Urban building energy modeling using a 3D city model and minimizing uncertainty through Bayesian inference

A case study focuses on Amsterdam residential heating demand simulation

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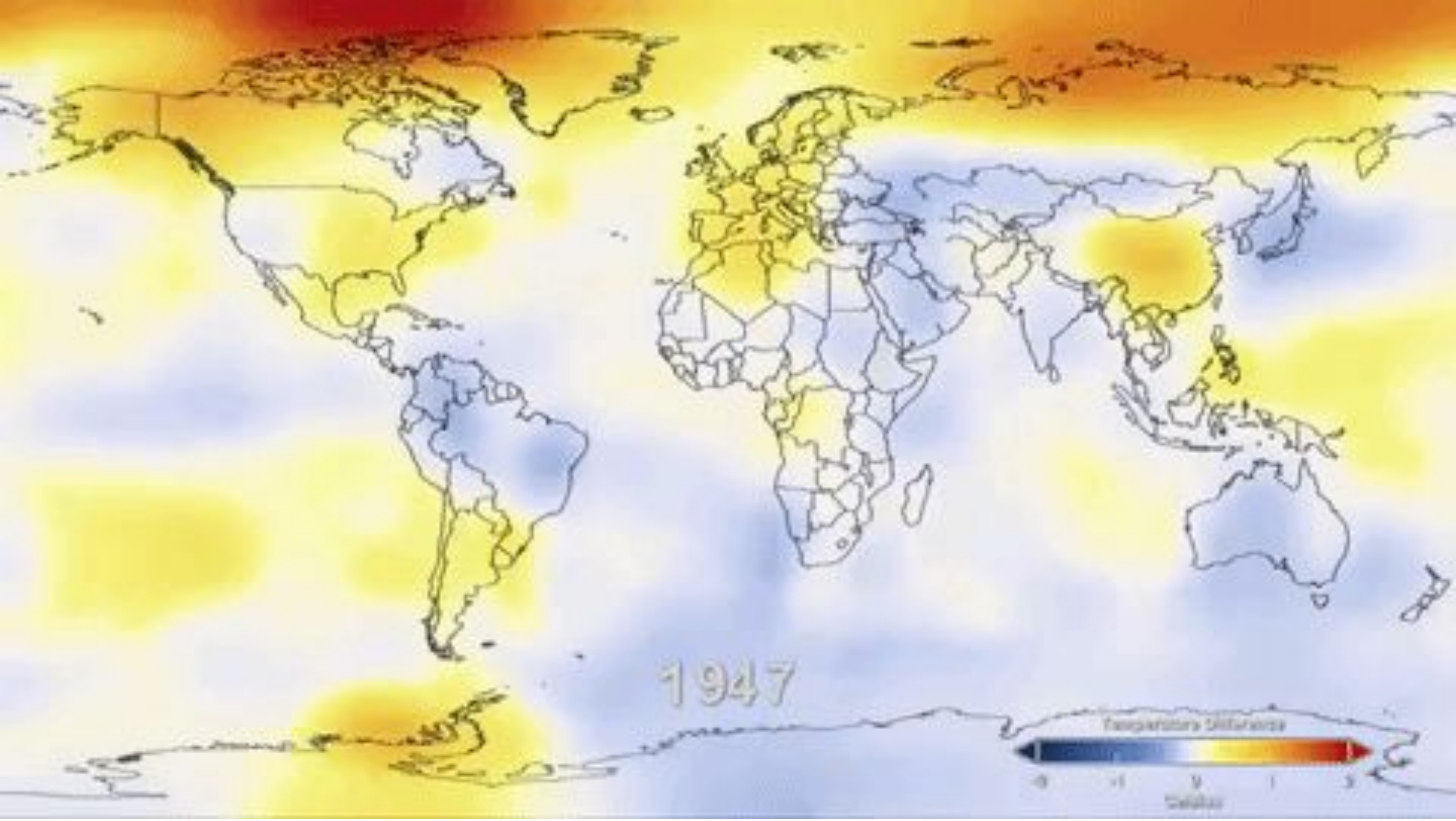
NUS National University of Singapore

54% ▶ **66%**

2014 2050

Source: [1][2]

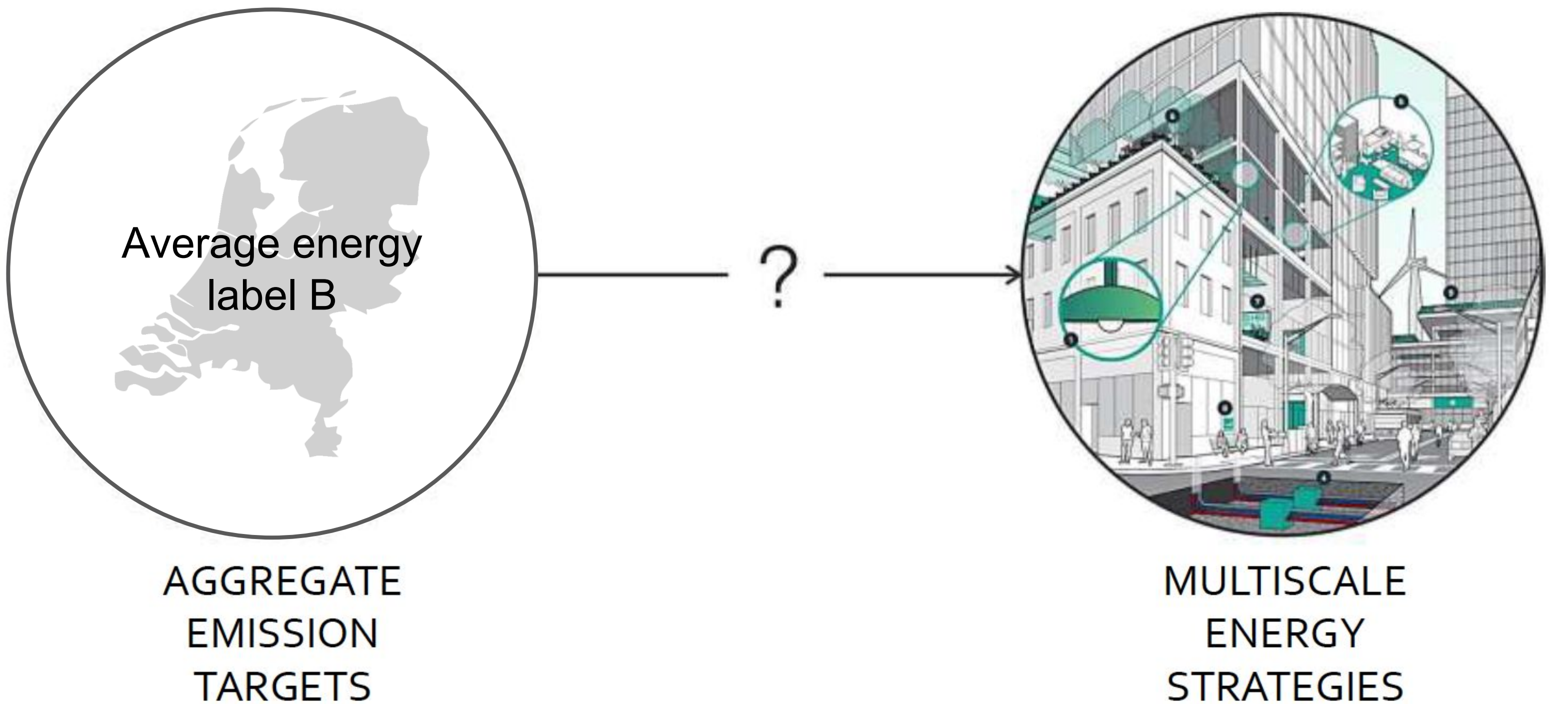


Increased energy demand per capita in the last 40 years

32%

Source: [3][4]

