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Research Insights and Perspectives of Urban Digital Twins

Filip Biljecki
Assistant Professor
National University of Singapore
Urban Analytics Lab

This mosaic was formed using 5,720 street view images contributed by Mapillary and KartaView users.

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Urban informatics with a strong geospatial foundation

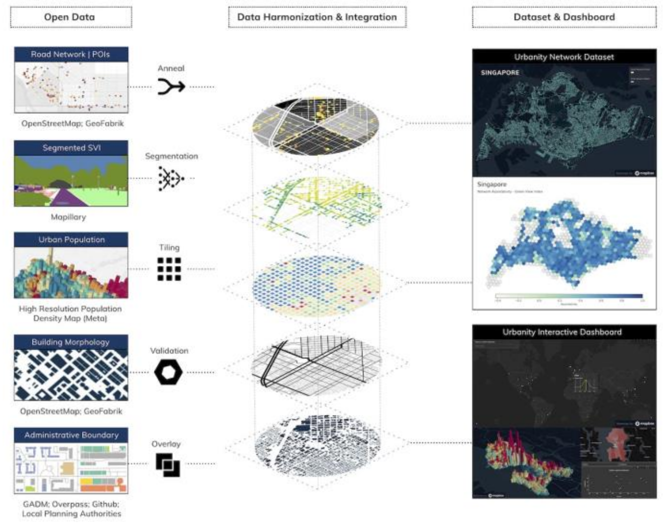
Research strands

Buildings / 3D GIS / DT

Street view imagery

VGI, spatial data quality

Some of our open-source software / open data



Urbanity

Global Building Morphology Indicators; Roofpedia; Urbanity

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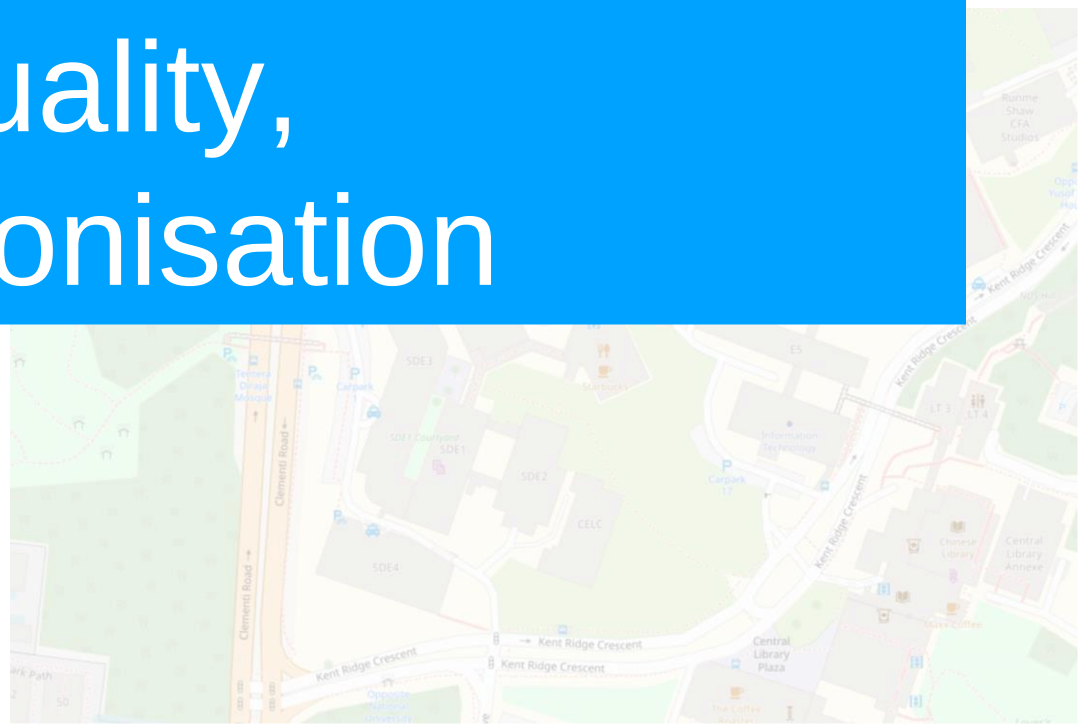
Urban informatics with a strong geospatial foundation

Research strands

Data acquisition,
Data quality,
Data harmonisation

Buildings / 3D GIS / DT

Street view imagery



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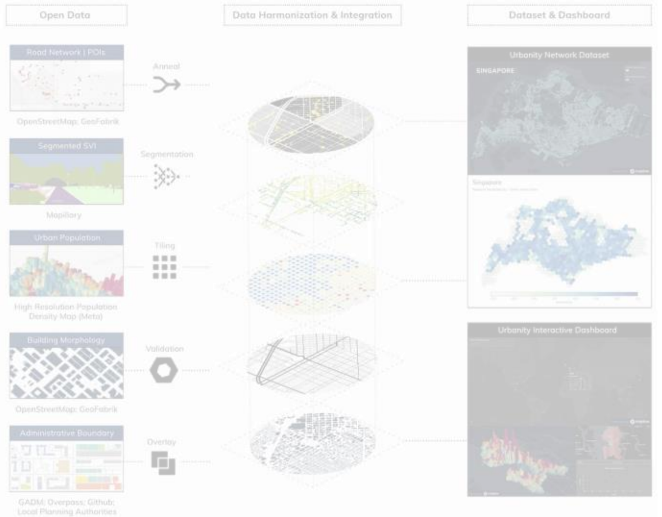
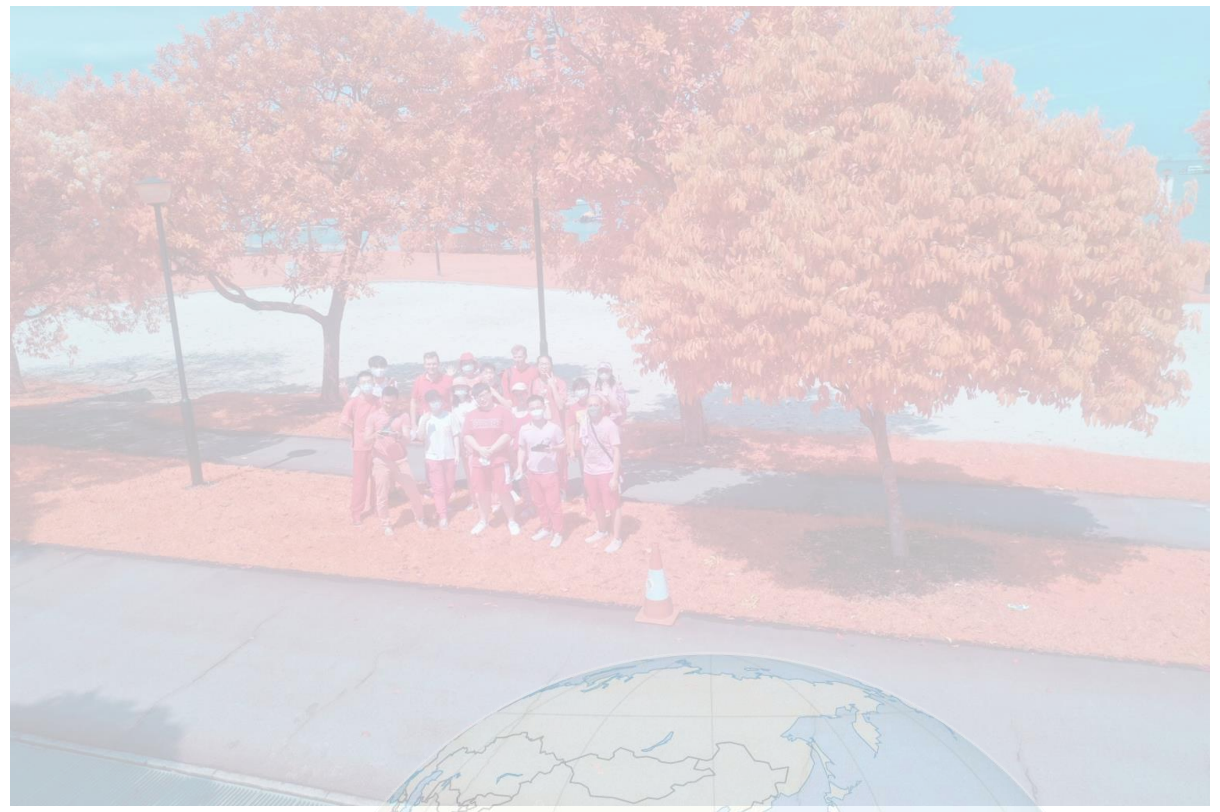


Urbanity

Global Building Morphology Indicators; Roofpedia; Urbanity



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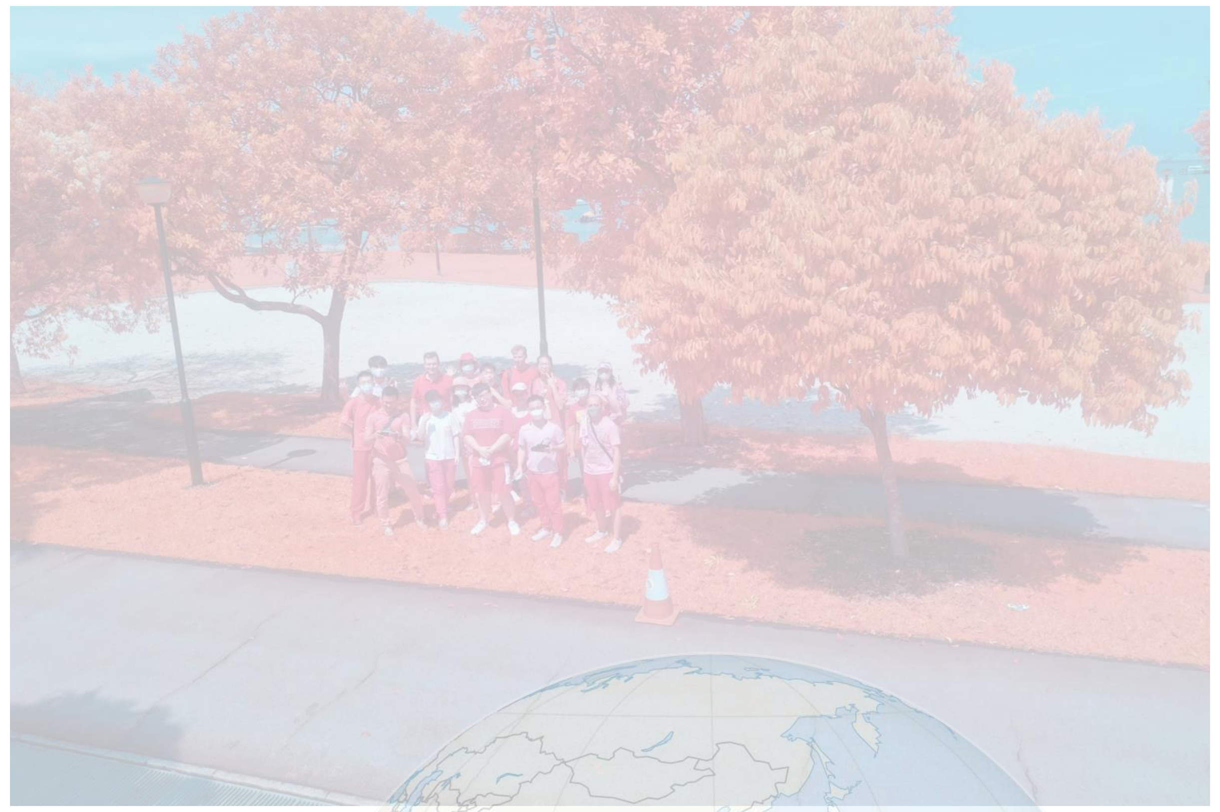

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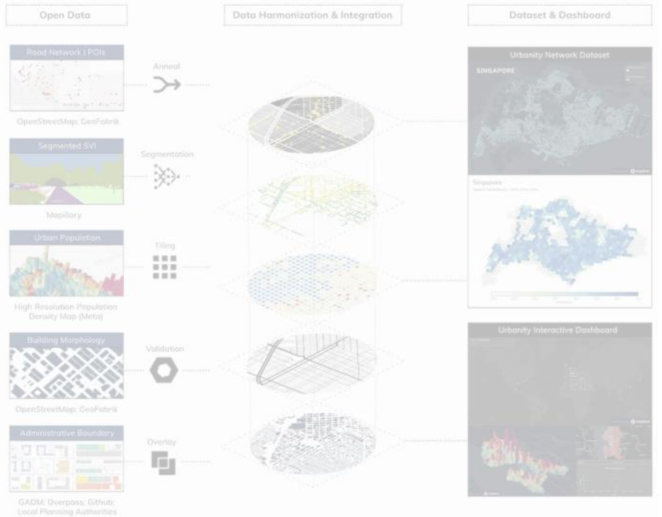
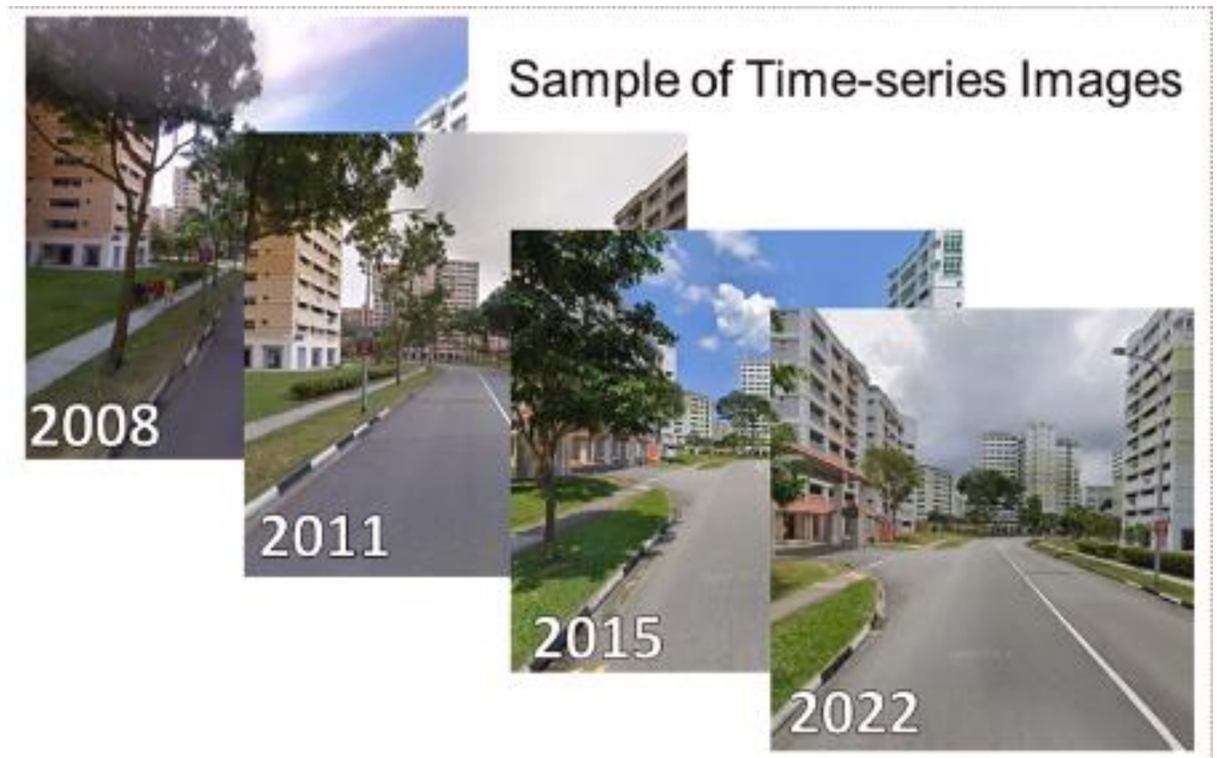


Global Building Morphology Indicators; Roofpedia; Urbanity

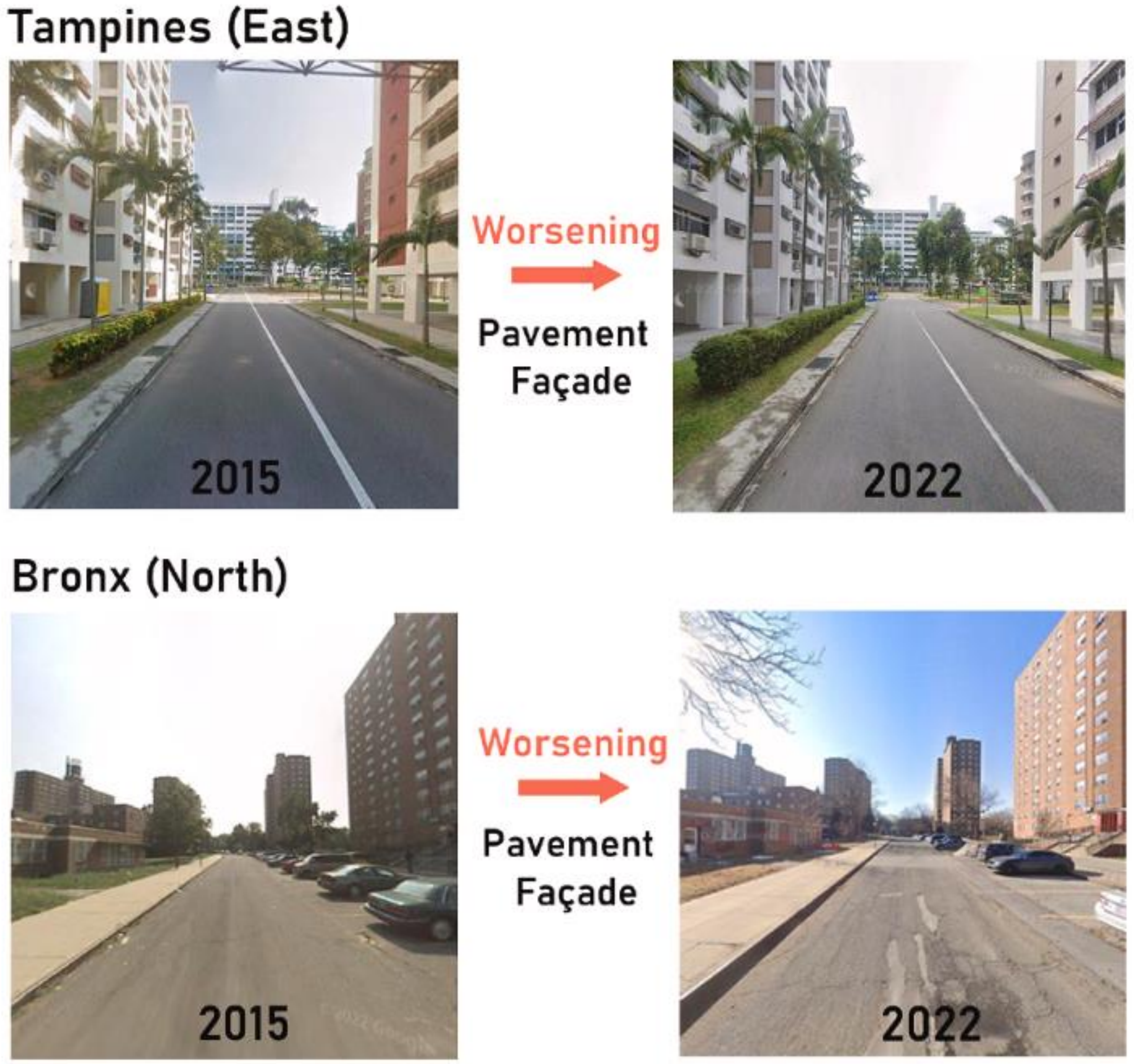
Change detection with SVI

Research by Xiucheng Liang & Zeyu Wang



Physical measures

Perceptual measures



Imagery source: Google Street View

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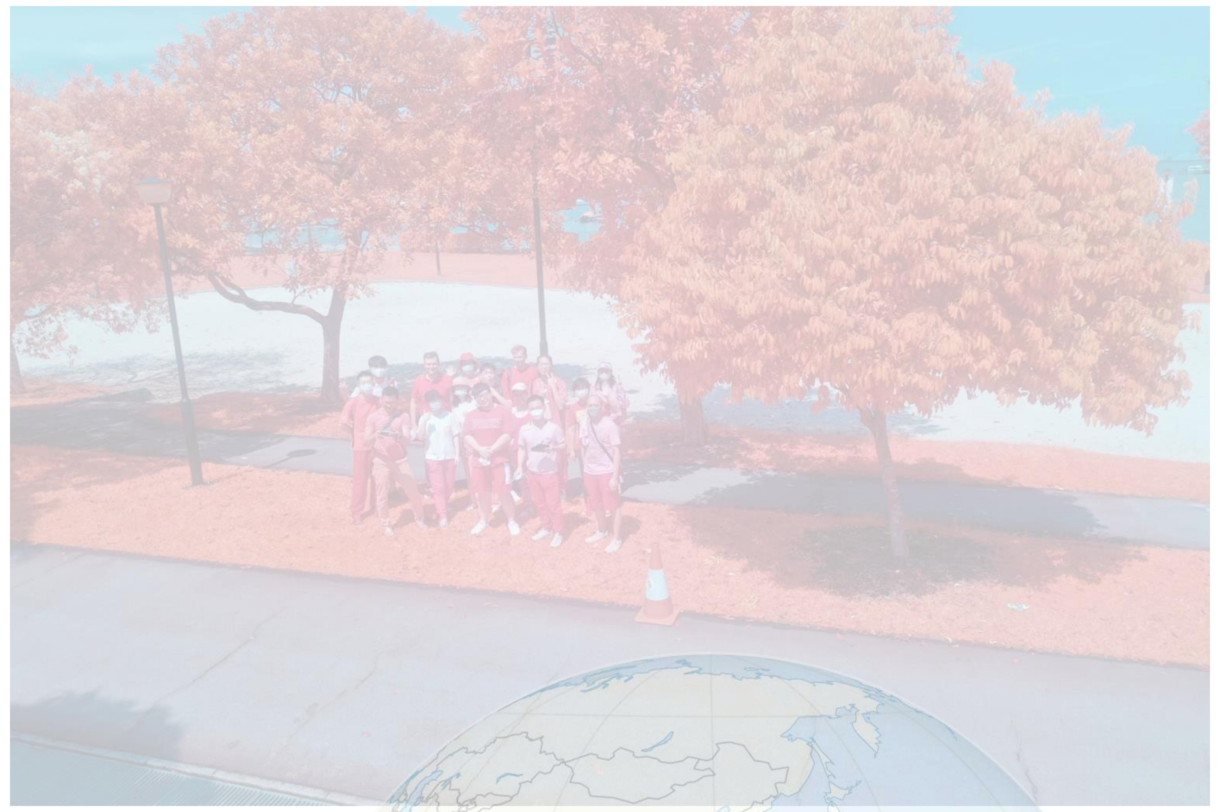

