

Understanding Cities by Urban Sensing and Analytics

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@Begin Seminar, University of St Andrew
01/04/25

Who I am?

- Undergraduate study (B.E., Remote Sensing, Photogrammetry, and GIS) at Wuhan University (2009-13)
- Postgraduate study at Arizona State University (both M.A. and Ph.D. in GIScience, 2013-17)
- Postdoc training (Social Science and Community Resilience) at Arizona State University (2017-19)
- Urban Studies (UBDC) and University of Glasgow (2019 onwards, associate prof 2022, prof 2024)



My research interest and focus – Cities, Sensors, and Data

- **New forms of data/smart data**
 - Create **research-ready** open/licensed/control datasets for the data service
 - Showcase the possibility of working with these data to answer new or traditional questions in cities
- **(Open-source) Analytical methods**
 - Open source location modelling Python package (**PySAL/spopt**)
 - Sensor-enhanced surveys (longitudinal housing survey, multilingual mobility survey)
 - Open-source deep learning methods for 3D city modeling and building energy efficiency prediction
- **Impact driven research**
 - **Hot-home project** to look at heat inequality in London (Southwark Council and TBIJ)
 - Glasgow **Low Emission Zone** traffic flow and air quality analysis
 - Mobile phone app data to understand human movement during and after pandemic (Glasgow City Council)
 - Analytical strategies for improving third-sector employability services in the post-COVID-19 recovery (the Salvation Army)

Urban Sensing & Analytics - UBDC

■ Current Projects

Housing

- Housing energy efficiency models from urban sensing – drive-by sensing, remote sensing, and AI
- Sensor-enhanced housing survey – ambient sensing, hardware, and social survey/interview
- Glasgow 3D city modelling – LIDAR, deep learning, and data infrastructure

Mobility

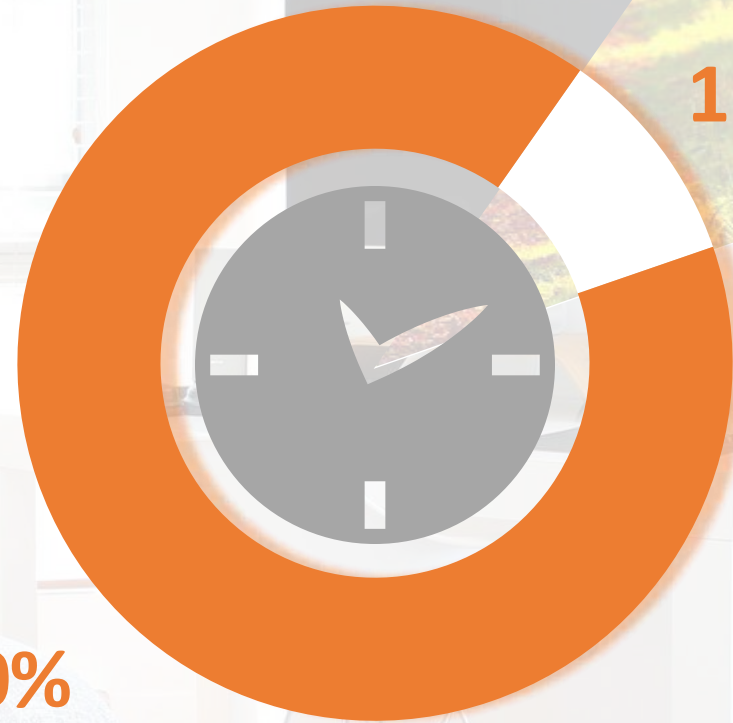
- Glasgow traffic flow and low emission zone analysis (lead by Dr Hyesop Shin)
- New geographies of language in multilingual cities (lead by Prof Bernadette O'Rourke) – portable sensing, AI, and privacy-preserving monitoring
- Exploring the use of urban greenspace by mobile sensing (lead by Dr Michael Sinclair)

Global South

- IDEAMAPS: Urban slum modelling in Nigeria and Kenya (lead by Prof. Joao Porto de Albuquerque) – remote sensing, participatory urban analytics

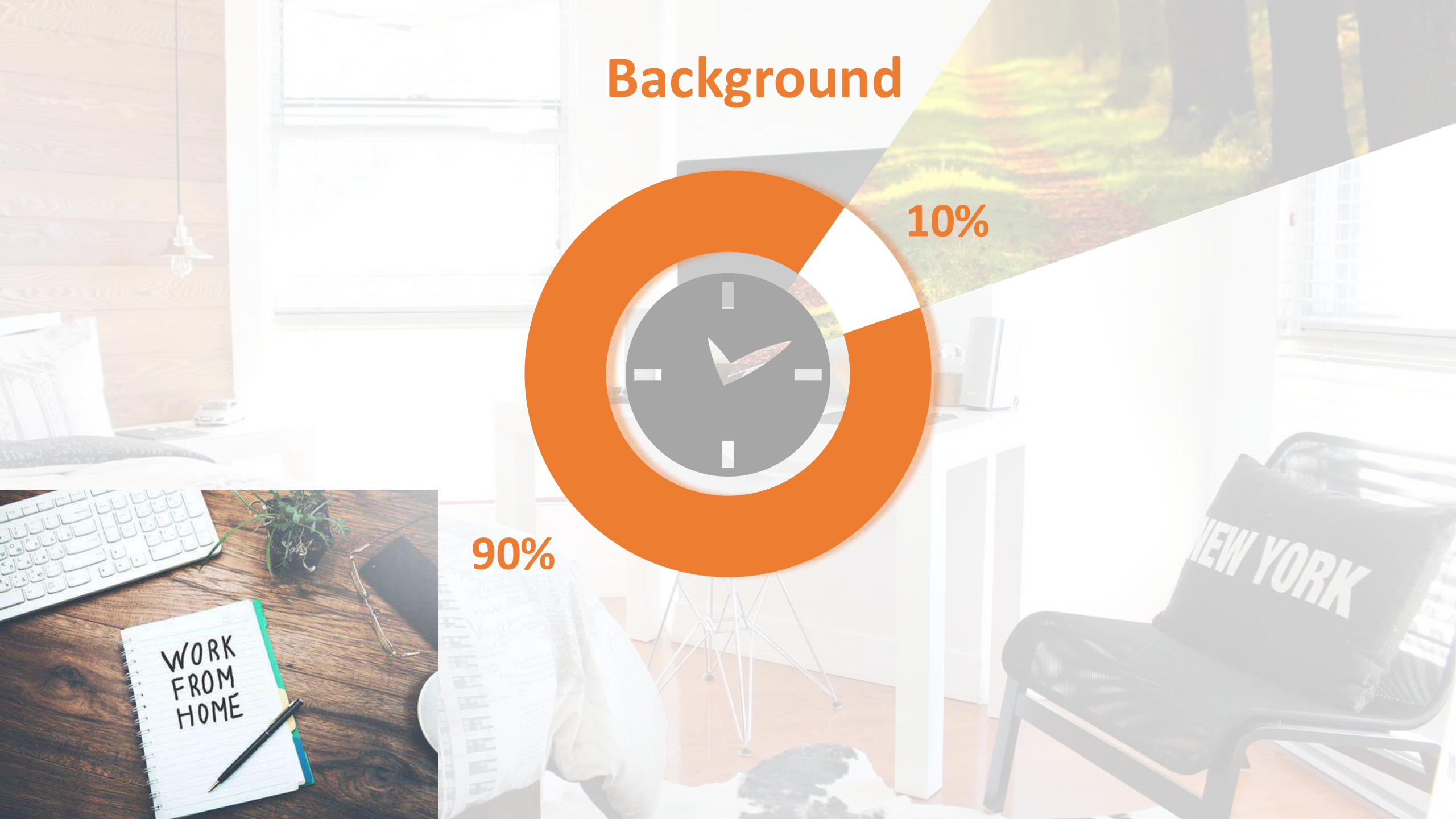


Background



10%

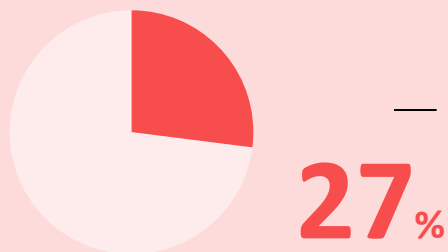
90%



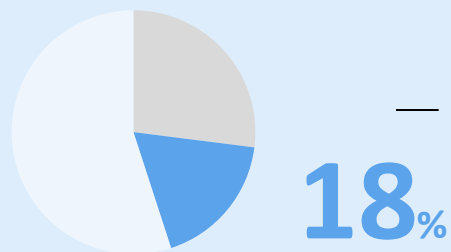
Objective 1: Air quality in the home environment and its impact on health

3.8M people a year die prematurely from illness attributable to the household air pollution (WHO, 2021)

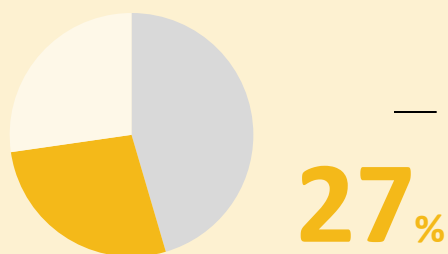
Pneumonia



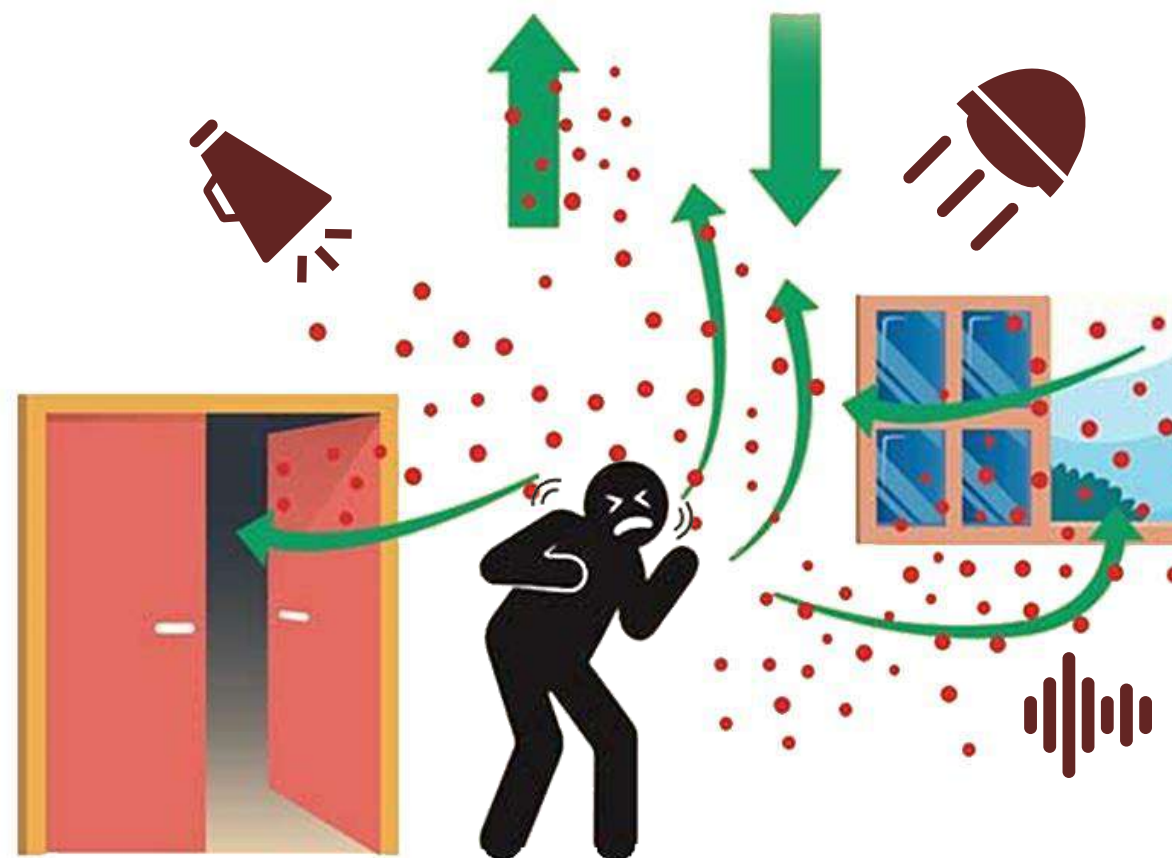
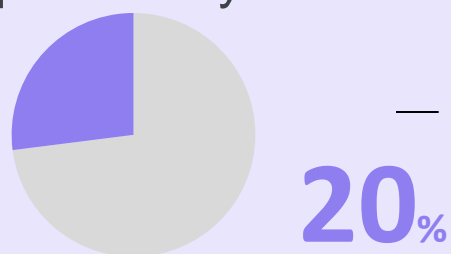
Stroke



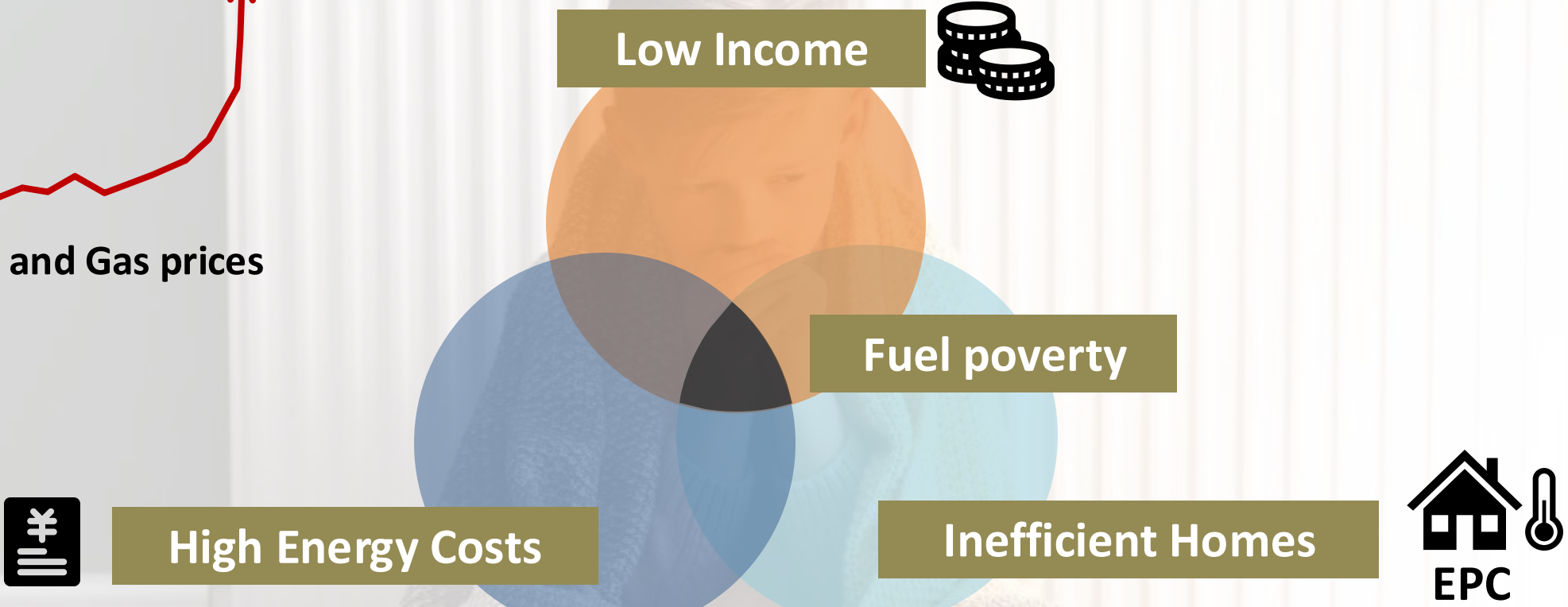
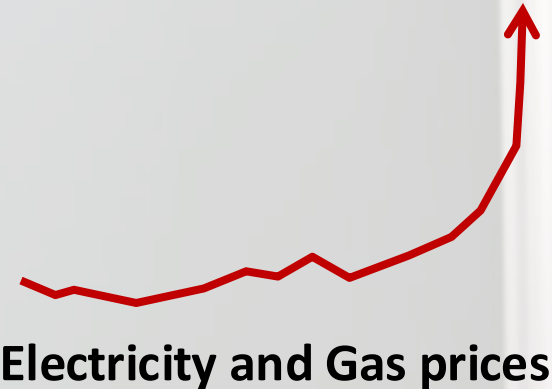
Ischaemic Heart



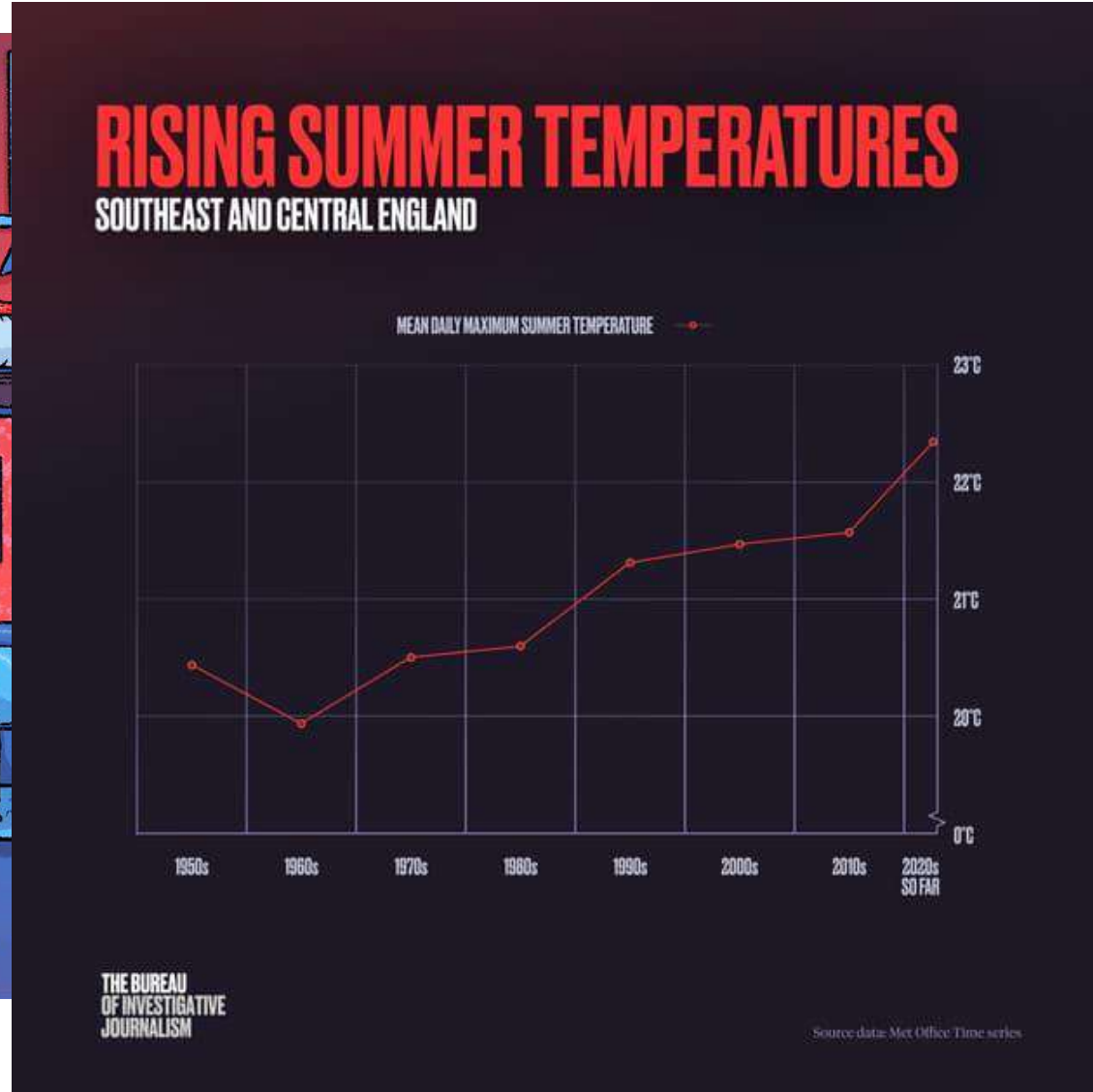
Chronic obstructive pulmonary



Objective 2: Relationship between energy consumption, building energy efficiency, and fuel poverty