Challenges and opportunities



Adapted from Carlos Cerezo Davila, 2017 [5]

Simulation performance gap can deviate from the measurement

4% up to 66%

Fonseca and Schlueter, 2015

Research question

"How to realize Urban Building Energy Modeling (UBEM) using 3D city model and minimizing parameter and simulation uncertainties based on the Bayesian theorem?"

https://www.wallpapervortex.com

Intro. to energy simulation

▼

Data preparation
3D city model

▼

Uncertainty
Sensitivity analysis

▼

Bayesian inference and calibration

▼

Discussion and conclusion

Overview of (urban) building energy modeling

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Modeling approaches

Approach	• Advantage	• Disadvantage
Top-down	• Long term forecasting in the absence of any discontinuity • Inclusion of macroeconomic and socioeconomic effects • Simple input information • Encompasses trends	• Reliance on historical consumption information • No explicit representation of end-uses • Coarse analysis
Bottom-up statistical	• Determination of typical end-use energy contribution • Encompasses occupant behaviour • Inclusion of macroeconomic and socioeconomic effects • Uses billing data and simple survey information	• Reliance on historical consumption information • Multicollinearity • Large survey sample to exploit variety
Bottom-up engineering	• Determination of each end-use energy consumption by type, rating, etc • "Ground-up" energy estimation • Model new technologies • Determination of end-use qualities based on simulation	• Assumption of occupant behaviour and unspecified end-uses • Detailed input information • Computationally intensive

Swan and Ugursal, 2009

Urban building energy modeling (UBEM)