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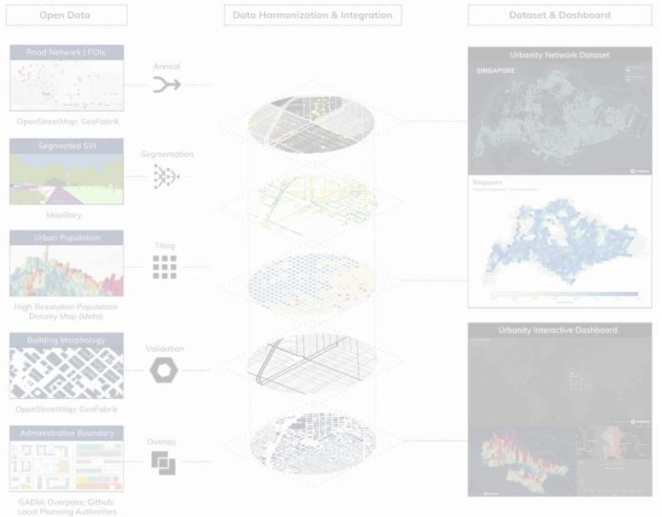

Global Building Morphology Indicators; Roofpedia; Urbanity

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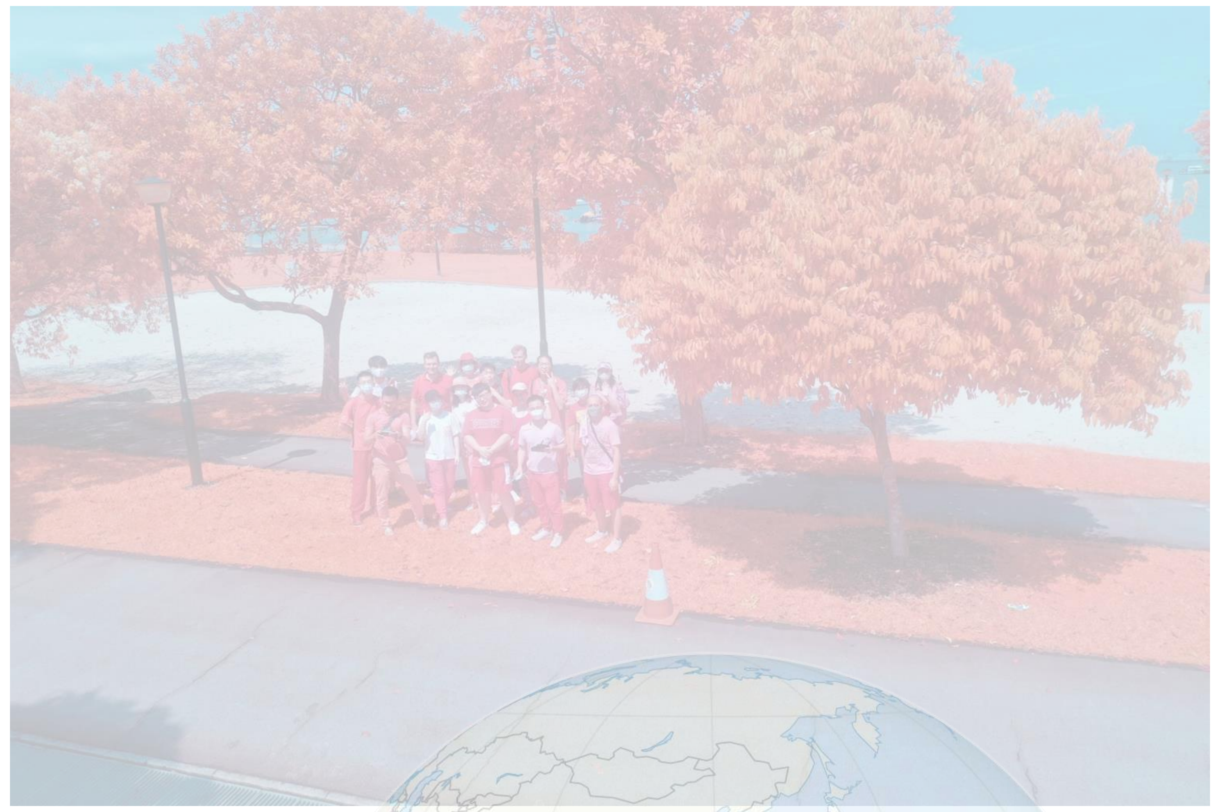

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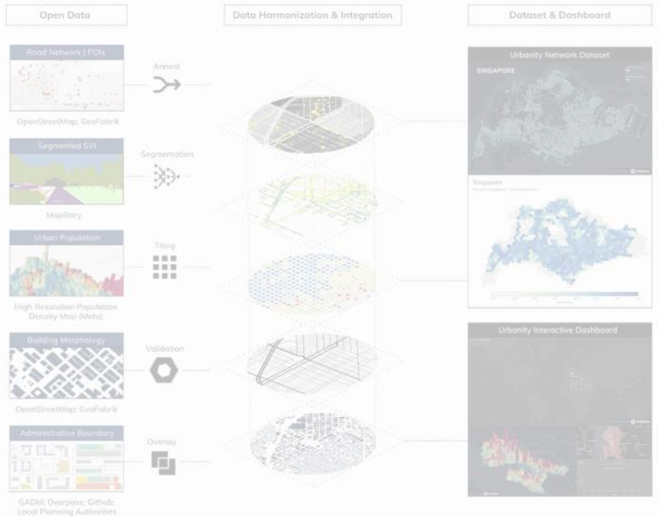

Global Building Morphology Indicators; Roofpedia; Urbanity

Roofpedia

Global open registry of roofs for urban sustainability

Roofpedia

Global open registry of roofs for urban sustainability

Published in Landscape and Urban Planning. Credit: Abraham Noah Wu by Abraham Noah Wu

ROOFPEDIA

Automated Roof Mapping + Geospatial Roof Registry + Sustainable Roof Index

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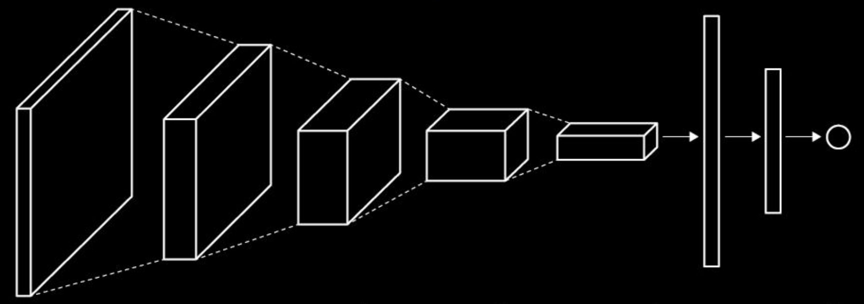
Automated Classification

Satellite Images



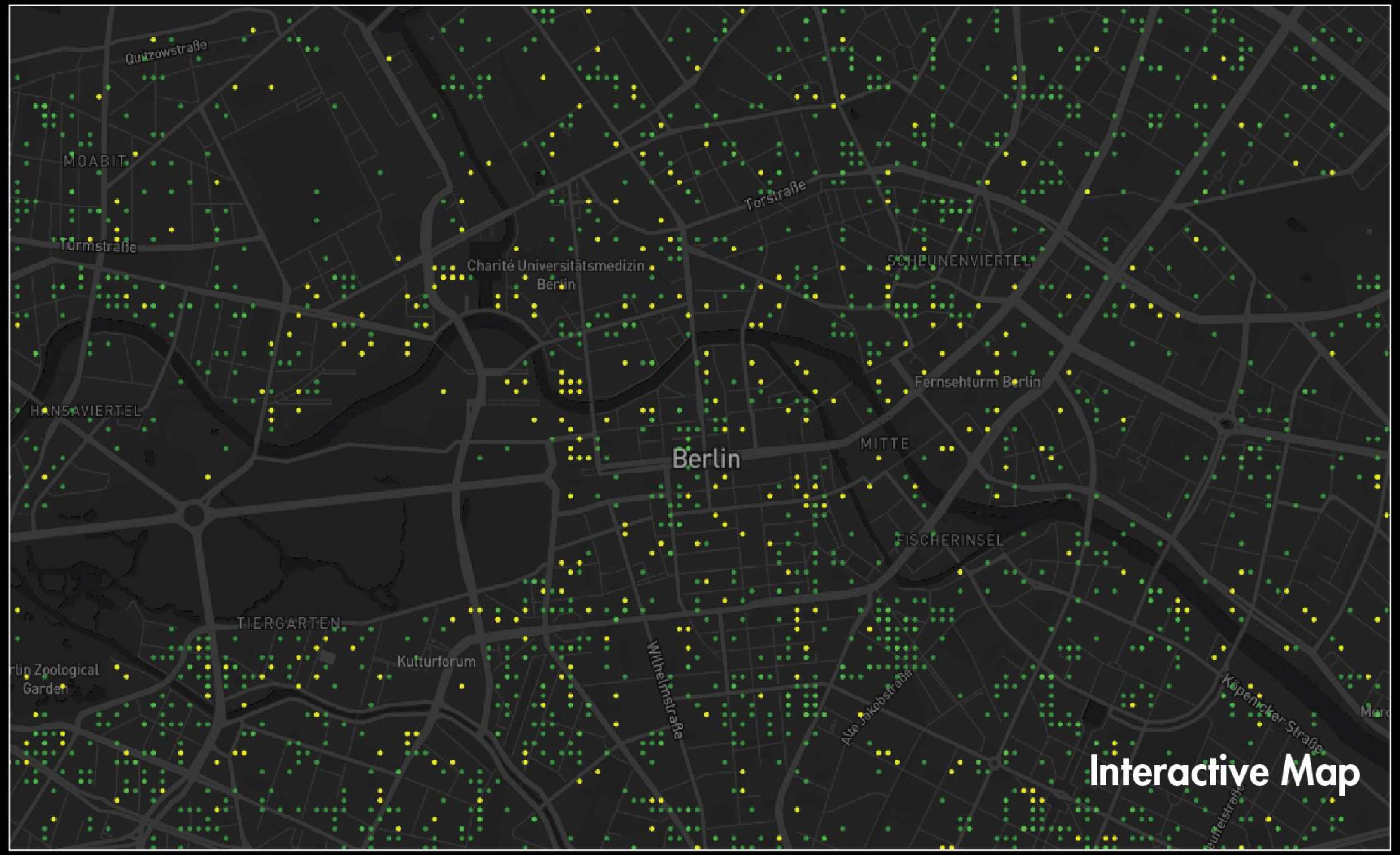
Convolutional Neural Network

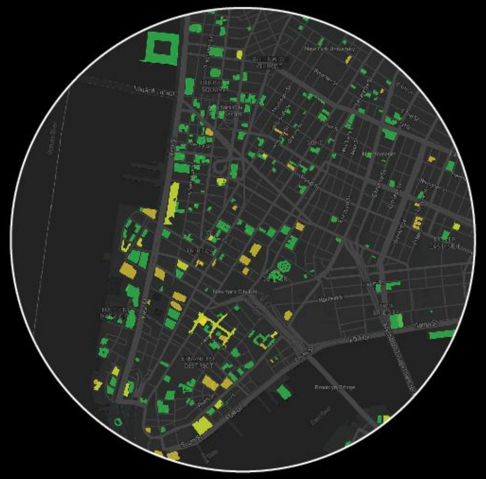
Rooftop Solar Panels | Rooftop Vegetation

GIS Processing

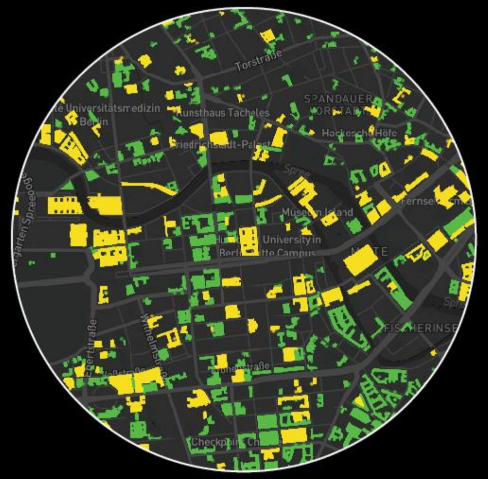
Solar Roofs | Green Roofs

Roofpedia Registry

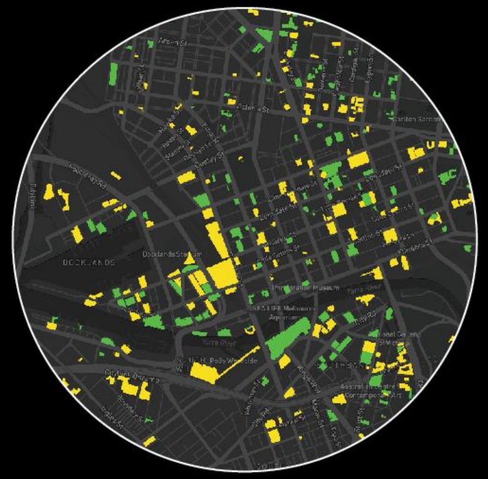




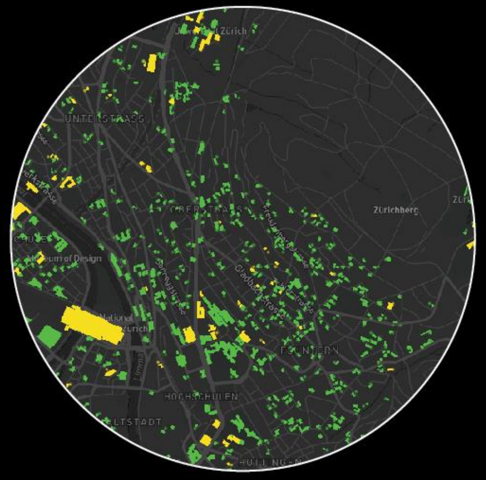
New York



Berlin

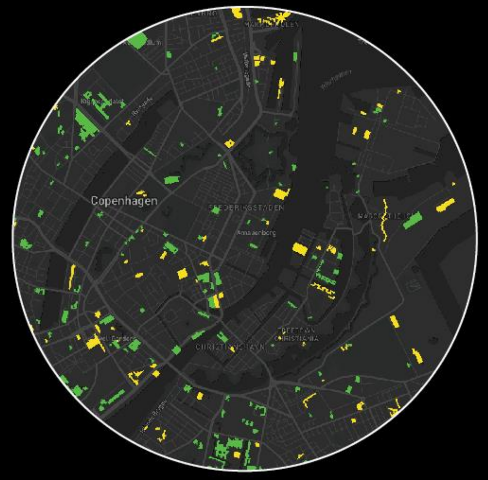


Melbourne



Zurich

Las Vegas



Copenhagen

Roofpedia Indices

Solar Roof Index

Las Vegas	86
Zurich	81
Singapore	75
Phoenix	75
Melbourne	74
Berlin	57
Copenhagen	45
New York	42
Paris	42
San Diego	24
Los Angeles	20
Seattle	13
San Jose	12
Portland	10
San Francisco	9
Luxembourg City	7
Vancouver	0

Green Roof Index

Zurich	100
Berlin	51
New York	28
Copenhagen	22
Paris	18
San Diego	14
San Jose	13
Phoenix	13
Melbourne	11
Las Vegas	9
Seattle	6
Los Angeles	6
Luxembourg City	4
Portland	3
San Francisco	2
Vancouver	0

Data sources: Mapbox and OpenStreetMap contributors

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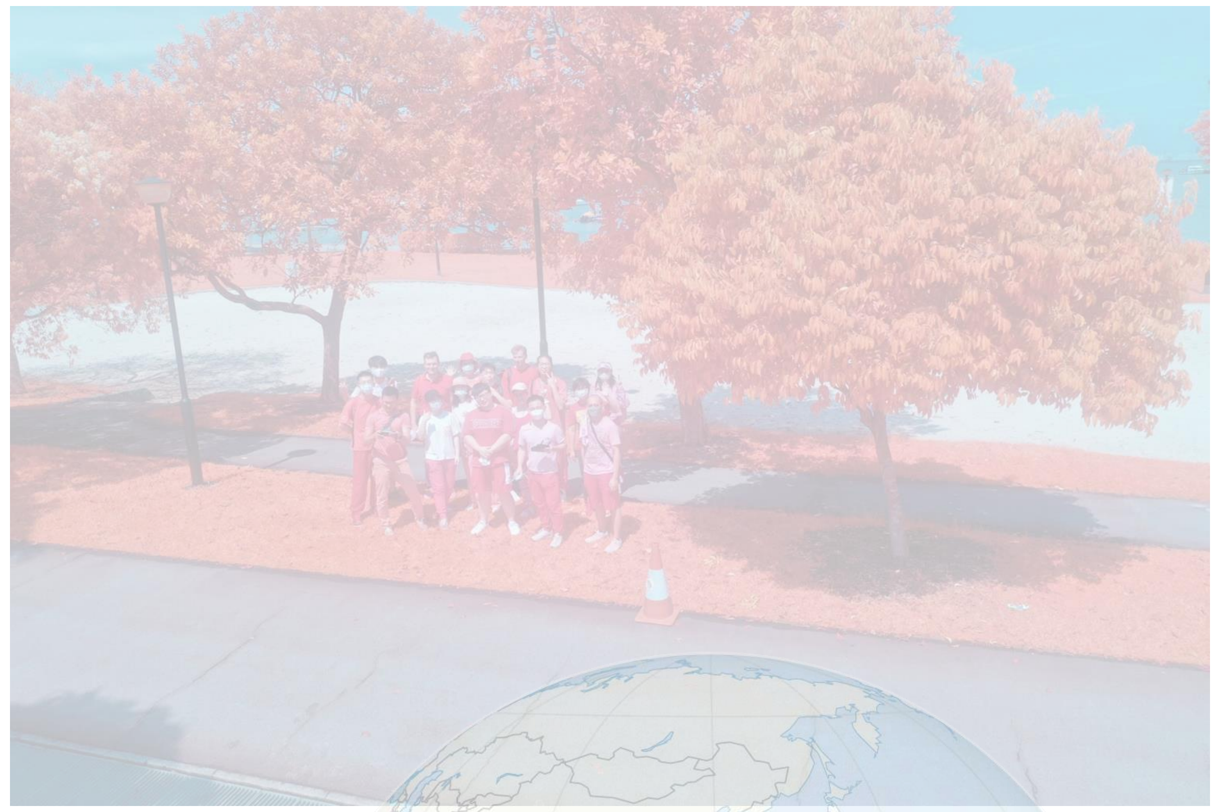

