Informational issues and interoperability: separated systems or 3D models of a city without a 'communication channel' cannot be regarded as a successful sharable DT data environment, where data is the valuable asset in DTs and indeed bring financial benefits. For example, informational issues like data standardisation, data exchange and data synchronisation are the foremost challenges.
- Functional issues: unlike lots of building DTs that are mainly evolved from BIM-based O&M systems, city-level DTs' functional objectives may come from areas like facility management, urban planning, geographic engineering, government, sustainability. Therefore, targetting the accurate functions or application services requirements from stakeholders is critical and challenging.
- Technical issues: challenges in these categories have been noticed in a recent couple of years. Many studies focus on improving the data collection, data visualisation, storage capability via graphic engineering techniques. The cross-disciplinary applications of these issues with computer science and software engineering fields are valuable but challenging. The technological competitions may be fierce in terms of effectiveness, extensibility, effort and flexibility [34]. Moreover, key technology like machine learning and artificial intelligence are waiting to be applied more in the dynamic city DT to create a smarter city.
- Organisational: a practical challenge from the organisational aspect is how the DT will be collaborated among the stakeholders. For example, in a governmental organisation, how to embed the application of the DT into the management workflow is questionable, and will affect the development and iteration of the DT.

5.2. Generation of city level CDE

Based on the challenges generated from Section 5.1, a fact can be pointed out that the development of a city level DT is not merely a technical puzzle, but a more sophisticated creation of a whole dynamic digital environment that federates the city's synergy. Socio-technological aspects should be considered like people, connections, sustainability and digitalisation [35]. A concept of common data environment (CDE) derived from ISO 19650 and PAS 1192 [36] by the UK Government BIM Working Group has been developed for asset information management [37], where the interoperability, function, technical and organisational aspects were addressed in a "functional requirement" framework of a building-level CDE. The framework could be considered for a dynamic city-level DT as well based on this paper's review. In the proposed framework, five phases are included to identify city CDE elements properly and address the main challenges for DT development (Figure 1). To be specific, the stakeholders of the proposed CDE will be identified in the first place and the current information exchange condition among the stakeholders of the targeting physical environment (e.g., a region or a city) will be concluded (i.e., the information procurement module). According to these outcomes, the data management method (including data collection sources, data integration, security and synchronisation etc.) will be determined and executed in the following modules. Then, the data visualisation requirements of the city CDE from stakeholders will be specified in the user functionality module. And the proposed CDE can be utilised through the output APPs or APIs. Therefore, with the proposed city level CDE framework, all the stakeholders may have a sharable environment to store, present and exploit the digital information of the corresponding physical world.

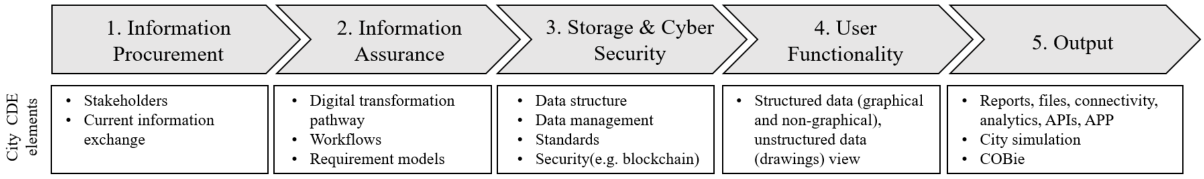

Figure 1. Proposed dynamic city-level CDE framework

6. Conclusion
In this paper, we reviewed recent studies on building and city level DTs from a data management (i.e., data source and data integration) perspective. A transforming trend from building level DT to city level DT has been concluded based on the review. In addition, this paper generated the dynamic city DT challenges in terms of interoperability, functionality, technology and organisational issues. In order to address the issues, we proposed a framework of dynamic city-level CDE derived from building asset information management by the UK government, which could be developed as an integrated, shared and safe data environment for city DTs.

Acknowledgments
The work described in this paper was supported by the grant from the UCL-ZhiuTech Research Fund and ICE Research and Development Enabling Fund.

References
[1] Kunzmann K R 2020 Smart cities after covid-19: ten narratives *disP-The Planning Review* **56**(2): p. 20-31
[2] Ozturk G B 2021 Digital Twin Research in the AECO-FM Industry *Journal of Building Engineering* **40**: p. 102730
[3] Jiang F, Ma L, Broyd T and Chen K 2021 Digital twin and its implementations in the civil engineering sector *Automation in Construction* **130**: p 103838
[4] Callcut M, Cerceau Agliozzo J P, Varga L and McMillan L 2021 Digital Twins in Civil Infrastructure Systems *Sustainability* **13**(20): p 11549
[5] Pan Y. and L Zhang 2021 A BIM-data mining integrated digital twin framework for advanced project management *Automation in Construction* **124**: p 103564
[6] Kang T W and Hong C H 2015 A study on software architecture for effective BIM/GIS-based facility management data integration *Automation in construction* **54**: p 25-38
[7] Lu Q, Parlikad A K, Woodall P, Ranasinghe G D, Xie X, Liang Z, Konstantinou E, Heaton J and Schooling J 2020 Developing a digital twin at building and city levels: Case study of West Cambridge campus *Journal of Management in Engineering* **36**(3): p 05020004
[8] Bolton A, Butler L, Dabson I, Enzer M, Evans M, Fenemore T, Harradence F, Keaney E, Kemp A, Luck A and Pawsey N 2018 *Gemini principles*
[9] Dembski F, Wössner U, Letzgus M, Ruddat M and Yamu C, 2020 Urban digital twins for smart cities and citizens: The case study of Herrenberg, Germany *Sustainability* **12**(6): p 2307.
[10] Zhu J and Wu P 2021 Towards Effective BIM/GIS Data Integration for Smart City by Integrating Computer Graphics Technique *Remote Sensing* **13**(10): p 1889