Weather

Building geometry

Construction

System

Operation

Metered data

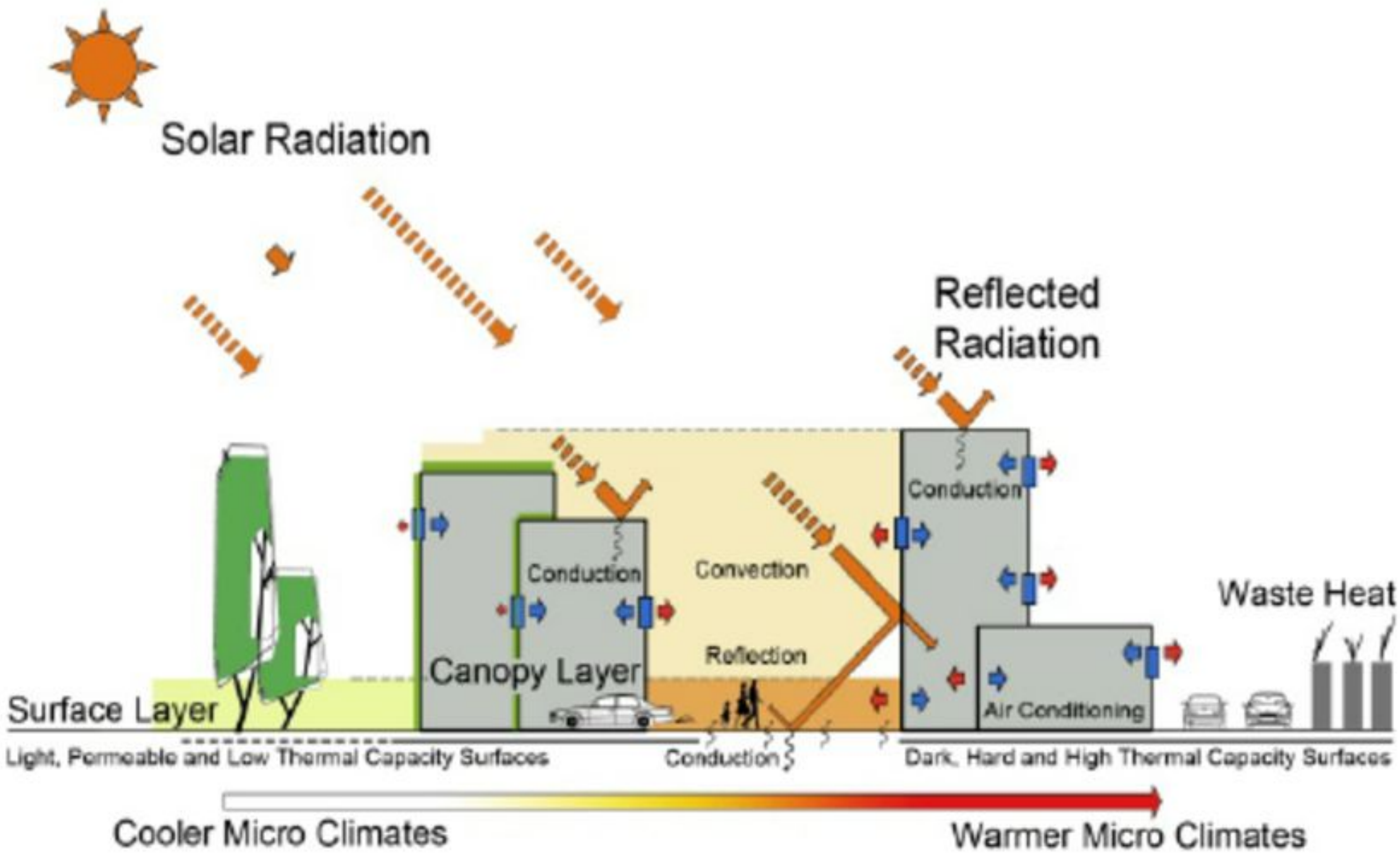
Simulation engines & CitySim

D	Detailed model
S	Simplified model
L	Link to other program
X	Not included

	External air flow	SW radiation	LW radiation	Building thermal	User behaviour	Building system	Thermal network	Electrical network	Gas network	District plant	Thermal storage	Window power	Photovolatics	Ground source	Spatial	Transportation	Embodied energy	
CitySim	X	D	D	S	D	S	S	X	X	X	S	S	S	S	D	X	X	City energy simulation for groups of buildings / city quarters
EnergyPlus	S	D	S	D	D	D	S	X	X	S	S	S	S	D	S	X	X	Detailed building simulation, limited interactions
ESP-r	S	D	S	D	D	D	S	D	X	S	D	S	S	S	S	X	X	Detailed building simulation, thermal and elec networks possible
IDA ICE	S	D	S	D	D	D	D	X	X	S	S	X	S	D	S	X	X	Detailed building simulation, thermal networks possible
Polysun	X	D	S	S	D	D	D	S	X	S	D	X	D	D	X	X	X	Detailed solar thermal and hydraulic systems
TRNSYS	L	D	D	D	D	D	D	S	X	D	D	D	D	D	X	X	X	Detailed simulation tool for systems and single buildings
Envi-met	S	S	S	S	X	X	X	X	X	X	X	X	X	X	S	X	X	Microclimate model
KULeuven IDEAS lib	S	D	D	D	D	D	S	D	X	S	S	X	D	D	X	X	X	District level Modelica library
LBNL District lib	S	D	D	D	S	D	S	D	X	S	S	S	D	D	X	X	X	District (and building) Modelica libraries
energyPro	X	X	X	L	X	D	D	D	X	D	D	D	D	S	S	X	X	Techno-economic simulation of energy systems
RETScreen	X	X	X	S	X	S	S	X	X	S	S	S	S	S	X	X	X	Energy, life cycle cost, emissions, fiance and risk analysis
HOMER	X	X	X	L	X	X	X	X	X	S	X	D	D	X	X	X	X	Microgrid design optimization
Termis	X	X	X	L	X	X	D	X	X	S	S	X	X	X	L	X	X	Operate, simulate and optimise district heating networks
Neplan	X	X	X	L	X	X	D	D	D	S	X	D	S	X	L	X	X	Simulate and optimise electrical, water, gas and heating networks
NetSim	X	X	X	L	X	X	D	X	X	D	X	X	X	X	L	X	X	District heating, cooling and steam simulation environment
EnerGis	X	X	X	S	X	S	S	X	X	S	X	X	S	S	D	X	X	GIS-based urban energy and district heat network design tool
SynCity	X	X	X	S	D	S	S	S	S	S	D	S	S	S	D	D	X	Integrated tool for holistic urban energy systems modeling
EPIC-HUB	X	X	X	L	X	S	S	S	S	S	X	L	L	X	S	X	X	Middleware platform for multi-carrier infrastructure systems
MEU	X	L	L	L	S	S	S	S	X	S	X	X	S	X	D	X	X	Energy management tool for cities and multi-energy utilities
UMI	X	L	L	L	X	X	X	X	X	X	X	X	L	X	D	D	S	Rhino-based link to Radiance and EnergyPlus
Radiance	X	D	D	X	X	X	X	X	X	X	X	X	D	X	D	X	X	Powerful ray-tracing program
Solene	L	D	D	S	S	X	X	X	X	X	X	X	X	X	D	X	X	Energy simulation for city quarters
Fluent	D	D	D	X	X	X	X	X	X	X	X	X	X	X	X	X	X	CFD software
OpenFOAM	D	X	D	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Extensible CDF software

Allegrini et al., 2015

Simulation engines & CitySim



Sharifi and Lehmann, 2015

CitySim energy simulation features

SW radiation
LW radiation
Spatial
User behaviour

Detailed

Building thermal
Building system
Thermal network
Thermal storage
Wind power
Photovoltaics
Ground source

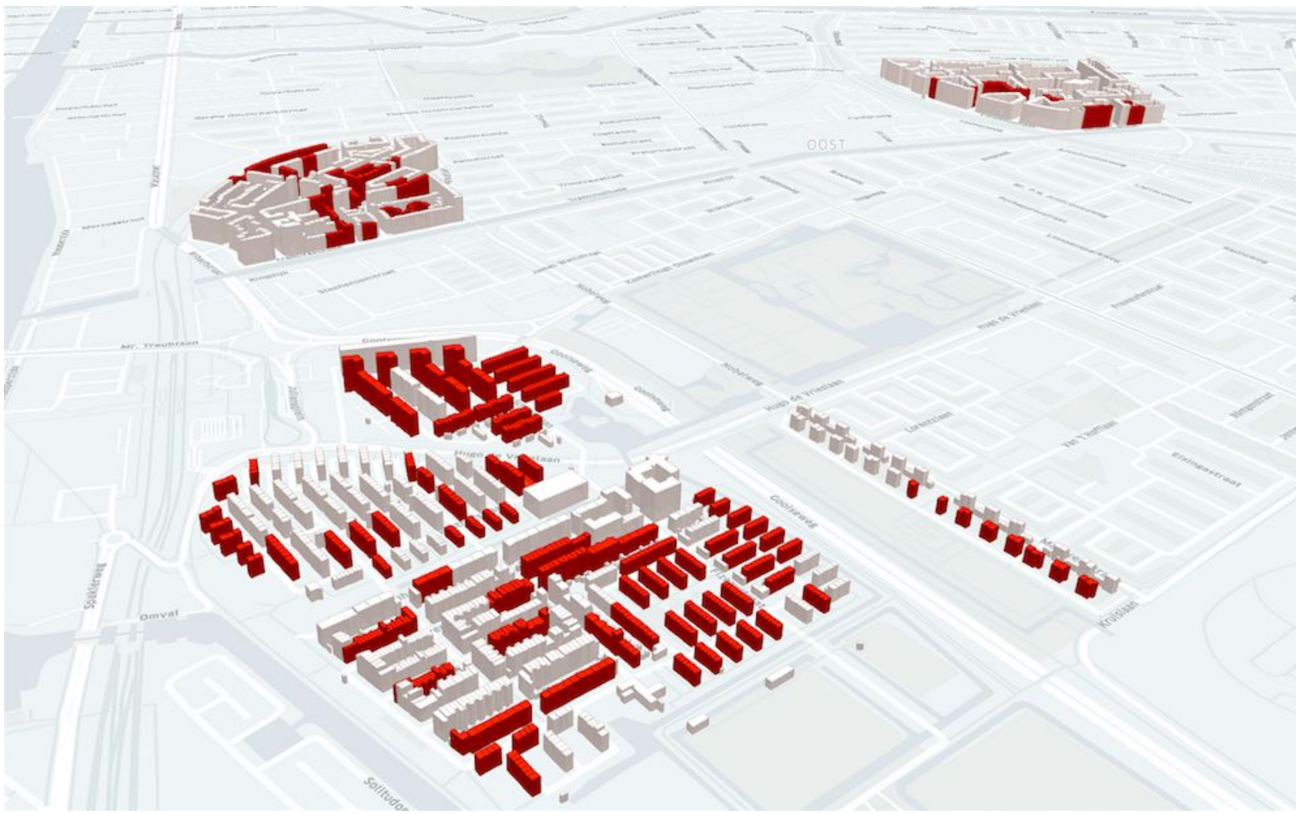
Simplified

External air flow
Electrical network
Gas network
District plant
Transporation
Embodied energy

Not included

Test area

- 2178 residential buildings in Amsterdam-Oost
- At least 84 postcodes have enough data to go through the complete simulation and calibration process



Data preparation & 3D city model

https://www.wallpapervortex.com

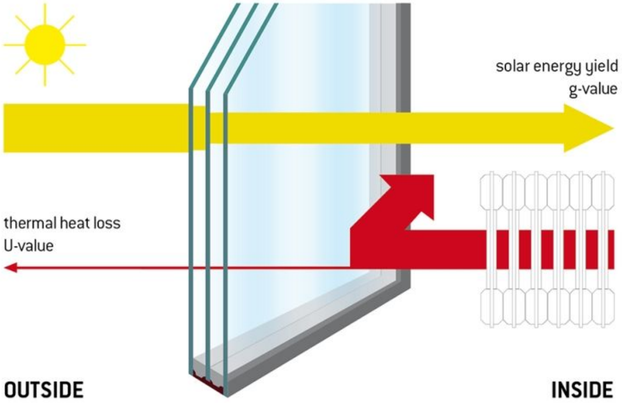
Weather	Annual hourly observation data Irradiance data	-	-
Building geometry	Building footprint Building height	- B_h	- m
System	Heating system type and efficiency	Eta	-
Operation	Building occupant numbers Occupancy schedule Minimum thermostat setting Window openable ratio	- - Tmin WOR	person - °C -
Construction	Window to wall ratio Window to roof ratio Thermal transmittance coefficient of roof Thermal transmittance coefficient of wall Thermal transmittance coefficient of floor Thermal transmittance coefficient of window Solar energy transmittance of window glazing Surface shortwave reflectance Ground surface shortwave reflectance Infiltration rate (air change rate)	WWR WRR Uroof Uwall Ufloor Uwindow Gwindow SW GSW Ninf	- - W/m^2K W/m^2K W/m^2K W/m^2K - - - volume/h
Metered data	Postcode 6 annual gas consumption	-	m^3/yr

