MY FEATURED RESEARCH

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HUMAN-CENTRIC URBAN DIGITAL TWINS

Humans as sensors in urban digital twins

Authors: Binyu Lei, Yunlei Su, Filip Biljecki

Humans As Sensors in Urban Digital Twins

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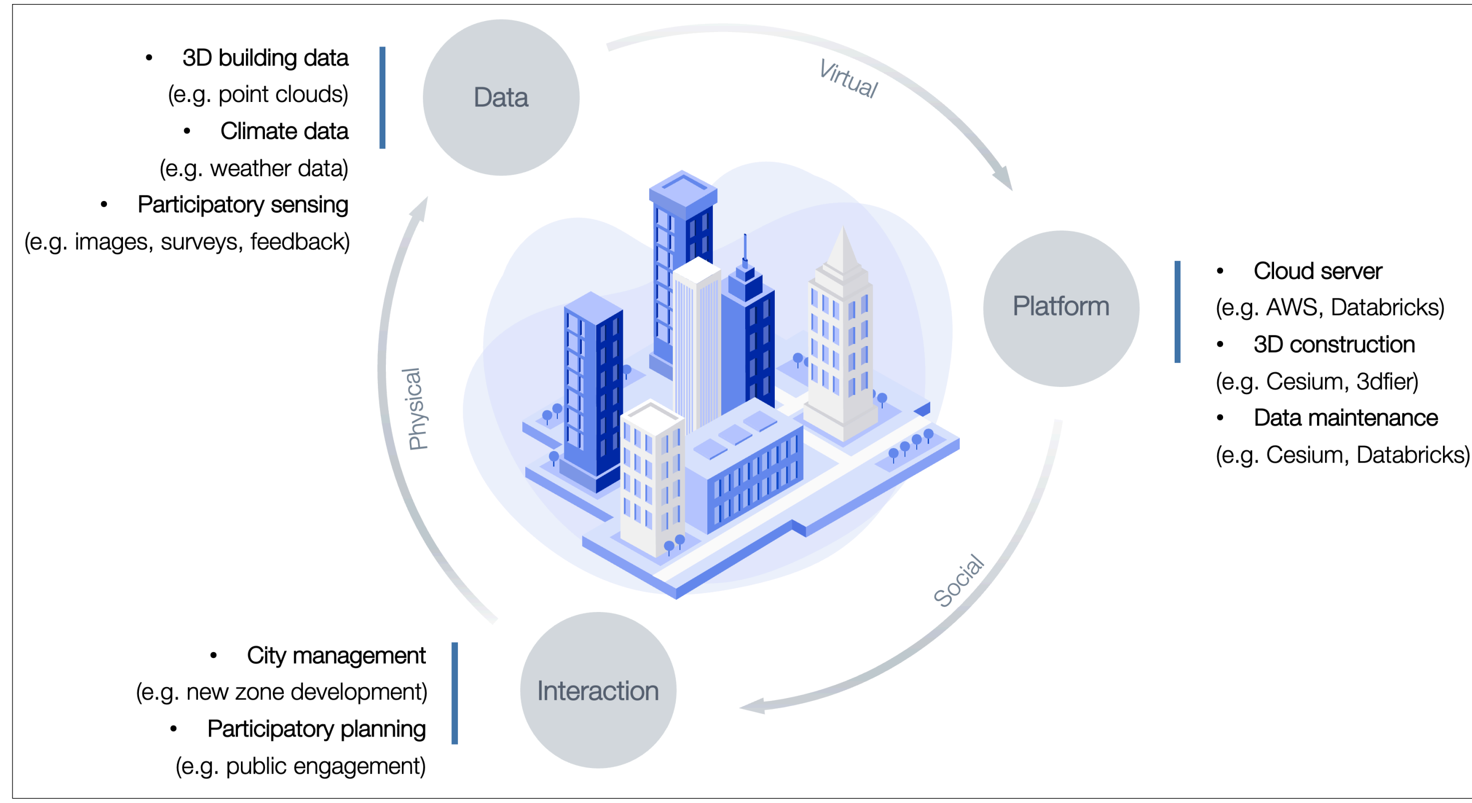
Binyu Lei, Yunlei Su, and Filip Biljecki