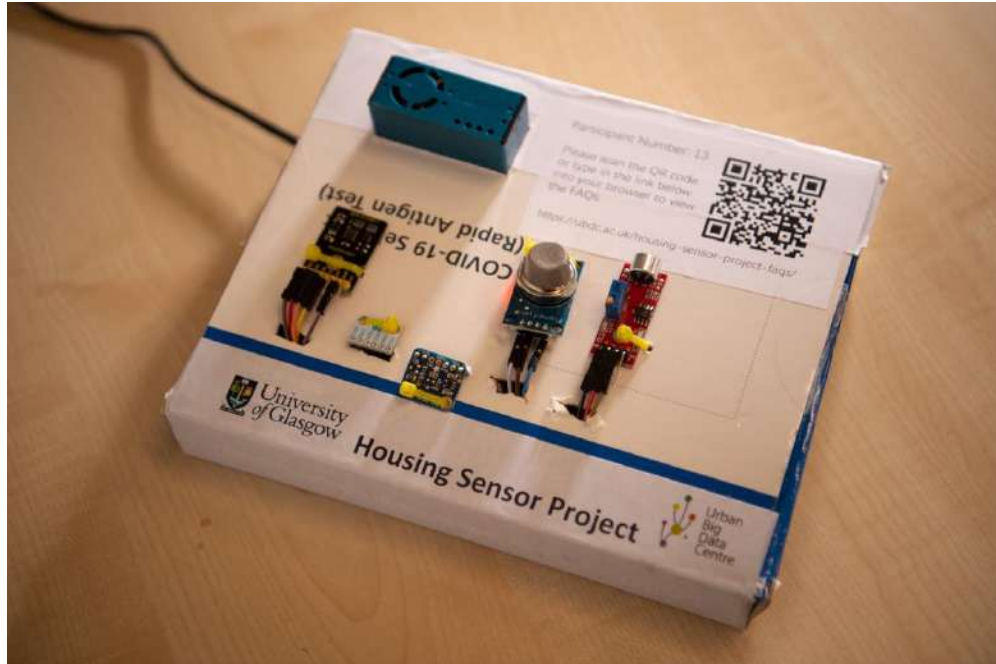
Objective 3: Extreme weather and urban overheating



Sensor-enhanced Housing Survey

- Incorporate integrated indoor housing sensors with UK household longitudinal social survey
 - Arduino or Raspberry Pi based
 - Measure indoor air temperature, relative humidity, and air quality (PM, NO_x, VOC, CO₂, etc.)
 - Light and sound
 - Survey – energy consumption, energy performance, socio-demographics
 - Ideally at an affordable price to allow large scale sensor roll out in the future

Phase 1: Sensor-enhanced Housing Survey - Indoor Environment Monitoring (winter 2021, Glasgow)



SIMD: 3rd

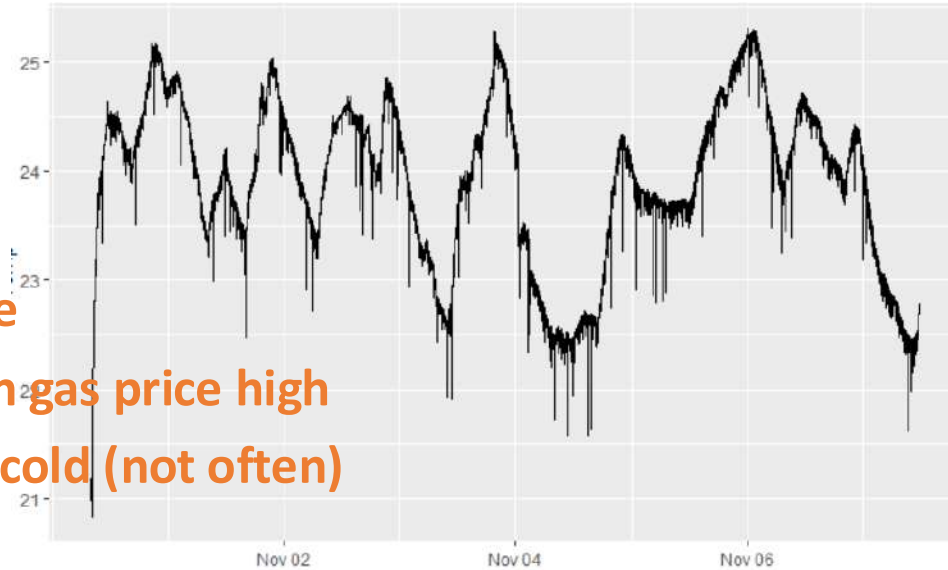
Income ££

Fuel cost £

Turn it off when leave

Reduce heating when gas price high

Go to bed when feel cold (not often)



Social Rent Semi-detached

Double glazing
Gas central heat



EPC: D



Phase 2: Sensor-enhanced Housing Survey - Indoor Environment Monitoring (Summer 2023, London)

- Monitoring **heat wave** in the south of London in 2023 from late July to mid-September
- Focus on elderly people and people with medical conditions
- Besides the physical sensor measurements and social survey, more in-depth interviews around human health were done by TBIJ and multiple media stories and academic outputs will be generated.
- Funded by Impact on Urban Health, Google News Initiative, the Bill & Melinda Gates Foundation and Necessity

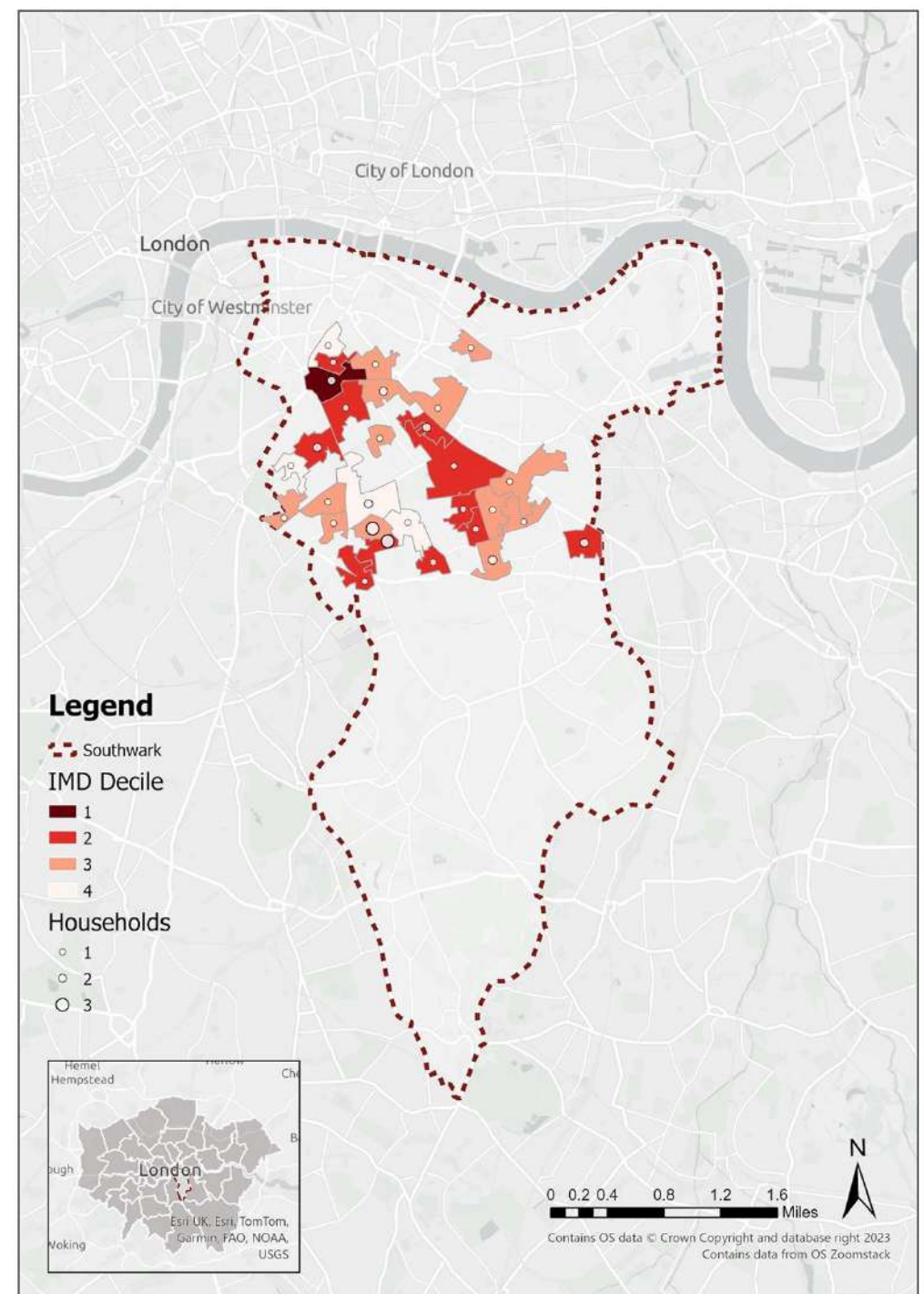


**THE BUREAU
OF INVESTIGATIVE
JOURNALISM**

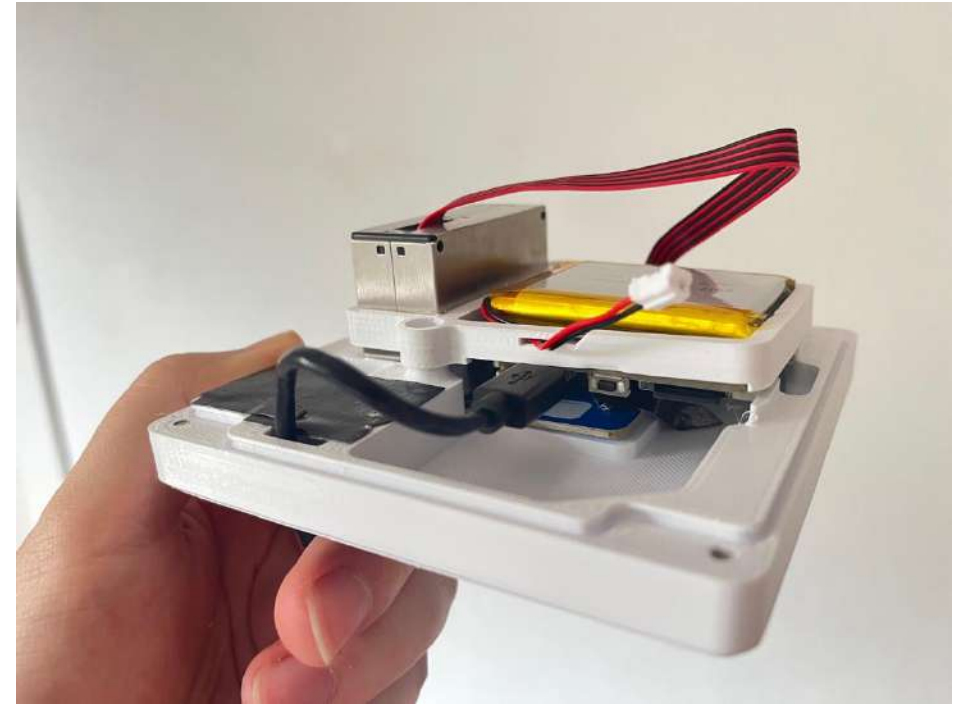
Location

We worked with people in **Southwark**, in inner London, to place monitors in households from late July to early September, which will measure heat, humidity, sound and light intensity, and air pollution.

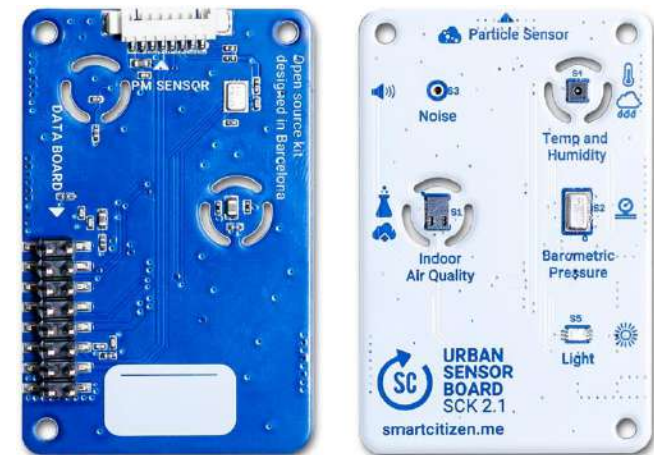
Combining the data from the monitors with people's personal reflections from the survey will show how residents experience heat in their indoor environment.



Sensors

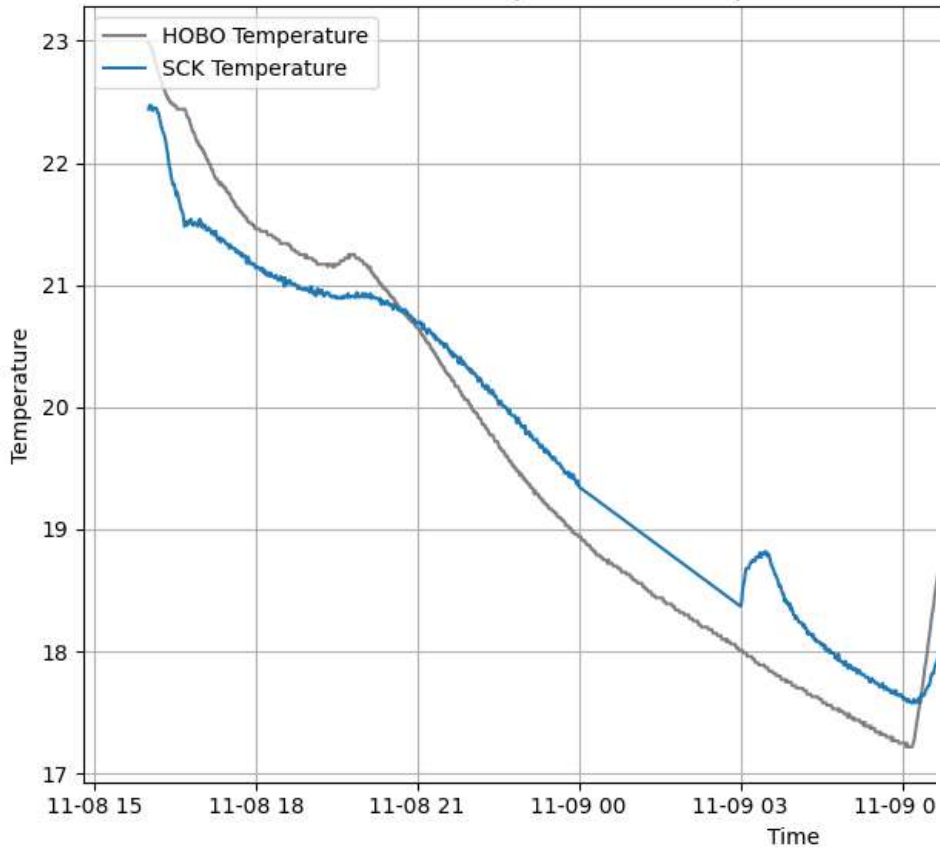


We utilized Smart Citizen kits developed by Fablab Barcelona to monitor and record the indoor environment data.