[11] Brazauskas, J., et al. 2021 *Data Management for Building Information Modelling in a Real-Time Adaptive City Platform.*
[12] Gao, X., et al. 2019 *A scalable cyber-physical system data acquisition framework for the smart built environment*, in *Computing in civil engineering: Smart cities, sustainability, and resilience*. 2019, American Society of Civil Engineers Reston, VA. p. 259-266
[13] Brazauskas J, Verma R, Safronov V, Danish M, Merino J, Xie X, Lewis I and Mortier R 2021 Data Management for Building Information Modelling in a Real-Time Adaptive City Platform *arXiv preprint* arXiv:2103.04924
[14] IBM 2020 *Making sense of IoT data* Available from: https://developer.ibm.com/tutorials/iot-lp301-iot-manage-data/
[15] Chevallier Z, Finance B and Boulakia B C 2020 A Reference Architecture for Smart Building Digital Twin. in *SeDiT@ ESWC*
[16] Hu Z Z, Tian P L, Li SW and Zhang J P 2018 BIM-based integrated delivery technologies for intelligent MEP management in the operation and maintenance phase *Advances in Engineering Software* **115**: p 1-16
[17] Lee D, Lee S H, Masoud N, Krishnan M S and Li V C 2021 Integrated digital twin and blockchain framework to support accountable information sharing in construction projects *Automation in construction* **127**: p 103688
[18] Zhang D, Zhang J, Guo J and Xiong H 2019 A semantic and social approach for real-time green building rating in BIM-based design *Sustainability* **11**(14): p 3973
[19] Biljecki F, Lim J, Crawford J, Moraru D, Tauscher H, Konde A, Adouane K, Lawrence S, Janssen P and Stouffs R, 2021. Extending CityGML for IFC-sourced 3D city models *Automation in Construction* **121**: p. 103440
[20] Al Furjani A, Younsi Z, Abdulalli A, Elsaeh M, Almahdi A, Jouil K and Lashihar S B, 2020 Enabling the City Information Modeling CIM for Urban Planning with OpenStreetMap OSM The Fourth International Conference for Geospatial Technologies – Libya GeoTec 4, Tripoli, Libya
[21] Gao X, Pishdad-Bozorgi P, Shelden D R and Tang S 2021 Internet of Things Enabled Data Acquisition Framework for Smart Building Applications *Journal of Construction Engineering and Management* **147**(2): p 04020169
[22] Shahat E, Hyun C T and Yeom C 2021 City digital twin potentials: A review and research agenda *Sustainability* **13**(6): p 3386
[23] Pan Z, Shi J and Jiang L 2020 A Novel HDF-Based Data Compression and Integration Approach to Support BIM-GIS Practical Applications *Advances in Civil Engineering* **2020**
[24] Lehner H and Dorffner L 2020 Digital geoTwin Vienna: Towards a digital twin city as Geodata Hub *Springer PFG* **88**, 63–75
[25] Smart M and R Priebbenow 2018 Designing a 3D Cadastral System Demonstrator: A Case Study in *Conference Proceedings of The 6th International FIG Workshop on 3D Cadastres*, TU Delft.
[26] White G, Zink A, Codecá L and Clarke S, 2021 A digital twin smart city for citizen feedback *Cities* **110**: p 103064
[27] Austin M, Delgoshaei P, Coelho M and Heidarinejad M, 2020 Architecting smart city digital twins: Combined semantic model and machine learning approach *Journal of Management in Engineering* **36**(4): p 04020026
[28] Seto T, Sekimoto Y, Asahi K and Endo T 2020 Constructing a digital city on a web-3D platform: simultaneous and consistent generation of metadata and tile data from a multi-source raw dataset in *Proceedings of the 3rd ACM SIGSPATIAL International Workshop on Advances in Resilient and Intelligent Cities*
[29] Chen Y, Chen Y, Shooraj E, Rajabifard A and Sabri S 2018 From IFC to 3D Tiles: An Integrated Open-Source Solution for Visualising BIMs on Cesium *ISPRS International Journal of Geo-Information* **7**(10): p 393
[30] Soon K and V Khoo 2017 CityGML modelling for Singapore 3d national mapping *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences* **42**

[31] Deng Y, Cheng J C P and Anumba C 2016 Mapping between BIM and 3D GIS in different levels of detail using schema mediation and instance comparison *Automation in Construction* **67**: p 1-21
[32] Schrotter G and Hürzeler C 2020 The digital twin of the city of Zurich for urban planning *PFG–Journal of Photogrammetry, Remote Sensing and Geoinformation Science* **88**(1): p 99-112
[33] Volk R, Stengel J and Schultmann F 2014 Building Information Modeling (BIM) for existing buildings—Literature review and future needs *Automation in construction* **38**: p 109-127
[34] Liu X, Wang X, Wright G, Cheng J C, Li X and Liu R 2017 A State-of-the-Art Review on the Integration of Building Information Modeling (BIM) and Geographic Information System (GIS) *ISPRS International Journal of Geo-Information* **6**(2): p 53
[35] Schooling J, Enzer M and Broo D G 2021 Flourishing systems: Re-envisioning infrastructure as a platform for human flourishing *Proceedings of the Institution of Civil Engineers-Smart Infrastructure and Construction* **173**(1): p 166-174
[36] NBS 2016 What is the Common Data Environment (CDE)? Available from: https://www.thenbs.com/knowledge/what-is-the-common-data-environment-cde
[37] UK Government 2018 Asset Information Management - Common Data Environment Available from: https://www.cdbb.cam.ac.uk/news/2018AugCDE