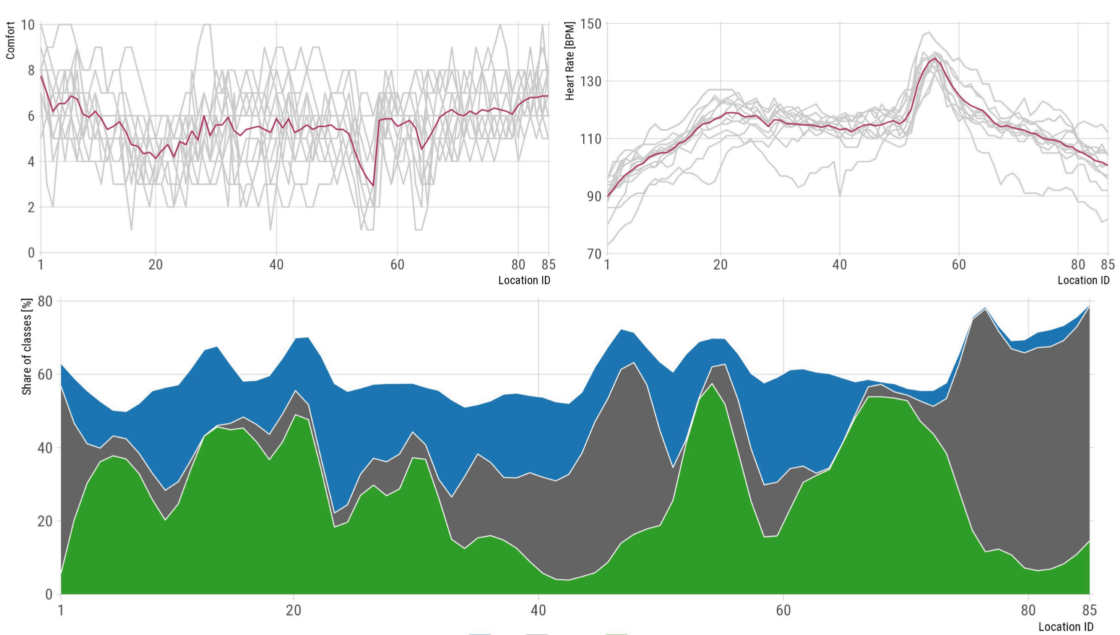
Abstract Digital twins have gained increasing attention as a tool to facilitate decision-making in the cities. However, the current discourse predominantly focuses on technical aspects while overlooking the human aspect in urban digital twins. This work proposes a conceptual framework that addresses the role of humans in relation to the urban environment, therefore highlighting the social value of urban digital twins. The proposed framework is subsequently implemented in a specific case study of outdoor walking comfort at National University of Singapore, validating its feasibility in practice. By incorporating human sensing data, such as participatory data, urban digital twins have the potential to represent the dynamic interaction between people and environments, generating a holistic physical-social-virtual system.

Keywords Urban planning · Participatory process · Human sensing data · Data integration · 3D city modelling

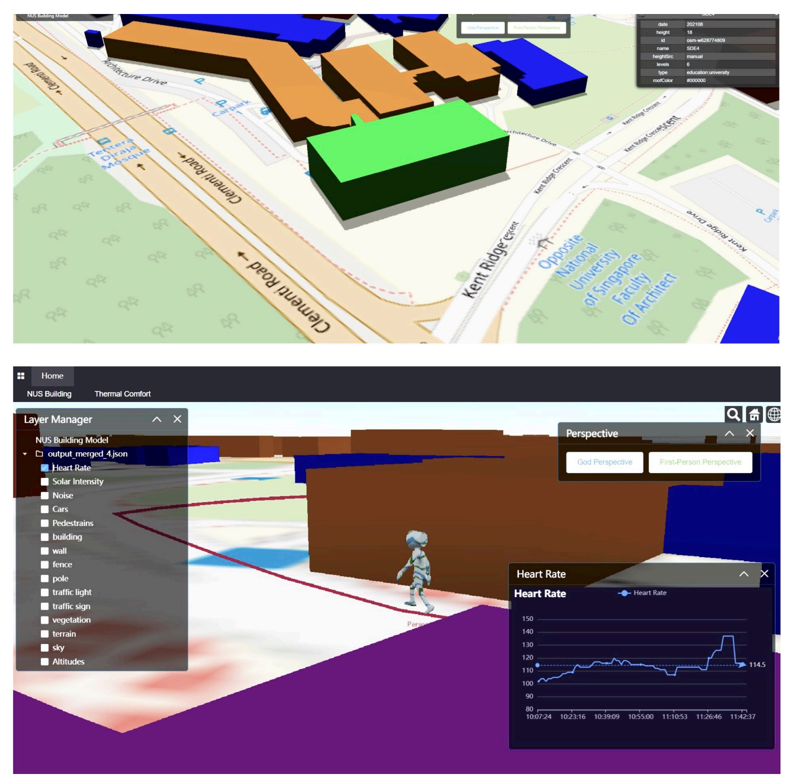
A framework of human-centric urban digital twins



Collecting participatory data from human sensing



The implementation of the concept at NUS campus. Source: OpenStreetMap, Cesium



Lei, B., Su, Y., & Biljecki, F. (2023, September). Humans As Sensors in Urban Digital Twins. In *International 3D GeoInfo Conference* (pp. 693-706). Cham: Springer Nature Switzerland.

HUMAN-CENTRIC URBAN DIGITAL TWINS

Integrating human perception in 3D city models and urban digital twins

NUS National University of Singapore — urban analytics lab

Authors: Binyu Lei, Xiucheng Liang, Filip Biljecki

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Integrating human perception in 3D city models and urban digital twins

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Keywords: Data integration, Data standard, Data extension, CityJSON, Architectural perception, 3D GIS.

Abstract

Urban digital twins, and 3D city models underpinning them, provide novel solutions to urban management but tend to overlook the human element. The trending research on human perception reveals people's perspective towards interpreting and experiencing the built environment. Advancing the representation of building physics and descriptive information in 3D city models and urban digital twins, we establish the addition and integration of the notion of how humans perceive buildings. Unlocking a new dimension in our domain, this new concept can facilitate a broader adoption of semantic 3D data in socio-economic fields across various domains, and advance existing use cases in 3D GIS. This work is the first instance of integrating such attributes in 3D city models, which have traditionally been confined to physical and objective measures. The visual perception of each building is evaluated based on building images extracted from street view images. We add such information as new attributes to an existing CityJSON dataset representing thousands of 3D buildings in Amsterdam, the Netherlands. To facilitate a robust and sustainable integration, we develop a CityJSON Extension to accommodate the new data and validate its schema successfully, and we visualise the semantic 3D dataset. Further, we present two use cases to demonstrate the usability of our new data for downstream analysis. One is the concurrent clustering of buildings based on 3D morphology and human perception, while the other is conducting an attribute-based query that enables various stakeholders to identify a particular building of interest combining both traditional and perception attributes.