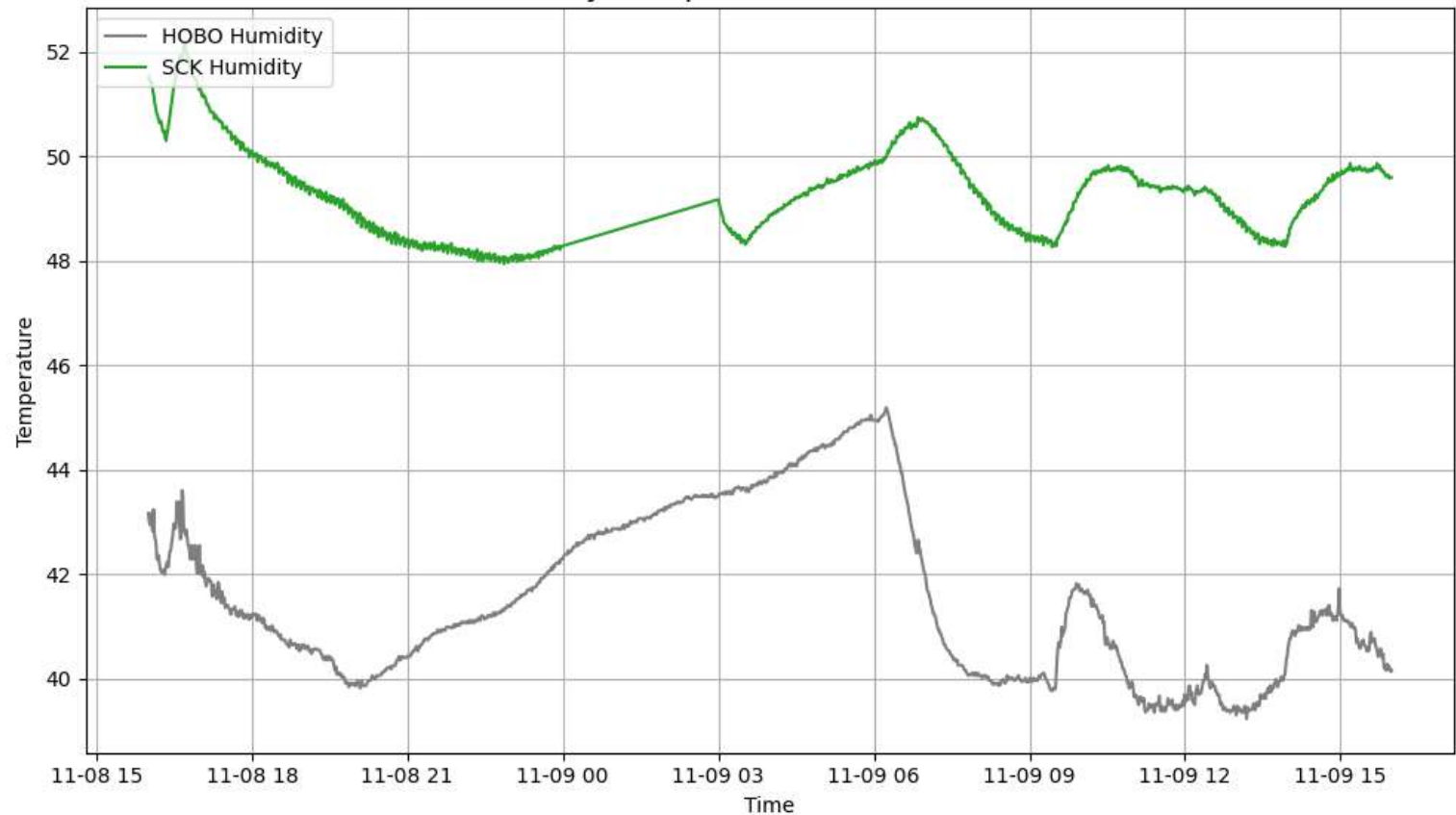


Sensor comparison and validation

Recorded Temperature Comparison Between SCK-52 and HOBO



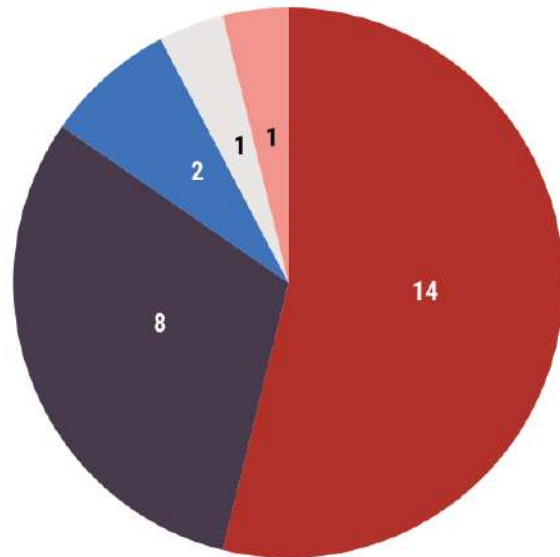
Recorded Humidity Comparison Between SCK-52 and HOBO



Some survey findings

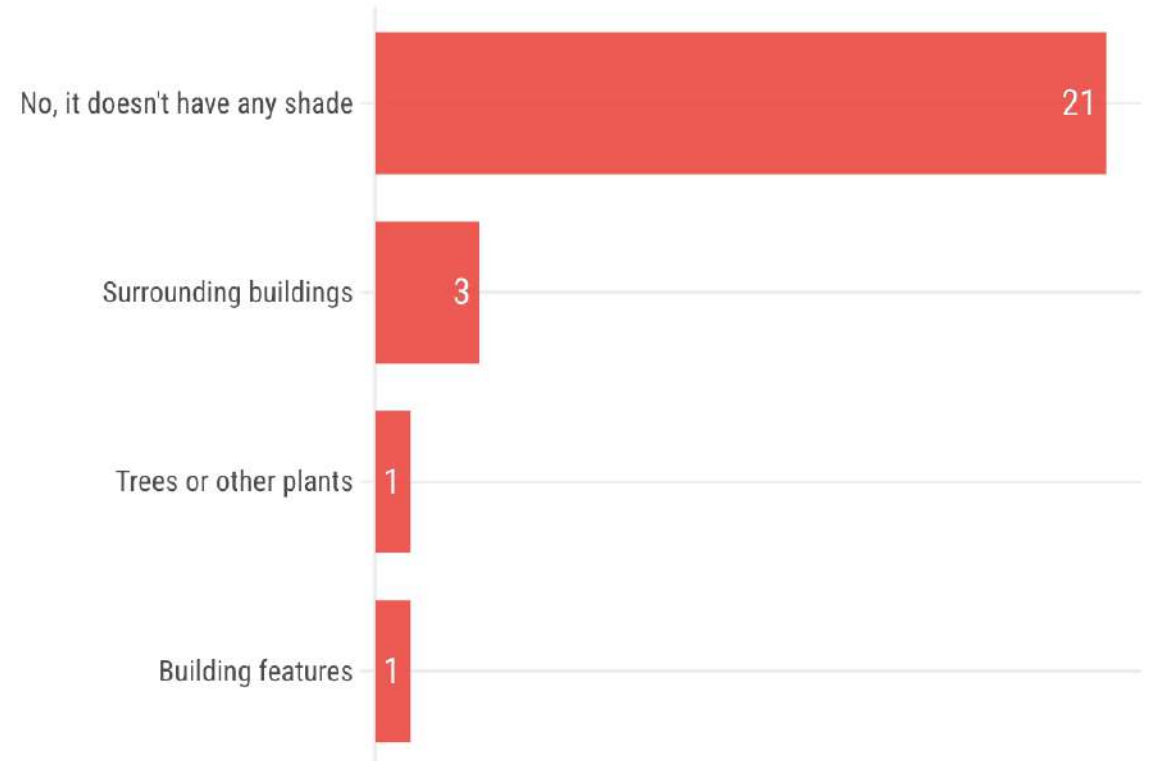
Where participants said was the hottest room in their home

- Bedroom
- Living room
- Office/study/spare room
- Kitchen
- Dining room
- Upstairs hallway



Source: TBIJ survey

What our participants said gives their home shade



Source: TBIJ survey

Mo

On 10 September, the hottest day of 2023, 8 homes were over 32.5C -

Extreme Caution on the Heat Stress Index - and 25 were over 27C, **Caution** on the Index

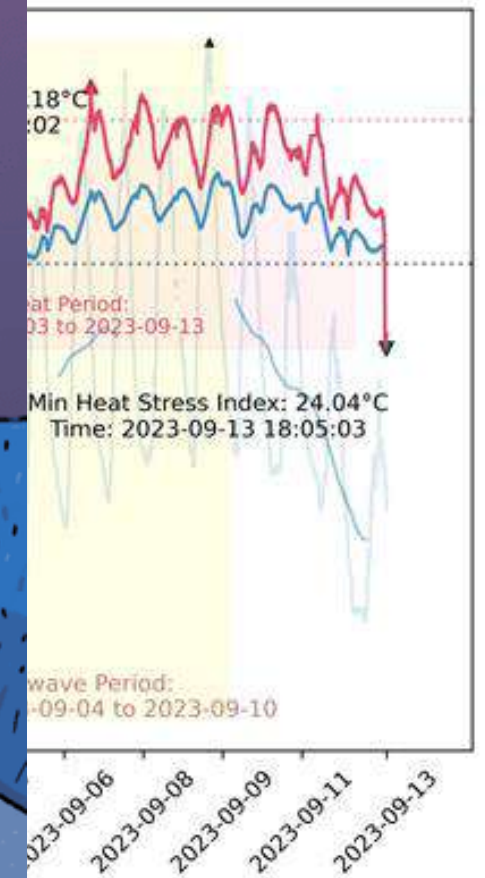
Category	Heat Index
Extreme Danger	130°F or higher (54°C or higher)
Danger	105 - 129°F (41 - 54°C)
Extreme Caution	90 - 105°F (32 - 41°C)
Caution	80 - 90°F (27 - 32°C)

Temperature (°C)



old

Heatwave



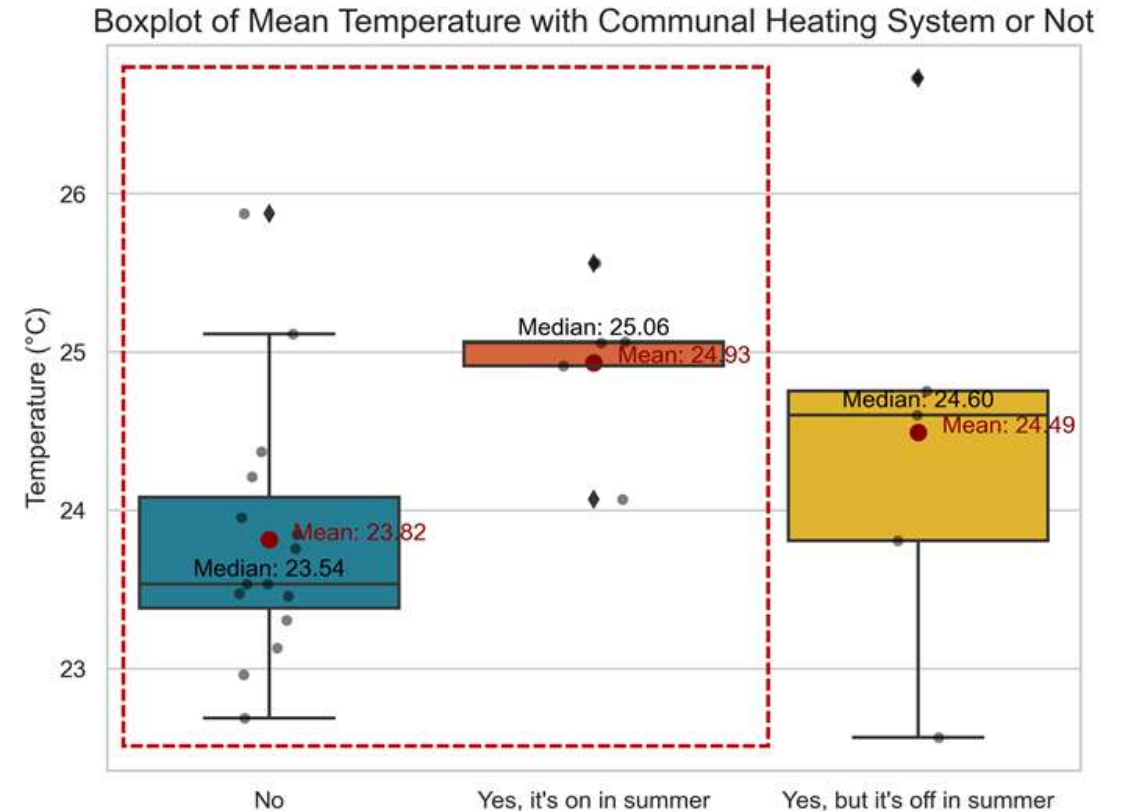
<https://www.thebureau.org.uk>
Heat stress index: <http://www.met.rdg.ac.uk/~hpa14/heatstress/>

summers-on-uk-housing

Communal/district heating

Out of the **40 available Smart Citizen Kit sensors**:

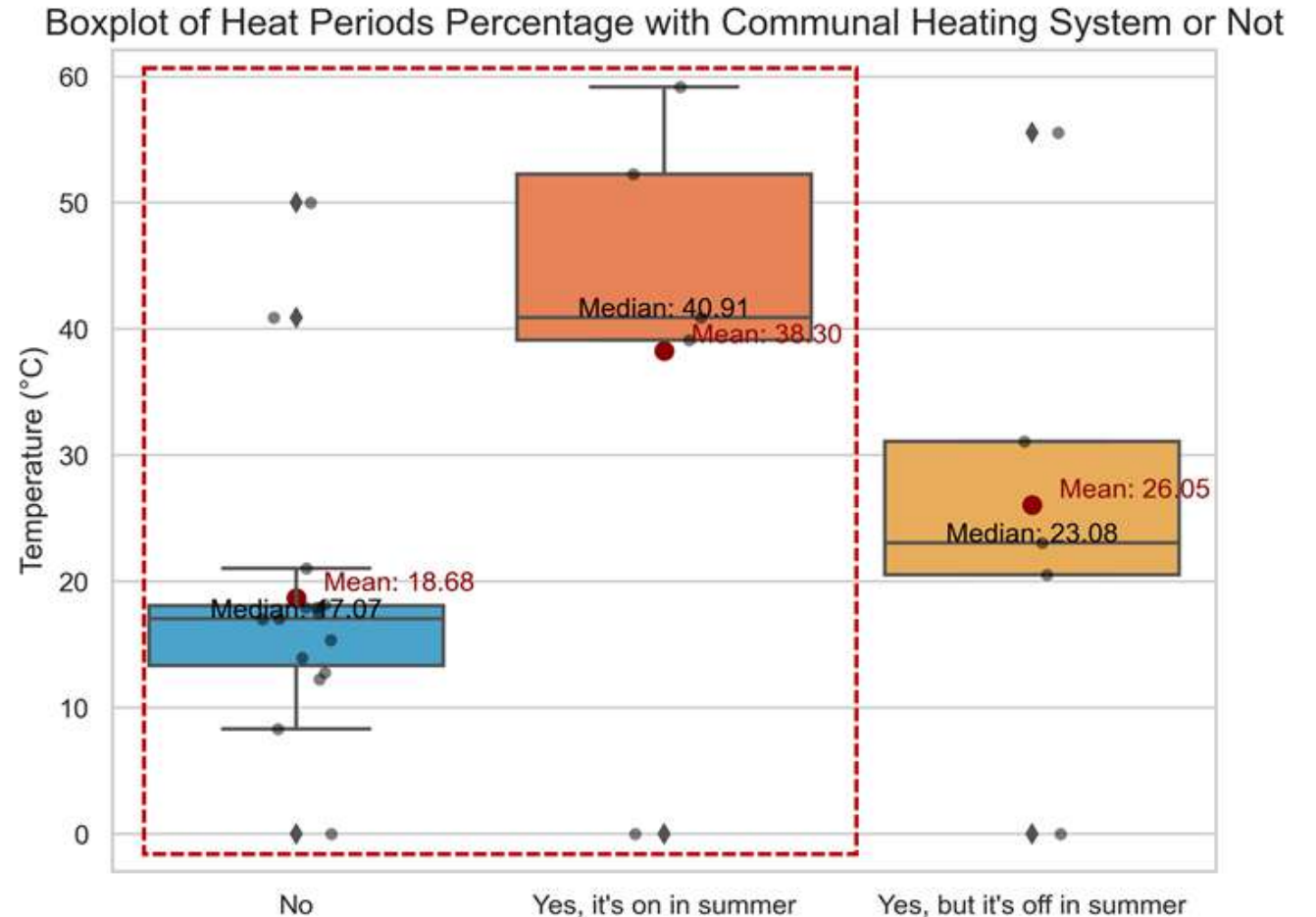
- **25 households** provided information about their communal heating status.
- **15 households** have no communal heating system.
- Among the **10 households** with a communal heating system, only 5 households can turn off their system during the summer.



Communal/district heating

The sustained heat period here is defined as more than 3 continuous days of **average daily rolling mean temperature higher than 25 Celsius degrees.**

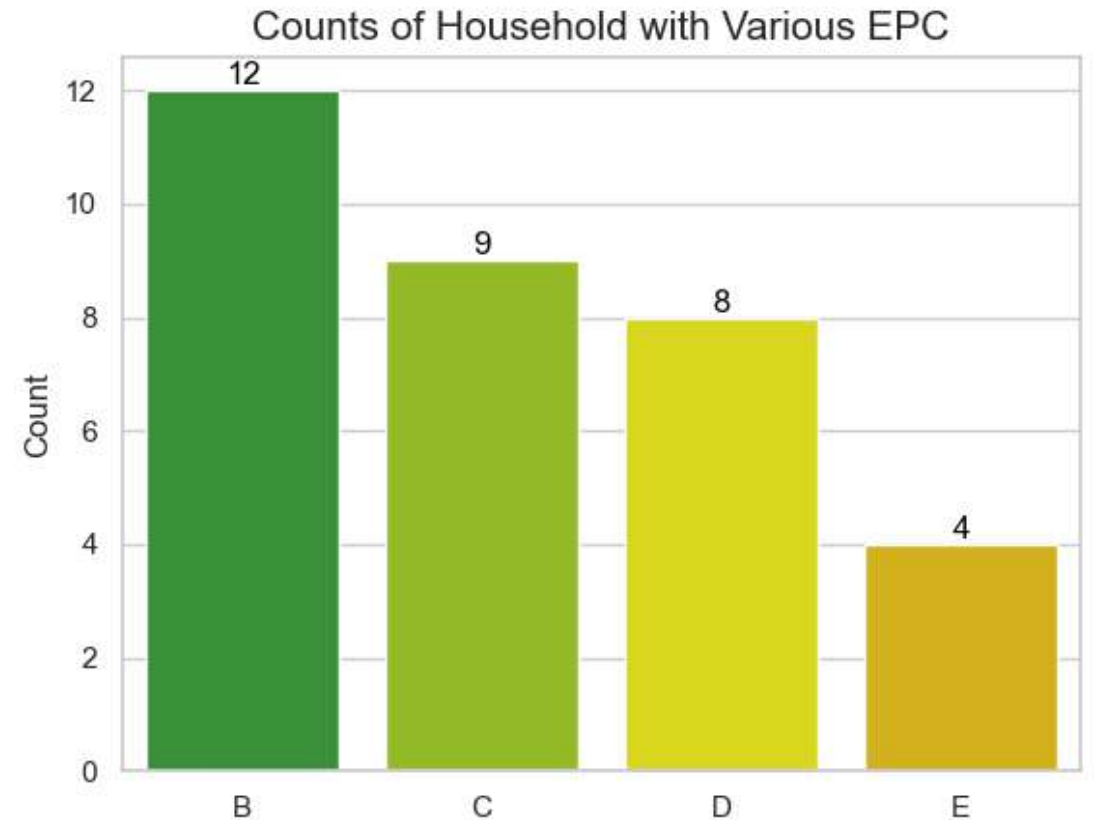
The households who cannot turn the communal heating off experienced an **average 20%** more for the sustained heat period during our monitoring time.