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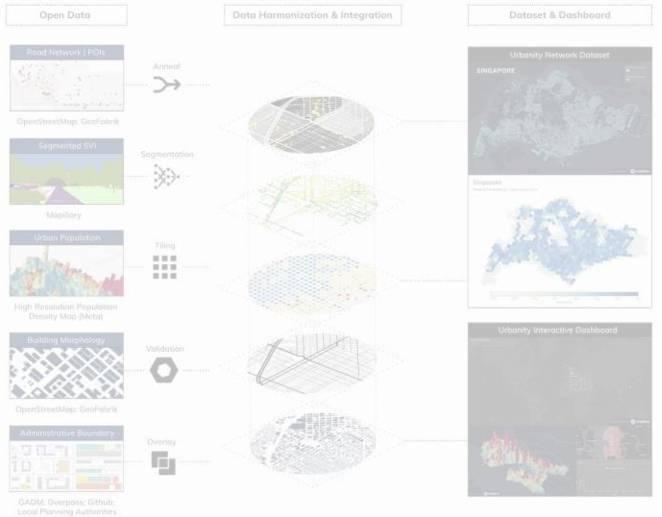
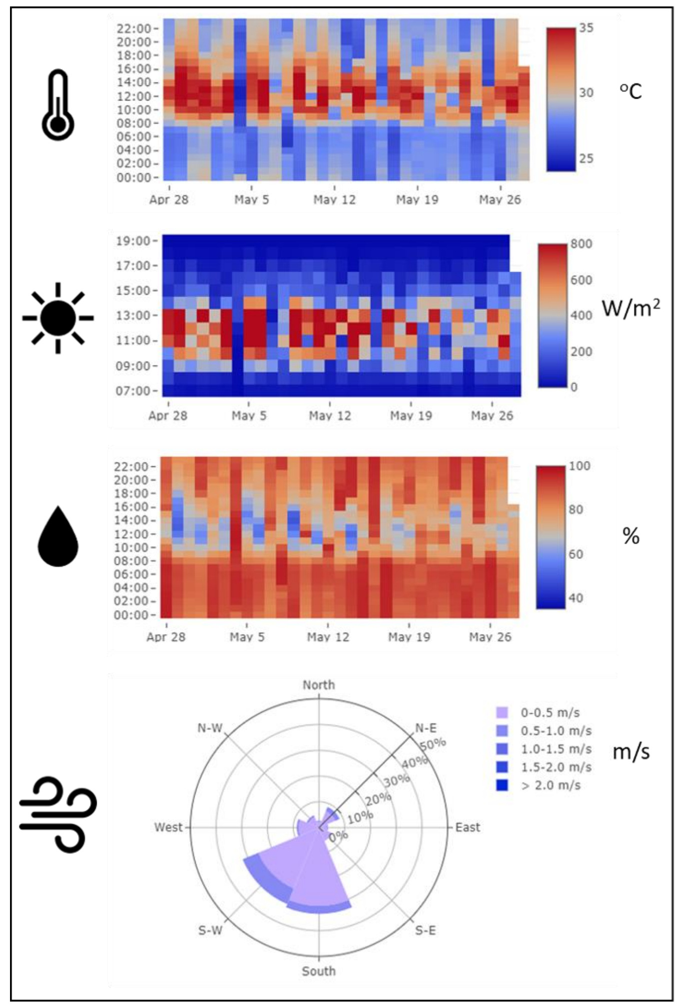
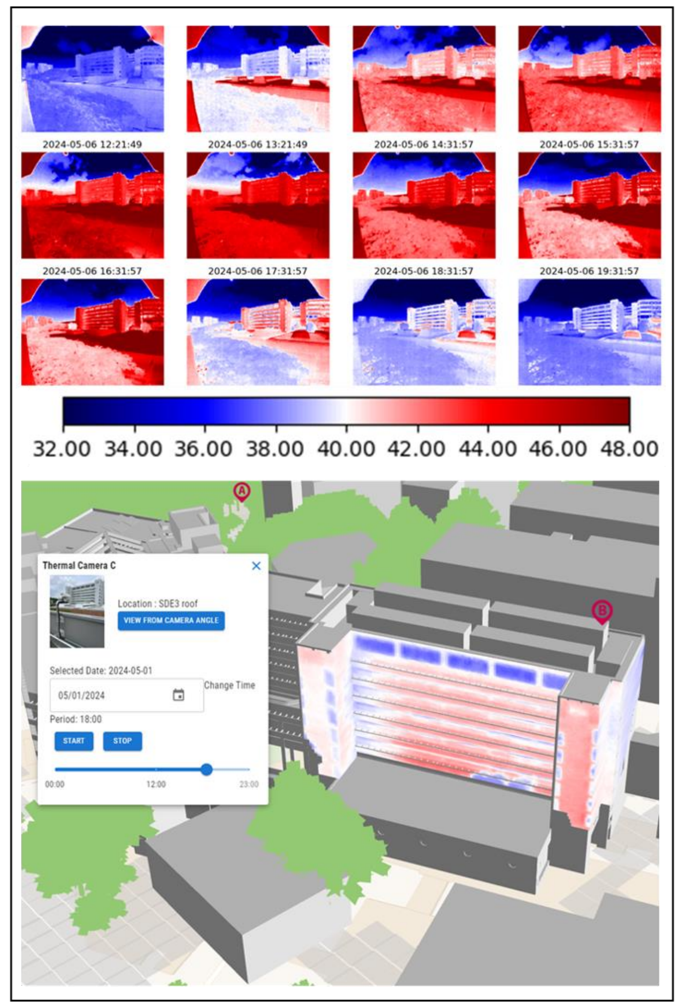


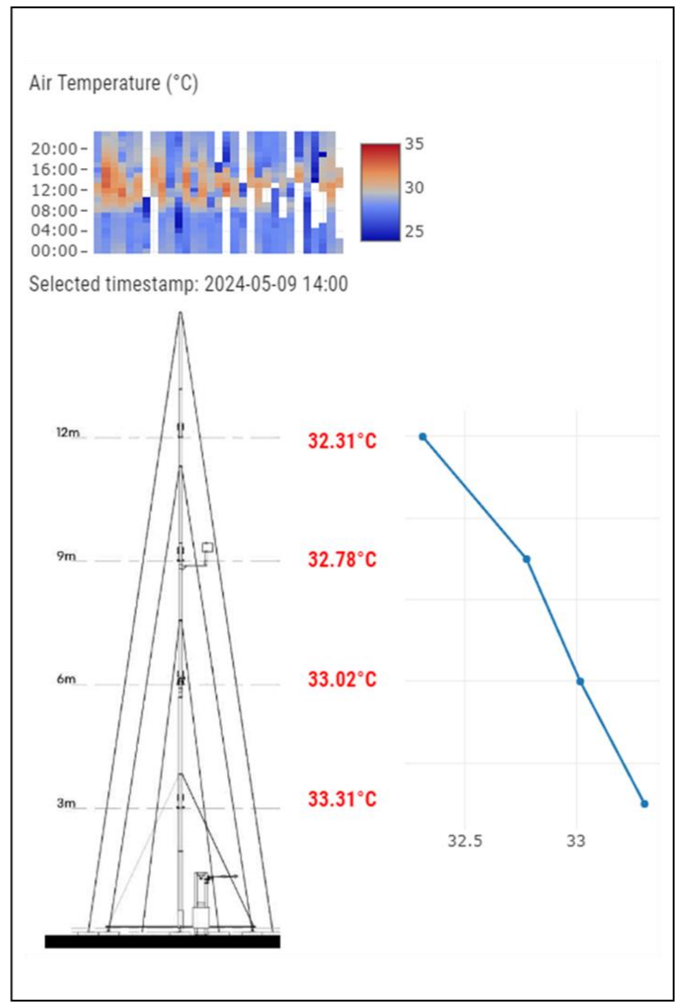
Global Building Morphology Indicators; Roofpedia; Urbanity

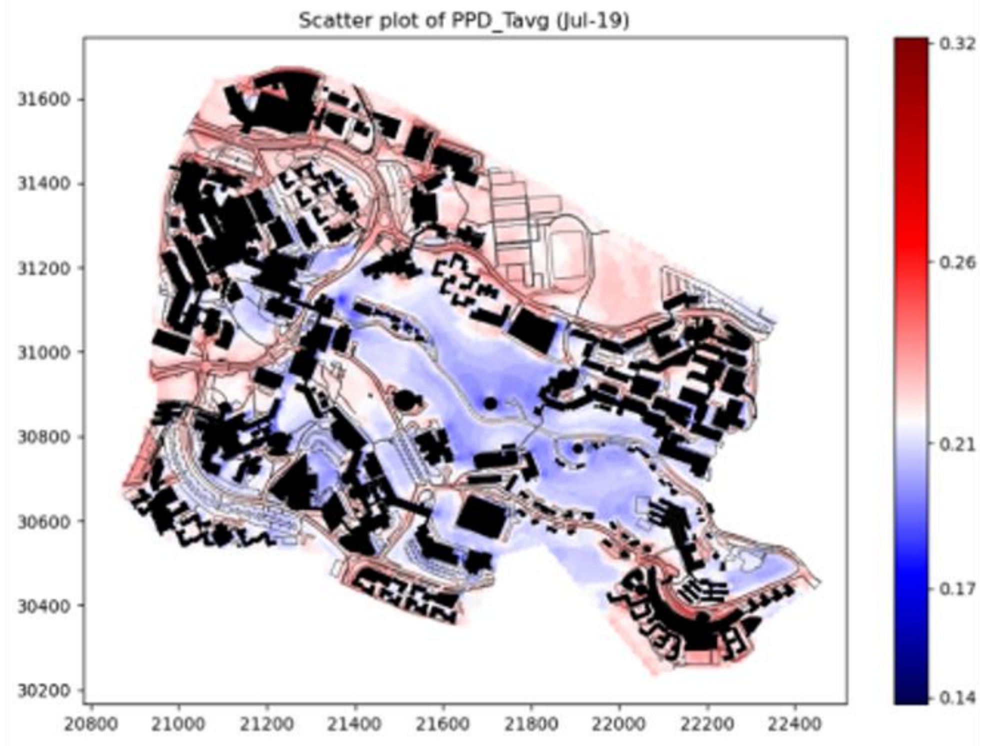
BEAM

FY22	B	E	A	M	FY25
	Establishing the Baseline	Identifying hot and cool spots	Simulation, planning & application of mitigation measures	Monitoring and benchmarking of applied mitigation measures	
	BASELINING	**EVALUATING**	**ACTION**	**MONITORING**	

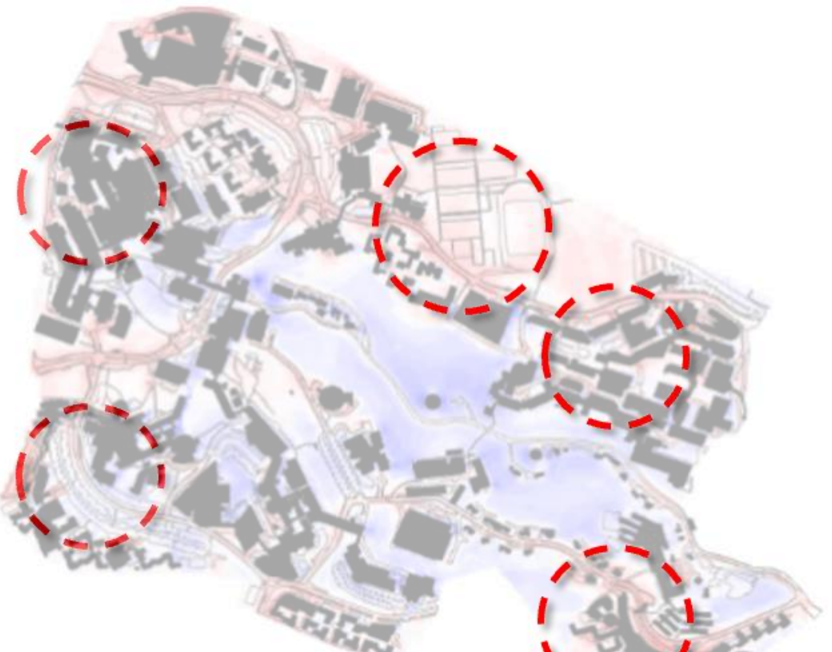








NUS Climatic Maps



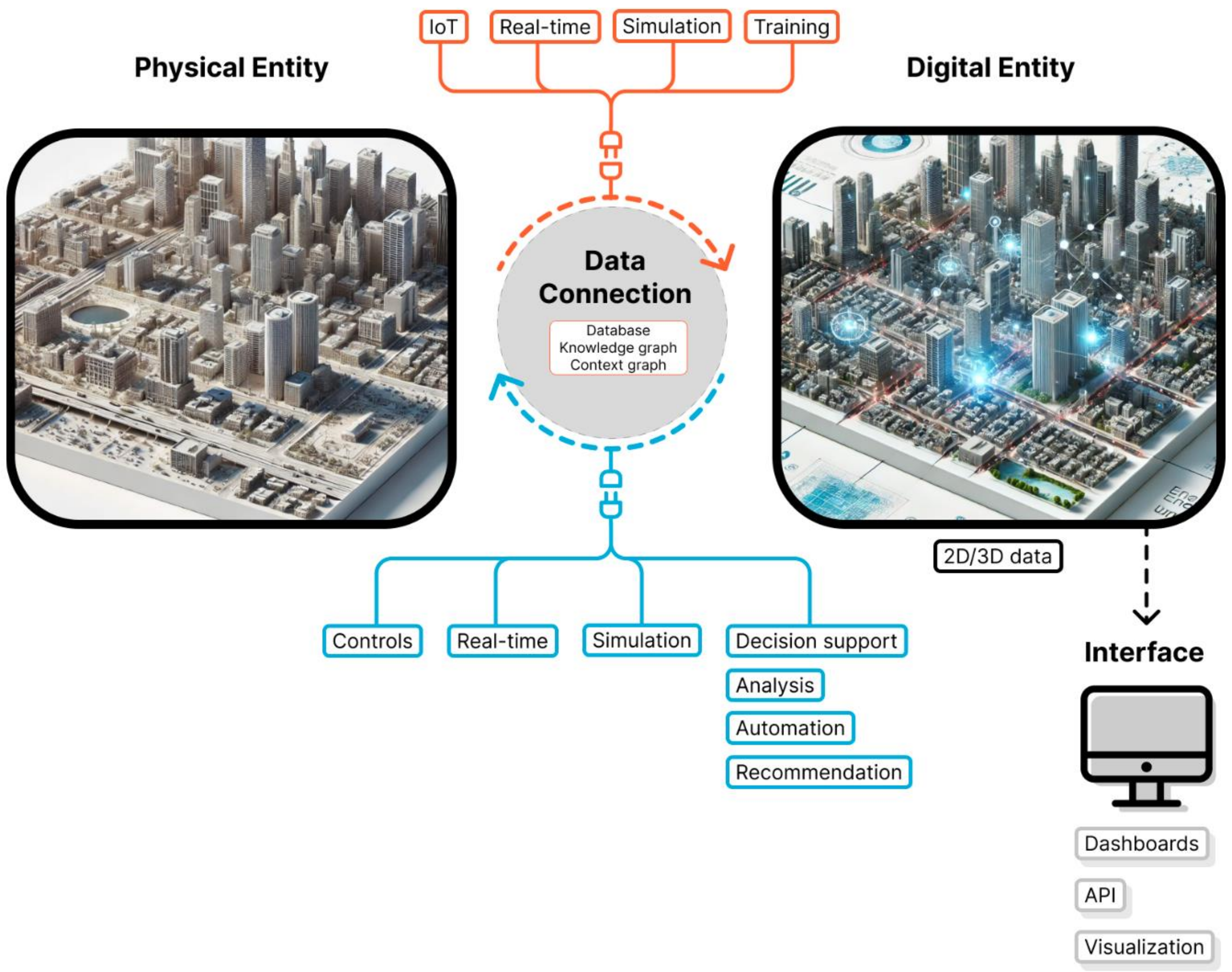
Hot Spots Identification

https://sustainability.nus.edu.sg/campus-sustainability/coolnus/

What is a Digital Twin Anyway? Deriving the Definition for the Built Environment from over 15,000 Scientific Publications

Mahmoud Abdelrahman[a], Edgardo Macatulad[a,b], Binyu Lei[a], Matias Quintana[c], Clayton Miller[d], Filip Biljecki[a,e,*]

[a] *Department of Architecture, National University of Singapore, 4 Architecture Drive, Singapore, 117566, Singapore*
[b] *Department of Geodetic Engineering, University of the Philippines, Diliman, Quezon City, 1101, Philippines*
[c] *Singapore-ETH Centre, Future Cities Lab Global Programme, CREATE campus, #06-01 CREATE Tower, Singapore, 138602, Singapore*
[d] *Department of the Built Environment, National University of Singapore, 4 Architecture Drive, Singapore, 117566, Singapore*
[e] *Department of Real Estate, National University of Singapore, 15 Kent Ridge Dr, Singapore, 119245, Singapore*



Definition *A **City/Urban Digital Twin** is a spatial-temporal virtual representation of a real-world urban area or city, mirroring its states during its lifecycle through IoT sensors. It is used to monitor and analyze urban systems across different time spans to aid in decision-making and can be extended to simulate and predict various states and scenarios.*

Gaps & opportunities in digital twins

- Potential for integrating new data streams — wearables, **crowdsourced** data, dynamic data, street view imagery
- Human-centric DTs
- More use cases
- Lack of data to build and maintain them

https://www.linkedin.com/feed/update/urn:li:activity:7089518664827199488/ & https://www.keanw.com/2021/11/want-to-see-dasher-inside-tandem-tell-us-what-you-need.htm