1. Introduction

Urban digital twins have permeated through multiple domains, from transportation, disaster management, energy consumption to virtual tourism (Dembski et al., 2020, Ferré-Bigorra et al., 2022, Hämäläinen, 2021, Nochta et al., 2021, Ketzler et al., 2020, Rahmadian et al., 2023, Caprari et al., 2022). Integrating a large collection of data and techniques, urban digital twins advance urban analytics towards a dynamic and interactive way of building and managing smart cities. However, they are described to be techno-optimistic but overlook social and human aspects (Lei et al., 2023a, Stoter et al., 2021, Charitonidou, 2022, Nochta et al., 2021). Among various human aspects, perception has been studied in strands of domains, from medicine to social science (Redelmeier and Dickinson, 2011, Galesic et al., 2021). In urban research, humans play a role in delivering their sensations and experience towards the living environments (Goodchild, 2007, Zhang et al., 2018). Exploiting the active and explicit information from a human perspective may bridge the gap in urban digital twins, leading to a human-centric direction for further applications across multidisciplines.

From the standpoint of buildings, which are a key element in both the physical environment and urban digital twins, integrating perception and sentiments as additional building characteristics will be valuable in multiple ways. Buildings serve as the foundation of urban environment for a variety of use cases. Their physical facets, such as economic value, energy consumption and building geometry, are measurable and quantifiable for scientific studies (Zhao and Magoulès, 2012, Biljecki and Chow, 2022, Liang et al., 2023, Helbich et al., 2013). However, the less objective aspects of buildings are difficult to evaluate, e.g. emotions and perceptions towards them, which are associated with the architectural aesthetics (i.e. the art of buildings) and the surroundings. Buildings as objects in the city are identifiable, nevertheless the experience of buildings and individual perceptions are dynamic and personal, reflecting how people define and interpret them (Grütter, 2020, Kotseruba et al., 2016, Lu and Sperling, 1995).

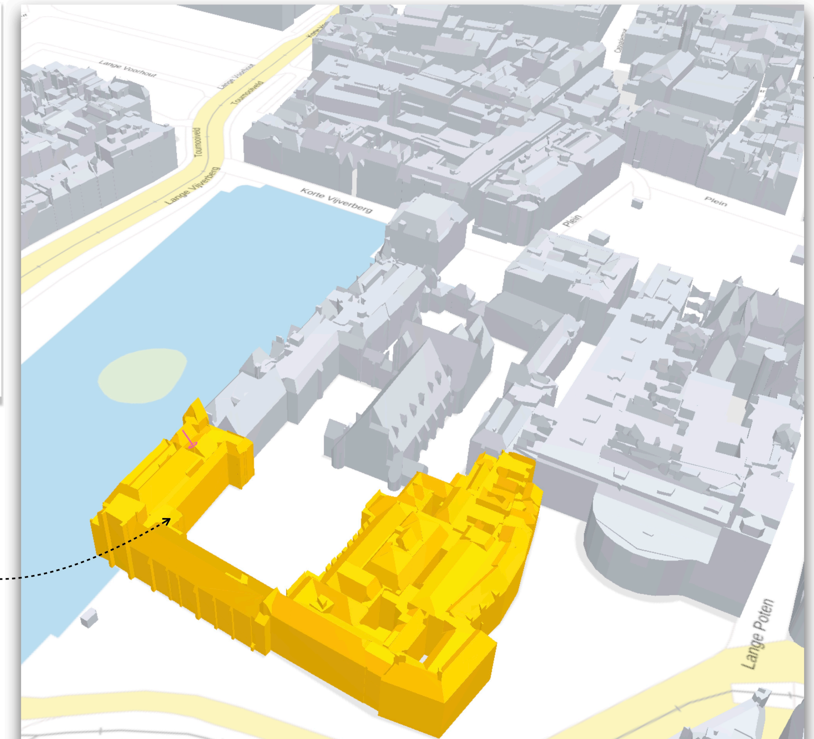
Perception- and sentiment-related urban studies are prevalent topics, contributing to understanding urban environments and reflecting activities in the city through a human perspective (Wei et al., 2022, Ma et al., 2021, Liu et al., 2016). The rise of urban sensing enables a gathering of insights from humans regarding how they perceive their living environments, such as generating urban vitality through volunteered geographical information, e.g. trajectory data, and exploring urban characteristics from social sensing data, e.g. social media platform, such as Airbnb reviews (Yan et al., 2020, Huang et al., 2020, Galesic et al., 2021, Liu et al., 2015). From a visual perspective, street view imagery (SVI) serves as a growing data source, collecting human perception on a large scale to evaluate urban settings and promote liveability (Kang et al., 2020, Liang et al., 2023). However, incorporating human sensing data in 3D city models and urban digital twins to a certain extent is limited. The state of the art of a human-centric urban digital twin puts a focus on leveraging it as a digital platform to represent cities to collect people feedback, e.g. supporting participatory planning and simulating community resilience (Dembski et al., 2020, Ye et al., 2023, Nochta et al., 2021). Several attempts are made to include human sensing data in an urban digital twin rather than adopting it as a visualisation tool, for example, integrating outdoor comfort data to reflect the impact of urban surroundings (Liu et al., 2023, Lei et al., 2023b). However, there remains a gap in making human sensing data analysable when adopting urban digital twins. In this work, we integrate human perceptual criteria previously used to evaluate building exteriors (Gifford et al., 2000, Heath et al., 2000, Ghomeishi, 2021, Arslan and Yıldırım, 2023) with a computer vision approach. The human perception of buildings is quantified with a score from 0 to 10 based on 5 perceptual indicators (i.e. original, pleas-

STREET VIEW IMAGERY

How do you perceive the building?