Energy simulation

Validate
Calibrate

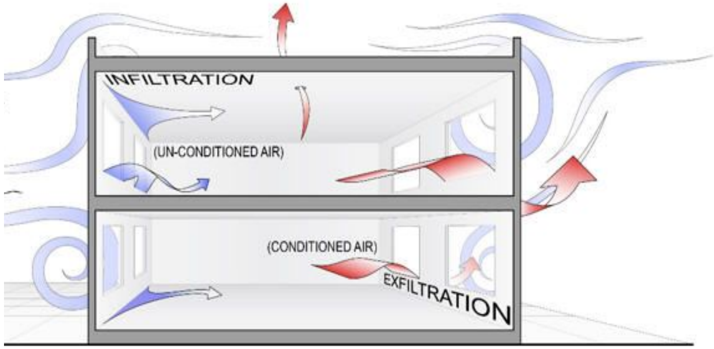
Operation

Minimum thermostat setting (**Tmin**)



Construction

Thermal transmittance coefficient of roof (**Uroof**)
Thermal transmittance coefficient of wall (**Uwall**)
Thermal transmittance coefficient of floor (**Ufloor**)
Thermal transmittance coefficient of window (**Uwindow**)

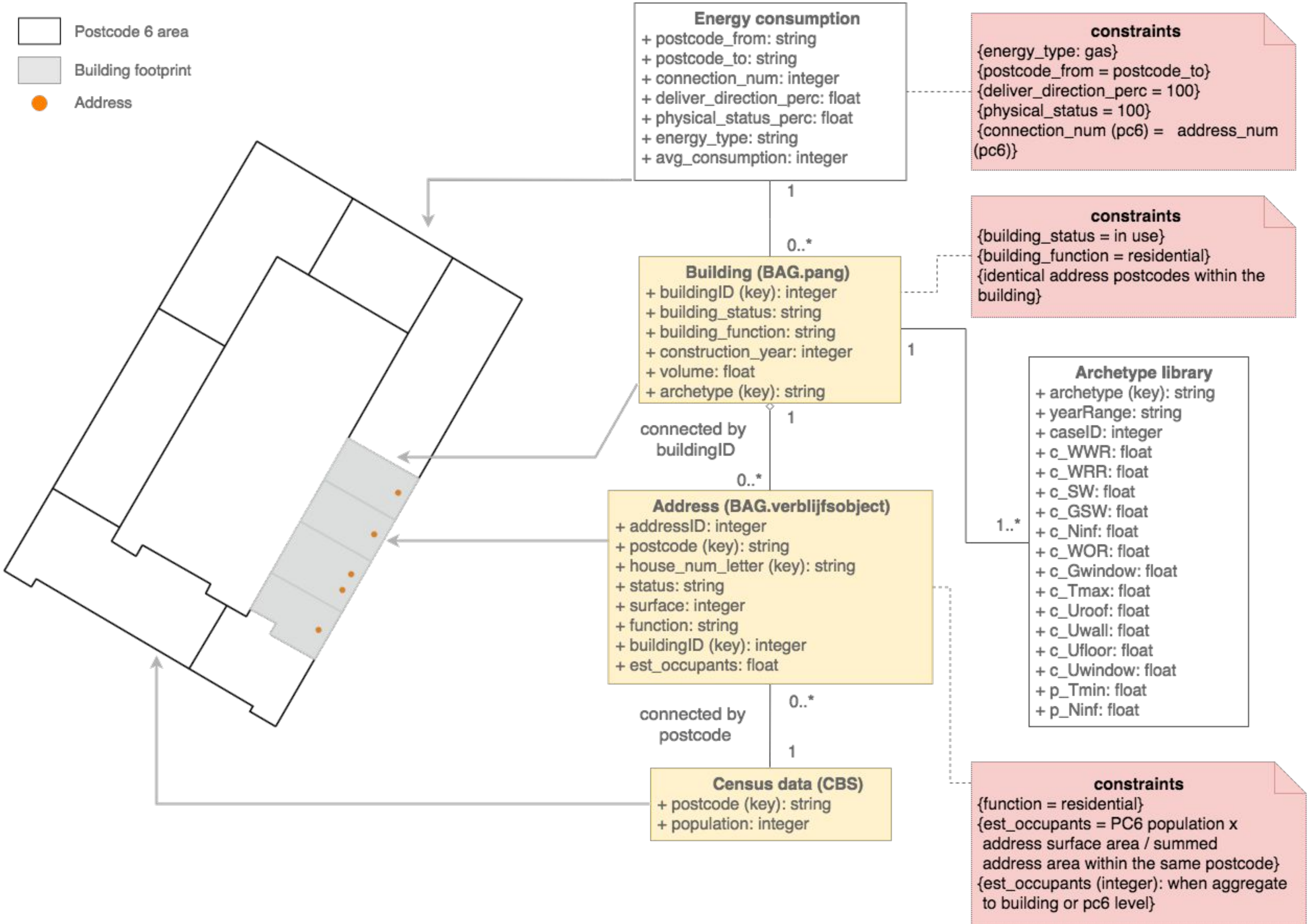


Construction

Infiltration rate (**Ninf**)

Image source [6, 7, 8]

Data integration



Data integration

- Standardized 3D city model: CityGML
- XML based 3D data standard for the representation, storage, and exchange of 3D city models/data
- Open data model (Open Geospatial Consortium, OGC standard)