Some recent efforts

1. Inferring information from real estate ads (crowdsourcing building data)

2. Integration of dynamic data / wearables / comfort information

3. Integration of perception (another human-centric focus)

4. Development of localised use cases

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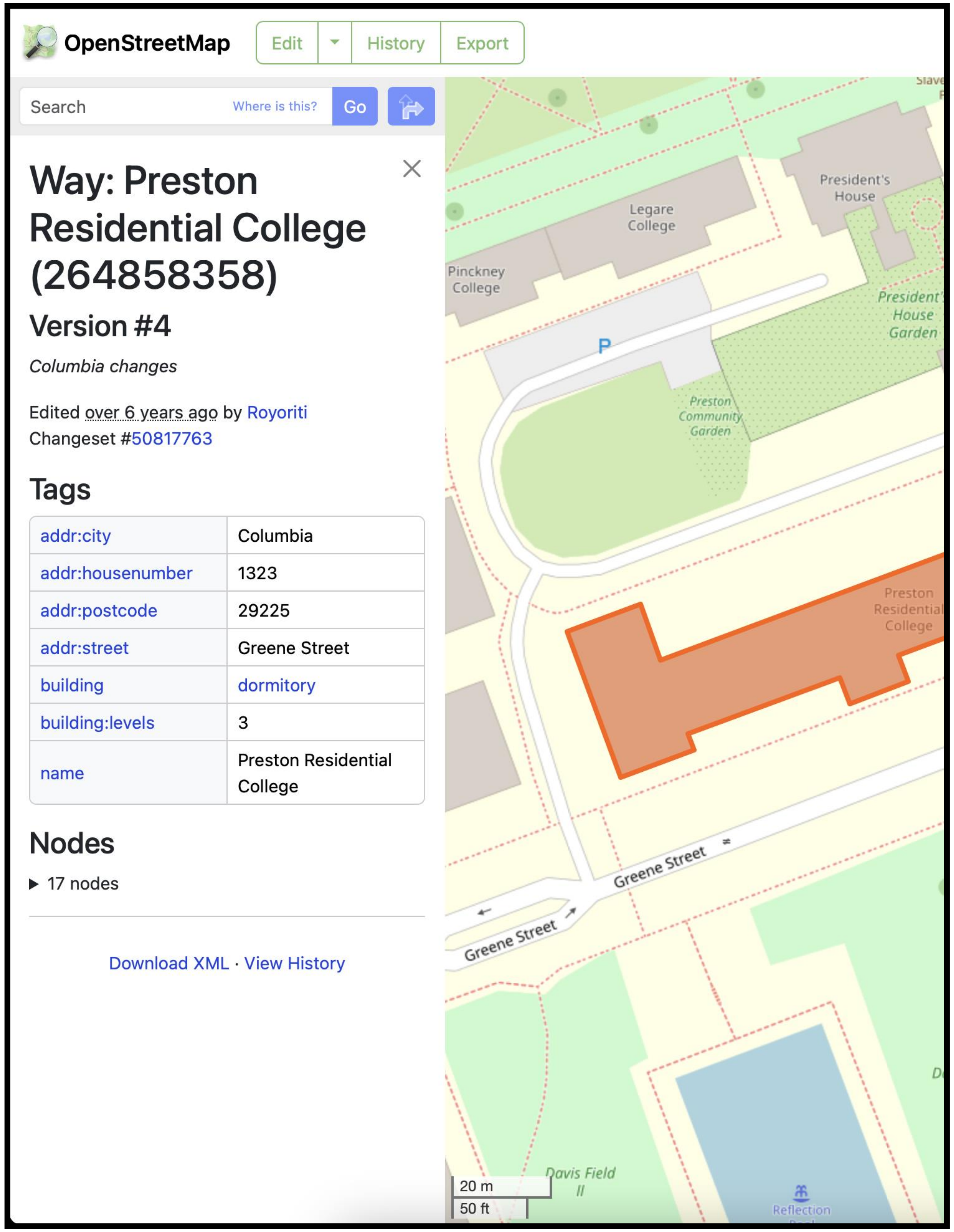
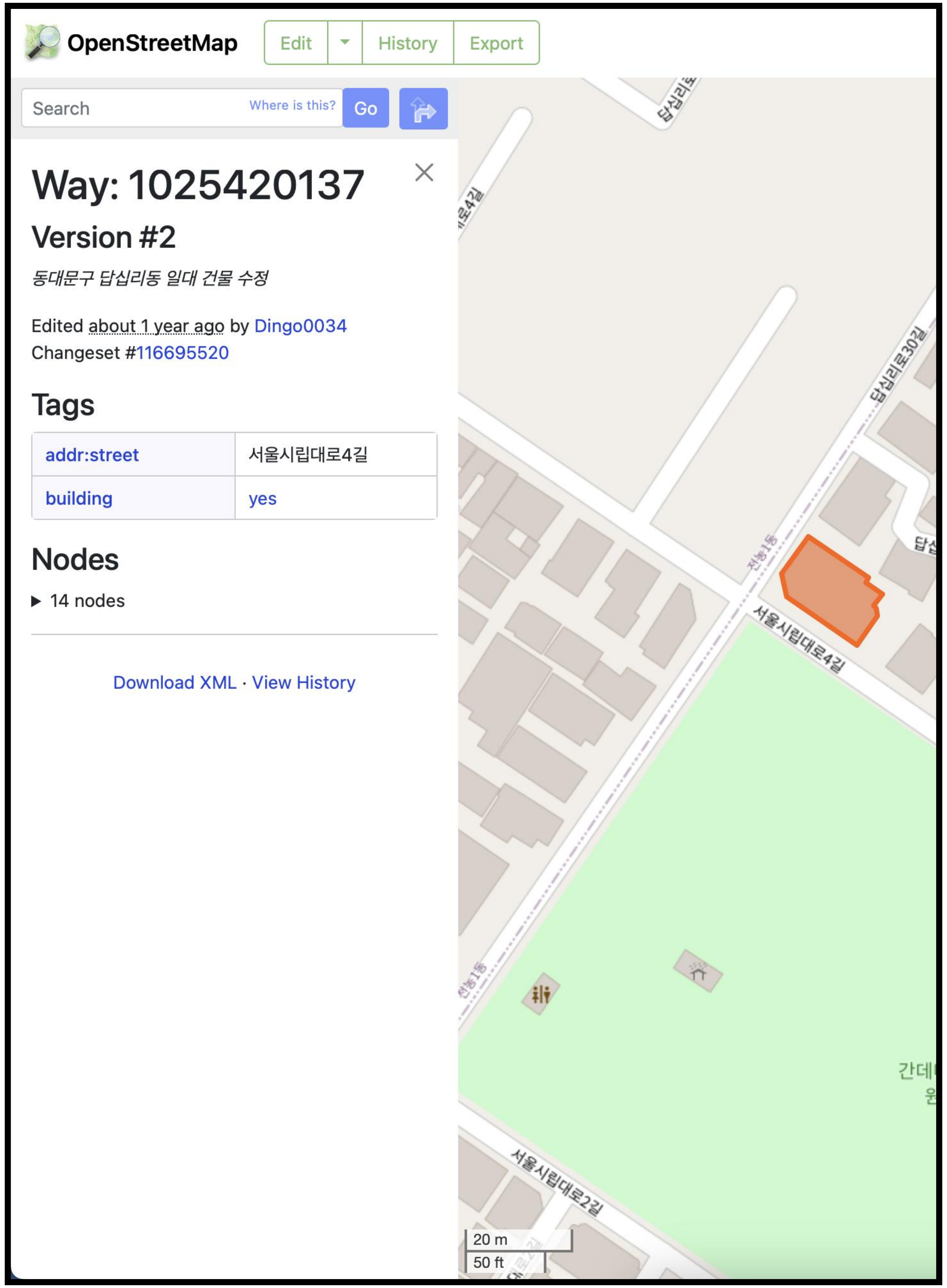


OpenStreetMap
Edit
History
Export
Search
Where is this?
Go
Way: Preston Residential College (264858358)
Version #4
Columbia changes
Edited over 6 years ago by Royoriti
Changeset #50817763
Tags
addr:city Columbia
addr:housenumber 1323
addr:postcode 29225
addr:street Greene Street
building dormitory
building:levels 3
name Preston Residential College
Nodes
▸ 17 nodes
Download XML · View History
Legare College
President's House
Pinckney College
President's House Garden
Preston Community Garden
Preston Residential College
Greene Street
Greene Street
Davis Field
20 m
50 ft
Reflection



OpenStreetMap
Edit
History
Export
Search
Where is this?
Go
Way: 1025420137
Version #2
동대문구 답십리동 일대 건물 수정
Edited about 1 year ago by Dingo0034
Changeset #116695520
Tags
addr:street 서울시립대로4길
building yes
Nodes
▸ 14 nodes
Download XML · View History
답십리로30길
서울시립대로4길
서울시립대로2길
20 m
50 ft

Are real estate ads a type of user-generated geographic information that has been ignored in GIScience?

Source: PropertyGuru

Introducing new means of acquisition of building data

By Xinyu Chen

Urban Informatics Paper of the Year Award (2023) 🥇

Chen and Biljecki *Urban Informatics* (2022) 1:12
https://doi.org/10.1007/s44212-022-00012-2

Urban Informatics
The International Society for Urban Informatics

ORIGINAL ARTICLE **Open Access**

Check for updates

Mining real estate ads and property transactions for building and amenity data acquisition

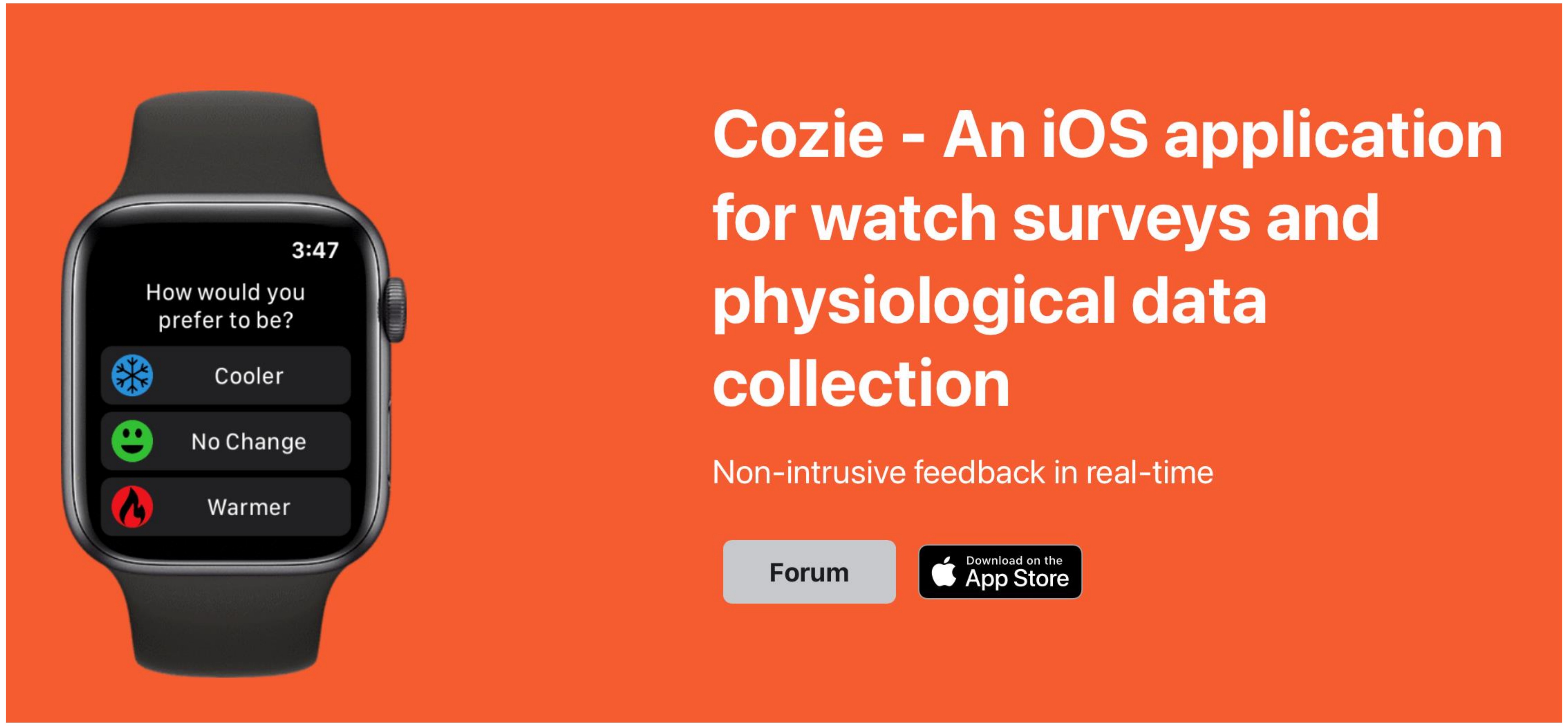
Xinyu Chen[1] and Filip Biljecki[2,3*]

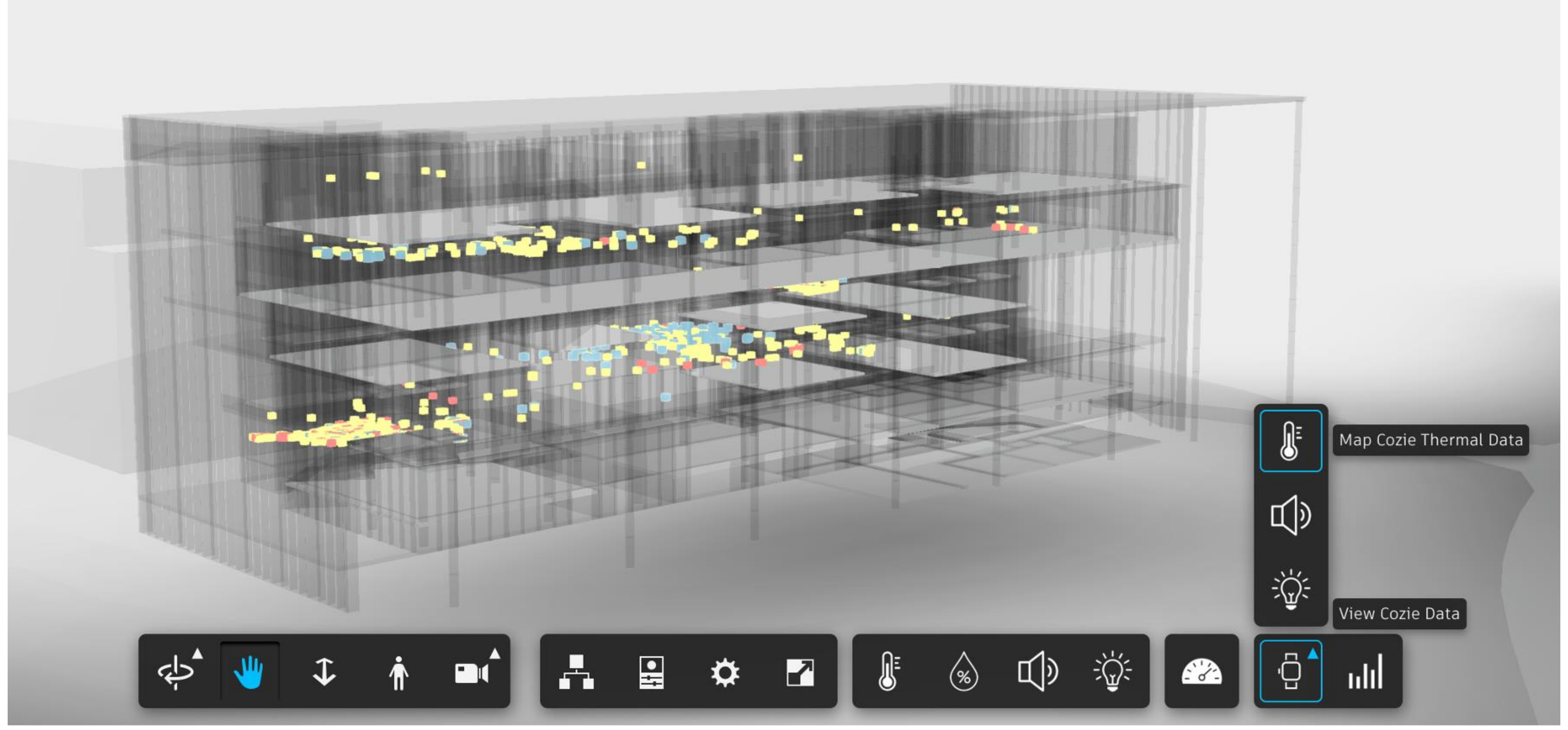
Abstract

Acquiring spatial data of fine and dynamic urban features such as buildings remains challenging. This paper brings attention to real estate advertisements and property sales data as valuable and dynamic sources of geoinformation in the built environment, but unutilised in spatial data infrastructures. Given the wealth of information they hold and their user-generated nature, we put forward the idea of real estate data as an instance of implicit volunteered geographic information and bring attention to their spatial aspect, potentially alleviating the challenge of acquiring spatial data of fine and dynamic urban features. We develop a mechanism of facilitating continuous acquisition, maintenance, and quality assurance of building data and associated amenities from real estate data. The results of the experiments conducted in Singapore reveal that one month of property listings provides information on 7% of the national building stock and about half of the residential subset, e.g. age, type, and storeys, which are often not available in sources such as OpenStreetMap, potentially supporting applications such as 3D city modelling and energy simulations. The method may serve as a novel means to spatial data quality control as it detects missing amenities and maps future buildings, which are advertised and transacted before they are built, but it exhibits mixed results in

Situation
Real estate data
(1) Real estate ads
(2) Property transactions
Extracting relevant data
(A) Detecting features (computer vision)
Swimming Pool
(B) Collecting the location of a building
N1.295423, E103.8357
(C) Mining descriptions/characteristics
e.g. building type and year of construction
Type
TOP
Condominium For Sale
1993
e.g. height from address and floor area
#24-63 42
#23-65 97
#23-64 84
#23-63 42
Spatial database and downstream applications
(i) Quality control: revealing unmapped features
detected missing swimming pool
River Valley Road
Jalan Kuala
The Morningside
(ii) Sensing future buildings
(e.g. planned ones that are not yet mapped)
(iii) Quality control of existing attributes
type condominium
start_date 1997
(iv) Data enrichment: new attributes
levels 24
avg_floor_area 80
Example use cases: supporting energy simulations and 3D model generation
Floor area provides value for energy consumption estimations
Number of floors, which can be inferred from corresponding property transactions, can be used to extrude existing footprints, resulting in 3D building models

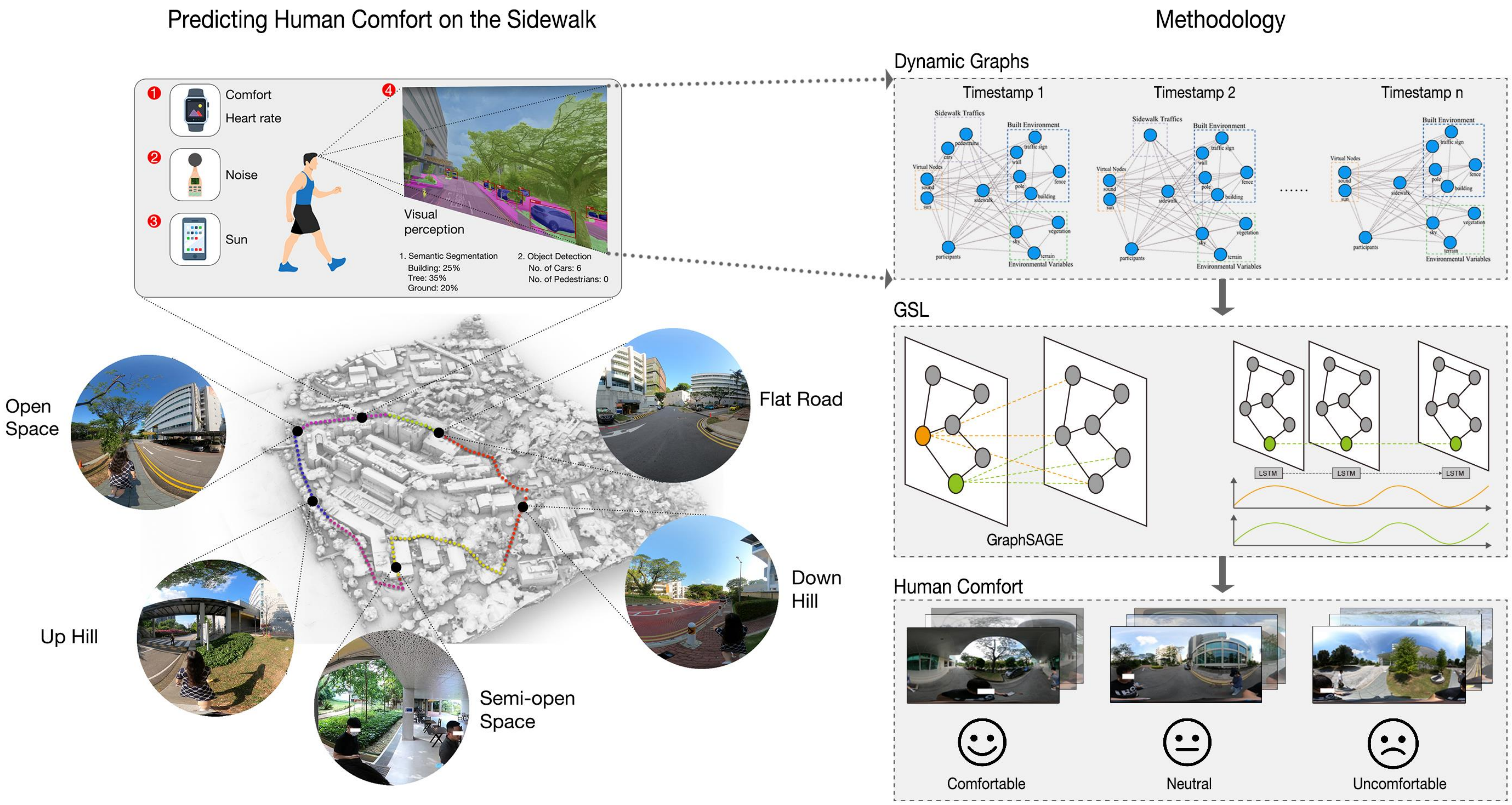
buds lab
building and urban data science