Indicator	Score
Original	5.2
Pleasing	5.1
Ordered	4.7
Boring	3.4
Complex	5.1

3D BUILDING MODEL



INTEGRATION

Perception values
+
3D building attributes

Extension

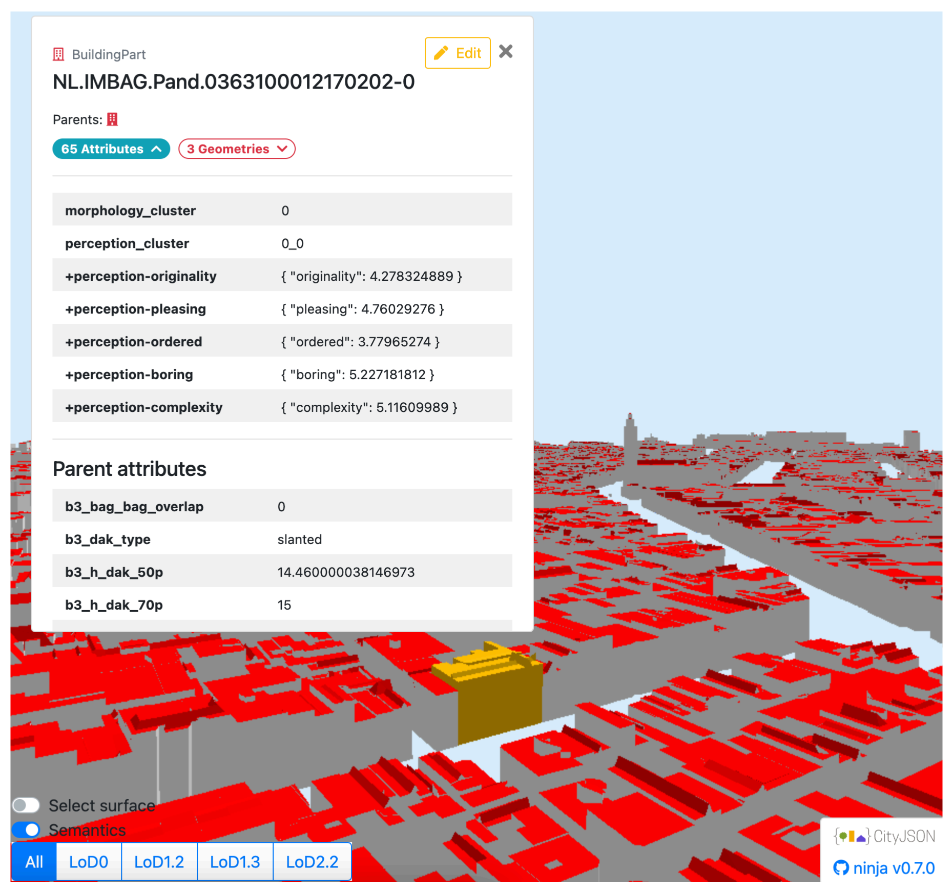
- Developing a CityJSON Extension to store data

Validation

- Validating the new data and its extension according to the standard and schema

Visualisation

- 3D visualising perception attributes associated with each building



CityJSON Extension: https://github.com/binyulei/3D_building_perception/blob/main/perception.ext.json

3D CITY INDEX

Assessing and benchmarking 3D city models

Authors: Binyu Lei, Rudi Stouffs, Filip Biljecki

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RESEARCH ARTICLE

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Assessing and benchmarking 3D city models

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[a]Department of Architecture, National University of Singapore, Singapore, Singapore; [b]Department of Real Estate, National University of Singapore, Singapore, Singapore

ABSTRACT

3D city models are omnipresent in urban management and simulations. However, instruments for their evaluation have been limited. Furthermore, current instances are scattered worldwide and developed independently, hampering their comparison and understanding practices. While there are developed assessment frameworks in open data, such efforts are generic and not applied to geospatial data. We establish a holistic and comprehensive four-category framework '3D City Index', encompassing 47 criteria to identify key properties of 3D city models, enabling their assessment and benchmarking, and suggesting usability. We evaluate 40 authoritative 3D city models and derive quantitative and qualitative insights. The framework implementation enables a comprehensive and structured understanding of the landscape of semantic 3D geospatial data, as well as doubles as an evaluated collection of open 3D city models. For example, datasets differ substantially in their characteristics, having heterogeneous properties influenced by their different purposes. There are further applications of this first endeavour to standardise the characterisation of 3D data: monitoring developments and trends in 3D city modelling, and enabling researchers and practitioners to find the most appropriate datasets for their needs. The work is designed to measure datasets continuously and can also be applied to other instances in spatial data infrastructures.