Housing energy efficiency and summer heating

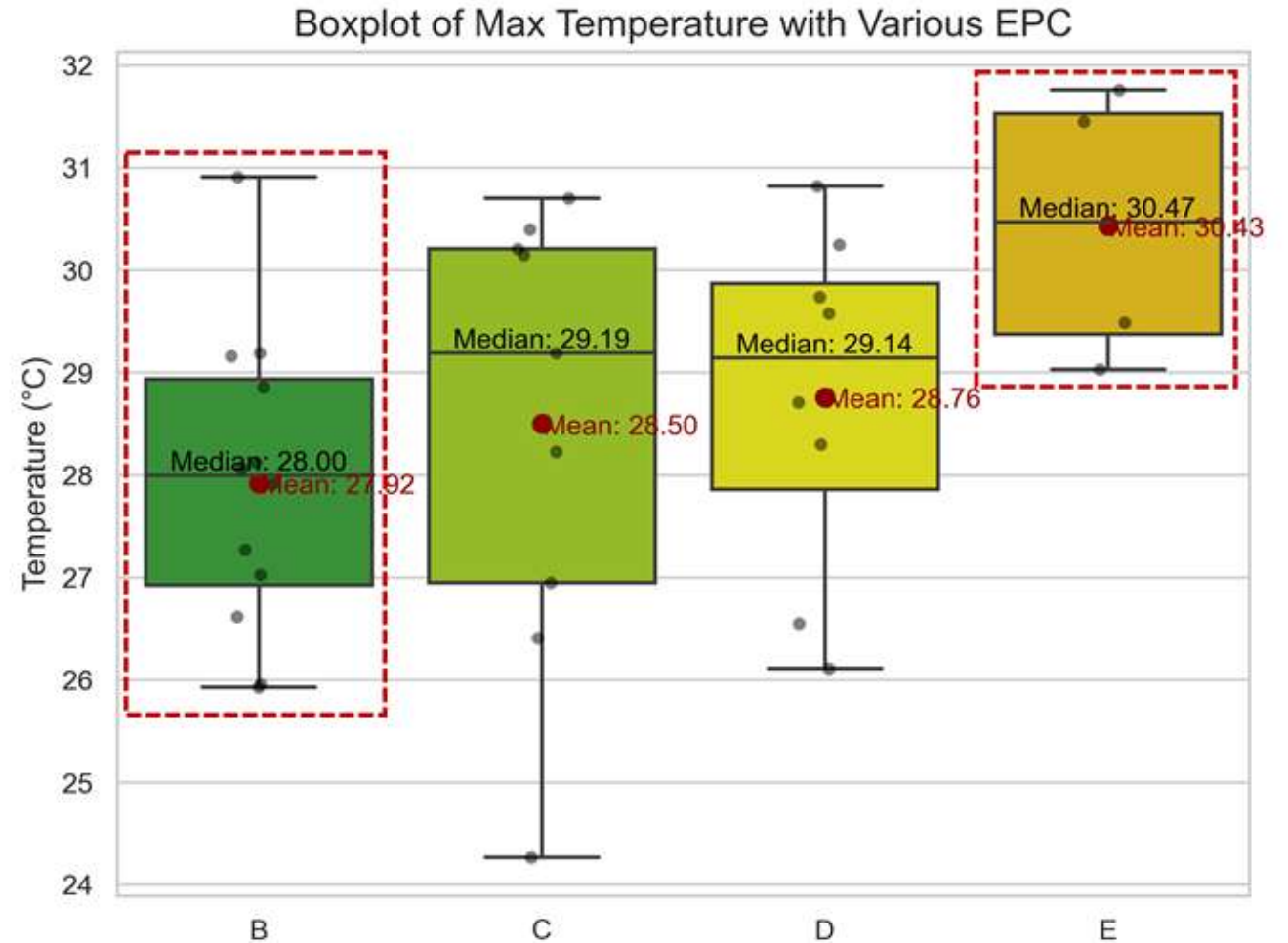
Out of the **40 available Smart Citizen Kit sensors**:

- **33 households** have valid Energy Performance Certificates (EPC).
- **7 households** have no EPC information.



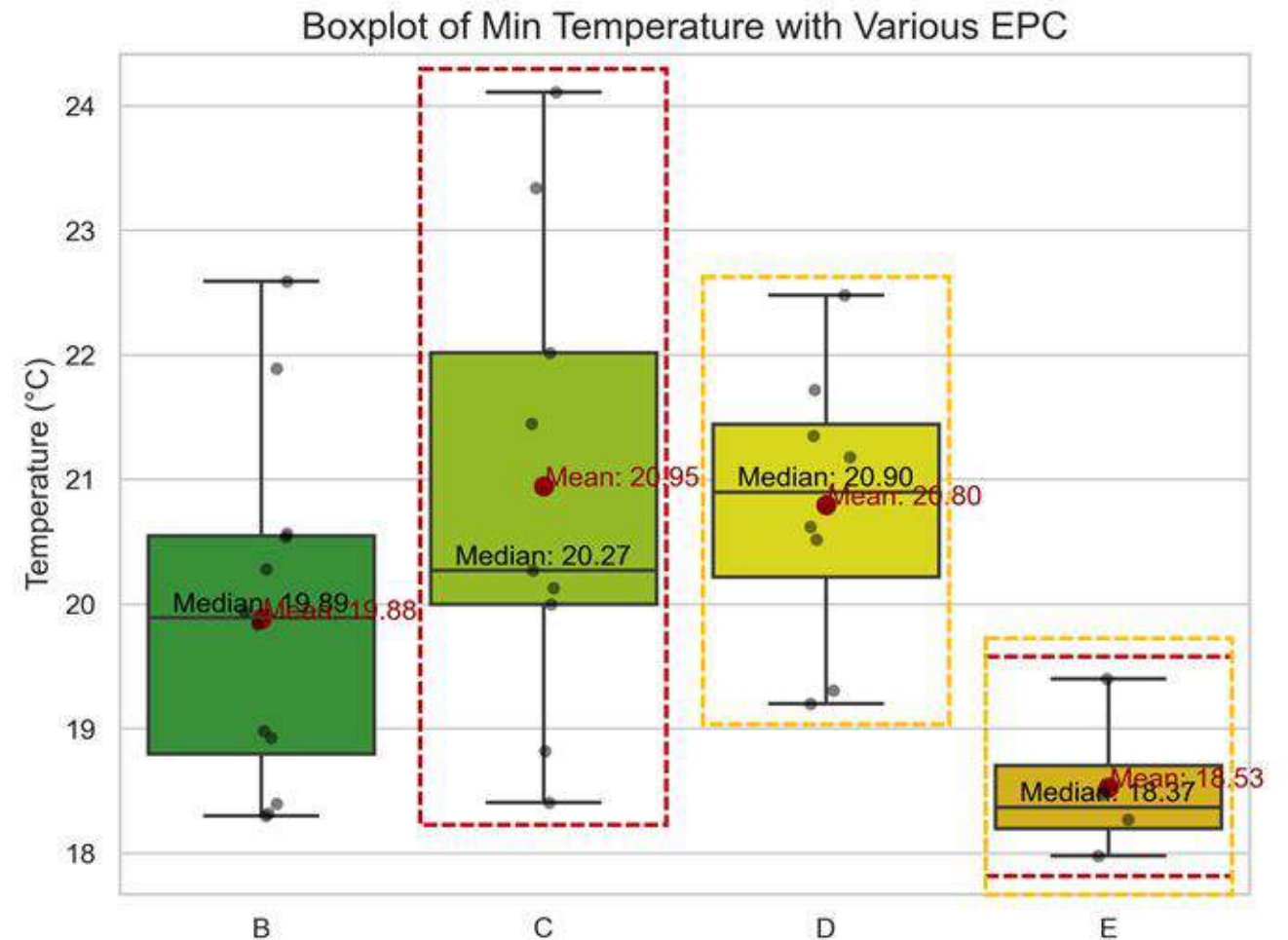
Housing energy efficiency and summer heating

- In the UK, most of the attention has been given to **winter heating** and there is **no AC system**.
- Well-insulated houses can “**trap**” heat inside if there is no effective **ventilation** during the summer
- Assumption: the temperature in better energy efficiency houses (with higher EPC) will **fluctuate less** compared to poor energy efficiency houses
- **EPC E houses have almost 3 Celsius degree higher maximum temperature than EPC B houses**



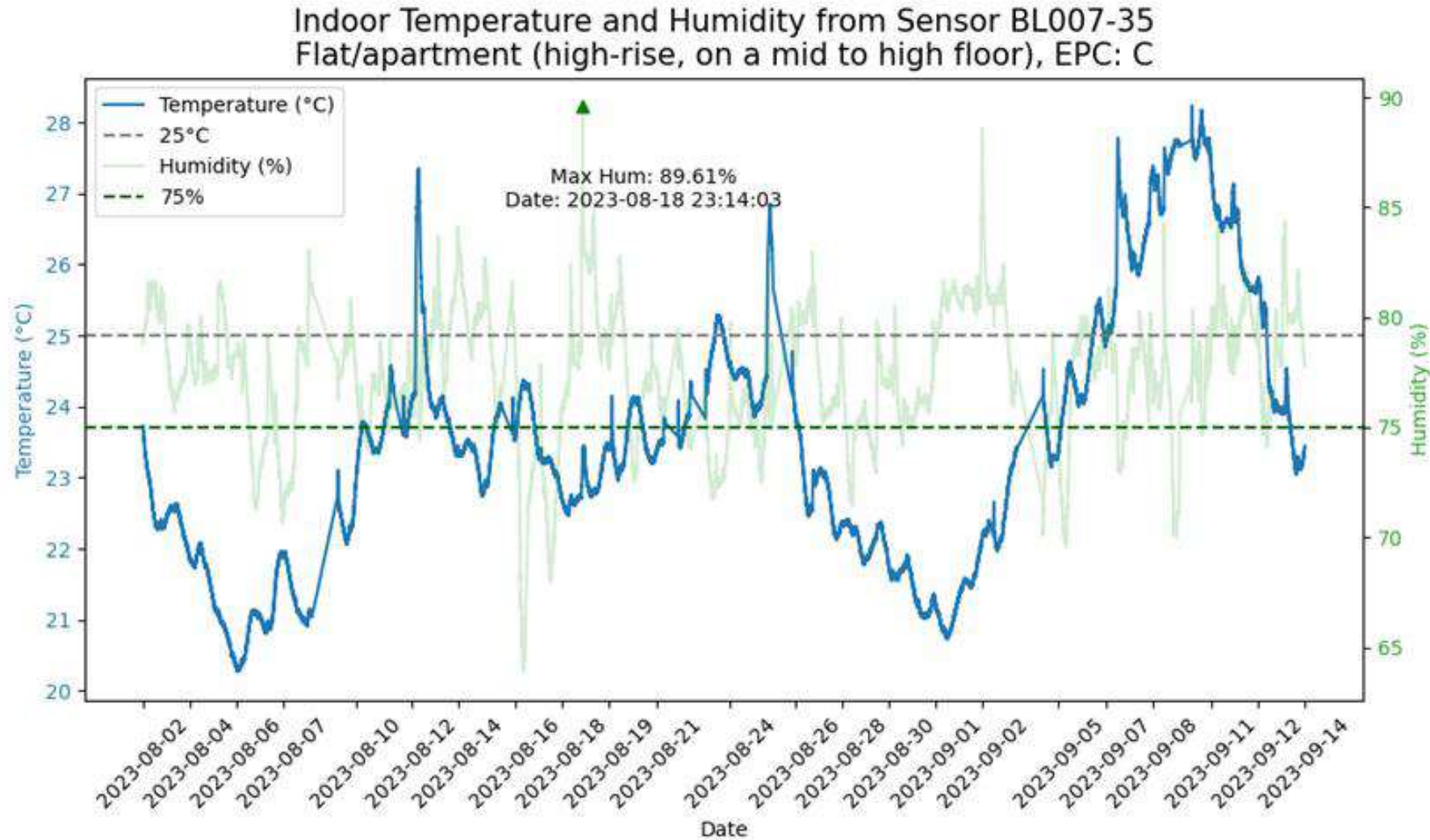
Housing energy efficiency and summer heating

- EPC C/D houses have about 2.5 Celsius degree higher Minimum temperature compared to EPC E houses
- Poorly insulated houses cool down quickly at night during the summer but become much hotter during the heat wave.



Mould detection

- From the WHO guidelines, a building should maintain **a relative humidity below 75%** to limit fungal growth.
- The finding from the sensor reading opens the door for using this type of indoor environment sensor to establish a **mould growth warning system**.



Data availability

- We have published open datasets in our UBDC data service.
- It contains the 40 indoor sensor measurement data and the look-up table to link the sensor data with the TBIJ survey and EPC.

Data and Metadata



Combined survey, EPC, and sensor ID look up table

Combined survey, EPC, and sensor ID look up table. During the summer months...

MORE INFORMATION

DOWNLOAD



Combined survey, EPC, and sensor ID look up table metadata

Combined survey, EPC, and sensor ID look up table metadata

MORE INFORMATION

DOWNLOAD



Household indoor sensor measurement data

During the summer months from July 2023 to September 2023 (including a mini...

MORE INFORMATION

DOWNLOAD



Household indoor sensor measurement metadata

Metadata for Household indoor sensor measurement data.

MORE INFORMATION

DOWNLOAD

Data availability

- We have linked the sensor data with the building EPC data if it exists in the open EPC database.
- We published licensed data that includes the building age and building insulation conditions from EPC. You can apply it via the UBDC data service.

This licensed dataset comprises building insulation and building age data in our survey households, linking with the open EPC dataset. You can access the [open dataset](#) to link them together for further usage. The unique ID is utilized as a linking mechanism between the SCK sensor data and the TBIJ survey data.

Existing Energy Performance Certificate (EPC) data is used to create this licensed dataset, based on the participants' home addresses and Unique ID, providing the energy conditions of homes. The EPC data was collected from [Energy Performance of Buildings Search Results](#)

Data and Metadata



Sensor-Enhanced Housing Survey Data for Urban Heat Investigation

-...

Metadata record for Sensor-Enhanced Housing Survey Data for Urban Heat...

 **PREVIEW**

 **DOWNLOAD**

<https://data.ubdc.ac.uk/dataset/sensor-safeguarded>

Data availability

You can cite our dataset and conference paper as follows:

Zhao, Q., Hu, C., Ou, Y., Livingston, M., Wang, M., Hamada, R., & Eccles, P. (2023). *Sensor-enhanced housing survey data for urban heat investigation* [Data Collection]. Urban Big Data Centre. <https://data.ubdc.ac.uk/dataset/sensor-enhanced-housing-survey-data-for-urban-heat-investigation>

Ou, Y., Hu, C., & Zhao, Q. (2024). Investigating the Impact of Housing Energy Efficiency on Indoor Environment at the Overheating Summer – A Study in Southwark, London. 32nd Annual Geographical Information Science Research UK (GISRUK), Leeds, United Kingdom. <https://doi.org/10.5281/zenodo.10926876>

Open methods and news reporting

Data

There are three datasets in the data folder: [Household Indoor Sensor Measurement Data](#), [SensorID_EPC_Survey_Open_Data](#), and [LIMBO \(Weather Station\) Data](#).

Please note that, for a specific section of the analysis in 'Analysis_for_UBDC_Report.ipynb' file, the communal heatmaps are shown directly, we have showcased the plots and results.

Household Indoor Sensor Measurement Data

This folder includes a variety of environmental parameters such as air temperature, relative humidity, air quality, CO2 level, etc.

SensorID_EPC_Survey_Open_Data

This csv file includes the IDs of the sensors, selected sensor locations, and [Energy Performance Certificate \(EPC\) ratings](#).

LIMBO (Weather Station) Data

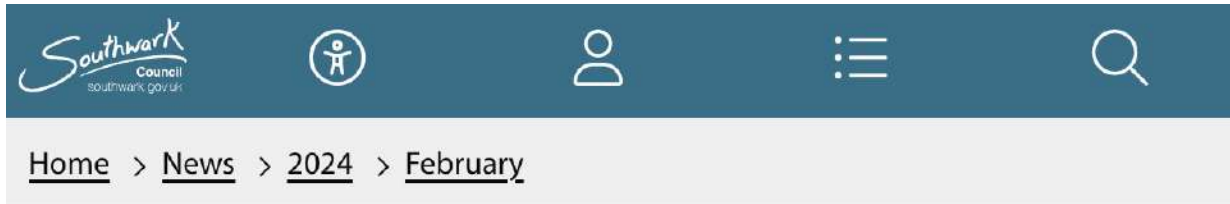
This csv file contains outdoor weather observation data.

News, Reports, and Resources

Find our detailed findings and analysis in the following news reports:

- **The Bureau of Investigative Journalism (TBIJ):** ['Stifling, suffocating, unliveable': Life in an overheating home; Revealed: escalating effects of hot summers on UK housing; The rising danger of hot summers; District heating leaves London residents sweltering during heatwave](#)
- **Urban Big Data Centre (UBDC):** [UBDC data analysis reveals concern for the UK's overheating homes and Sensor-enhanced housing survey for urban heat investigation](#)
- **Mirror:** [UK's overheating summer health crisis as half of UK homes hit 'sauna-like' temperatures](#)
- **Southwark Council:** [£1 million of funding to combat flooding and overheating in Southwark](#)
- **Impact on Urban Health:** [How overheating homes are turning the climate crisis into a health crisis](#)
- **University of Glasgow:** [Data Analysis Reveals Concern for the UK's Overheating Homes](#)
- **UBDC Research Page:** [Sensor Enhanced Housing Survey](#)

Research impact generation



£1 million of funding to combat overheating

6 February

A detailed action plan has been produced with a number of actions that build on resident feedback – such as developing an approach to address ‘hot homes’ in the borough. Something also highlighted by engagement with the Bureau of Investigative Journalism, whose [landmark study revealed the escalating effects of summers on UK housing.](#)

Southwark Council will invest £1 million in climate change projects that will protect the borough’s most vulnerable areas against the worst impacts of the climate crisis. This announcement is to help deliver the Climate Resilience and Adaptation Strategy, which after a period of consultation in the autumn, has been adopted by cabinet.



Phase 3: Understanding Society Innovation Panel (July 2024 to April 2025, ongoing)

- We have rolled out our sensors to 190 households through the Understanding Society Innovation Panel (UK “gold-standard” longitudinal social survey).
- Besides the social survey from USoc, we also collaborate with the UCL Smart Energy Research Lab/Energy Demand Observatory and Laboratory. We will link environmental sensor reading, social survey, and smart metre reading as a brand-new dataset.
- A new design of the sensor from Fablab Barcelona is used in this year’s survey, and they did the sensor lab calibration for our project.
- The final working paper and data will be released in summer 2025.



<https://www.understandingsociety.ac.uk/participants/projects/sensor/>
<https://edol.uk/>
<https://serl.ac.uk/>



Phase 3: Understanding Society Innovation Panel (July 2024 to April 2025, ongoing)



Future work

- We are developing a new generation of SCK sensors with the **LoRa-capability**. It will allow **zero infrastructure sensor network communication**, and make it possible to do long-term and low-cost environmental monitoring.
- Further work will be devoted to analysing the collected dataset, to understand emerging research questions including fuel poverty, working from home efficiency, and indoor health monitoring.