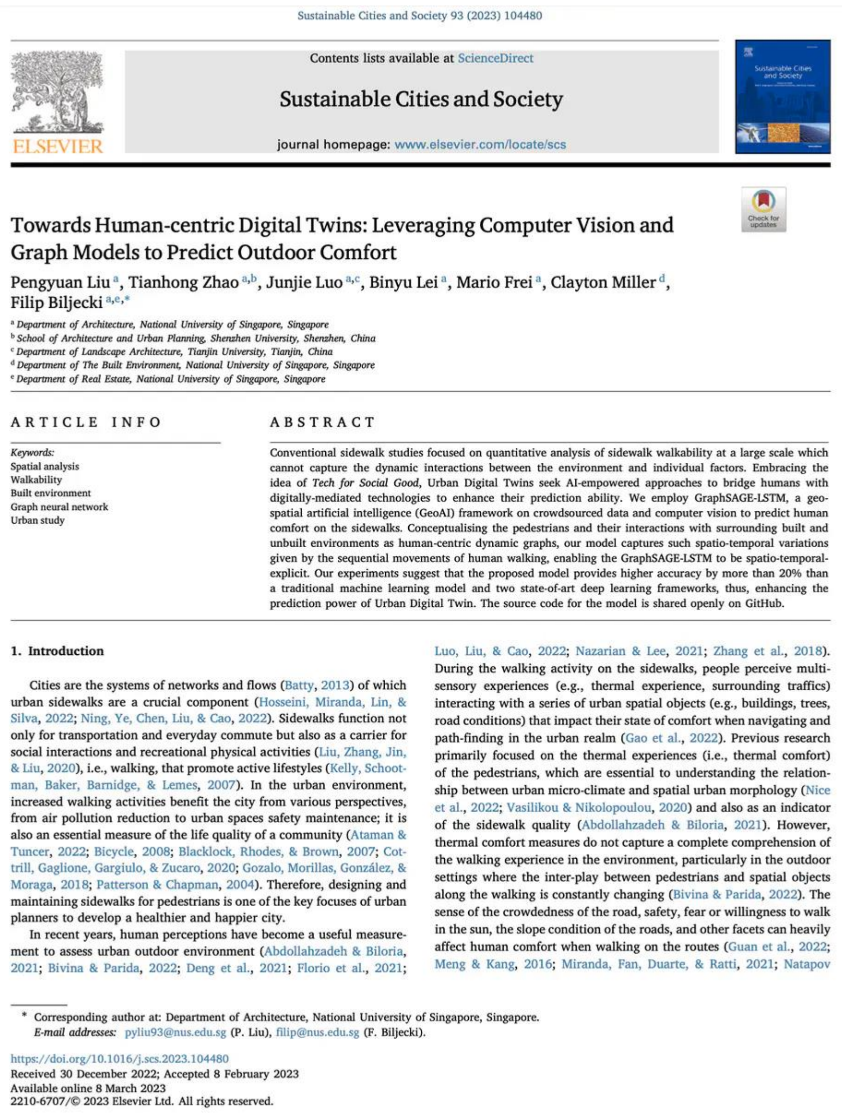




https://cozie-apple.app/
Jayathissa P, Quintana M, Abdelrahman M, Miller C. Humans-as-a-Sensor for Buildings—Intensive Longitudinal Indoor Comfort Models. Buildings. 10: 174, 2020. https://doi.org/10.3390/buildings10100174

- Momentum in research on comfort in the built environment
- Comfort is more than thermal comfort
- Comfort is influenced by myriads of factors




Sustainable Cities and Society 93 (2023) 104480

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Towards Human-centric Digital Twins: Leveraging Computer Vision and Graph Models to Predict Outdoor Comfort

Pengyuan Liu [a], Tianhong Zhao [a,b], Junjie Luo [a,c], Binyu Lei [a], Mario Frei [a], Clayton Miller [d], Filip Biljecki [a,e,*]

[a] Department of Architecture, National University of Singapore, Singapore
[b] School of Architecture and Urban Planning, Shenzhen University, Shenzhen, China
[c] Department of Landscape Architecture, Tianjin University, Tianjin, China
[d] Department of The Built Environment, National University of Singapore, Singapore
[e] Department of Real Estate, National University of Singapore, Singapore

ARTICLE INFO

Keywords:
Spatial analysis
Walkability
Built environment
Graph neural network
Urban study

ABSTRACT

Conventional sidewalk studies focused on quantitative analysis of sidewalk walkability at a large scale which cannot capture the dynamic interactions between the environment and individual factors. Embracing the idea of *Tech for Social Good*, Urban Digital Twins seek AI-empowered approaches to bridge humans with digitally-mediated technologies to enhance their prediction ability. We employ GraphSAGE-LSTM, a geo-spatial artificial intelligence (GeoAI) framework on crowdsourced data and computer vision to predict human comfort on the sidewalks. Conceptualising the pedestrians and their interactions with surrounding built and unbuilt environments as human-centric dynamic graphs, our model captures such spatio-temporal variations given by the sequential movements of human walking, enabling the GraphSAGE-LSTM to be spatio-temporal-explicit. Our experiments suggest that the proposed model provides higher accuracy by more than 20% than a traditional machine learning model and two state-of-art deep learning frameworks, thus, enhancing the prediction power of Urban Digital Twin. The source code for the model is shared openly on GitHub.

1. Introduction

Cities are the systems of networks and flows (Batty, 2013) of which urban sidewalks are a crucial component (Hosseini, Miranda, Lin, & Silva, 2022; Ning, Ye, Chen, Liu, & Cao, 2022). Sidewalks function not only for transportation and everyday commute but also as a carrier for social interactions and recreational physical activities (Liu, Zhang, Jin, & Liu, 2020), i.e., walking, that promote active lifestyles (Kelly, Schootman, Baker, Barnidge, & Lemes, 2007). In the urban environment, increased walking activities benefit the city from various perspectives, from air pollution reduction to urban spaces safety maintenance; it is also an essential measure of the life quality of a community (Ataman & Tuncer, 2022; Bicycle, 2008; Blacklock, Rhodes, & Brown, 2007; Cottrill, Gaglione, Gargiulo, & Zucaro, 2020; Gozalo, Morillas, González, & Moraga, 2018; Patterson & Chapman, 2004). Therefore, designing and maintaining sidewalks for pedestrians is one of the key focuses of urban planners to develop a healthier and happier city.

In recent years, human perceptions have become a useful measurement to assess urban outdoor environment (Abdollahzadeh & Biloria, 2021; Bivina & Parida, 2022; Deng et al., 2021; Florio et al., 2021; Luo, Liu, & Cao, 2022; Nazarian & Lee, 2021; Zhang et al., 2018). During the walking activity on the sidewalks, people perceive multi-sensory experiences (e.g., thermal experience, surrounding traffics) interacting with a series of urban spatial objects (e.g., buildings, trees, road conditions) that impact their state of comfort when navigating and path-finding in the urban realm (Gao et al., 2022). Previous research primarily focused on the thermal experiences (i.e., thermal comfort) of the pedestrians, which are essential to understanding the relationship between urban micro-climate and spatial urban morphology (Nice et al., 2022; Vasilikou & Nikolopoulou, 2020) and also as an indicator of the sidewalk quality (Abdollahzadeh & Biloria, 2021). However, thermal comfort measures do not capture a complete comprehension of the walking experience in the environment, particularly in the outdoor settings where the inter-play between pedestrians and spatial objects along the walking is constantly changing (Bivina & Parida, 2022). The sense of the crowdedness of the road, safety, fear or willingness to walk in the sun, the slope condition of the roads, and other facets can heavily affect human comfort when walking on the routes (Guan et al., 2022; Meng & Kang, 2016; Miranda, Fan, Duarte, & Ratti, 2021; Natapov

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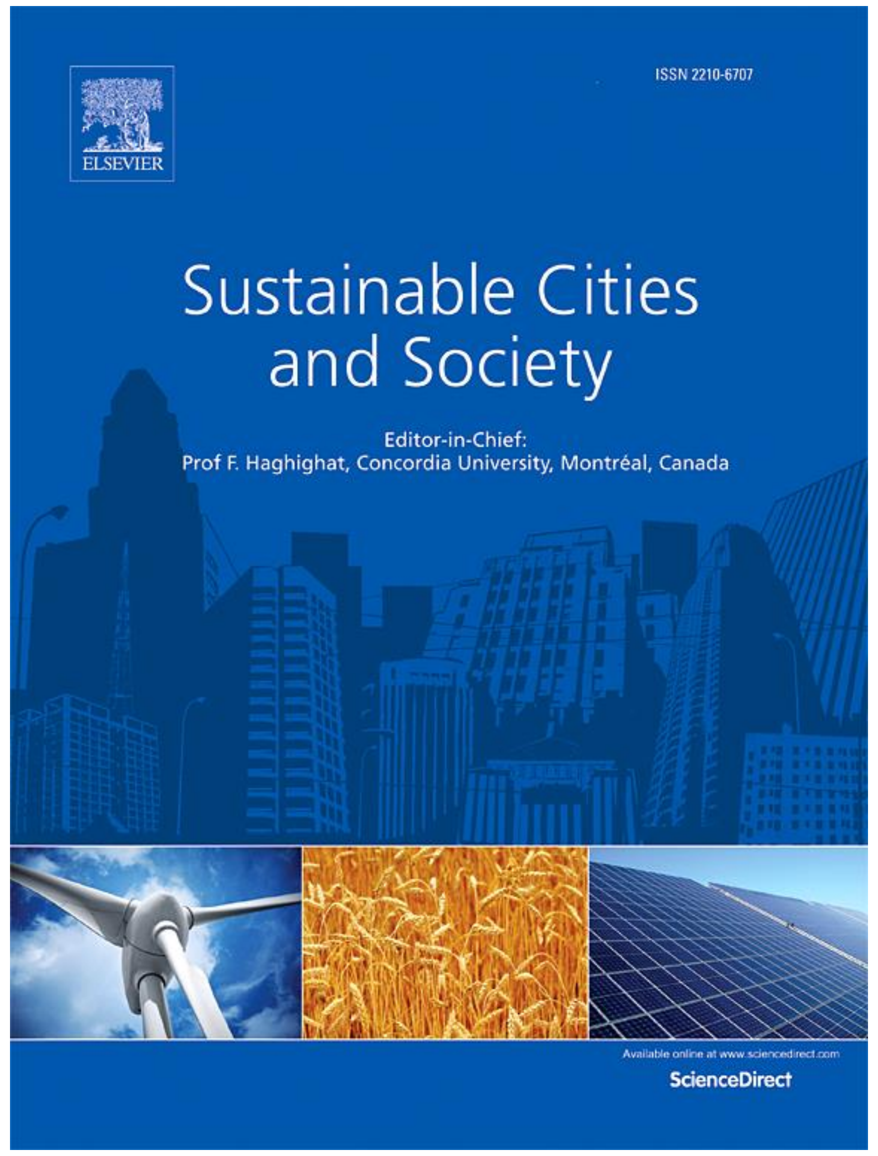
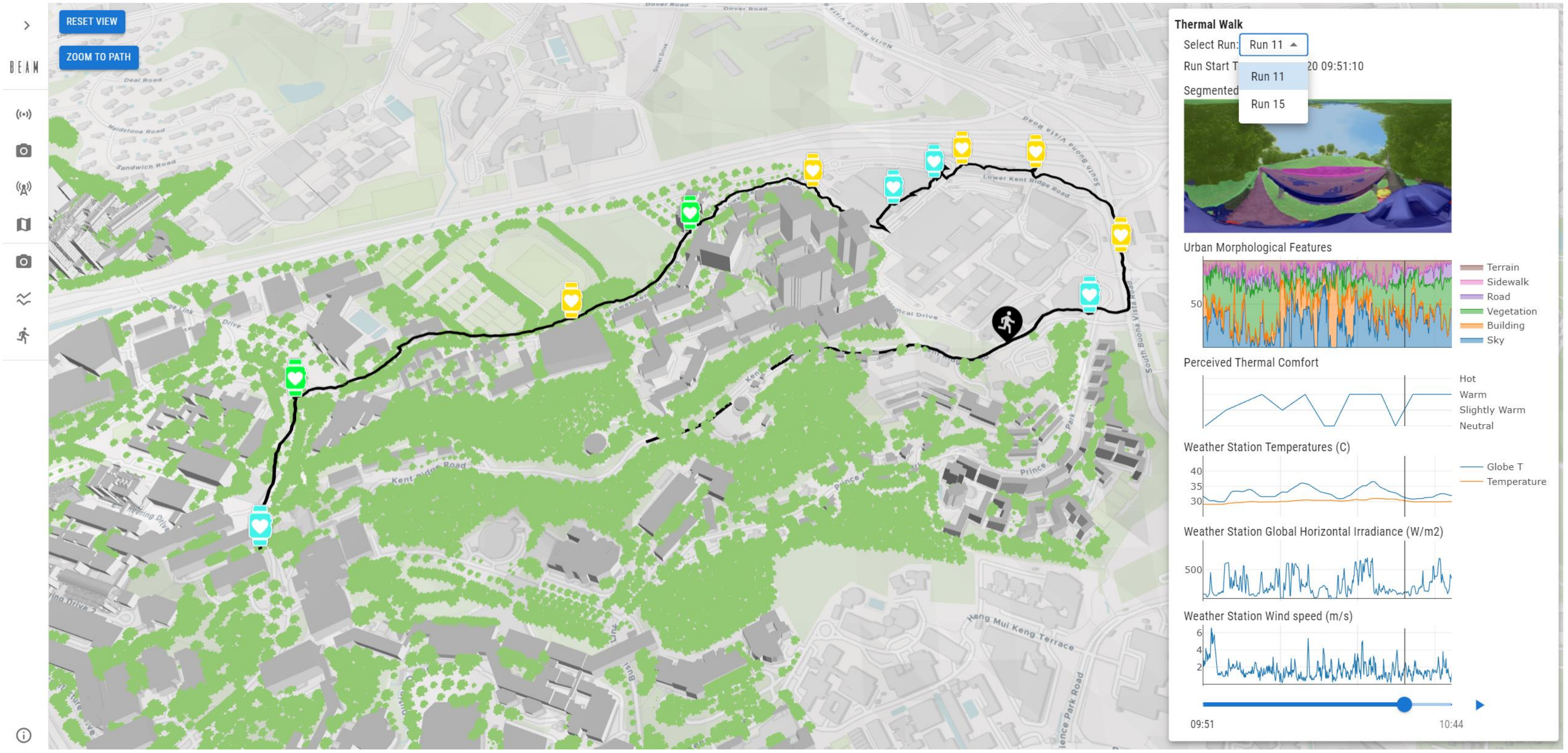
https://doi.org/10.1016/j.scs.2023.104480
Received 30 December 2022; Accepted 8 February 2023
Available online 8 March 2023



Liu P, Zhao T, Luo J, Lei B, Frei M, Miller C, and Biljecki F (2023): Towards Human-centric Digital Twins: Leveraging Computer Vision and Graph Models to Predict Outdoor Comfo

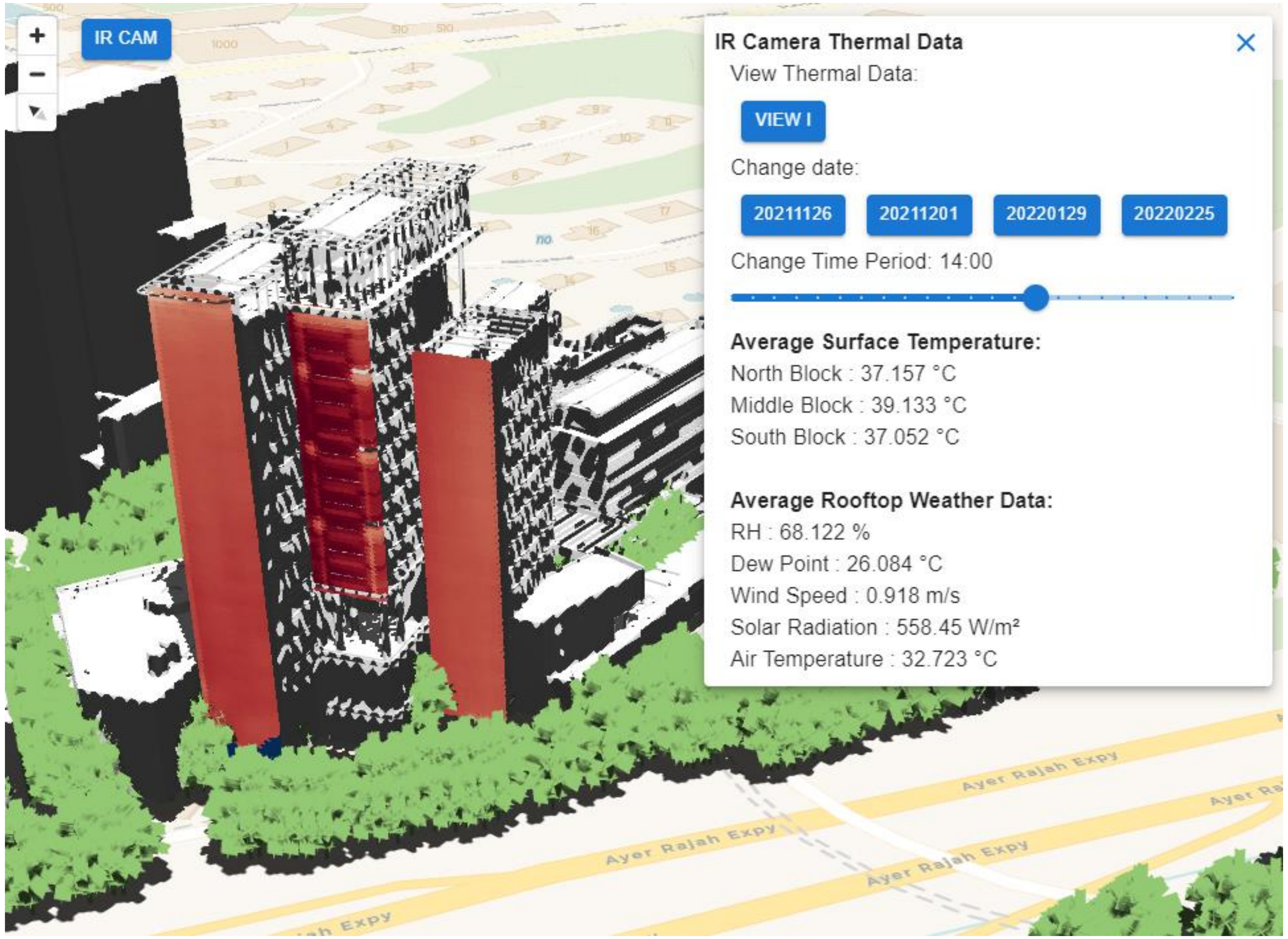
Goal of the work

Proof of concept of integrating wearable data, weather information, street view imagery / urban form data, etc. in an urban digital twin to support walkability/comfort studies



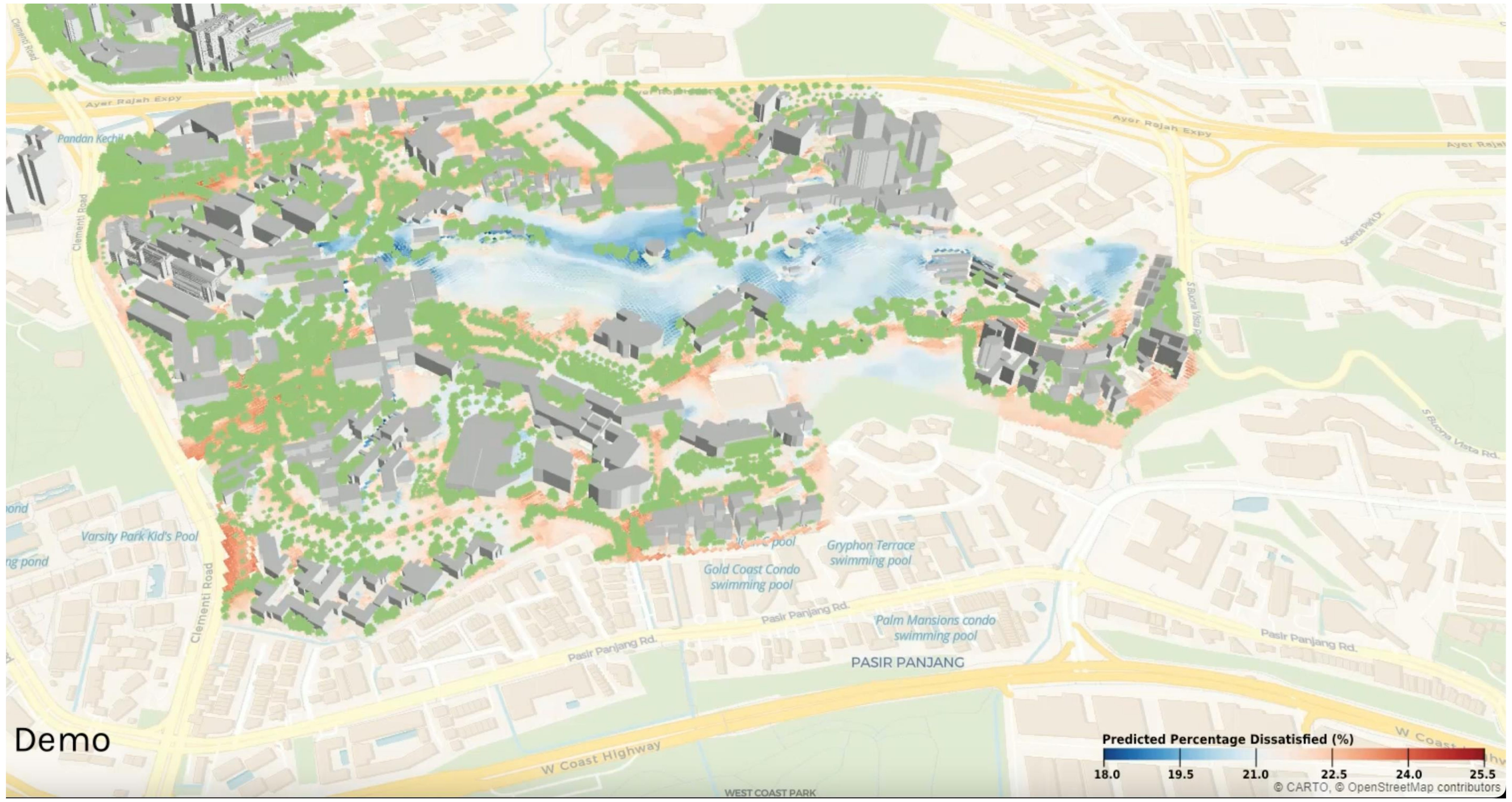
BEAM 14.12.2023 - Demo


CFD
IR CAM
IR Camera Thermal Data
View Thermal Data:
VIEW E1A
VIEW CREATE
Change Time Period: 09:00
19
02
05
04
11
03
Engineering Dr. 2
© CAR