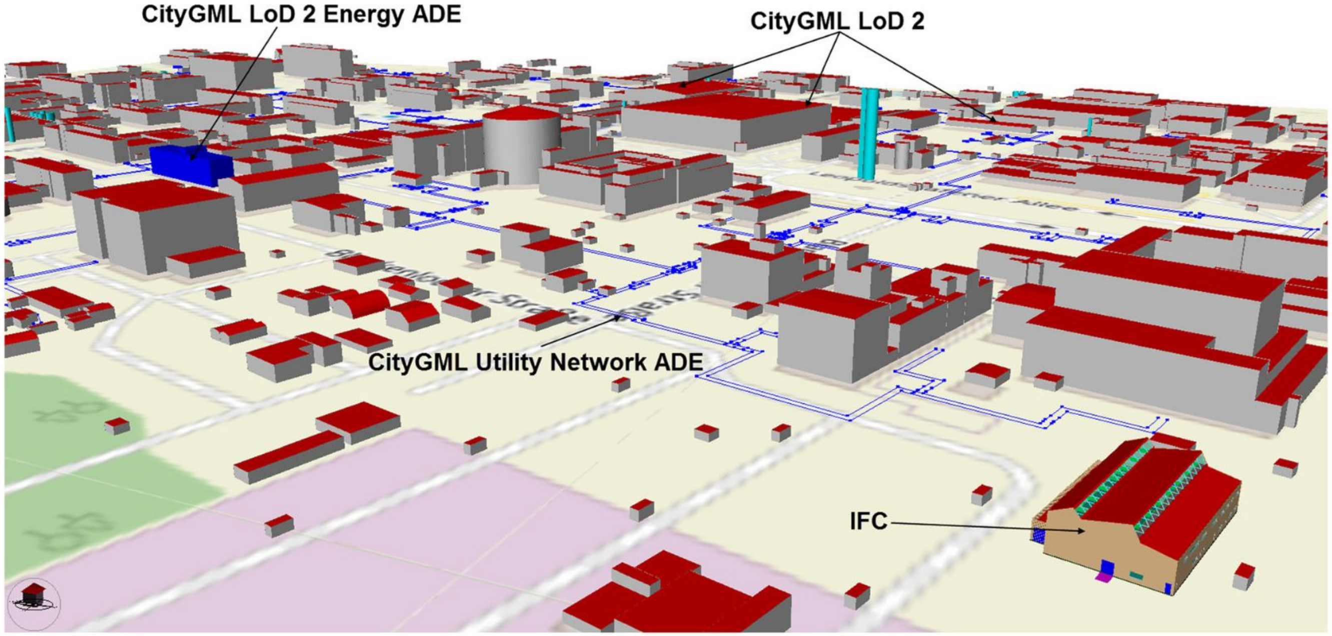


Fig. 16 Integration and visualisation of different geospatial data formats in the IFCExplorer

Agugiaro et al., 2018

Data integration

- Energy ADE (Application Domain Extension) is developed for:
  - Ease data interoperability for Urban Energy Modeling
  - Allow for multi-scales, multi-domains energy modeling

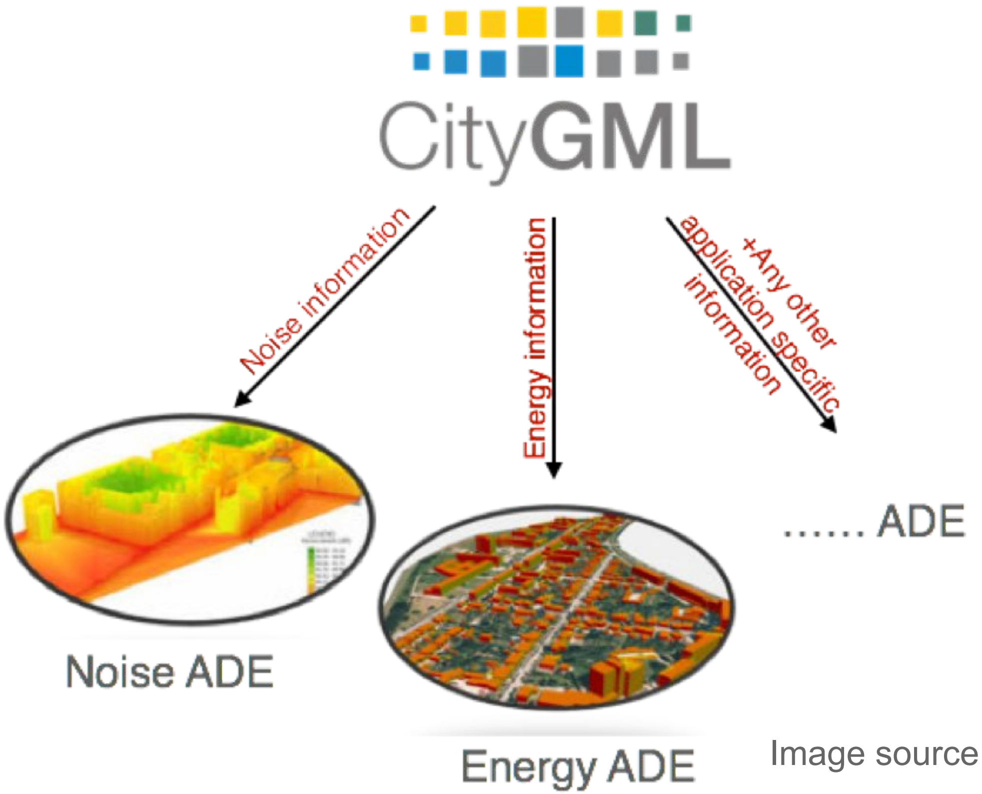
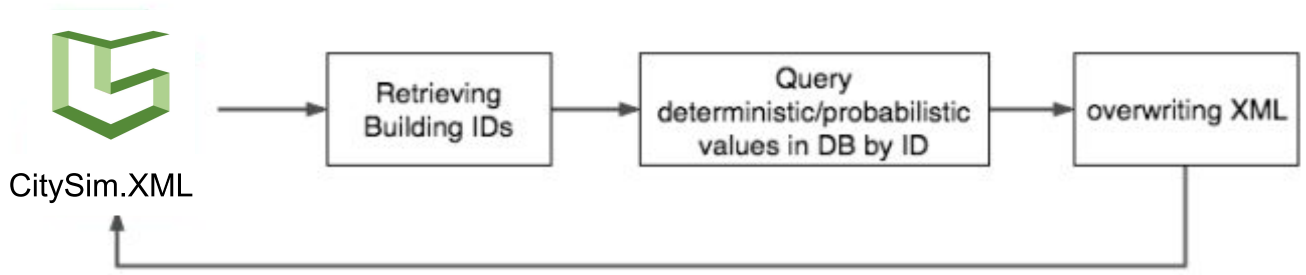