Building energy efficiency

- **Within EU**

The building sector accounts for around 40% of the union's energy consumption and 36% of its greenhouse gas (GHG) emissions.

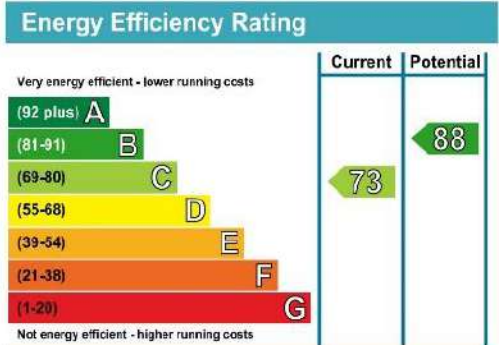
- **EPC Regulations in Scotland**

The Scottish government has dropped the original EPC minimum regulations. By 2028 (private landlords) and 2033 (owner-occupiers), they need to meet minimum energy efficiency standards (still in consultation).

The consultation proposes that this list could be:

- 270 mm loft insulation;
- cavity wall insulation;
- draught-proofing;
- heating controls;
- 80 mm hot water cylinder insulation;
- Suspended floor insulation

Energy Efficient Scotland
The Energy Efficiency (Domestic Private Rented Property)
(Scotland) Regulations 2020 and Draft Associated Guidance
Business and Regulatory Impact Assessment



Background

- **Current methods for energy analysis and estimation**

- Engineering calculation

- Simulation model-based benchmarking

- Data-driven statistical modellings

- Multiple Linear Regression

- **Artificial Neural Networks (deep learning)**



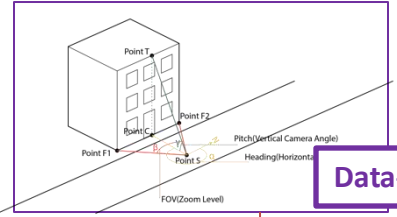
Limitations:

Data availability at large scale

Hard to incorporate human factors such as occupants' numbers without survey

Missing energy consumption data

Existing Research

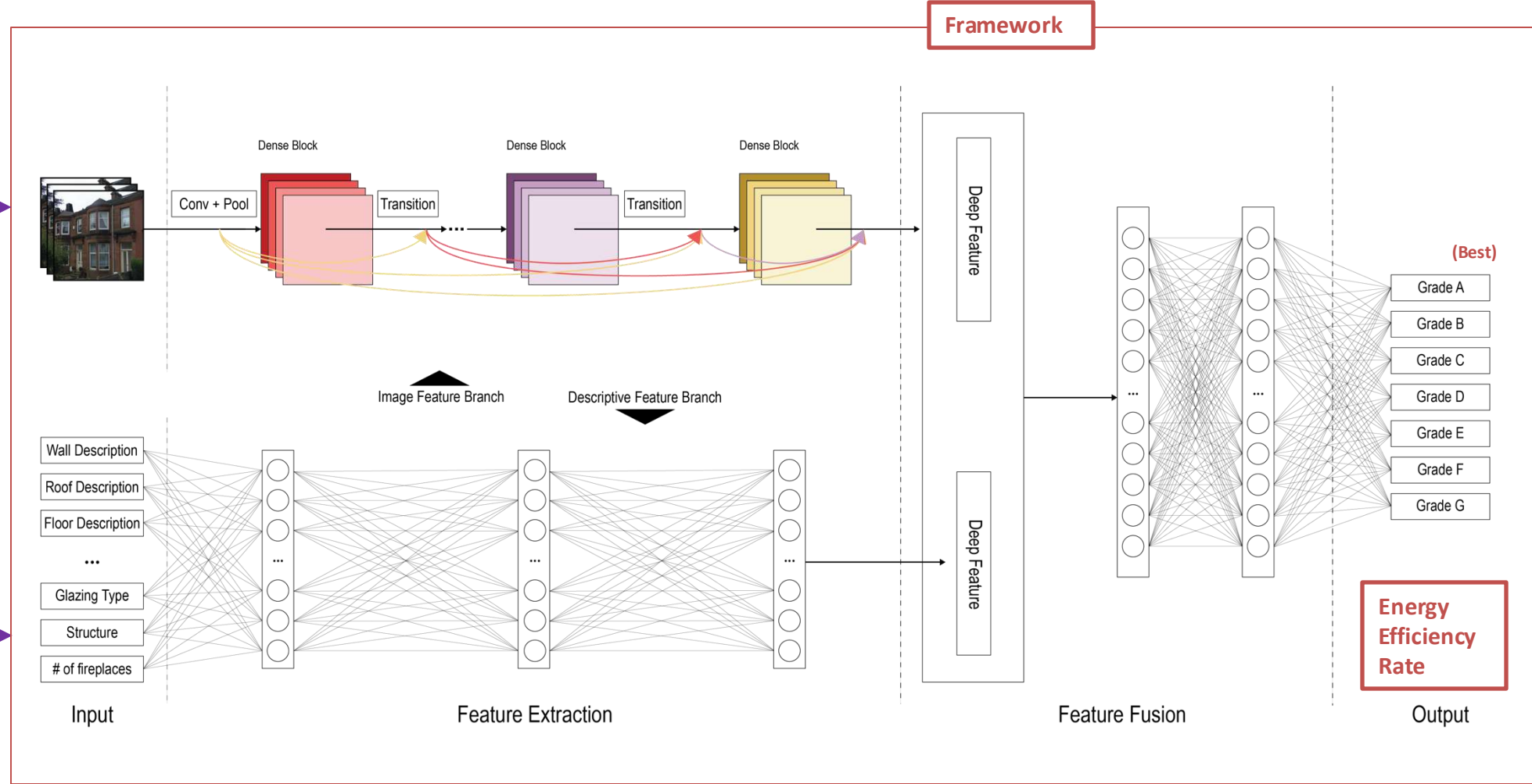


Data-GSV

Link by footprint from Geomni UK Buildings

Scottish Government
Energy Performance Register
Publication of Energy Performance Data for Domestic Buildings
Dataset - Q4 2012 to Q2 2021 - September 2021

Data-EPC



Framework

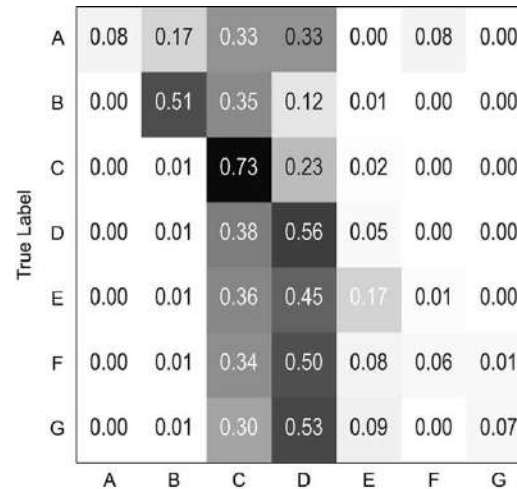
Energy Efficiency Rate

(Best)

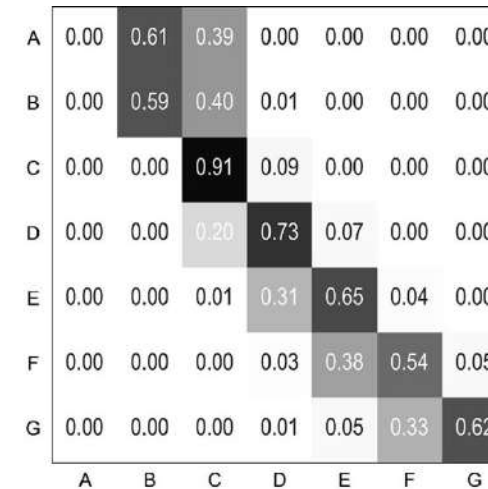
Existing Research

- Performance & Confusion Matrix

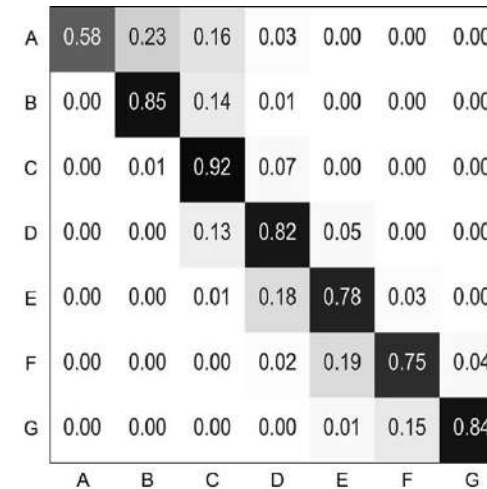
Input	Test Accuracy
Street View Images Only (External)	57%
EPC Features Only (Internal)	80%
Combined dataset (External + Internal)	88%



a. Image Feature Model



b. Descriptive Feature Model



c. Feature Fusion Model

Existing Research

- Using aerial images, street view images, 30 m thermal image from Landsat, and open street map as the building footprint.
- It was only classified into two classes at a precision of 68%.

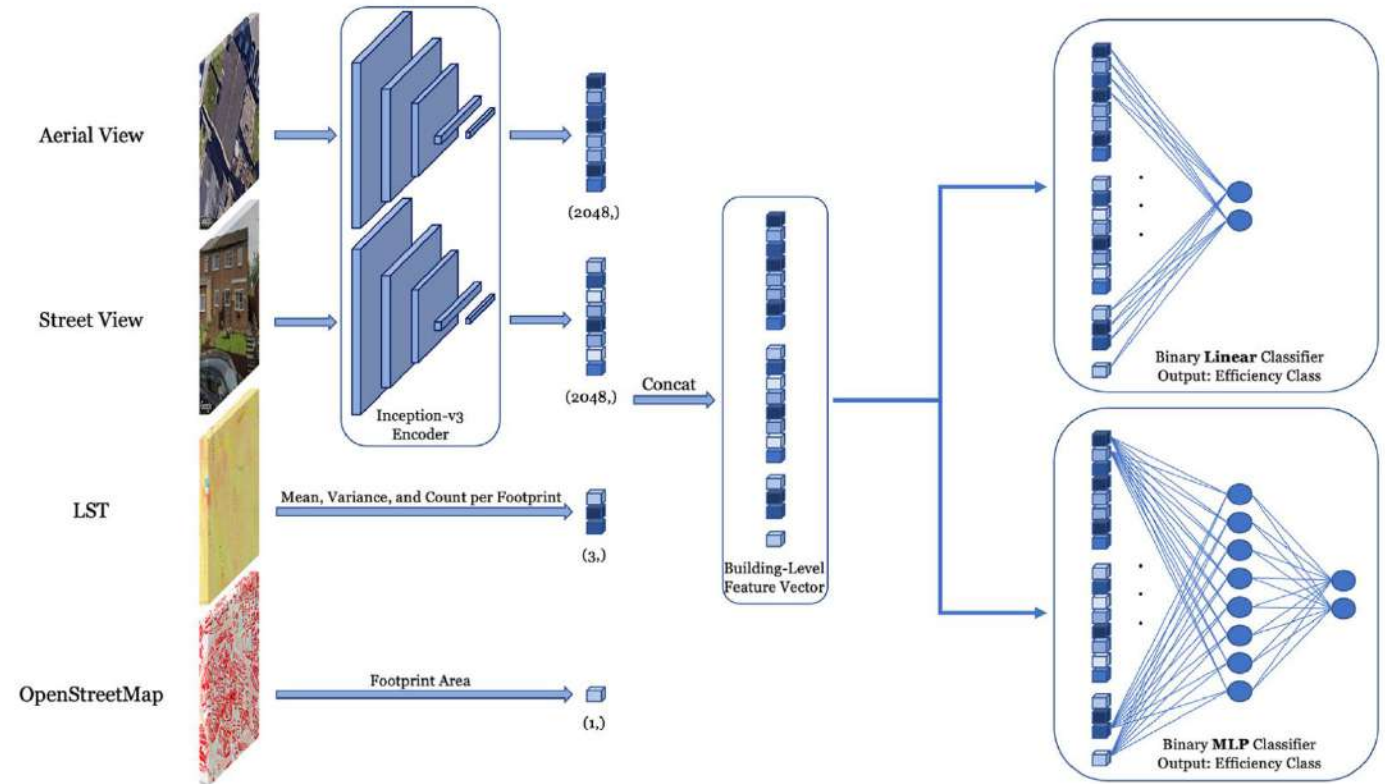


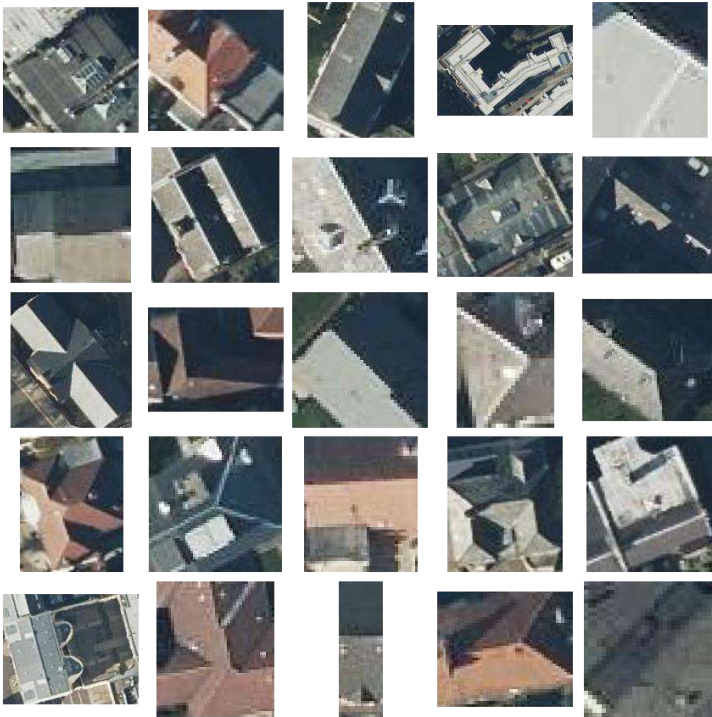
Fig. 5. End-to-end deep learning approach.

Research Objectives

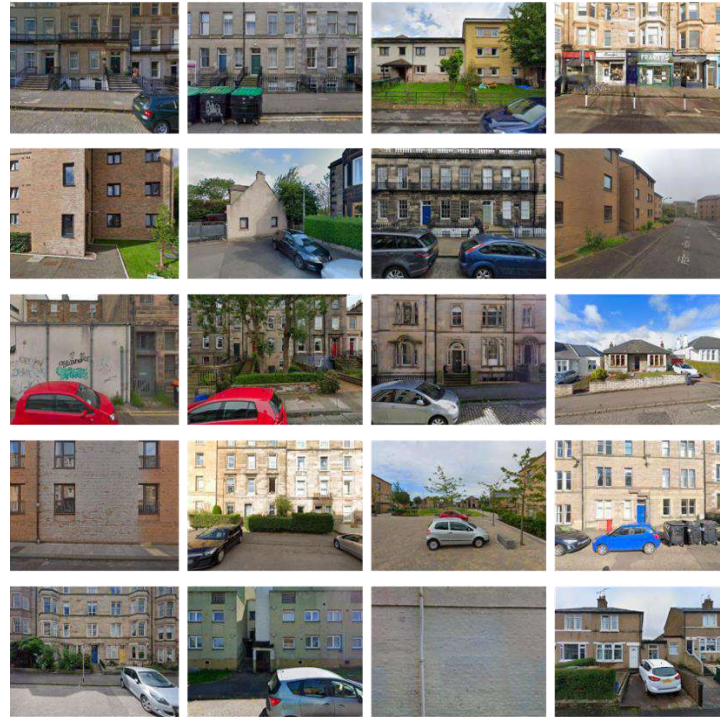
- Design a feature-fusion deep convolutional neural network to **estimate building energy efficiency** by multi-source data such as EPC, high-resolution thermal images, and Google Street View in large-scale
- Compare the model performance with multiple data sources and potentially predict **all the remaining building energy efficiency** by using deep learning framework