IR CAM
IR Camera Thermal Data
View Thermal Data:
VIEW I
Change date:
20211126
20211201
20220129
20220225
Change Time Period: 14:00
Average Surface Temperature:
North Block : 37.157 °C
Middle Block : 39.133 °C
South Block : 37.052 °C
Average Rooftop Weather Data:
RH : 68.122 %
Dew Point : 26.084 °C
Wind Speed : 0.918 m/s
Solar Radiation : 558.45 W/m²
Air Temperature : 32.723 °C
Ayer Rajah Expy

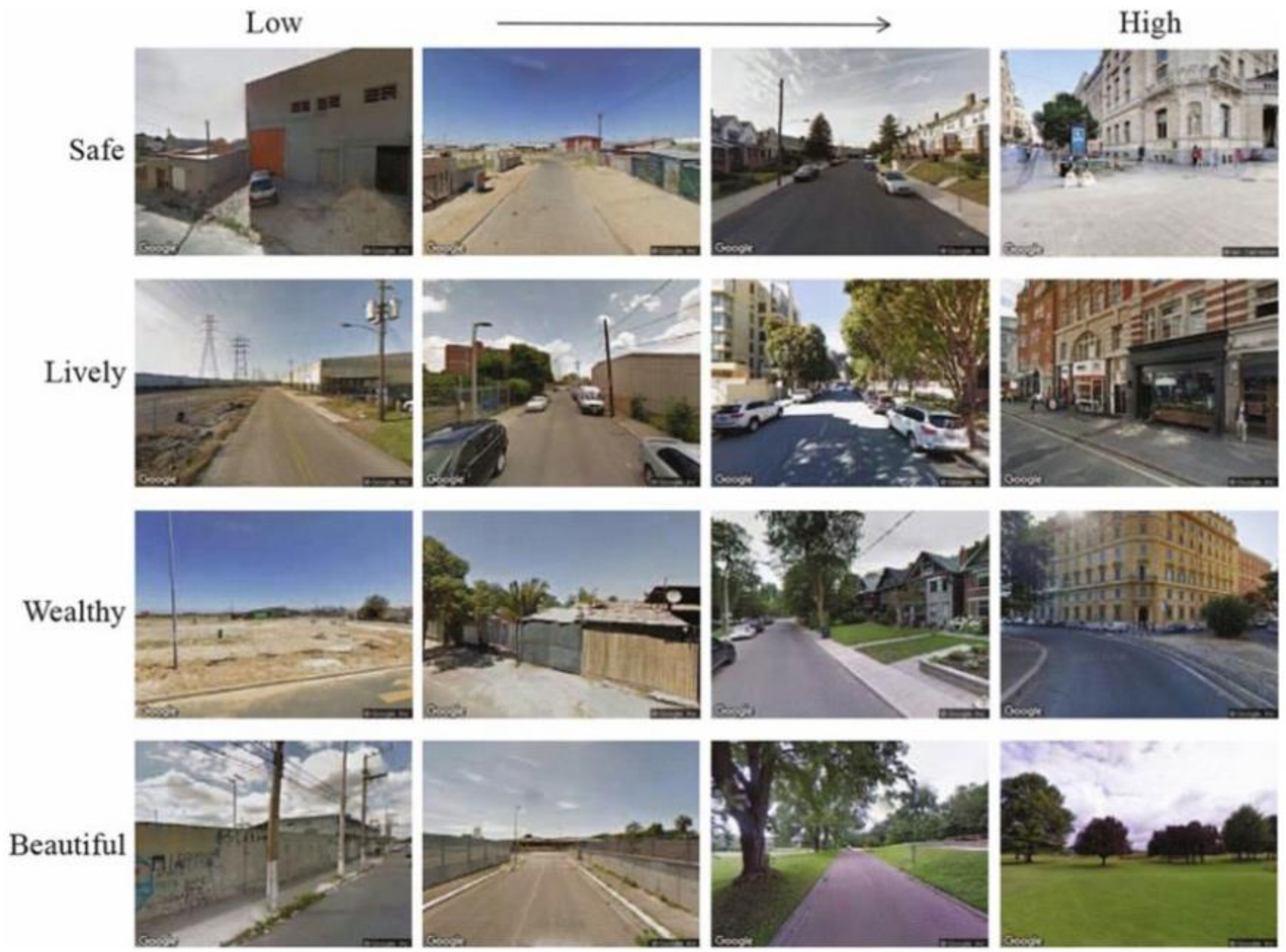
Potential of the work / Why do we need this?

- Work in progress
- Understand drivers of comfort in the built environment
- Support walkability studies
- Predicting comfort at detailed resolution — both spatially and temporally
- Human-centric aspect - tailored models based on profiles and personal preferences

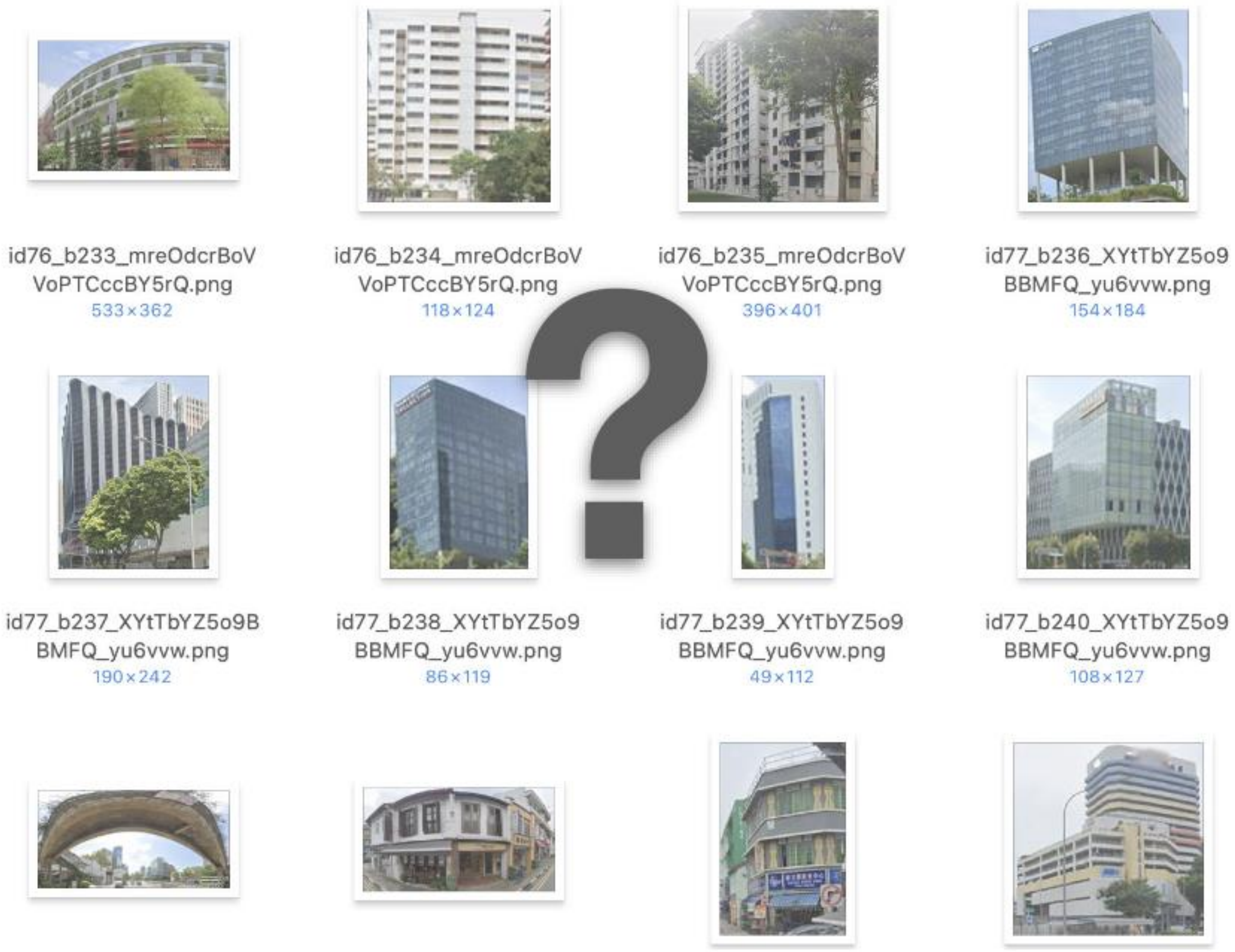


Evaluating Human Perception of Building Exteriors Using Street View Imagery

— *Xiucheng Liang, Jiat Hwee Chang, Song Gao, Tianhong Zhao, Filip Biljecki **



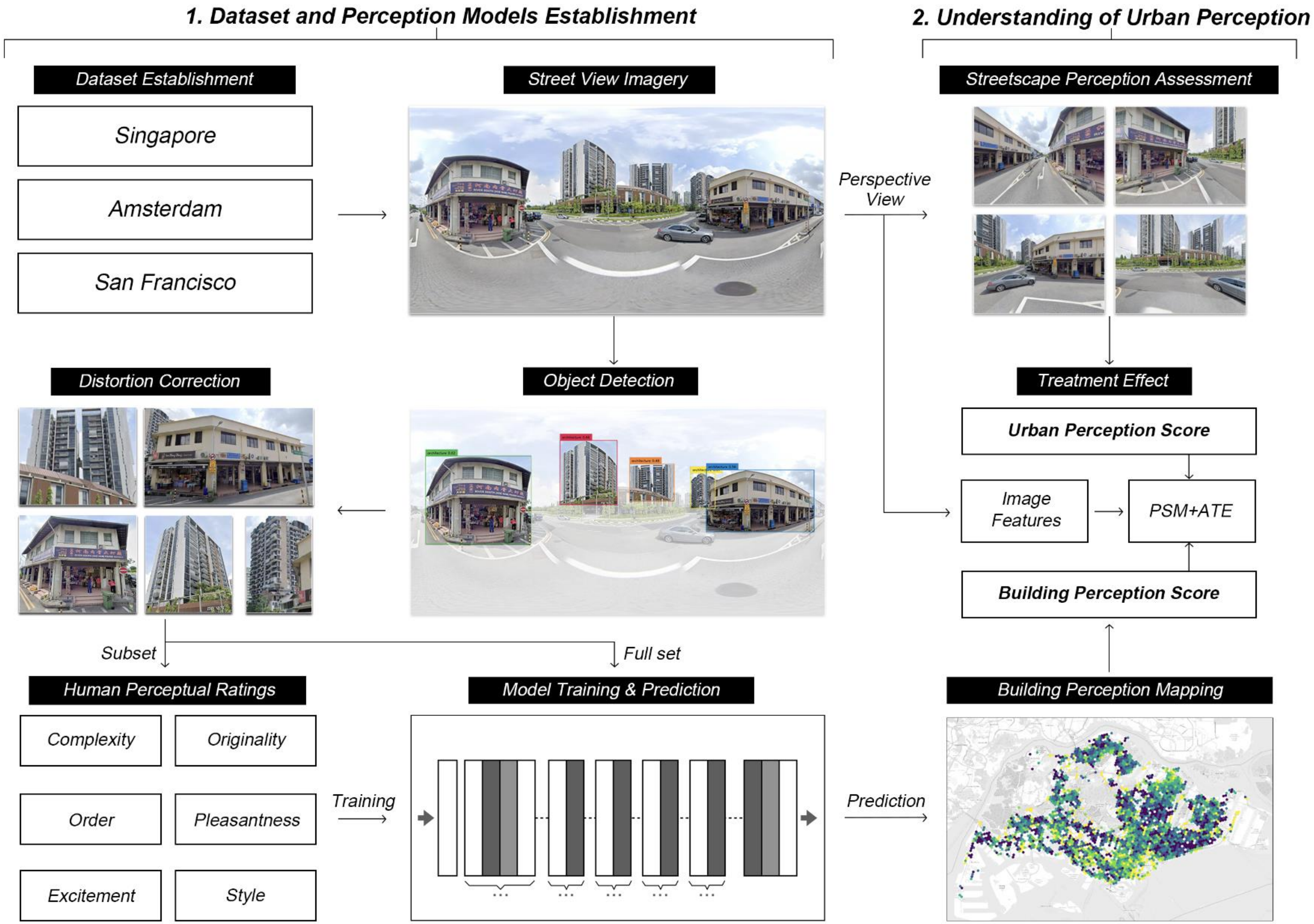
Urban streetscape perception dataset: Place Pulse 2.0



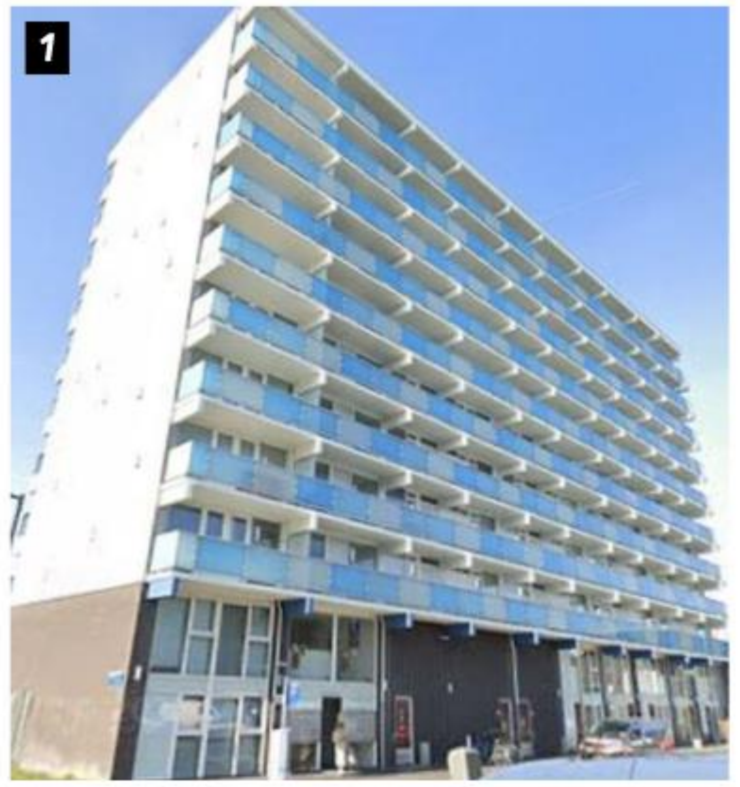
Building Facade ?

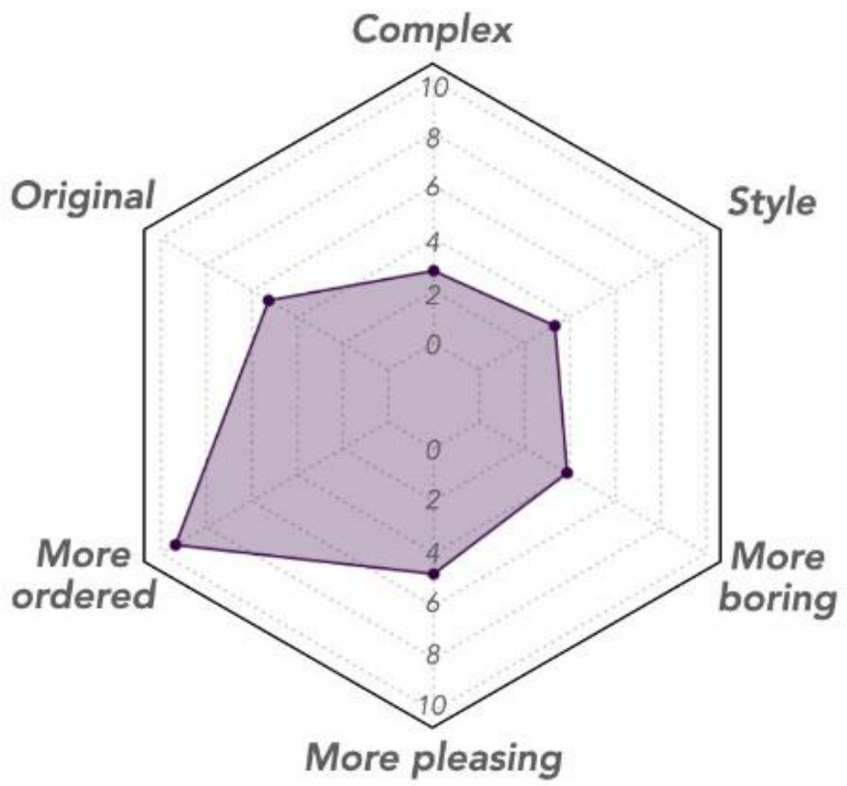
+ How well can machine learning be leveraged to describe and compare the exteriors of buildings in a detailed and scalable manner?
+ How do the human perceptions vary across cities that are constituted by different types of building exteriors?