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KEYWORDS
3D GIS; open data; digital twins; open government; data quality

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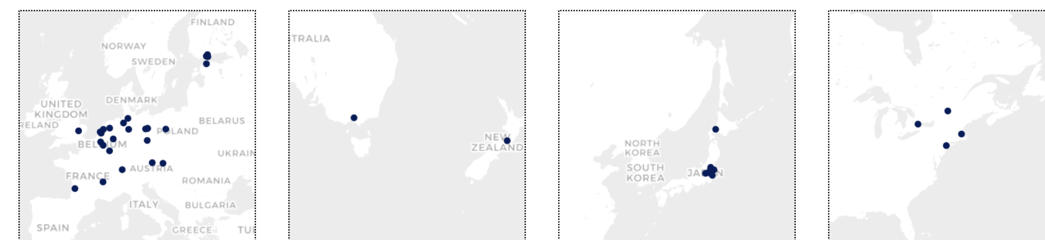
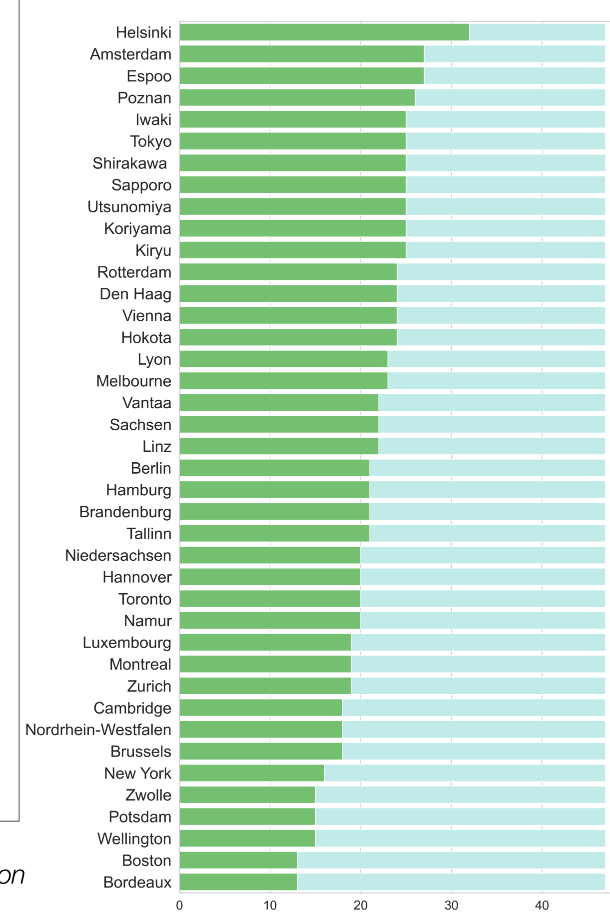
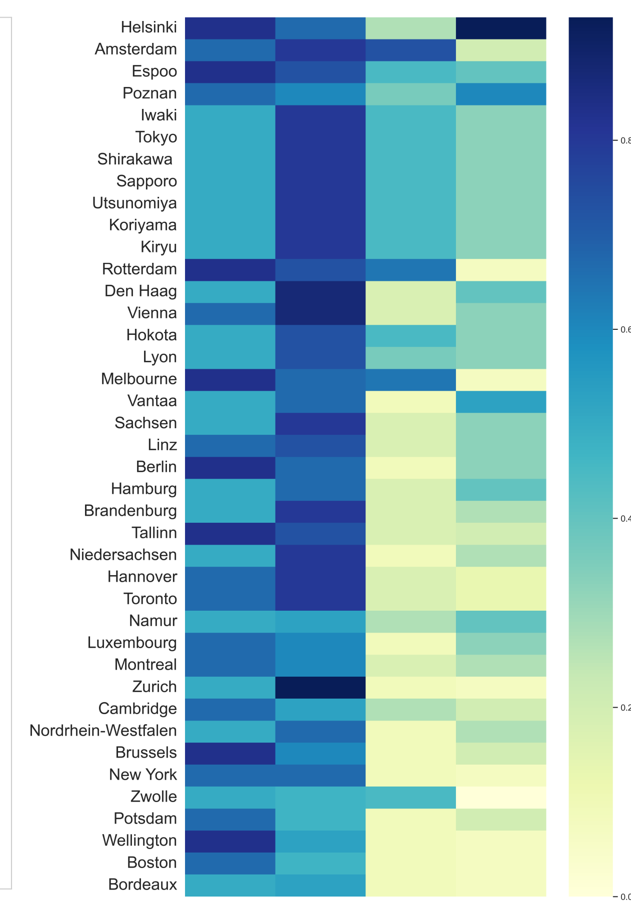
Category	Criteria
(1) Data Portal	1C1 — Does the dataset have a dedicated website?
	1C2 — Is there a web viewer in 3D?
	1C3 — Is there near real-time information in the viewer?
	1C4 — Is it available in local language?
	1C5 — Is it available in English?
	1C6 — Is there a way to leave feedback?
(2) Basic Information	2C1 — Is it a structured 3D city (information) model?
	2C2 — Is it a 3D mesh model?
	2C3 — Is it downloadable?
	2C4 — Is it free of charge?
	2C5 — Is it available to download without registration?
	2C6 — Is it available to download in more than one format?
	2C7 — Is it generated using open data standard?
	2C8 — Is it openly licensed?
	2C9 — Does it provide metadata?
	2C10 — Is it recently published (within latest 5 years)?
	2C11 — Has it been updated?
	2C12 — Does it have a plan to update?
	2C13 — Does it keep historical datasets?
	2C14 — Does it include more than one level of detail (LoD)?
	2C15 — Does it cover the entire jurisdiction?
(3) Thematic Content	3C1 — Are buildings modelled with semantically differentiated surfaces?
	3C2 — Does it contain bridges?
	3C3 — Does it contain land use?
	3C4 — Does it contain terrain?
	3C5 — Does it contain roads?
	3C6 — Does it contain tunnels?
	3C7 — Does it contain tracks?
	3C8 — Does it contain city furniture?
	3C9 — Does it contain vegetation?
	3C10 — Does it contain individual trees?
	3C11 — Does it contain water bodies?
(4) Attribute Content	4C1 — Does it contain the postal code?
	4C2 — Are buildings with texture?
	4C3 — Does it contain the ID of buildings?
	4C4 — Does it contain the year of construction?
	4C5 — Does it contain the address of buildings?
	4C6 — Does it contain the function of buildings?
	4C7 — Does it contain the height of buildings?
	4C8 — Does it contain the volume of buildings?
	4C9 — Does it contain the number of storeys?
	4C10 — Does it contain the area of walls?
	4C11 — Does it contain the area of roofs?
	4C12 — Does it contain the type of roofs?
	4C13 — Does it contain the area of grounds?
	4C14 — Does it contain gross floor areas?
	4C15 — Does it contain materials of buildings?