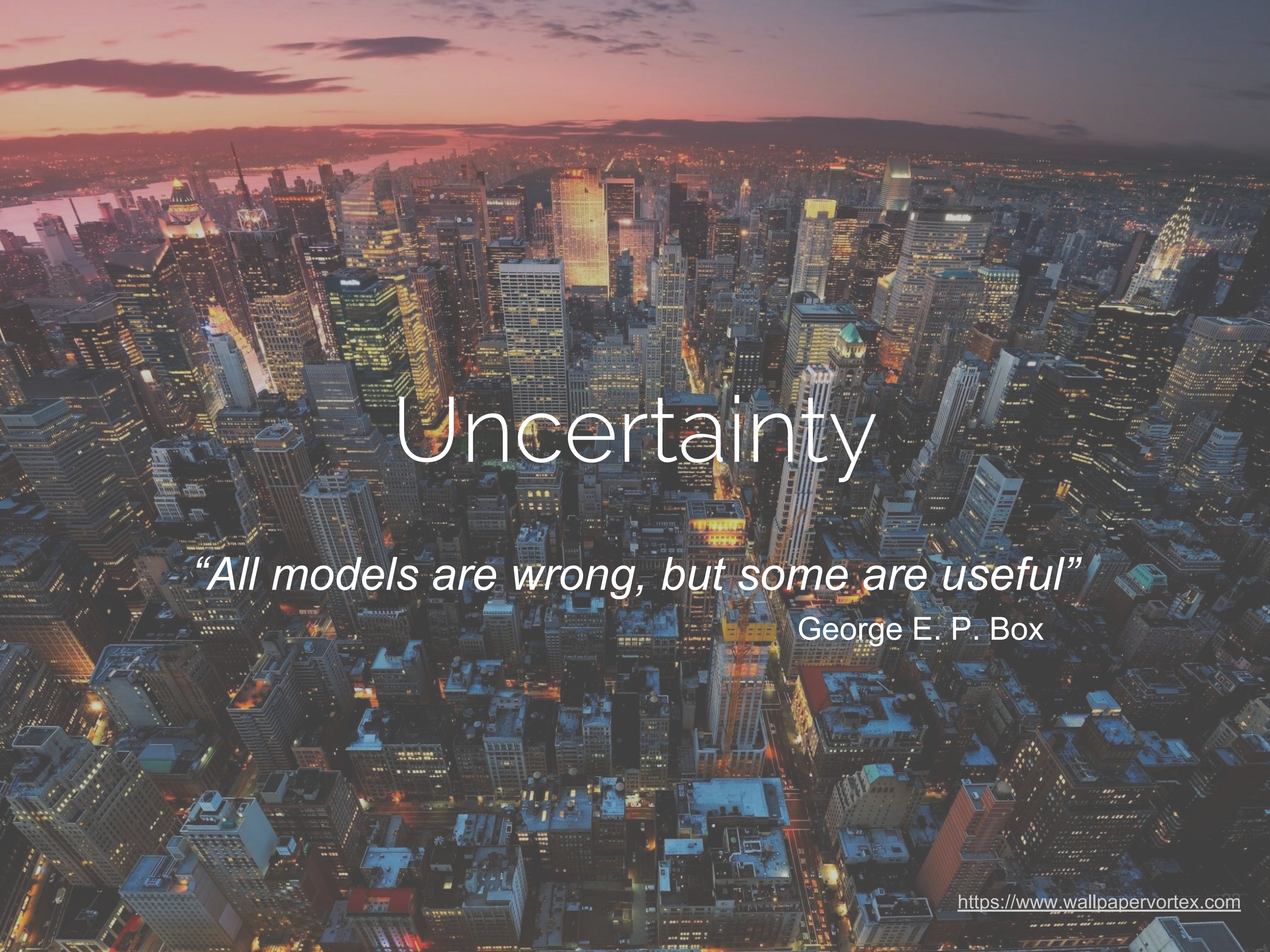
Image source: [9]

Data integration



BuildingID


```xml
<Building Name="" id="0" key="865" Vi="34976.9453" Ninf="0.1" BlindsLambda="0.2" BlindsIrradianceCutOff="100" Simulate="true">
    <HeatTank V="0.01" phi="20" rho="1000" Cp="4180" Tmin="20" Tmax="35"/>
    <CoolTank V="0.01" phi="20" rho="1000" Cp="4180" Tmin="5" Tmax="20"/>
    <HeatSource beginDay="1" endDay="365">
        <Boiler name="" Pmax="10000000" eta_th="0.95"/>
    </HeatSource>
    <Zone id="0" volume="34976.9" psi="0" Tmin="20" Tmax="26" groundFloor="true" >
        <Occupants n="0" d="0" type="0"/>
        <Wall id="596" type="4" ShortWaveReflectance="0.2" GlazingRatio="0" GlazingGValue="0" GlazingUValue="0" OpenableRatio="0">
            <V0 x="681822.75" y="246715.59" z="9.00"/>
            <V1 x="681819.69" y="246709.88" z="18.00"/>
            <V2 x="681822.75" y="246715.59" z="18.00"/>
        </Wall>
```



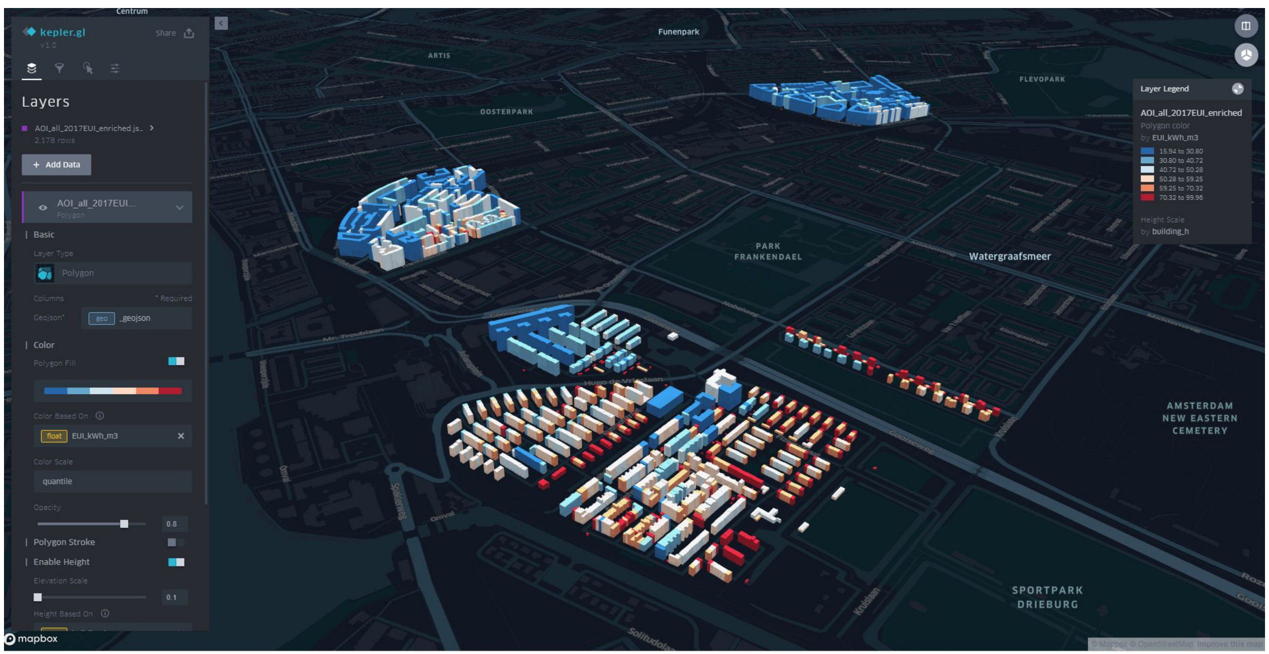
Uncertainty

“All models are wrong, but some are useful”