Data

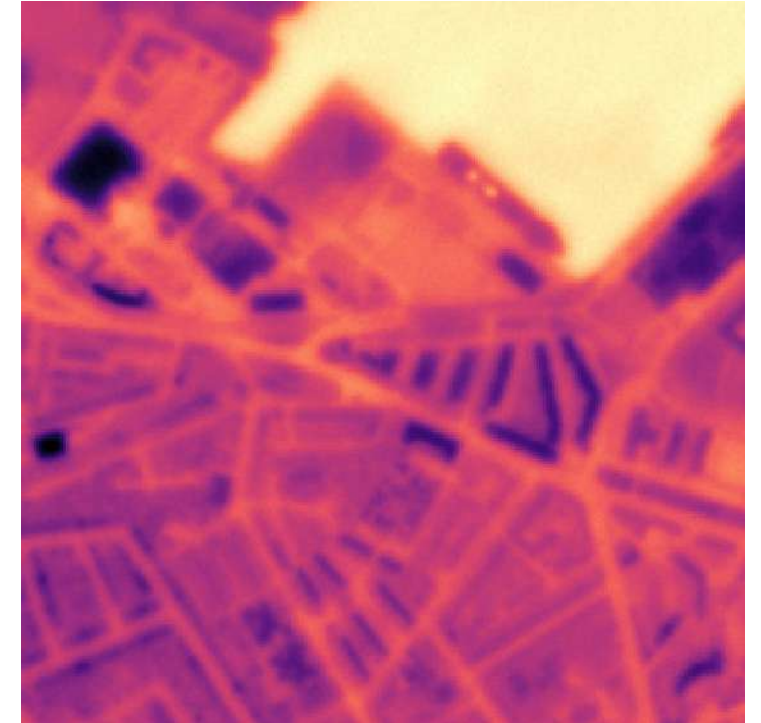
- **Satellite Images**



- **Street View**



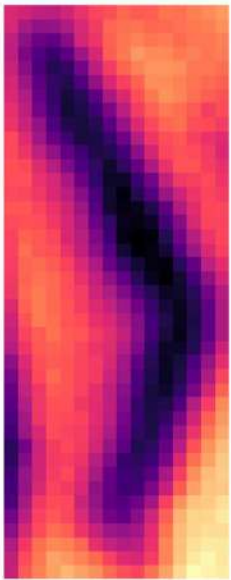
- **Land Surface Temperature**



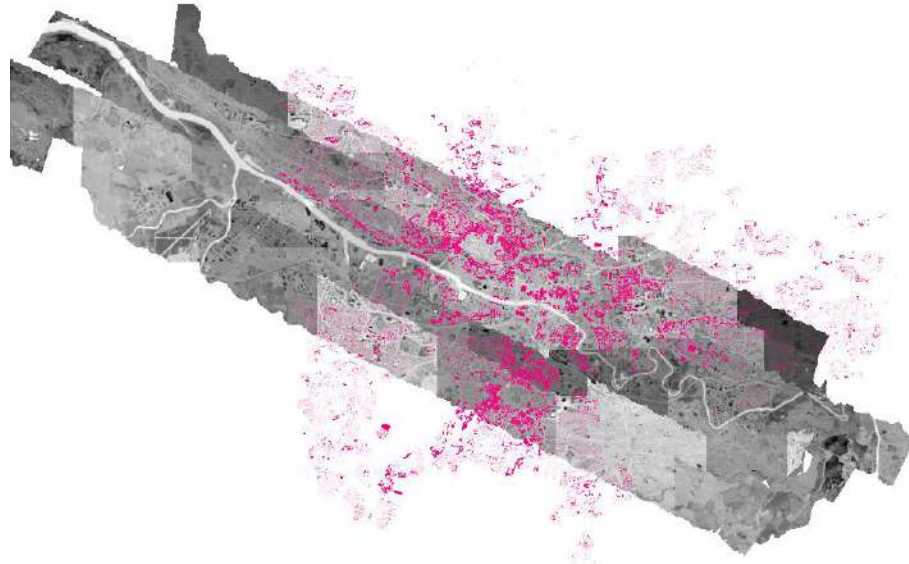
Data - HotSAT-1 and EPC

- **Thermal Satellite Image**

High resolution (3.5m) land surface temperature data is captured by Satellite-VU



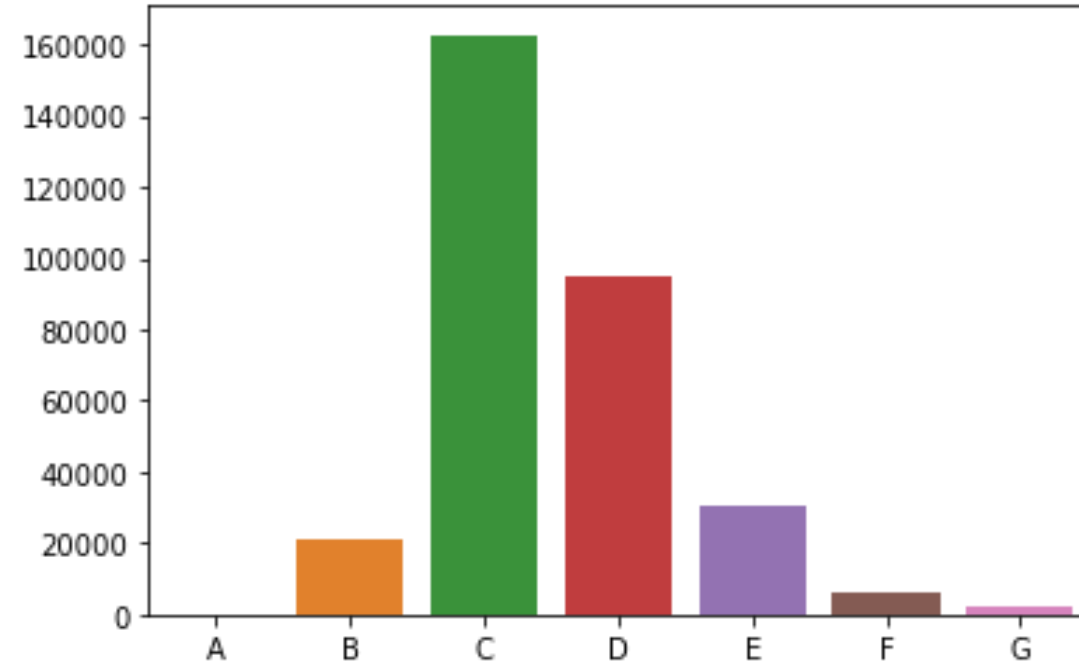
Cropped building-level image



Glasgow
March 2022

Sample size

Glasgow: 315,656



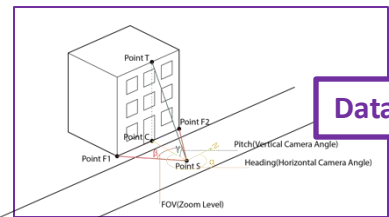
Glasgow EPC Distribution
(aggregated ABC and DEFG)

Data – Building Features

- Building Area
- Building Height
- Building Type
- Building Age

Res Building Class Type	Res Building Class Type Text
1	Very Tall Flats (point block)
2	Tall flats 6-15 storeys (slabs)
3	Medium height flats 5 – 6 storeys
4	Lower 3-4 storey and smaller flats, detached and linked
5	Tall terraces 3-4 storey
6	Lower terraces, 2 storey with large T rear extension
7	Lower terraces, small
8	Linked and step linked, 2-3 or mixed 2 and 3 storey
9	Planned balanced mixed estates
10	Standard size semi-detached houses
11	Semi type houses in multiples of 4,6,8 etc.
12	Large semi-detached houses
13	Standard size detached houses
14	Large detached houses
15	Very large detached houses
16	Mixed houses in small settlements
17	Non-residential building
18	Probably residential building, unknown classification

Age Values
HISTORIC
MIXED AGE PART HISTORIC
INTERWAR
MIXED AGE PART INTERWAR
POSTWAR
MIXED AGE PART POSTWAR
SIXTIES SEVENTIES
MODERN
NON BUILDINGS STRUCTURE
TEMPORARY BUILDING
UNCLASSIFIED



Data-GSV

Data-Satellite

Data-Thermal

Building feature + Sociodemographic

Geomni UK Buildings

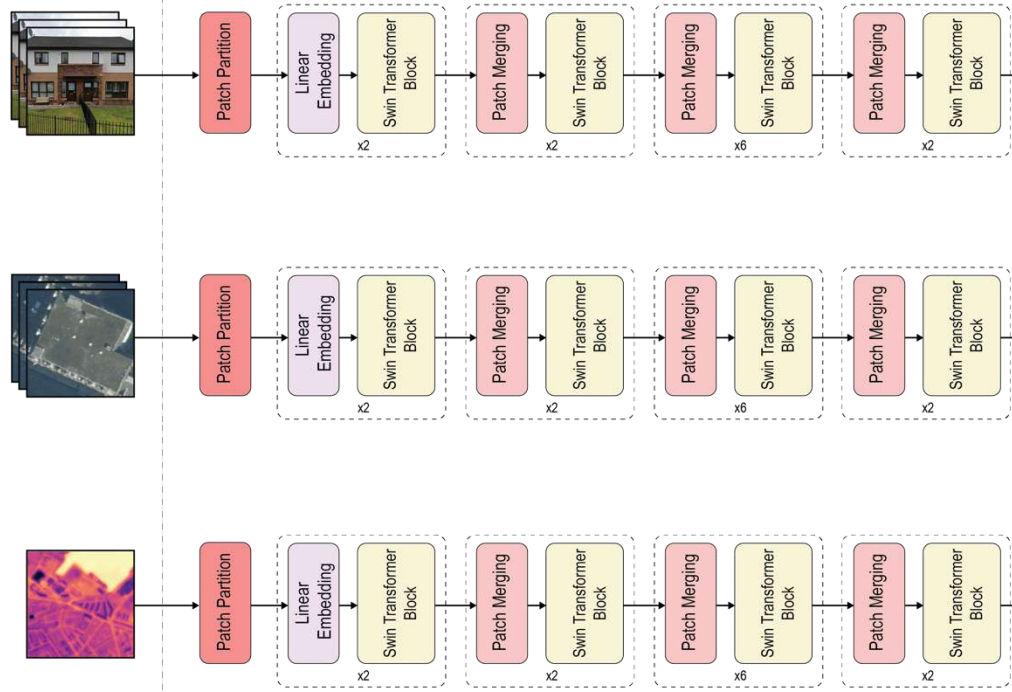
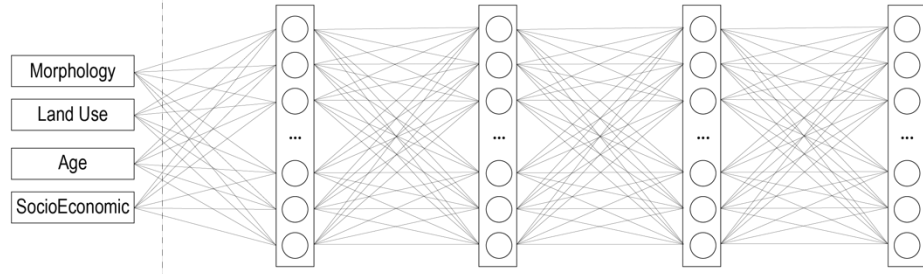


Image Feature Branches Tabular Feature Branch



Input

Feature Extraction

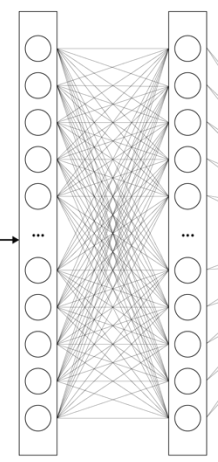
Deep Feature

Deep Feature

Deep Feature

Deep Feature

Framework



Feature Fusion

High Efficiency
Low Efficiency

Energy Rating

Output

Result – Ablation Test

- Performance & Confusion Matrix

Table 1. Ablation study (Glasgow)

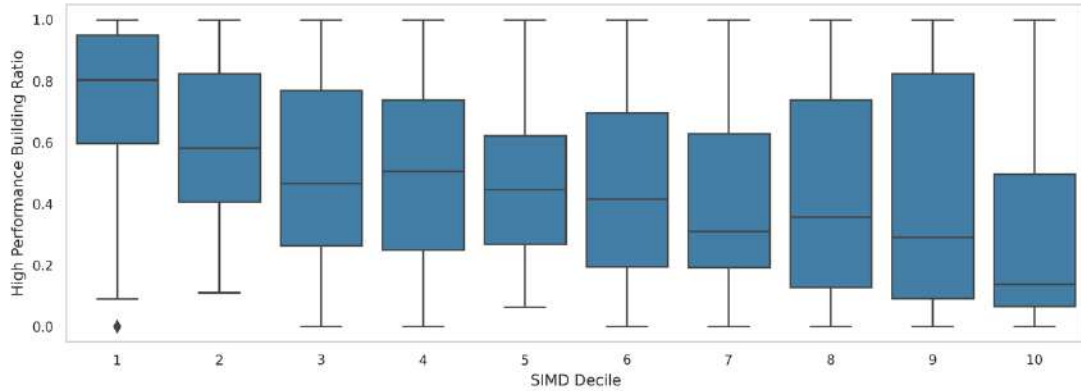
Data	Precision	Recall	F1 Score
Single source			
GSV	0.71	0.51	0.59
Thermal	0.52	0.70	0.60
Sate	0.67	0.56	0.61
Double source			
GSV + Satellite	0.73	0.58	0.65
GSV + Thermal	0.69	0.62	0.66
Sate + Thermal	0.66	0.56	0.61
Multiple source			
GSV + Sate + Thermal	0.72	0.57	0.63
GSV + Sate + Thermal + Socio	0.75	0.55	0.64

Table 2. Ablation study (Edinburgh)

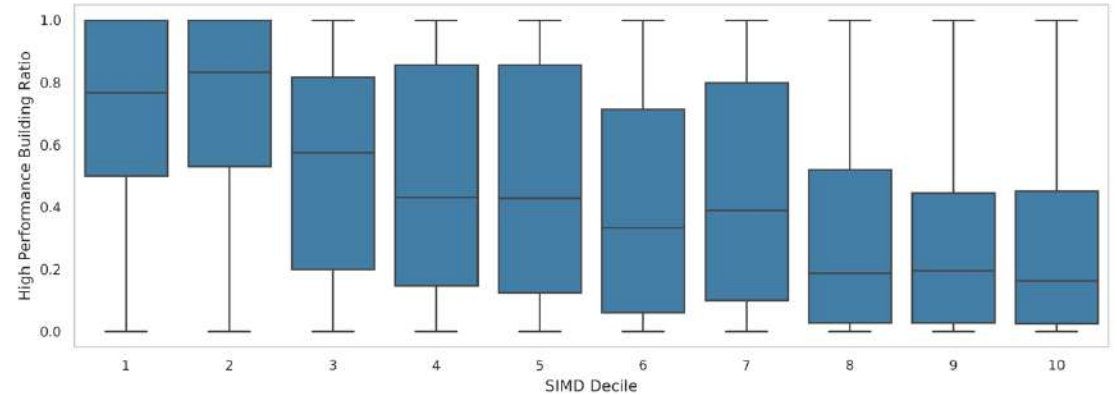
Data	Precision	Recall	F1 Score
Single source			
GSV	0.60	0.78	0.68
Thermal	0.52	0.91	0.67
Sate	0.59	0.68	0.63
Double source			
GSV + Satellite			
GSV + Thermal	0.62	0.67	0.64
Sate + Thermal	0.63	0.73	0.68
Multiple source			
GSV + Sate + Thermal	0.63	0.70	0.66
GSV + Sate + Thermal + Socio	0.61	0.81	0.69

Discussion – Energy Rating vs Deprivation

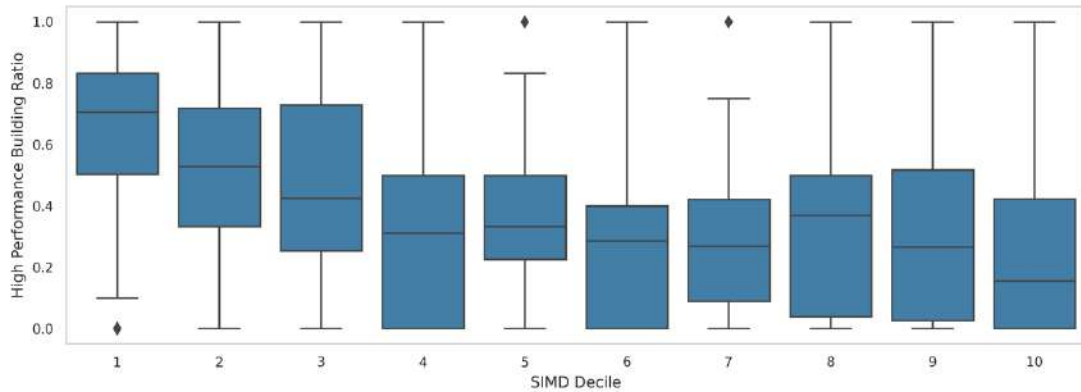
- The most deprived neighborhoods have best building energy performance