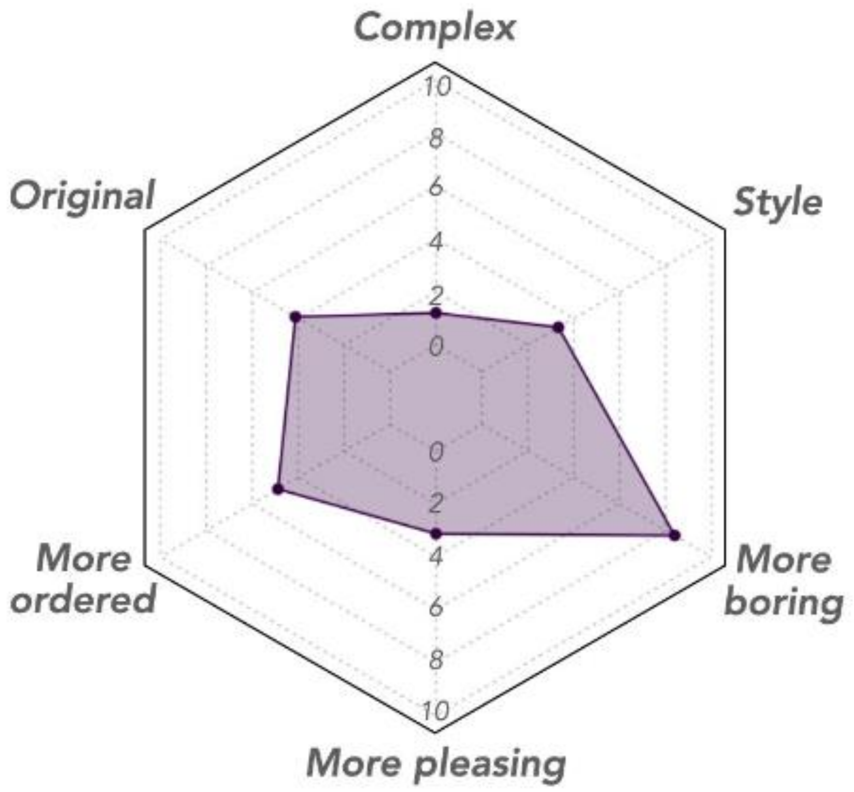
Research Framework

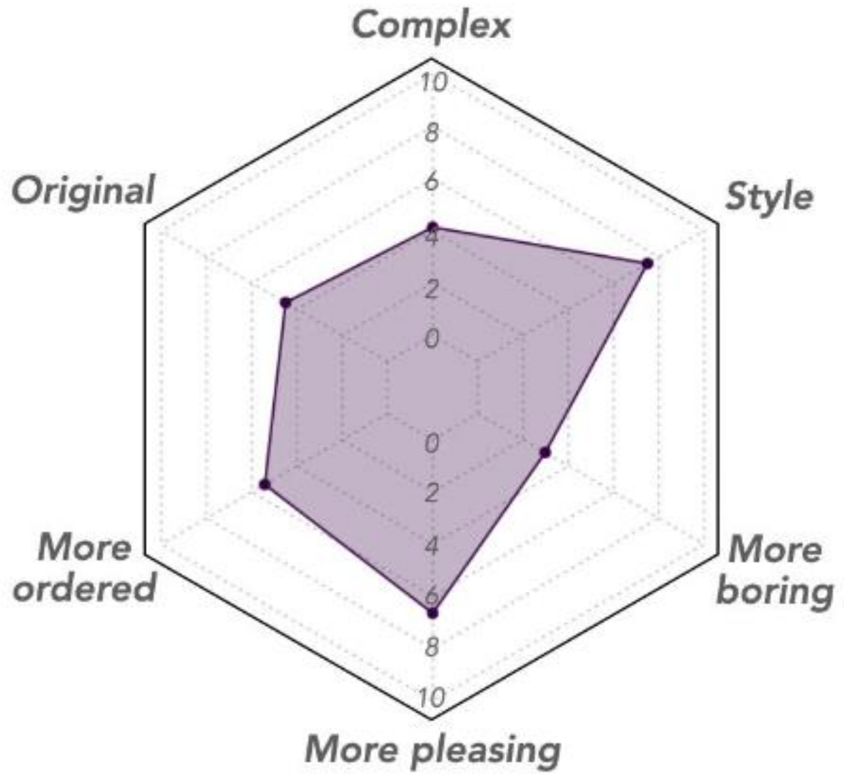


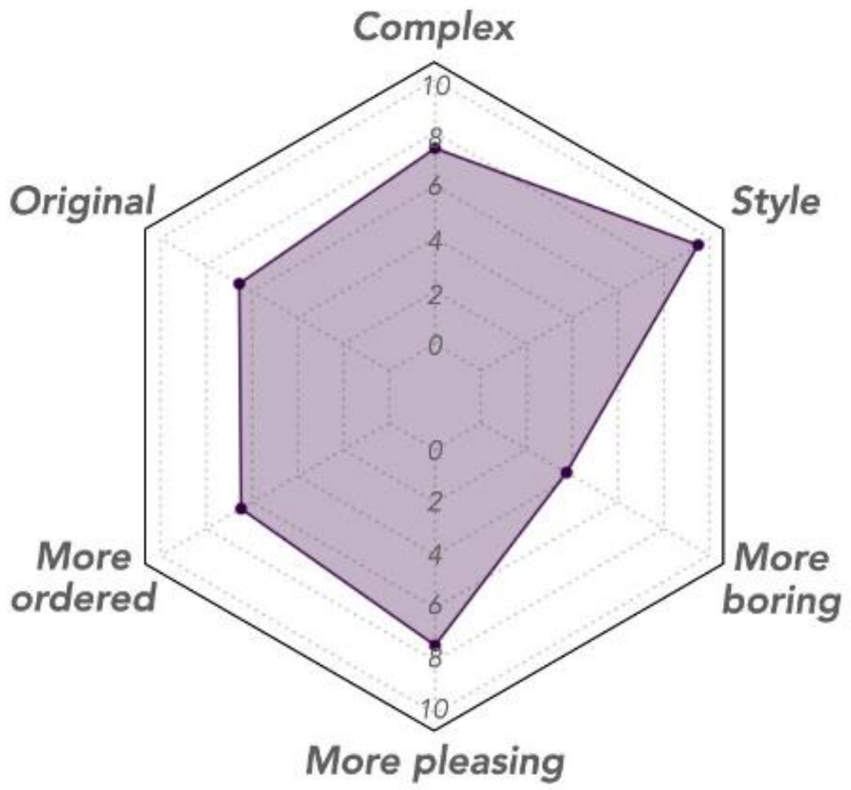
Survey result

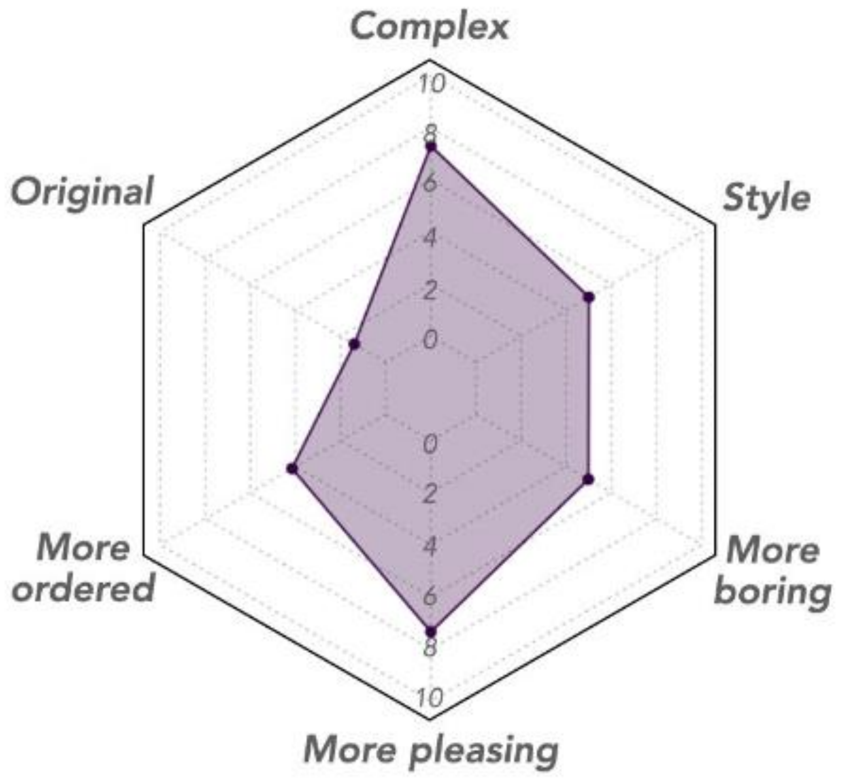


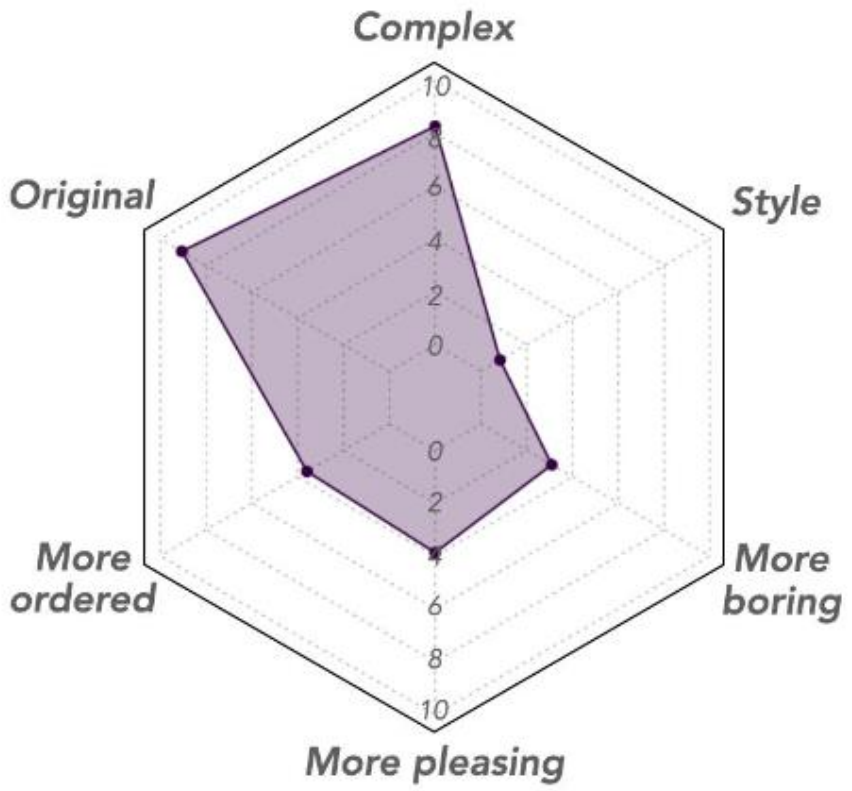













Singapore
San Francisco
Amsterdam
Low ordered score (≤ 3)
Medium ordered score (> 3 & ≤7)
High ordered score (> 7)

Integration in DT/3D

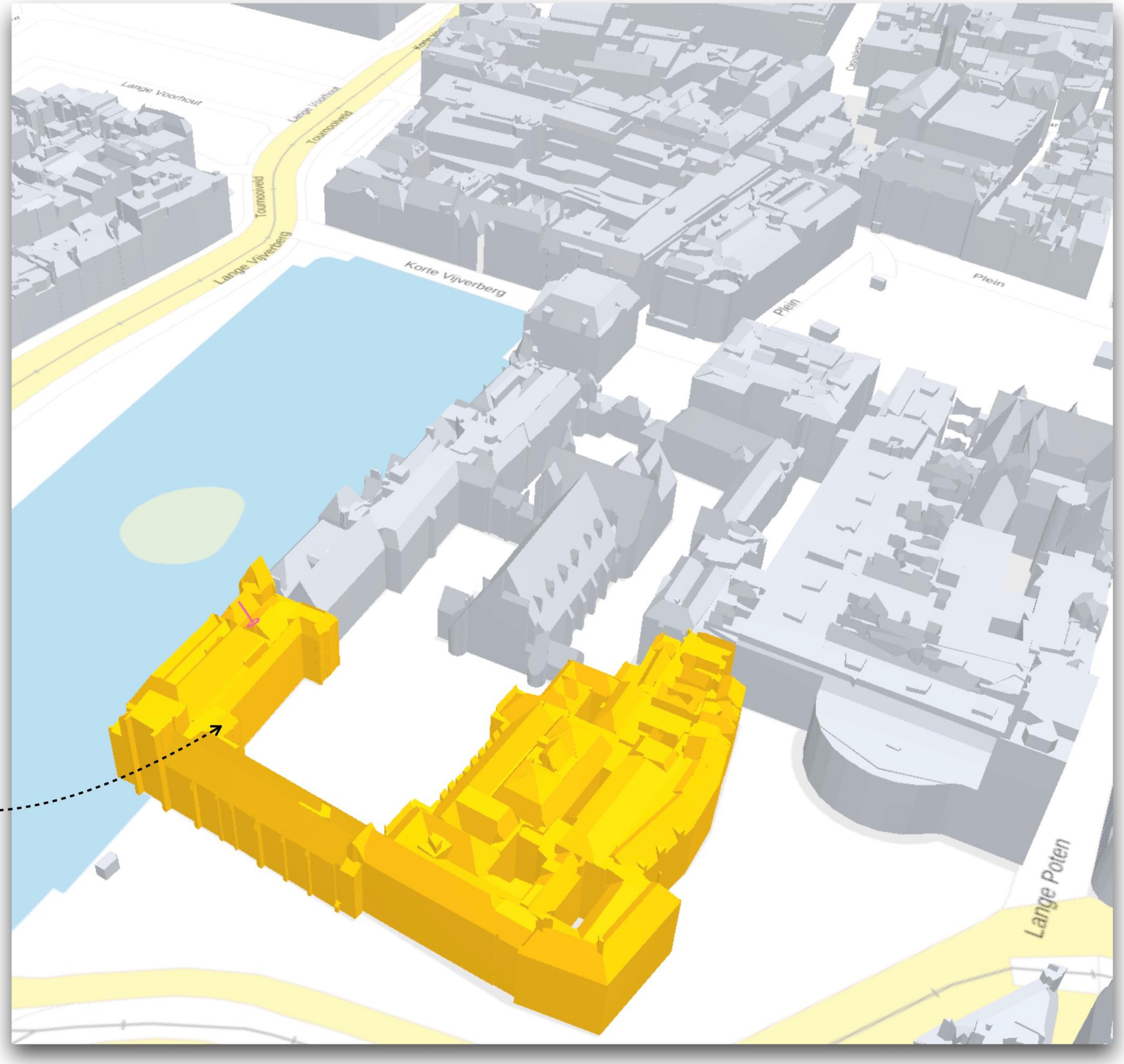
WORKFLOW

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

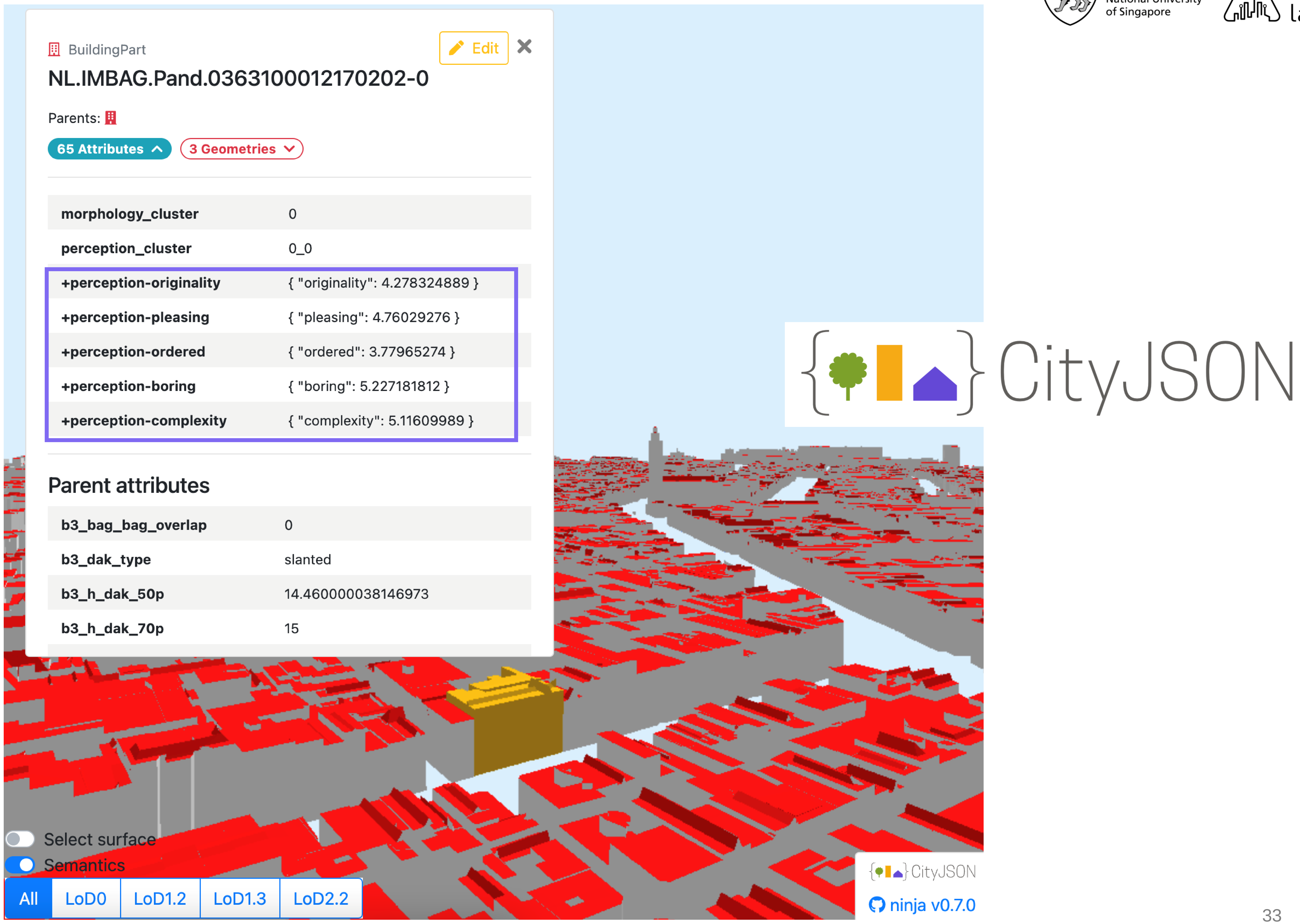
- Validating the new data and its extension according to the standard and schema

Visualisation

- 3D visualising perception attributes associated with each building

ADOPTION

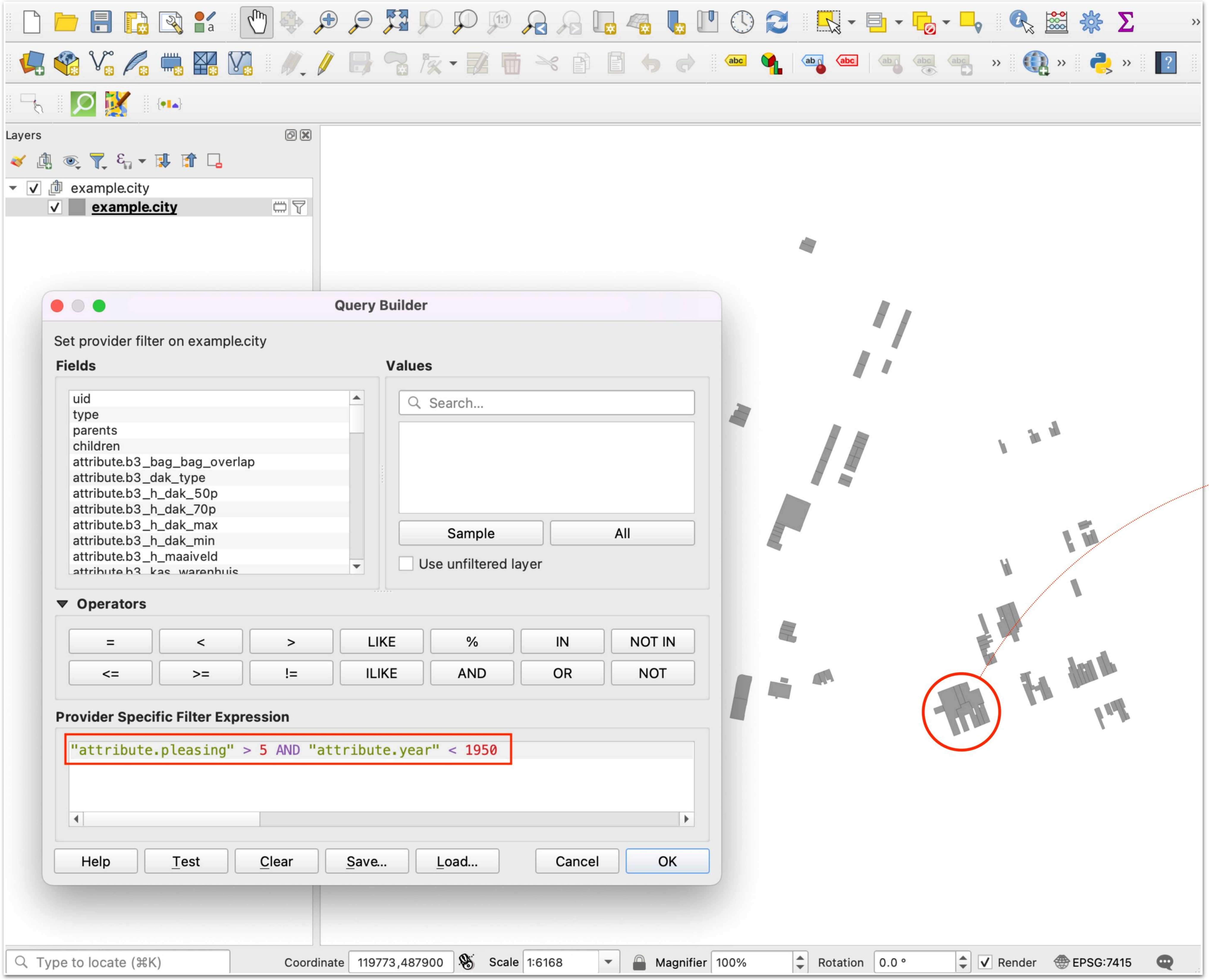
RESULTS



ADOPTION

USE CASES

An attribute-based query of buildings



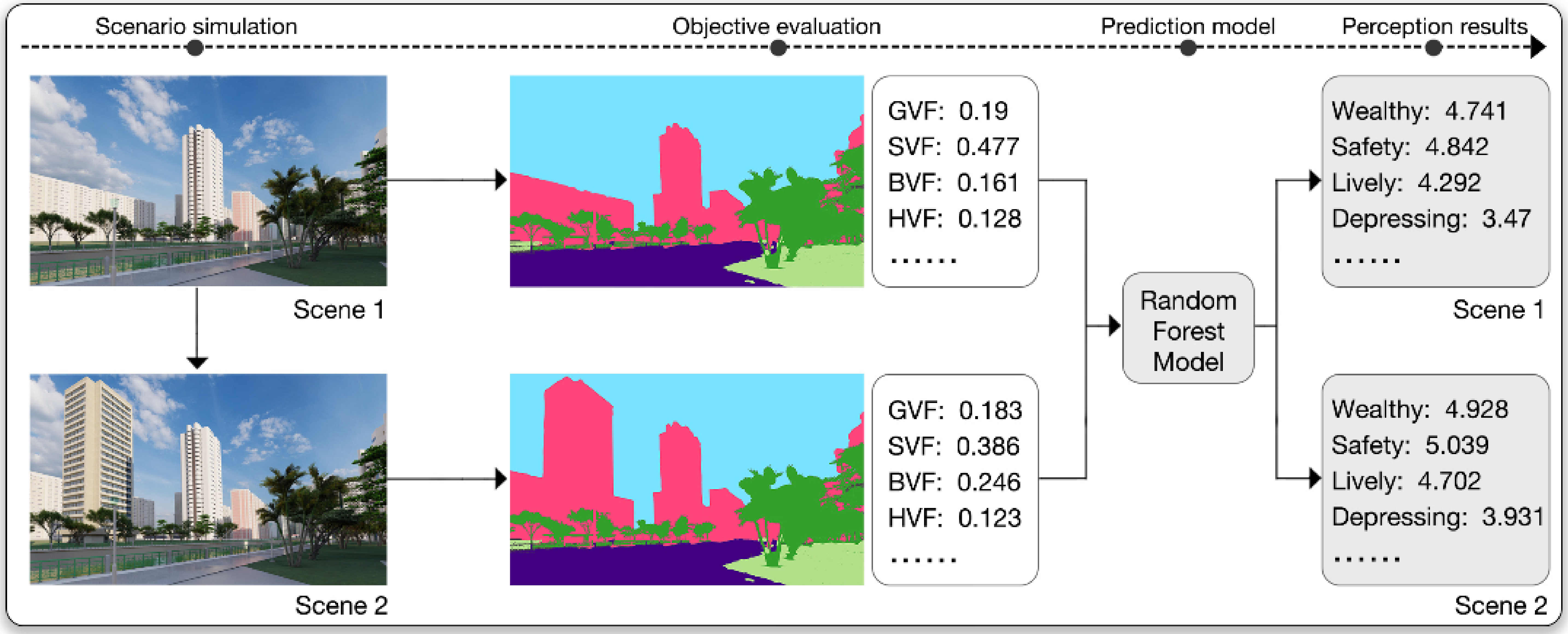
Incorporating Human Perception in Digital Twins

by Junjie Luo

(A). Photograph of an example location

(B). Virtual counterpart in UDT

A. Adding a new building



Geospatial technologies in urban farming

Supporting the 30 by 30 vision — Singapore’s 30% of nutritional needs by 2030

Credit: Ankit Palliwal

Geospatial technologies in urban farming

Supporting the 30 by 30 vision — Singapore’s 30% of nutritional needs by 2030

Credit: Song Shuang

New 3D GIS use case: urban farming simulations

by Ankit Palliwal


Computers, Environment and Urban Systems 86 (2021) 101584

Contents lists available at ScienceDirect

Computers, Environment and Urban Systems

journal homepage: www.elsevier.com/locate/ceus

ELSEVIER

3D city models for urban farming site identification in buildings

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ARTICLE INFO

Keywords:
3D GIS
Food security
OpenStreetMap
Solar exposure
Tropical climate
VI-Suite