George E. P. Box

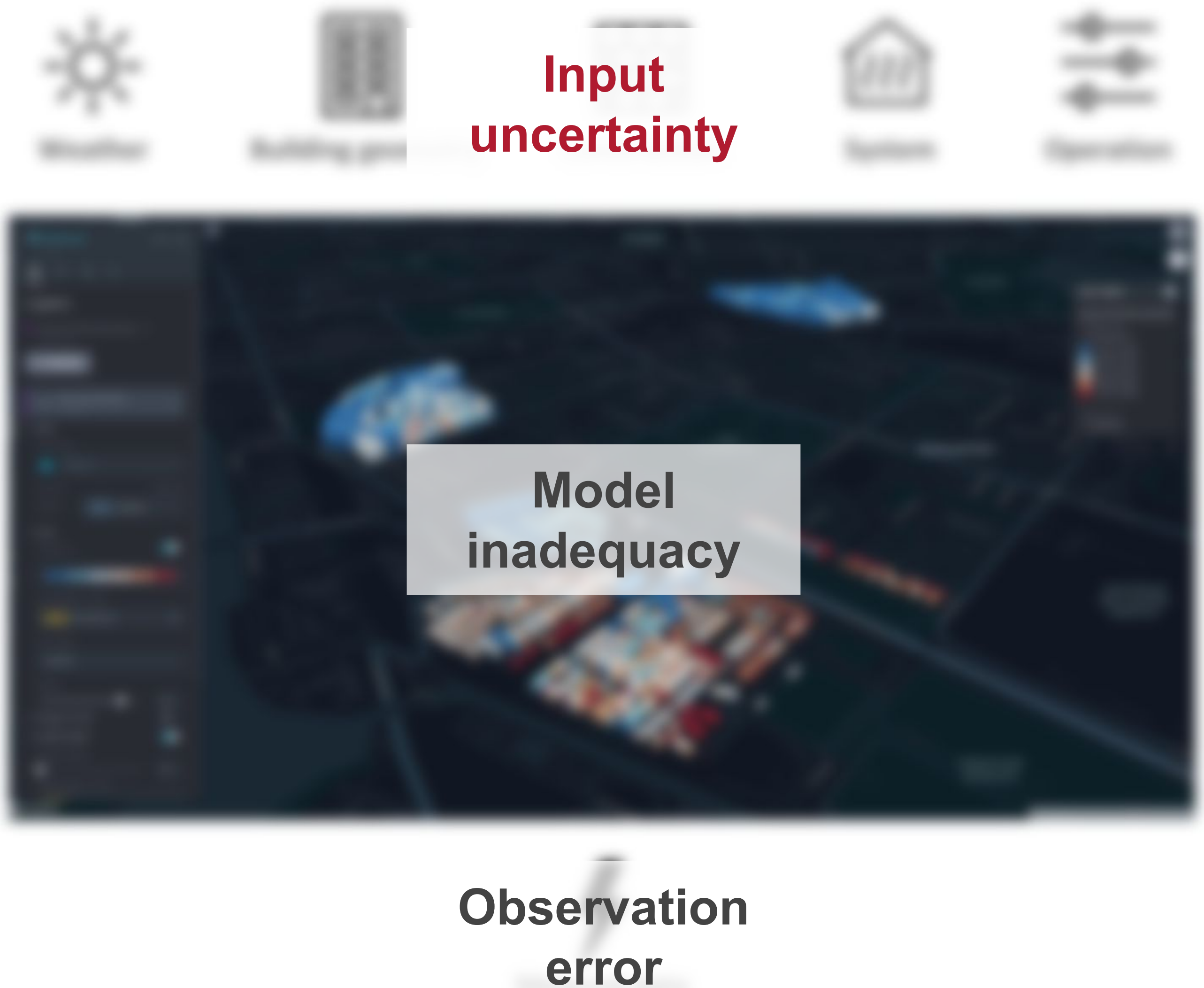
Uncertainty

Weather **Building geometry** **Construction** **System** **Operation**



Metered data

Uncertainty



Data preparation - Uncertainty ranges

Table 3.8: Uncertainty ranges of simulation inputs

Parameters	Symbol	Unit	Uncertainty
Building construction parameters			
Window to wall ratio	**WWR**	-	U(0.15-0.45)
Window to roof ratio	**WRR**	-	U(0.00-0.15)
Thermal transmittance coefficient of roof	**Uroof**	W/m^2K	U(0.16-2.60)
Thermal transmittance coefficient of wall	**Uwall**	W/m^2K	U(0.21-2.55)
Thermal transmittance coefficient of floor	**Ufloor**	W/m^2K	U(0.27-2.09)
Thermal transmittance coefficient of window	**Uwindow**	W/m^2K	U(1.68-3.80)
Solar energy transmittance of window glazing	**Gwindow**	-	U(0.30-0.85)
Surface shortwave reflectance	**SW**	-	U(0.20-0.50)
Ground surface shortwave reflectance	**GSW**	-	U(0.20-0.50)
Infiltration rate (air change rate)	**Ninf**	$Volume/h$	U(0.19-0.81)
Operation parameters			
Minimum set-point temperature	**Tmin**	°C	U(15.0-20.0)
Window openable ratio	**WOR**	-	U(0.00-0.35)
System parameter			
Heating system efficiency	**Eta**	-	U(0.80-0.95)
Geometry parameter			
Building height uncertainty	**B_h**	-	U(0.90-1.10)

Sensitivity analysis

https://www.wallpapervortex.com

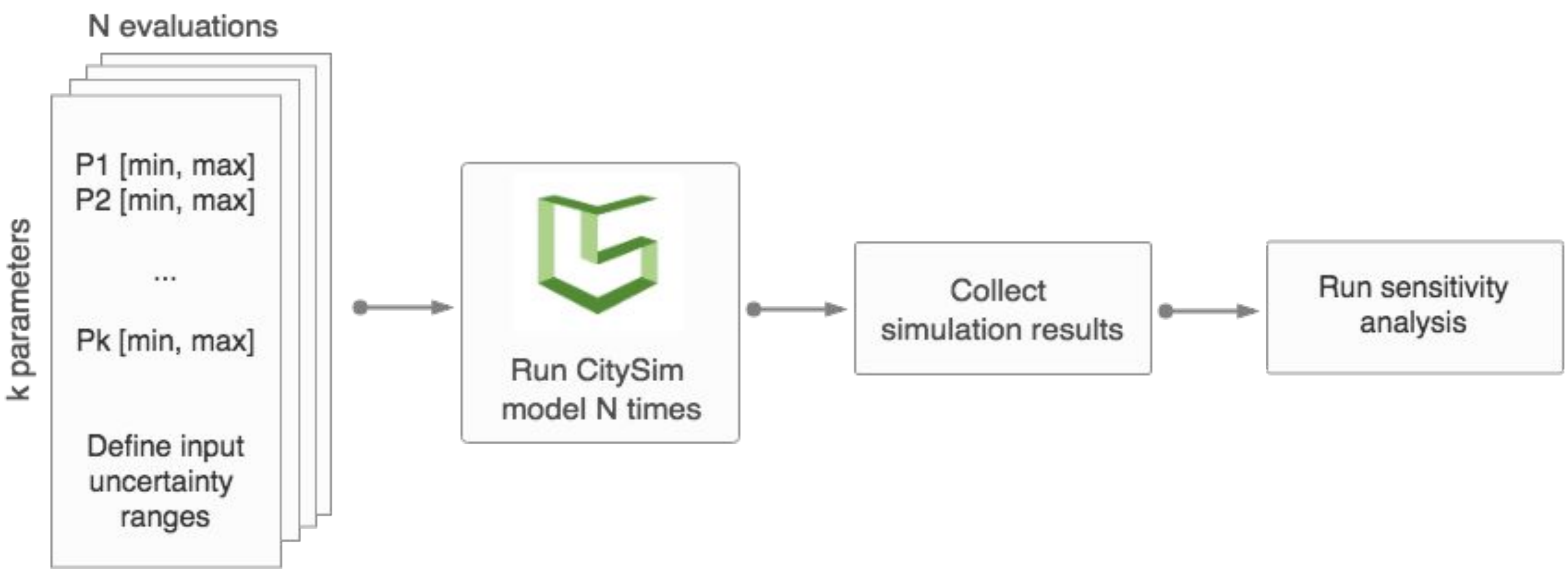
Sensitivity analysis

Table 2.4: Global sensitivity methods and characteristics. Adapted from Wei [2013]