An analysis of the worldwide state of open 3D city models — evaluating a set of 40 authoritative datasets







BUILDING CHARACTERISTICS PREDICTION

A method using graph neural networks and urban street-level context

Authors: Binyu Lei, Pengyuan Liu, Nikola Milojevic-Dupont, Filip Biljecki

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Predicting building characteristics at urban scale using graph neural networks and street-level context

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[b] Future Cities Lab Global, Singapore-ETH Centre, Singapore
[c] Mercator Research Institute on Global Commons and Climate Change, Germany
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Building semantics
Urban digital twins
Data availability
Deep learning
Urban morphology

ABSTRACT

Building characteristics, such as number of storeys and type, play a key role across many domains: interpreting urban form, simulating urban microclimate or modelling building energy. However, geospatial data on the building stock is often fragmented and incomplete. Here, we propose a novel and easily adaptable method to predict building characteristics in diverse cities, which attempts to mitigate such data gaps. Our method exploits the geospatial connectivity between street-level urban objects and building characteristics by employing graph neural networks, as they can model spatial relationships and leverage them for predictions. We apply this approach in three representative cities (Boston, Melbourne, and Helsinki) that offer a variety of building features as prediction targets (storeys, types, construction period and materials) and diverse urban environments as predictors. Overall, the magnitude of errors is acceptable for a series of use cases. In the prediction of building storeys, an average of 81.83% buildings in three cities have less than one-storey prediction error. We also find that the prediction of building type achieves an average of 88.33% accuracy across three cities. Meanwhile, an average of 70.5% of buildings are correctly classified by construction period in Melbourne and Helsinki, and the building material prediction accuracy is 68% in Helsinki. The results confirm that our approach is adaptable across different urban environments because comparable performance is achieved in the other two cities. Further, we assess the impact of varying local data availability on model performance. Our findings underscore the feasibility of the method in scenarios with sparse building data (10%, 30% and 50% availability). Our graph-based approach advances research on filling in incomplete building semantics from existing datasets, and showcases the potential to enable 3D city modelling. Given the broad applicability of the approach to predicting many building characteristics, diverse downstream applications exist, such as enhancing contemporary urban studies (e.g. exploring streetscapes) and facilitating the development of 3D GIS (e.g. maintaining and updating 3D building settings).

1. Introduction

Acquiring key characteristics of buildings is fundamental for supporting city planning, contributing to various urban research (Hudson et al., 2019; Kitchin, 2014; Nouvel et al., 2017). However, the availability of building characteristics widely varies across initiatives and regions (as illustrated in Fig. 1). Biljecki et al. (2021) investigated 140 open government geospatial datasets from 28 countries and found that only half of them contained more than one building feature. Detailed characteristics, such as building height, number of storeys, type, age, and status, while crucial for many analyses, are often not available.

Beyond 2D urban studies, a similar situation is observed in 3D GIS where only a few datasets offer semantic building information, while they mostly inform only the building geometry (Lei et al., 2023). In urban digital twins, where 3D city models play a role in representing the physical environment, data issues (e.g. scattered building data and varied accessibility) hinder their implementations (Chen et al., 2019; Gil, 2020; Hong et al., 2020; Kolbe & Donaubauer, 2021; Park & Guldmann, 2019; Schrotter & Hürzeler, 2020). Nevertheless, a comprehensive-enough set of building characteristics is fundamental for supporting use cases of 3D city models and urban digital twins, such as simulating energy consumption and analysing urban heat island effect

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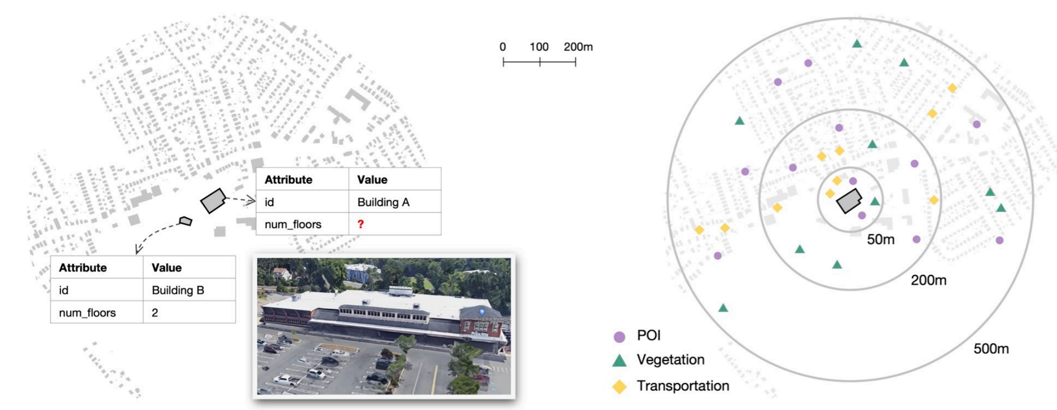
A three-step workflow for developing the graph-based method for predicting building characteristics, taking the prediction of building storeys as an example