ABSTRACT

Studies have suggested that there is farming potential in urban residential buildings. However, these studies are limited in scope, require field visits and time-consuming measurements. Furthermore, they have not suggested ways to identify suitable sites on a larger scale let alone means of surveying numerous micro-locations across the same building. Using a case study area focused on high-rise buildings in Singapore, this paper examines a novel application of three-dimensional (3D) city models to identify suitable farming micro-locations (level and orientation) in residential buildings. We specifically investigate whether the vertical spaces of these buildings comprising outdoor corridors, façades and windows receive sufficient photosynthetically active radiation (PAR) for growing food crops and do so at a high resolution. We also analyze the spatio-temporal characteristics of PAR, and the impact of shadows and different weather conditions on PAR in the building. Environmental simulations on the 3D model of the study area indicated that the cumulative daily PAR or Daily Light Integral (DLI) at a location in the building was dependent on its orientation and shape, sun's diurnal and annual motion, weather conditions, and shadowing effects of the building's own façades and surrounding buildings. The DLI in the study area generally increased with building's levels and, depending on the particular micro-location, was found suitable for growing moderately light-demanding crops such as lettuce and sweet pepper. These variations in DLI at different locations of the same building affirmed the need for such simulations. The simulations were validated with field measurements of PAR, and correlation coefficients between them exceeded 0.5 in most cases thus, making a case that 3D city models offer a promising practical solution to identifying suitable farming locations in residential buildings, and have the potential for urban-scale applications.

1. Introduction

Over the years, farming in and around urban buildings, particularly residential buildings, has gained popularity in high-density and high-rise environments (Khan, Aziz, & Ahmed, 2018; Kim, Lee, Lee, & Lee, 2018; Kosorić, Huang, Tablada, Lau, & Tan, 2019; Lim & Kishnani, 2010; Song, Tan, & Tan, 2018). This is primarily because with limited land available for agriculture, these buildings offer under-utilized horizontal and vertical spaces that may have farming potential (Fig. 1). In addition, improvement of emotional, mental and physical well-being of the occupants (Tan & Ismail, 2015), mitigation of the urban heat island effect (Diehl et al., 2020), creation of job opportunities (Tablada & Zhao, 2016), and reduction in carbon emissions associated with transportation of food (Lim & Kishnani, 2010) are counted among the other benefits of farming in these buildings. In Singapore, urban farming carries special significance as it has been adopted as one of the 'Grow Local' strategies to achieve the '30 by 30' vision of the Singapore Food Agency (SFA) (Zulkifli, 2019). This vision aims to locally produce 30% of Singapore's nutritional needs by 2030.

Situated at 1° North of equator, Singapore is an arable land-scarce and densely populated island city-state which accommodates a population of about 5.7 million (Singapore Department of Statistics, 2019a) over its land area of 722.5km^2 (Singapore Department of Statistics, 2019b). Having only 1% of land set aside for agriculture (Diehl et al., 2020), Singapore meets 90% of its food requirements through imports (Kosorić, Huang, Tablada, Lau, & Tan, 2019) leaving it vulnerable to external food price fluctuations and disruptions in the food supply chain. To reduce this heavy reliance on food imports and inline with SFA's vision, Singapore's numerous high-rise residential buildings, which accommodate almost its entire population, emerge as promising sites for

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https://doi.org/10.1016/j.compenvurbsys.2020.101584
Received 26 July 2020; Received in revised form 10 November 2020; Accepted 11 December 2020
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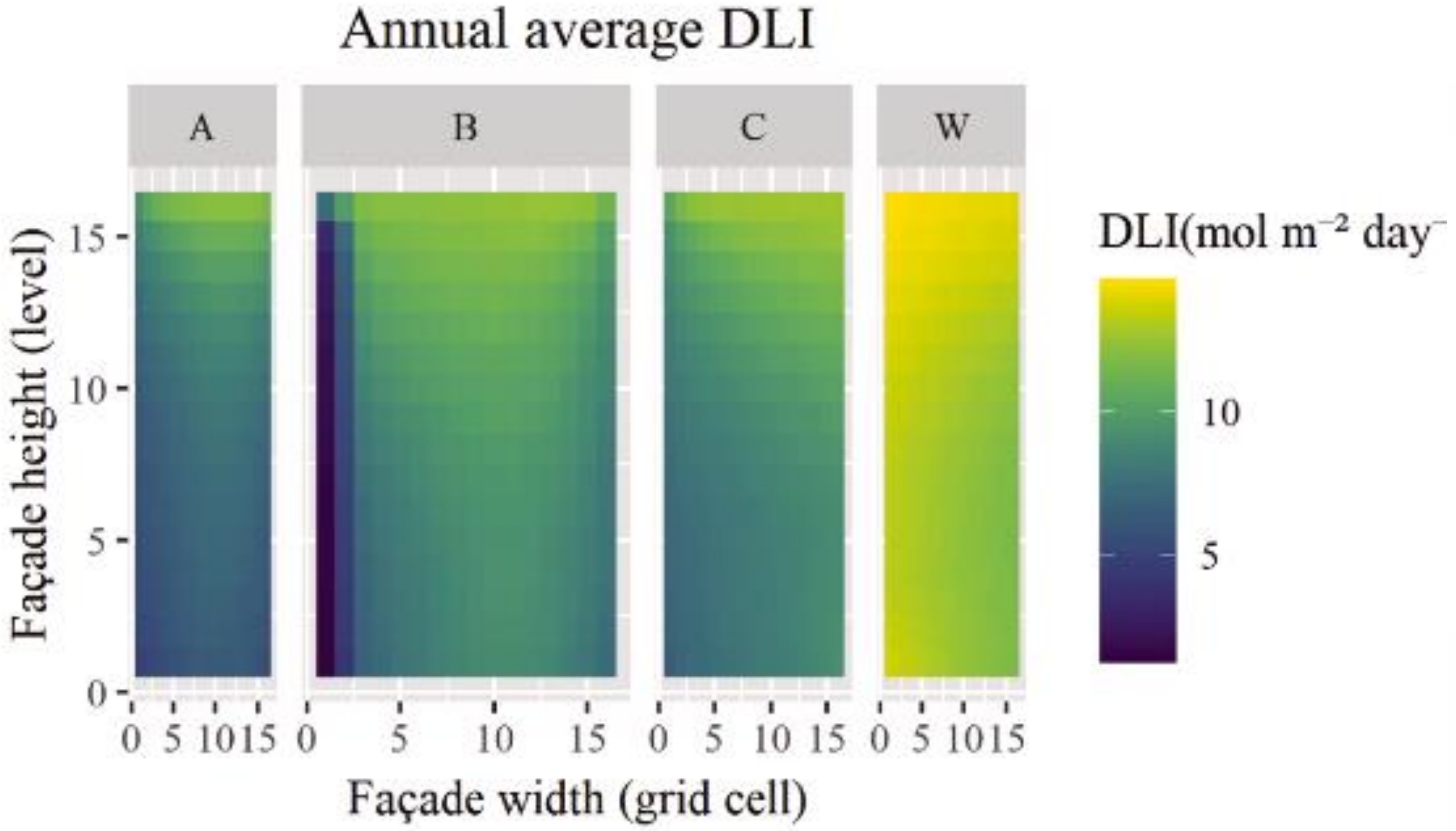
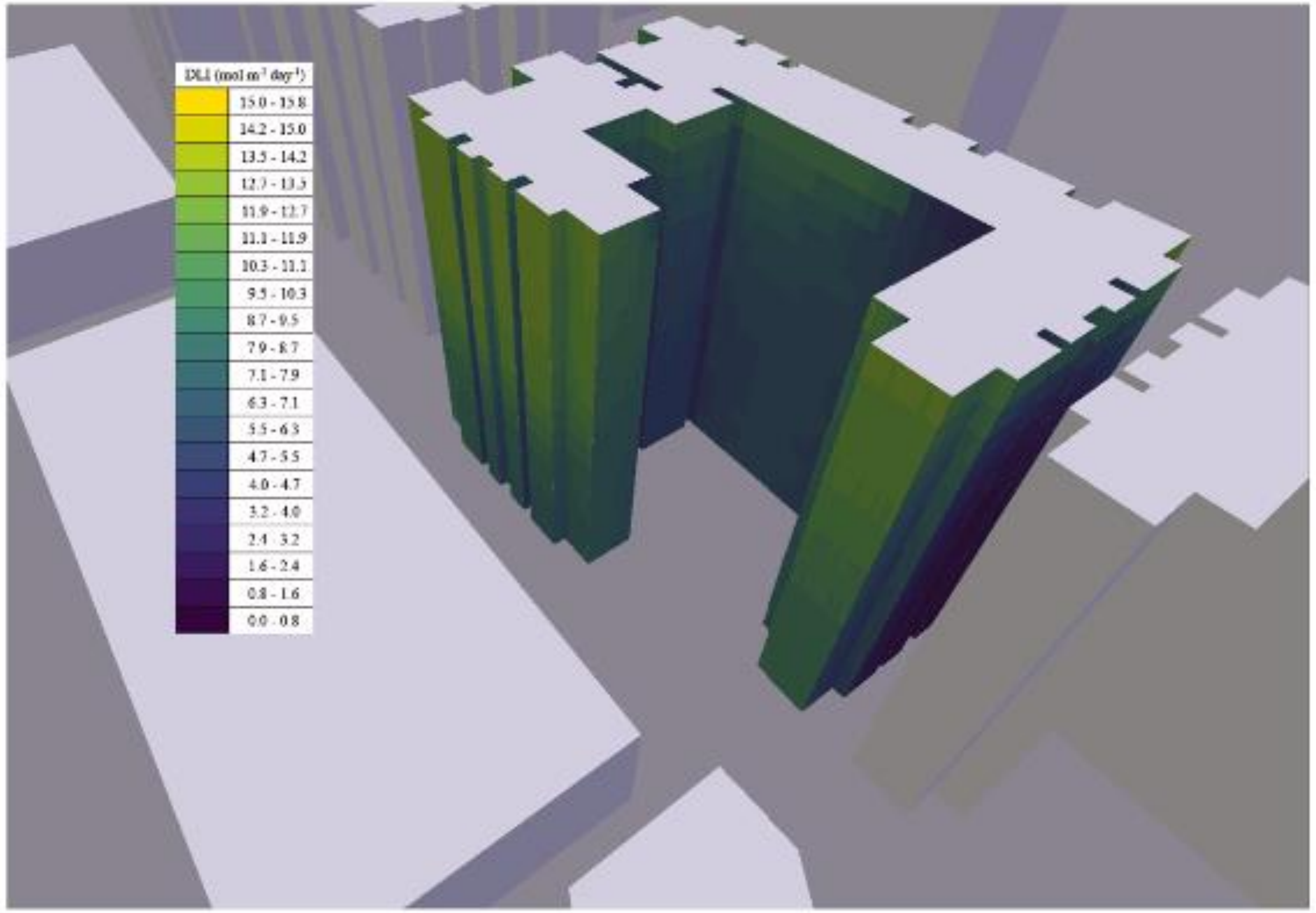
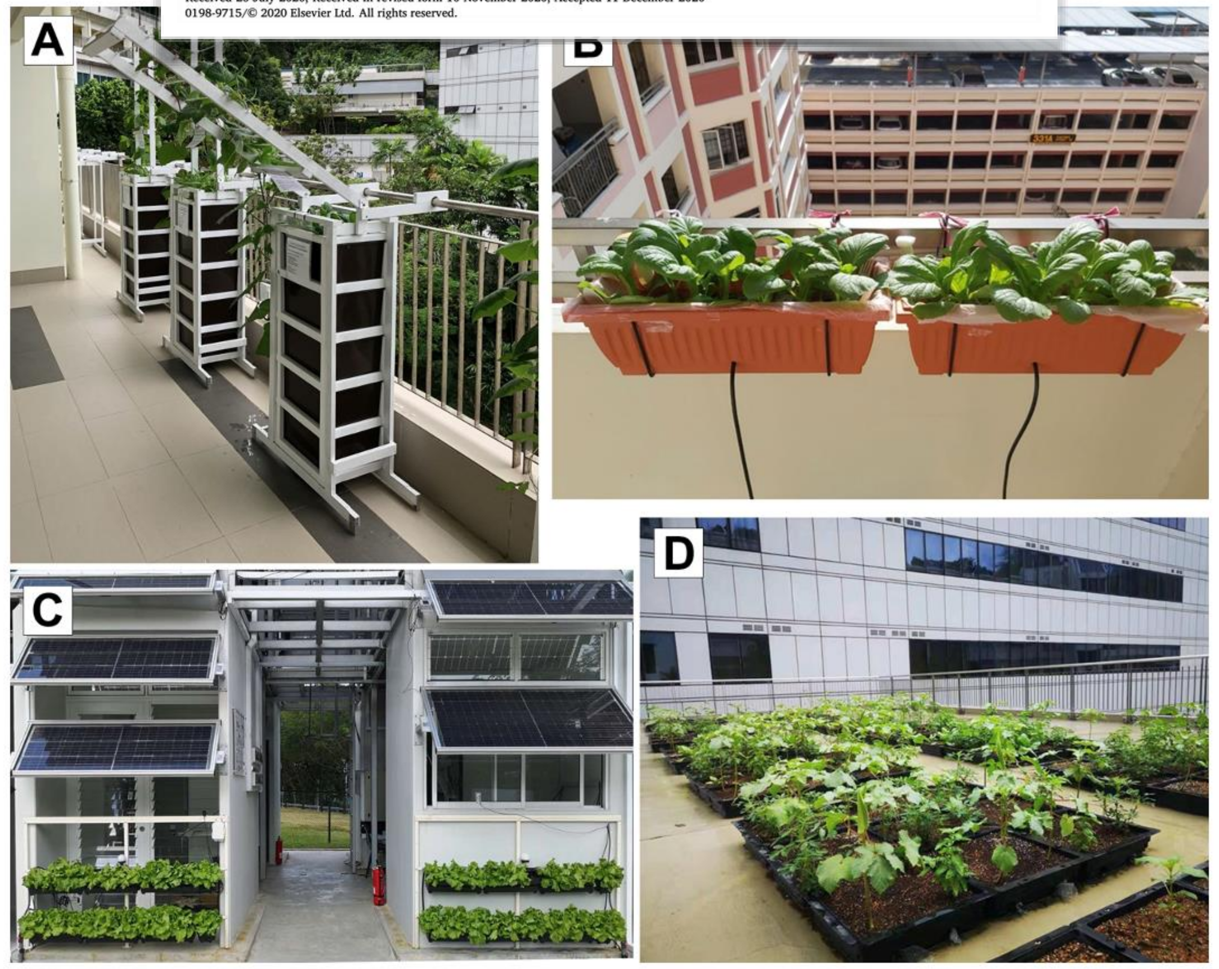
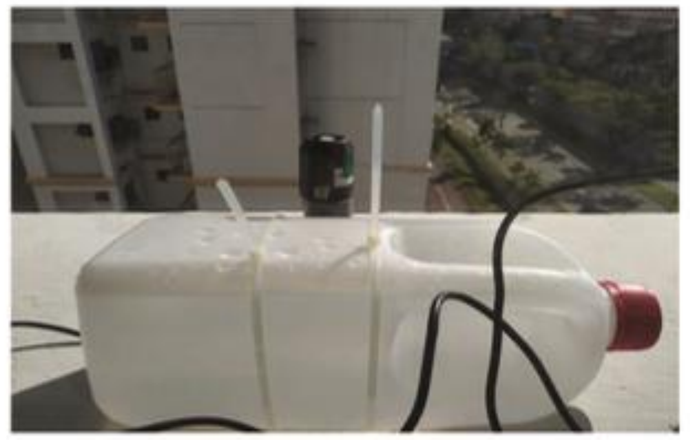






(a) PAR sensor placement along the corridors.



(b) PAR sensor placement on the window ledge.

Credit: Song Shuang

Palliwal A, Song S, Tan HTW, Biljecki F (2021): 3D city models for urban farming site identification in buildings. Computers, Environment and Urban Systems 86: 101584

Conclusion and lessons learned

- Achieving a mature ('true') digital twin is difficult. Real-time/dynamic data and feedback loop remain the key obstacles
- Breaking silos is *de facto* 'a must' but challenging
- DT is well beyond 3D. Marriage of lots of data sources and types that are difficult to integrate and make sense of
  - Novel integration of thermal walks into urban digital twins to analyse and improve pedestrian thermal comfort and walkability in urban environments
    - Wearables, street view imagery, precise weather data, …
- Unlike traditional 3D GIS, DTs entail more attention on stakeholders, organisational issues, business models, …

Acknowledgements: The research is supported by the NUS Resilience and Growth Postdoctoral Fellowship - Smart Cities and Urban Analytics project (funded by the Singapore NRF), the Multi-scale Digital Twins for the Urban Environment: From Heartbeats to Cities project (funded by the Singapore Ministry of Education (MoE) Academic Research Fund Tier 1 grant), the Development of Integrated Multi-scale and Multiphysics Urban Microclimate Model project, and the Supporting Cooling NUS with BEAM initiative project (funded by the National University of Singapore and supported by the University Campus Infrastructure (UCI) and Office of the Deputy President - Research & Technology). Furthermore, we gratefully acknowledge the support of Chua Yun Xuan and Mario Frei for the Cozie administration and technical inquiries.

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Acknowledgements

Team and Alumni: Binyu Lei, Edgardo G Macatulad, Jiani Ouyang, Jintong Han, Koichi Ito, Marcel Ignatius, Mario Frei, Mathieu Bubert, Mengbi Ye, Winston Yap, Yujun Hou, Zeyu Wang, Zicheng Fan, Abraham Noah Wu, Ankit Palliwal, April Zhu, Balakrishnan Naveen Mani Kumar, Chen Shuting, Chen Wangyang, Damon Lim Wei Da, Ethan Chen Wai Hoong, Felix Hammer, Huang Zhiye, Junjie Luo, Kay Lee, Lawrence Chew, Leon Gaw, Li Jialin, Li Yangyang, Liang Xiucheng, Noée Szarka, Pang Hui En, Patrick Ahrend, Pengyuan Liu, Shiyue Zhong, Tianhong Zhao, Wang Jiaxuan, Wang Jing, Wang Shantong, Wang Xinru, Xiaofan Liang, Xinyu Chen, Yan Zhang, Yoong Shin Chow

Funding & support: NUS, Takenaka Corporation, NRF, FCL Global, AWS, Google