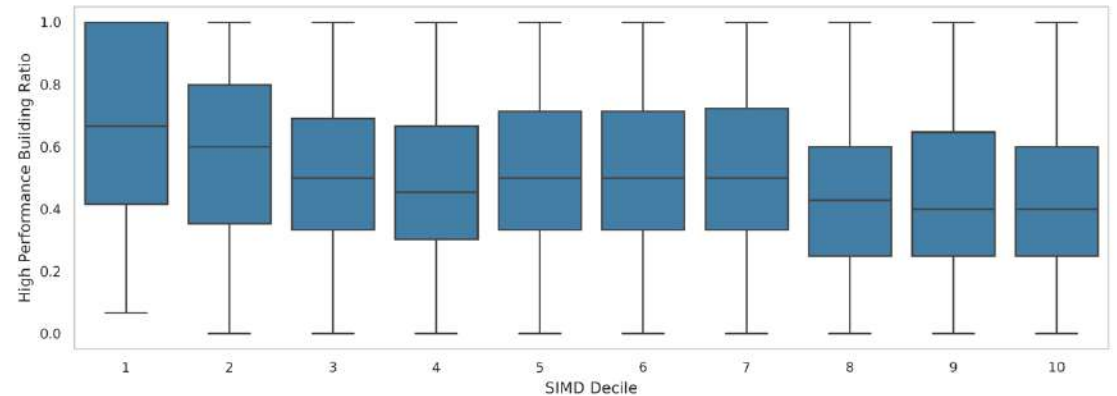
Glasgow Prediction Result



Edinburgh Prediction Result



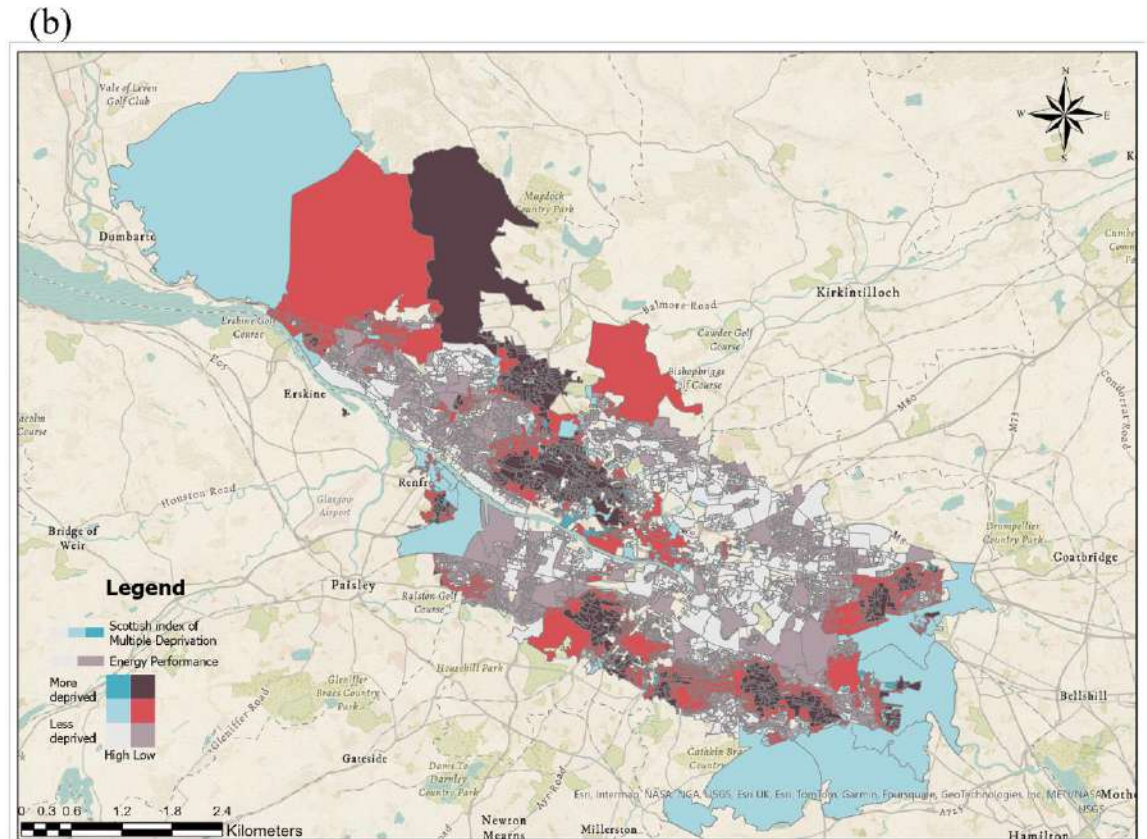
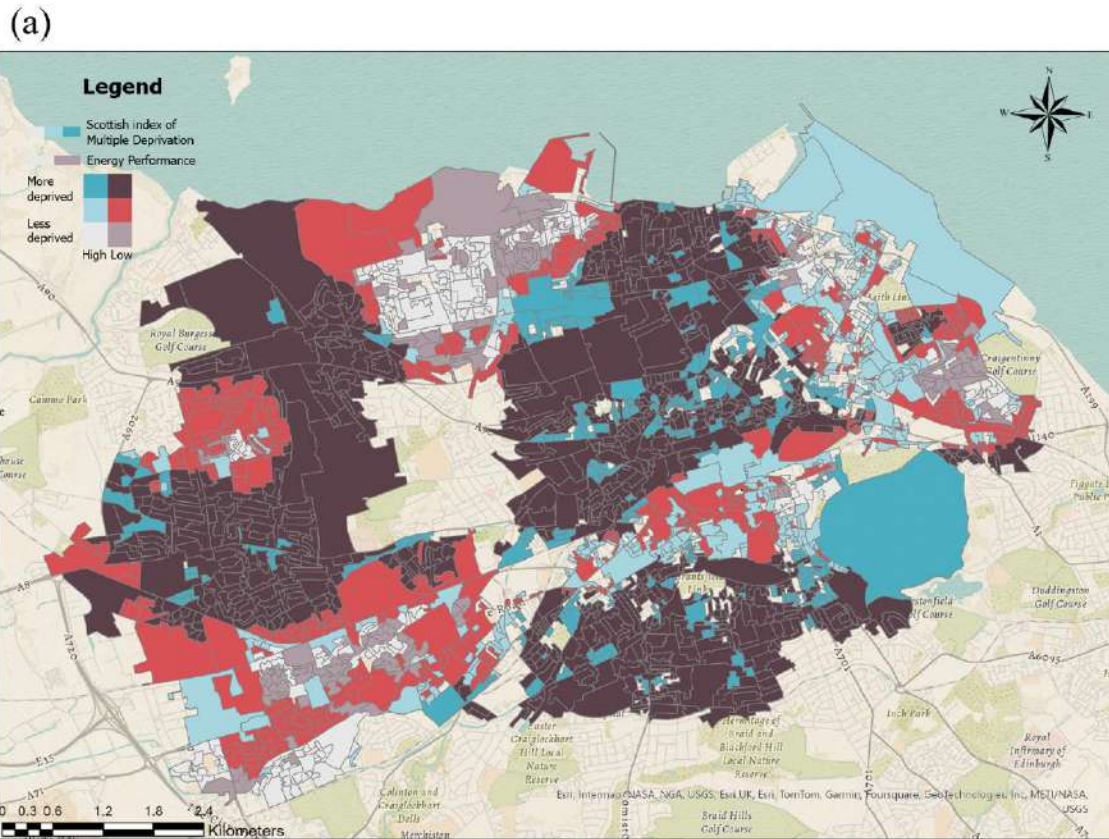
Glasgow Ground Truth



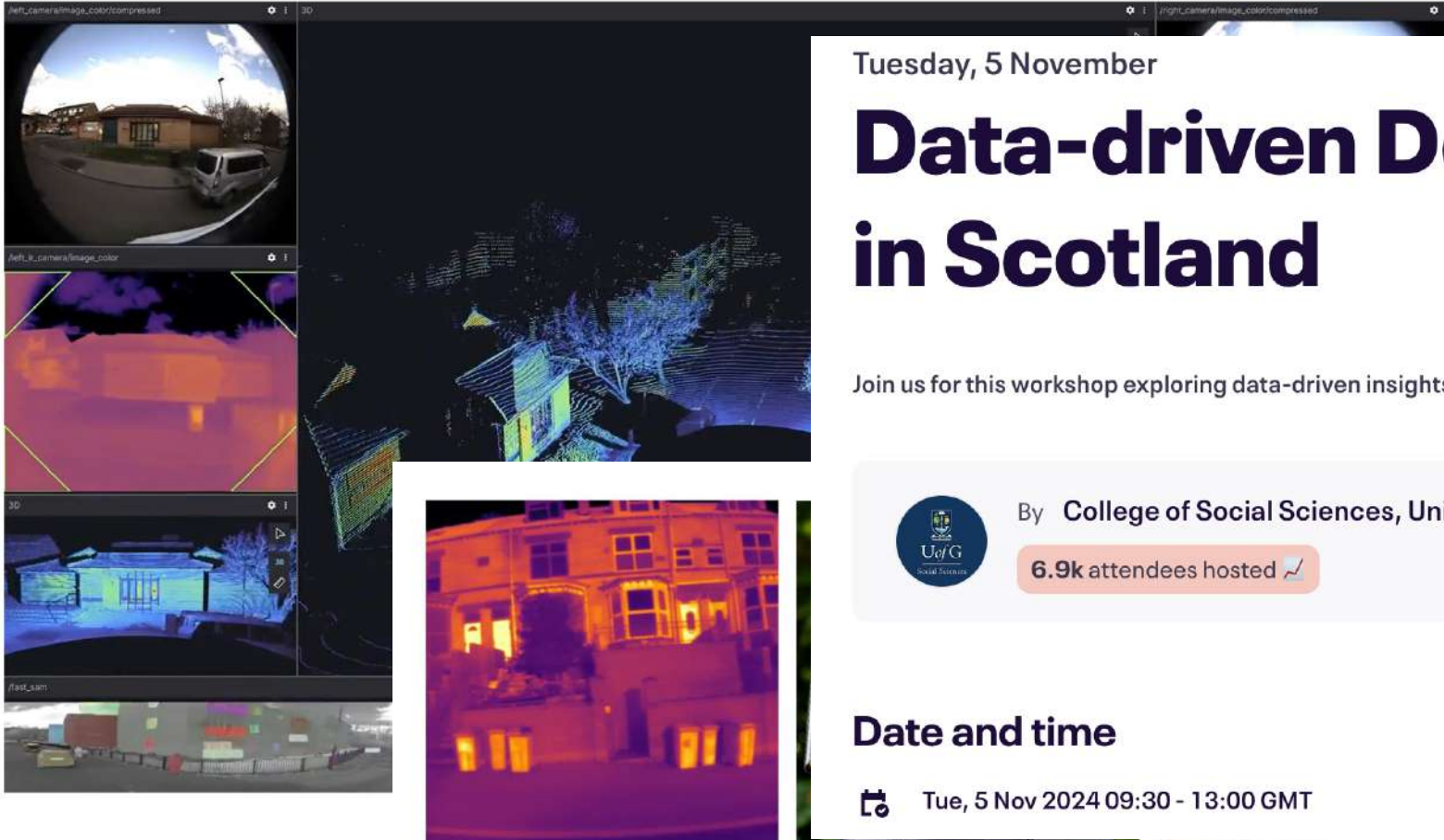
Edinburgh Ground Truth

Prediction results

- The most deprived neighborhoods have best building energy performance



Next step – Thermal Street view images



<https://www.xri.online/>

<https://www.eventbrite.co.uk/e/data-driven-decarbonisation-in-scotland-tickets-1043750163837?aff=oddtcreator>

Next step – SpaceEPC

SatVu's Unique Infrared Constellation



HotSat-1 On Orbit

HotSat-2 Q4 2024

HotSat-3 – HotSat-10 by 2027

SatVu

SPECIFICATIONS

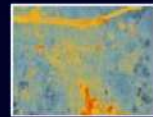
High resolution: 3.5m GSD (NADIR)
Single band: 3.4-5.0 μm
Video:
Imaging time:

CONSTELLATION

First launch completed
10 satellite constellation
10 – 20 revisits/day
Global coverage
Agile bus/camera
Fully tasked from orbit

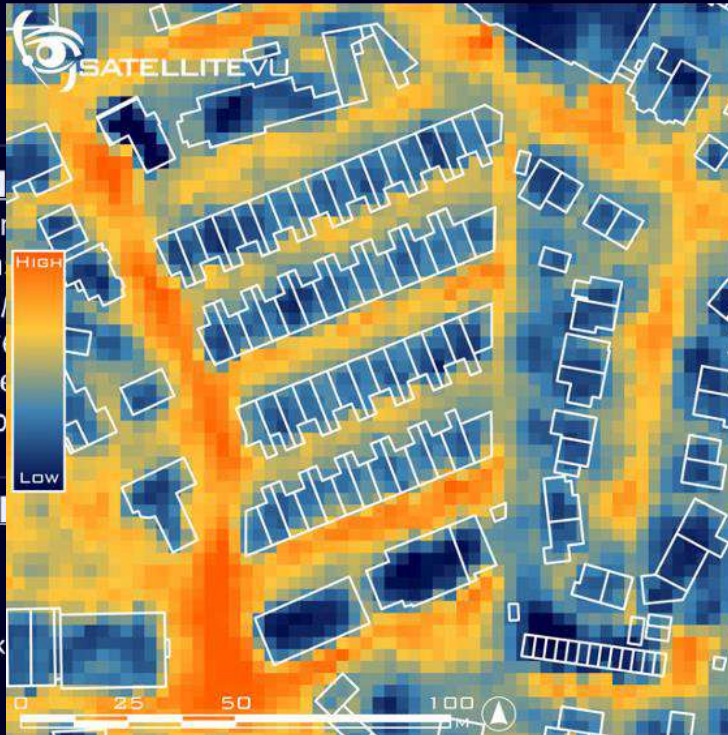
IMAGING MODES

4.4km



Single Image

3.5km

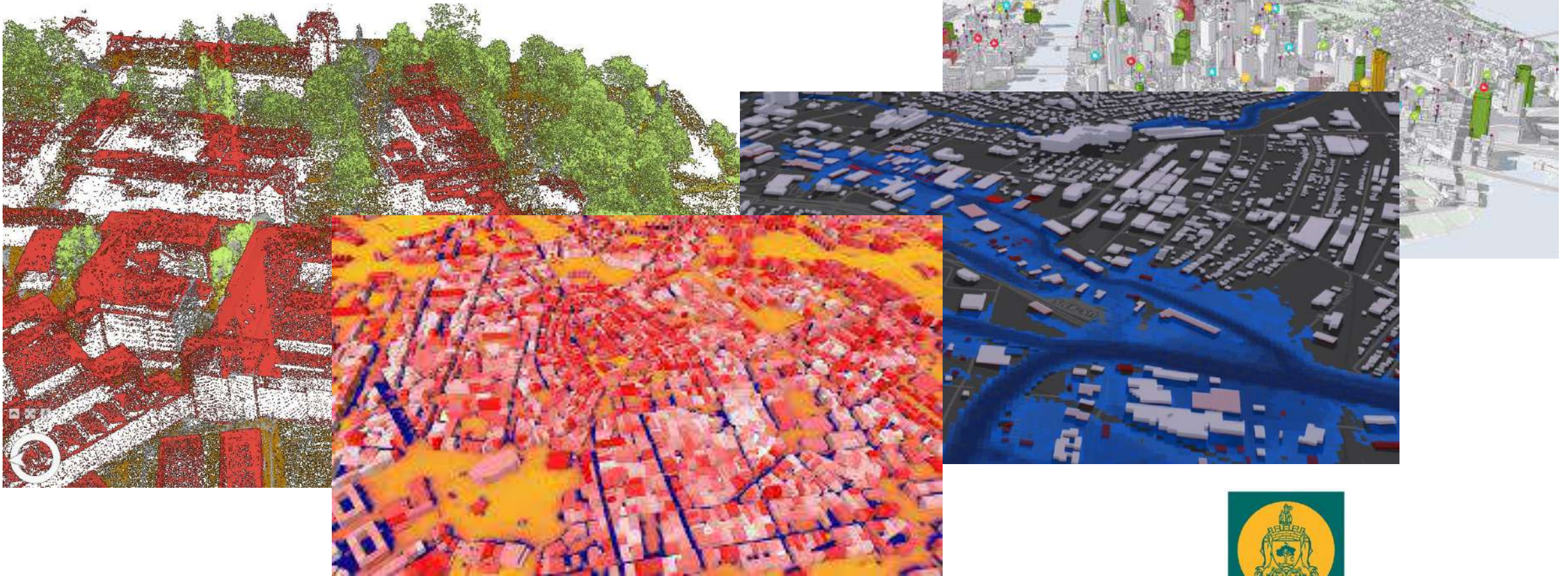


Video Mode

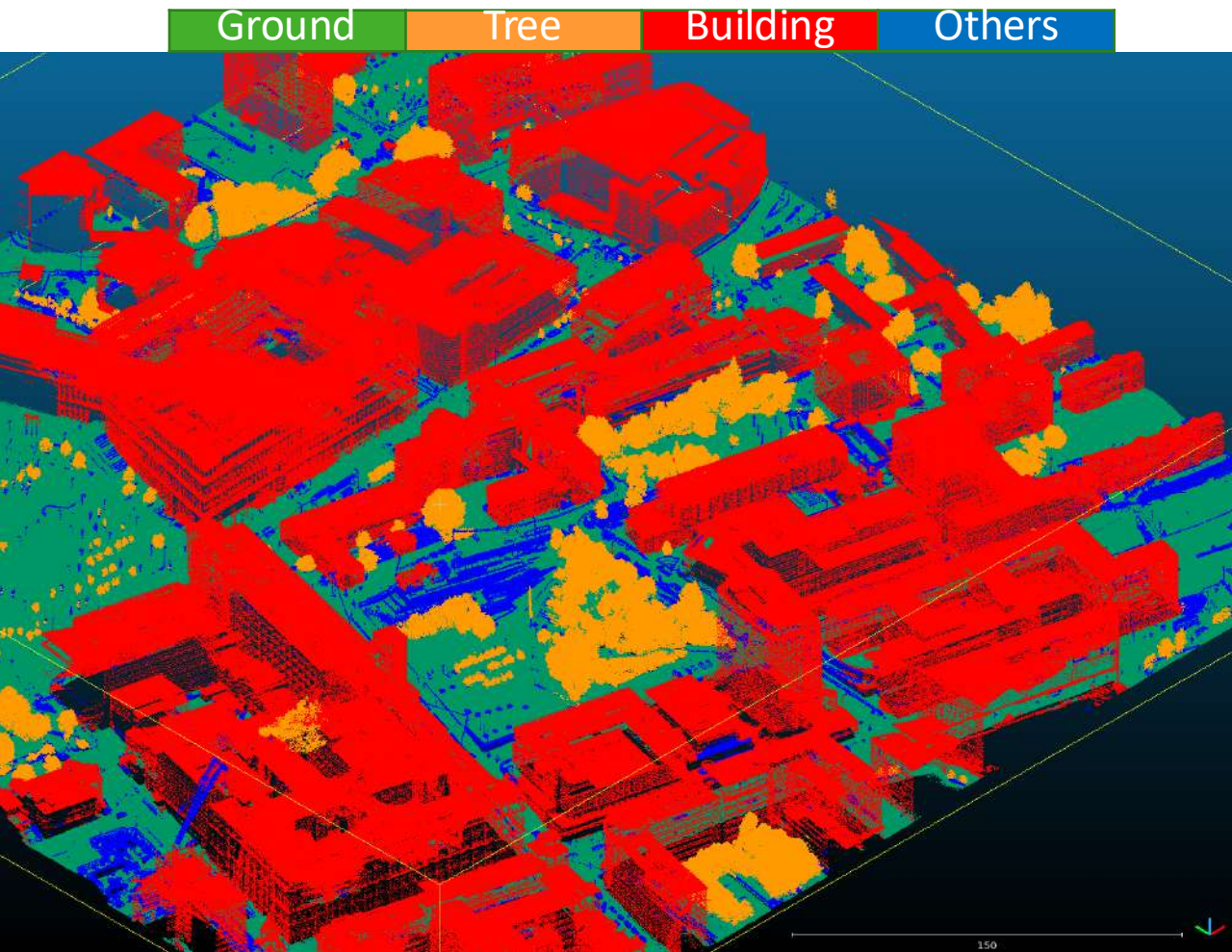
Strip Mode



Glasgow 3D City Modeling – basis of the digital twins

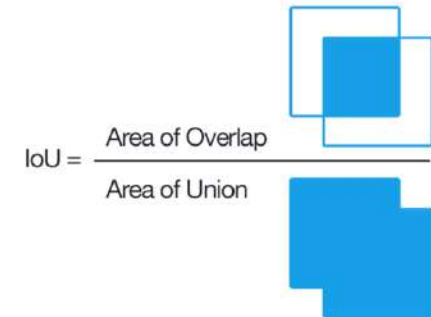


Prediction Result and Accuracy



		Predicted Class			
		Car	Cat	Dog	n/c
Actual Class	Car	152	18	16	14
	Cat	13	167	5	15
	Dog	4	5	38	3

$$\text{Accuracy} = \frac{\sum_i \# \text{correct}(i)}{\# \text{classified}}$$

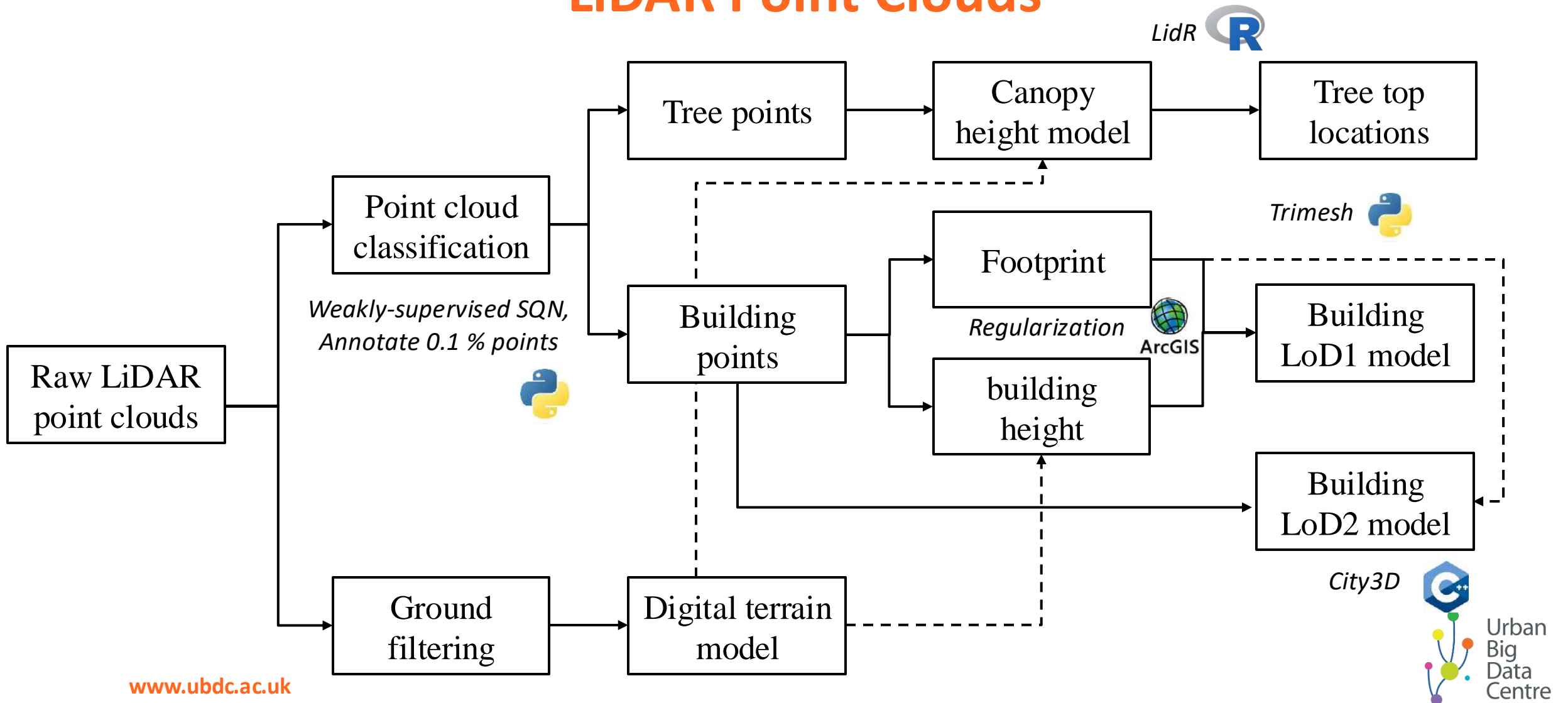


Overall accuracy (OA) and intersect over union (IoU)