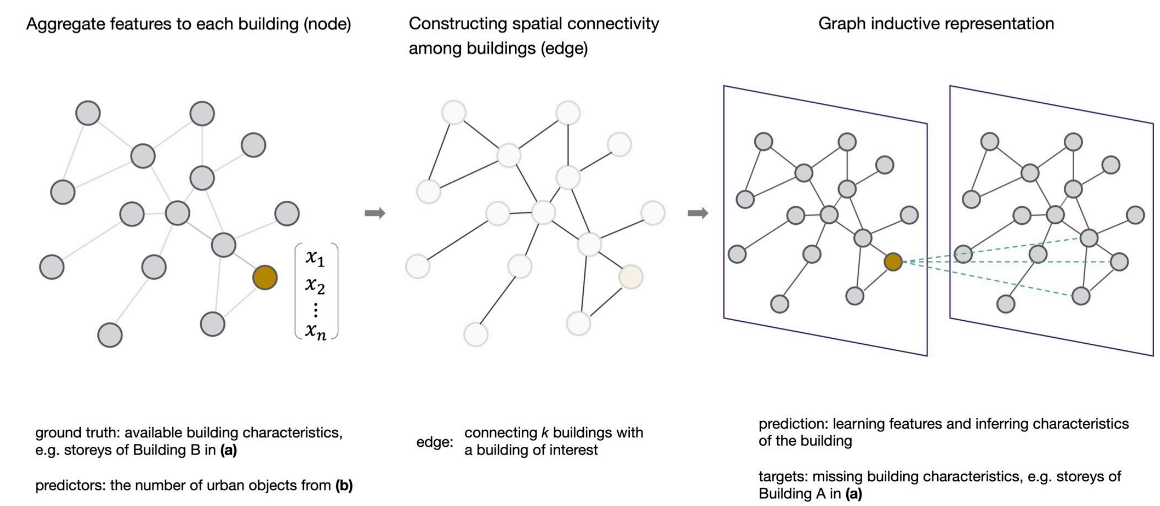
Step 1: Input dataset selection

(a) Geospatial building information
- e.g. Open government data, commercial data

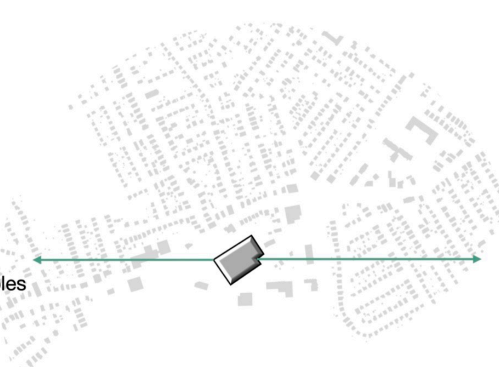
(b) Street-level urban features
- e.g. OpenStreetMap data



Step 2: Spatial connectivity construction (GraphSAGE)



Step 3: Building characteristics prediction



Regression task:

Predicting numeric target variables (e.g. storey and height)

Classification task:

Inferring discrete class labels (e.g. type and construction period)

Open-sourced code: https://github.com/binyulei/gnn-building-characteristics-prediction

CHALLENGES OF URBAN DIGITAL TWINS

A systematic review and a Delphi expert survey

Authors: Binyu Lei, Patrick Janssen, Jantien Stoter, Filip Biljecki

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Review

Challenges of urban digital twins: A systematic review and a Delphi expert survey

Binyu Lei [a], Patrick Janssen [a], Jantien Stoter [b], Filip Biljecki [a,c,*]

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3D city model
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Virtual replica
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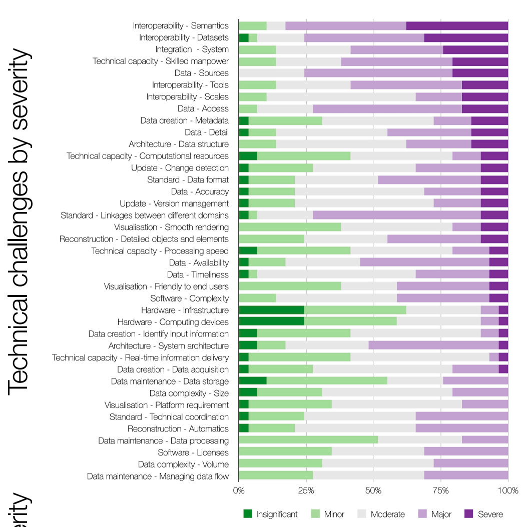
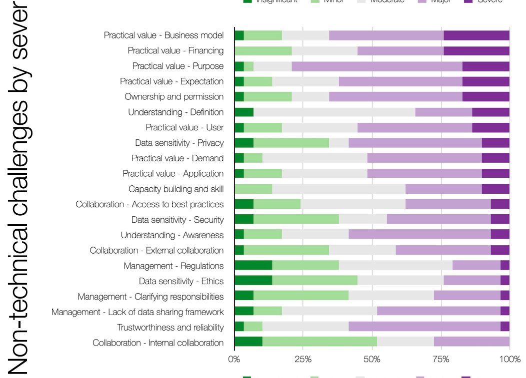
ABSTRACT

Many challenges to operate digital twins remain, hindering their design and implementation, and are rarely discussed. Furthermore, issues of social and legal nature are often overlooked. We identify the challenges of operating digital twins in the urban context through a bifurcated and multi-dimensional approach: a systematic literature review and an expert survey. The review organises the identified challenges across technical and non-technical dimensions. As the topic is novel, the corpus is rather small and lacking the contextualisation of challenges. Thus, we complement it with a survey based on the Delphi method, involving a diverse panel of domain experts covering academia, industry and government organisations. Combining the results, we identify 14 technical and 9 non-technical challenges and map them to phases of the digital twin's life cycle. The most severe challenges appear to be related to interoperability (e.g. disparate semantic standards) and practical value (e.g. lack of business models).





Technical challenges

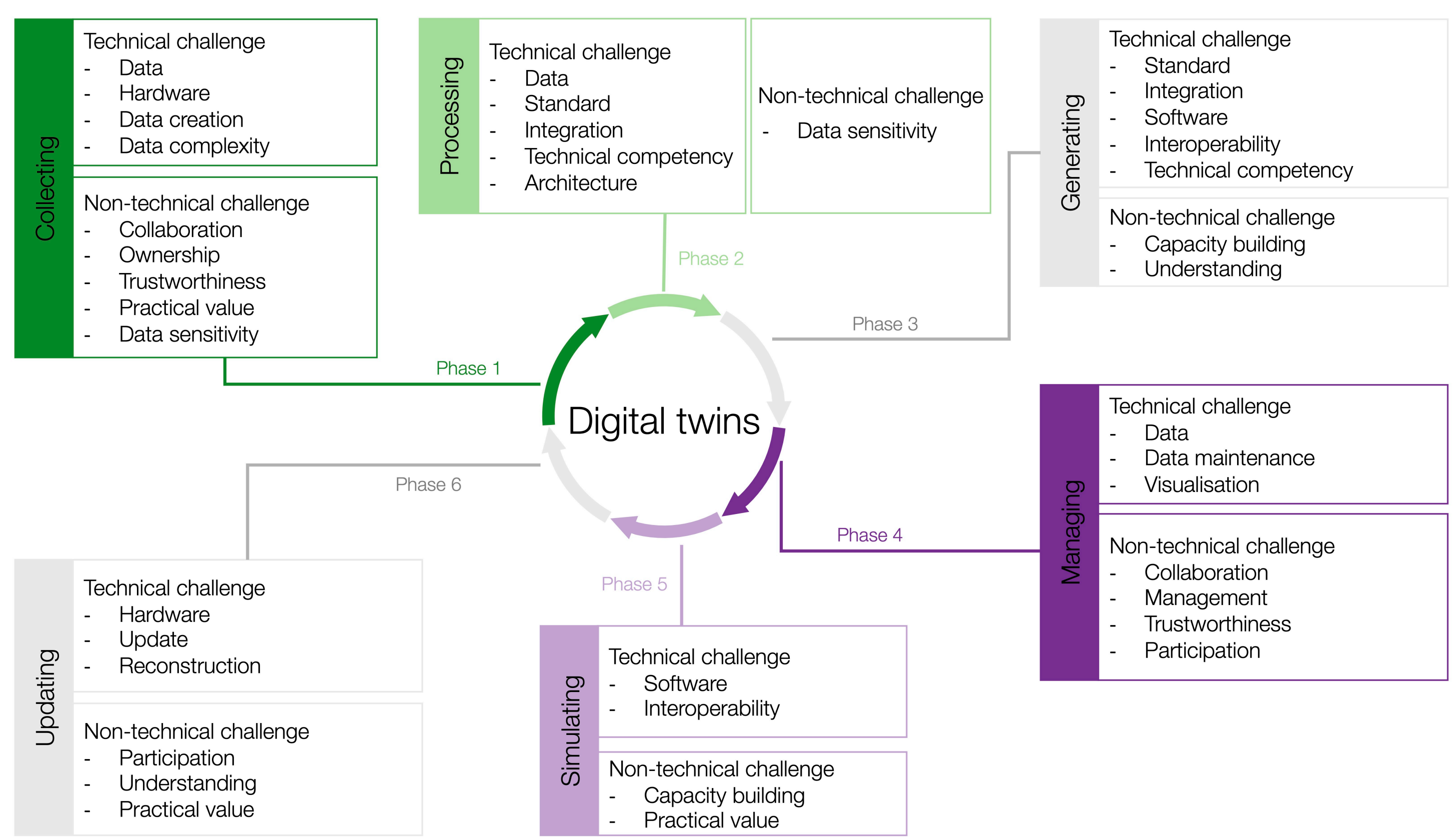
- Data
- Integration
- Interoperability
- Software
- Technical competency
- Standard
- Update
- Data creation
- Data complexity
- Architecture
- Data maintenance
- Hardware
- Reconstruction
- Visualisation

Non-technical challenges

- Understanding
- Practical value
- Collaboration
- Capacity building
- Management
- Data sensitivity
- Ownership
- Trustworthiness
- Participation

Invited feature article for GIM International magazine

Mapping technical and non-technical challenges with the life cycle of urban digital twins



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