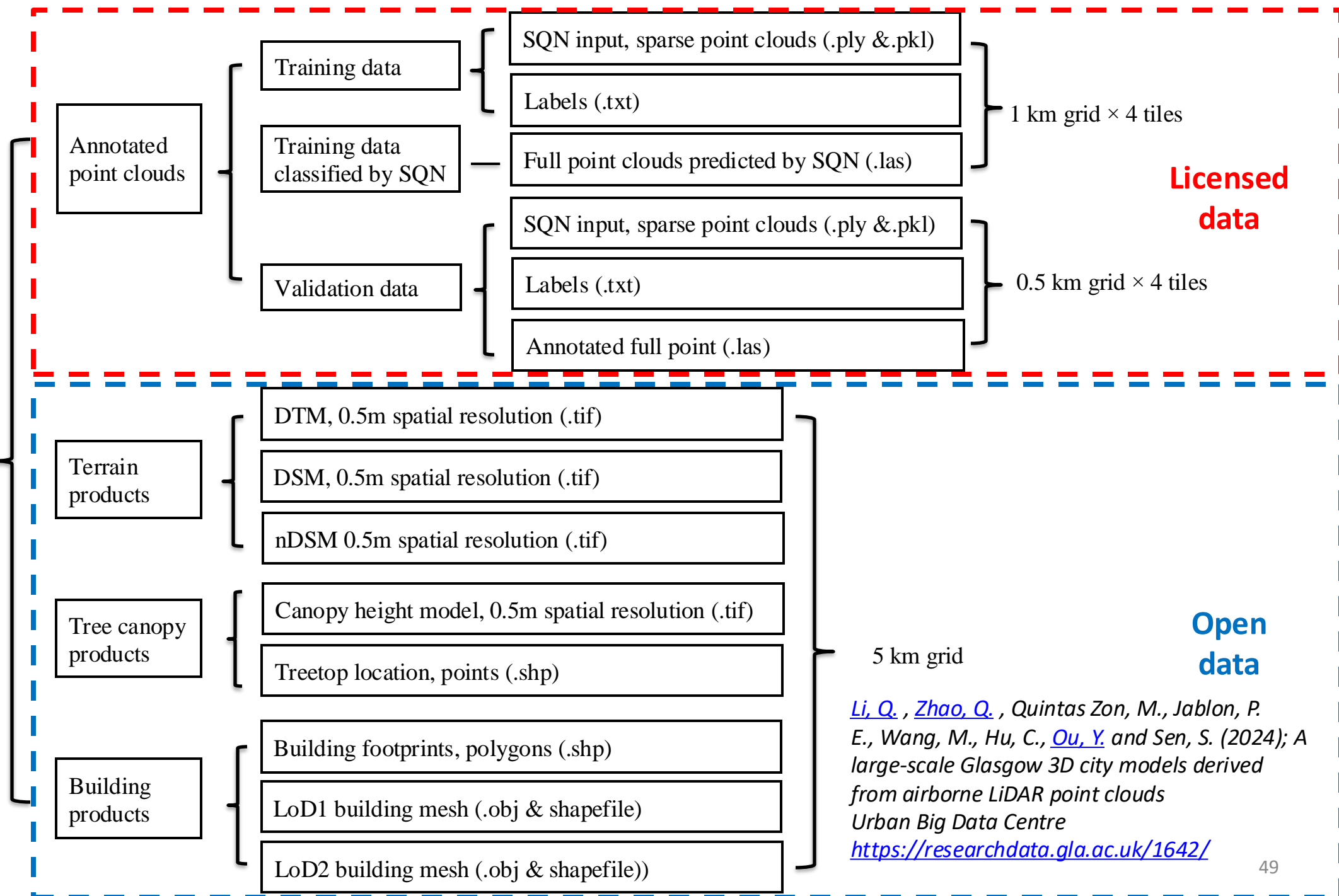
OA% = 97.32 MIoU % = 89.83

IoU %			
Ground	Trees	Buildings	Others
97.25	94.13	96.15	71.79

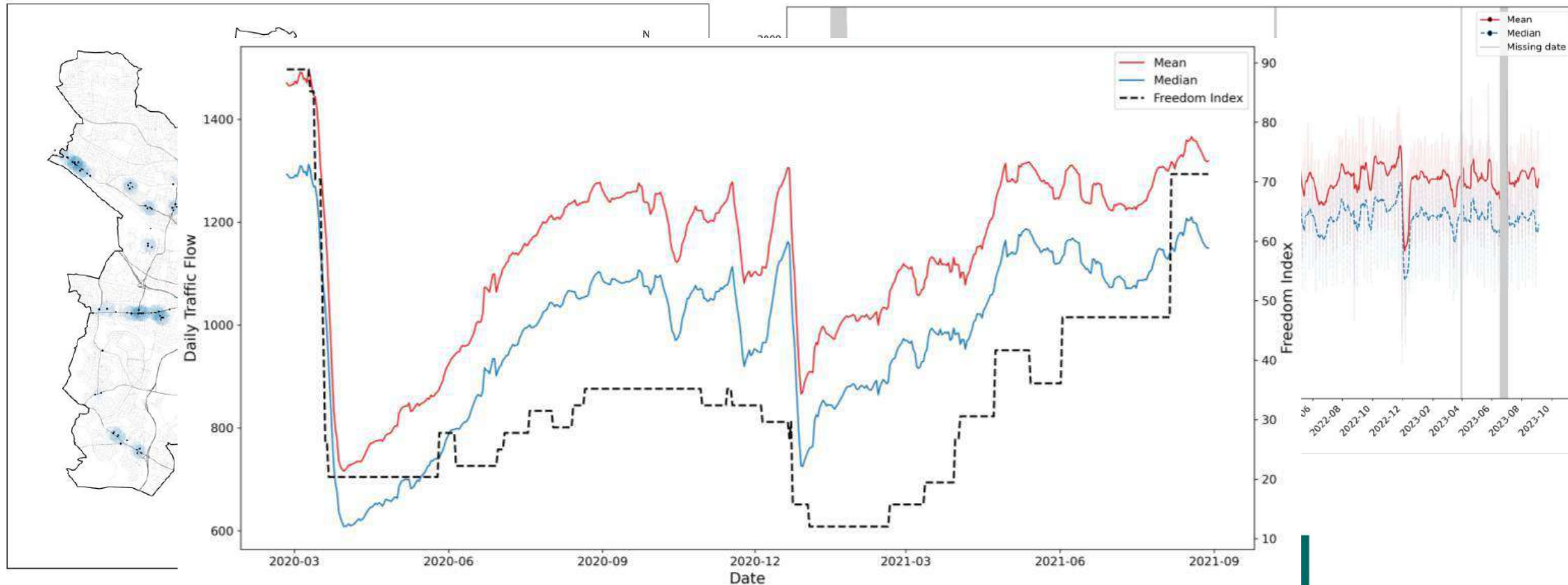
Workflow of construction Glasgow 3D city model from LiDAR Point Clouds



Source data:
raw LiDAR data



Traffic flow datasets from road sensors (SCOOT)



Glasgow Low Emission Zone Analysis

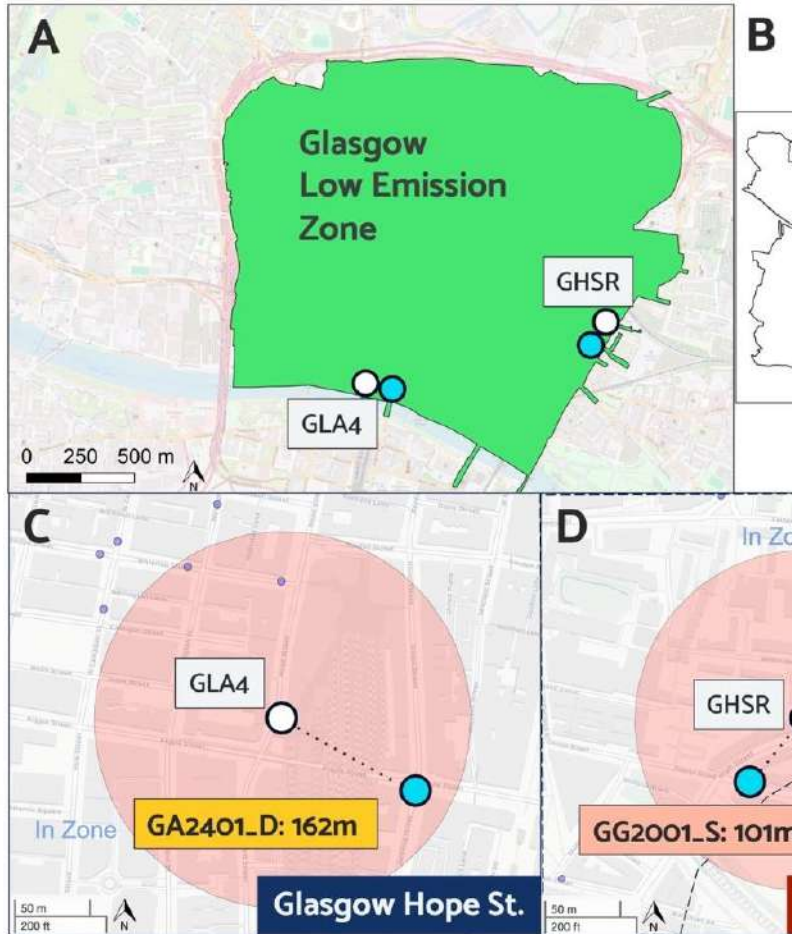


Table 2. Wilcoxon signed rank test results for daily traffic by week groups and years

Area	Week Group	Observations		Median Counts		W-statistics	p-value
		2022	2023	2022	2023		
High Street	Core Weekdays	27	27	709	617	359	<0.001***
	Other Weekdays	17	17	745	609	122	0.03*
	Weekends	16	16	670	664	106	0.051

Table 3. Wilcoxon test results for normalized NO₂ by week groups and years

Area	Week Group	Observations		Median NO ₂ (µg/m ³)		W-statistics	p-value
		2022	2023	2022	2023		
High Street	Core Weekdays	27	27	19.5	14.2	373	<0.001***
	Other Weekdays	17	17	19.1	14.3	153	<0.001***
	Weekends	16	16	18.4	11.9	130	<0.001***
Hope Street	Core Weekdays	27	27	37.4	32.6	338	<0.001***
	Other Weekdays	17	17	36.9	33.5	141	0.0017**
	Weekends	16	16	34.9	30.9	128	<0.001***

Simple analysis, but the media likes it...

Transport

The street where Scotland's first low emission zone has had the biggest impact on pollution

Air quality improving from Glasgow's Low Emission Zone

24/09/2024

News > Glasgow News > Glasgow City Council

Glasgow LEZ impact 'encouraging' as report shows air pollution drop

The first annual report since

NEWS By [Drew Sandelands](#) Local
13:42, 19 SEP 2024



GLASGOW
CHAMBER OF COMMERCE

MEMBER LOGO

Membership Events Training



LEADERS

GENUINE SUPPORT AND THE CHANCE TO SHARE FIRST-HAND BUSINESS EXPERIENCE

HELP TO GROW

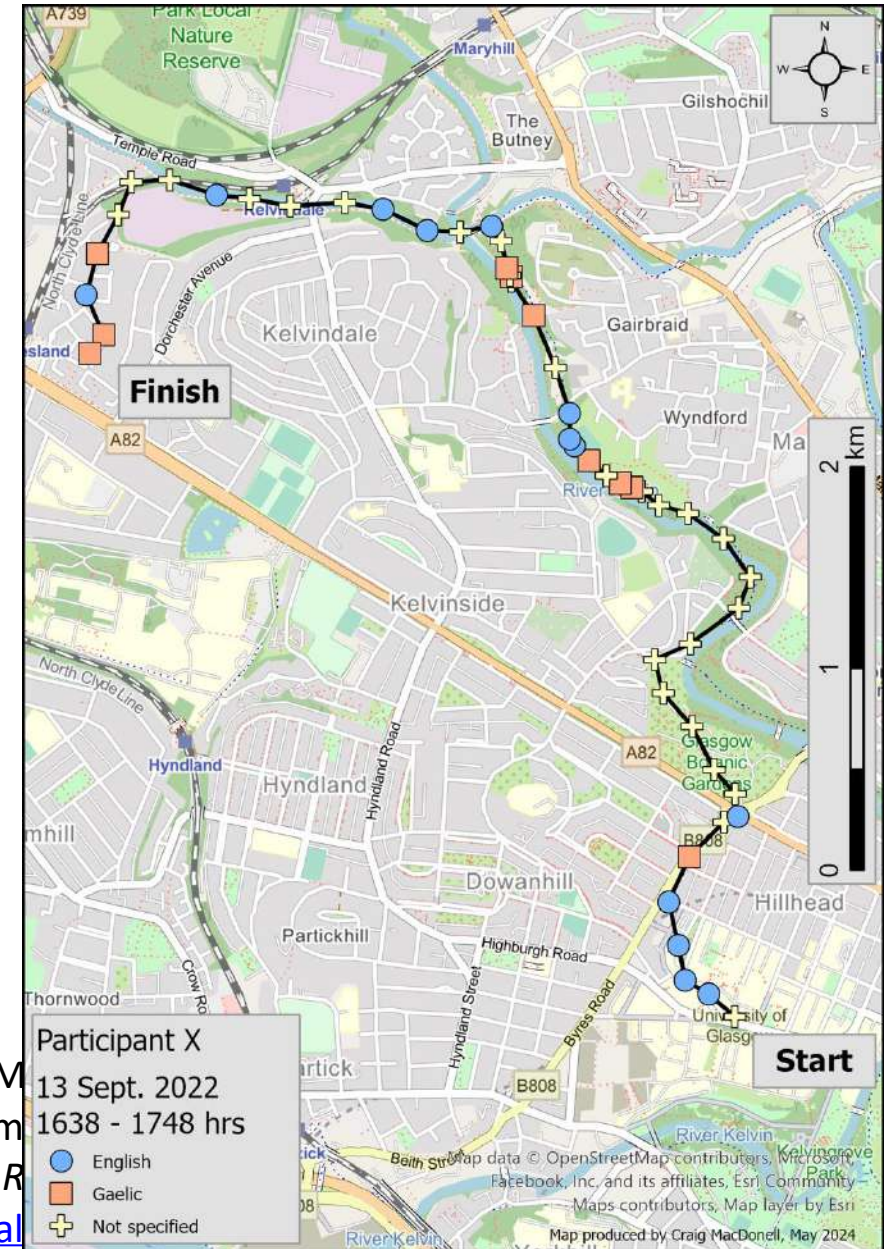
19 Sep 2024

New research exploring the effects of the Low Emission Zone (LEZ) in Glasgow has found that while traffic flow has remained largely unchanged since the Zone was enforced, air quality has improved.



Integrated Geospatial Methods for Multilingual Cities

- Limited understanding of the use of minority languages in cities.
- Identify a better strategy for promoting the use of minority languages and creating more inclusive minority communities.
- Leverage the existing portable sensing technologies, new forms of data and methods to analyse language usage patterns in cities.



Acknowledgements



The UK's global programme to study and work abroad



Acknowledgements



Congying Hu – Intern in Phase 2 Sensor-enhanced housing survey project



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Mark Livingston – Senior Lecturer in Urban Studies, leading the CCTV project and co-lead the housing sensor project



Mingkang Wang – Urban Sensing RA in UBDC, 3D city modelling and Phase 1 and 2 housing sensor projects



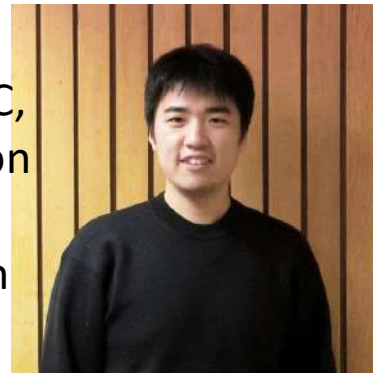
Mingyu Zhu – Urban Sensing RA, Phase 3 housing sensor and SpaceEPC project



Yunbei Ou, PhD in UBDC, Sensor-enhanced housing survey project.



Zixin Feng, PhD in UBDC, EV simulation and station optimisation



Maoran Sun, PhD in Cambridge, EPC project



Yue Li, PhD in UBDC, Traffic flow analysis in Glasgow

Thank you!
Questions?

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UBDC website: <https://www.ubdc.ac.uk/>