Method	Characteristics	Subtype
Regression	• Fast and easy to interpret • SRC and t-value are only suitable for linear models and can not be used in the presence of correlated factors • SRRC and PCC can be used for non-linear but monotonic functions • Applicable to observational study	SRC SRRC PCC t-value step-wise adjust R square AIC
Screening	• Qualitative measures to rank factors, not suitable for uncertainty analysis • Model free approach, suitable for large number of inputs and computationally intensive models • No self-verification	Morris
Variance	• Model free appraoch, suitable for complex non-linear and non-additive models • Quantify all the variance of the output and consider interaction effects among variables • Highest computational cost among all global methods • FAST is not suitable for discrete distribution and only consider non-linear effects, but not interaction effects	Sobol FAST
Meta-model	• Suitable for complex and computationally intensive models • Quantify output variance of different inputs • The accuracy dependent on the applied meta-model • Applicable to observational study	MARS ACOSSO SVM GP TGP

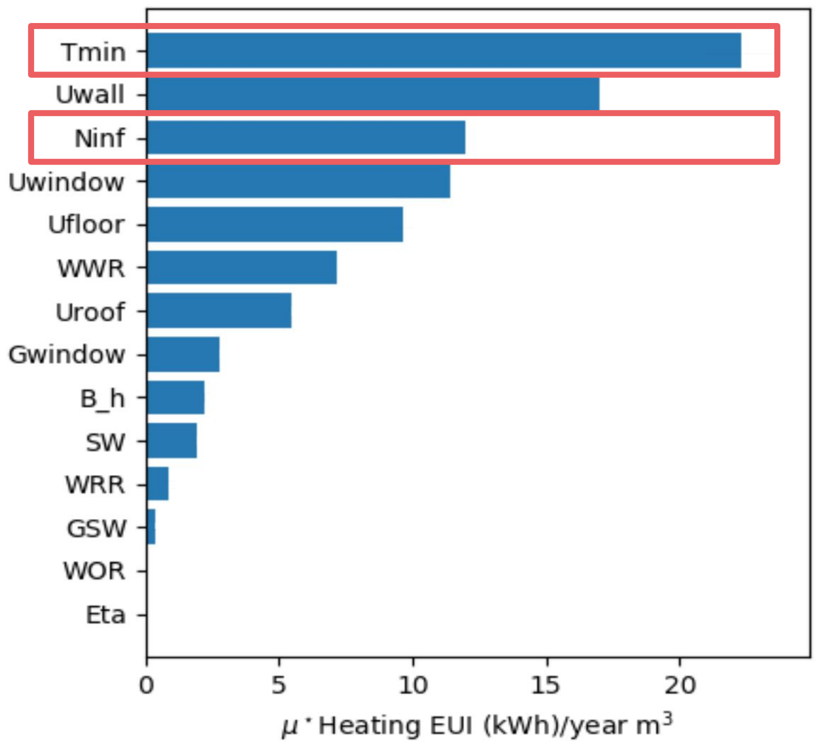
SRC: Standardized Regression Coefficients; SRRC: Standardized Rank Regression Coefficient; PCC: Partial Correlation Coefficients; AIC: Akaike Information Criterion; FAST: Fourier Amplitude Sensitivity Test; MARS: Multivariate Adaptive Regression Splines; ACOSSO: Adaptive Component Selection and Smoothing Operator; SVM: Support Vector Machine; GP: Gaussian Process; TGP: Treed Gaussian Process

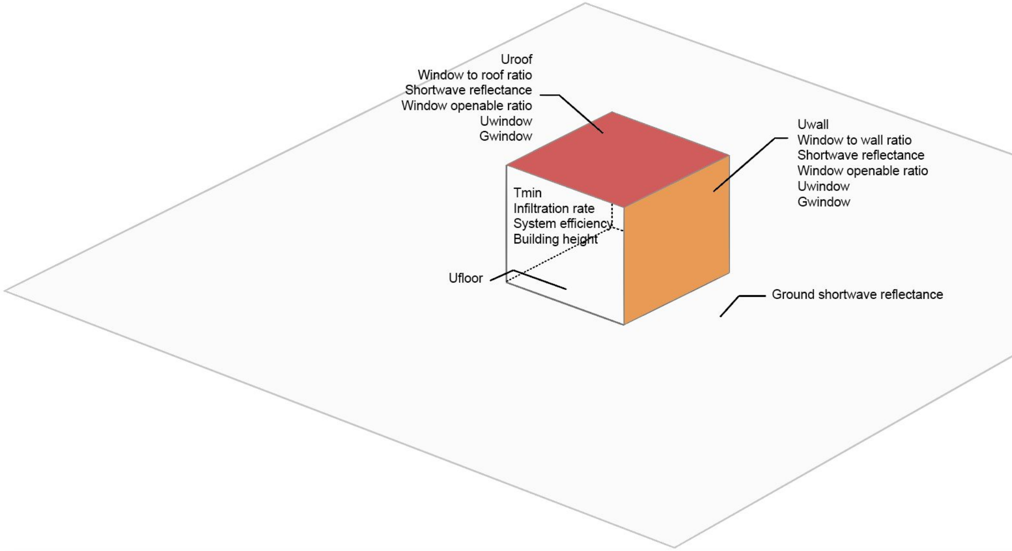
Sensitivity analysis - Morris method



Sensitivity analysis - Morris method

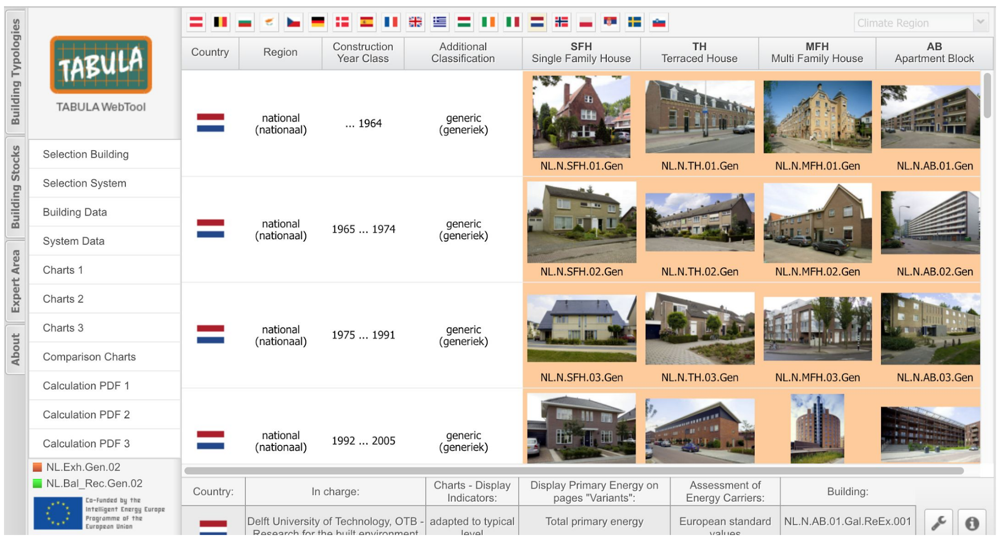
- Building dimension: 13.5m x 13.5m x 13.5m
- Building height (volume) varies between 90% ~ 110% of the reference height to consider building height estimation uncertainty



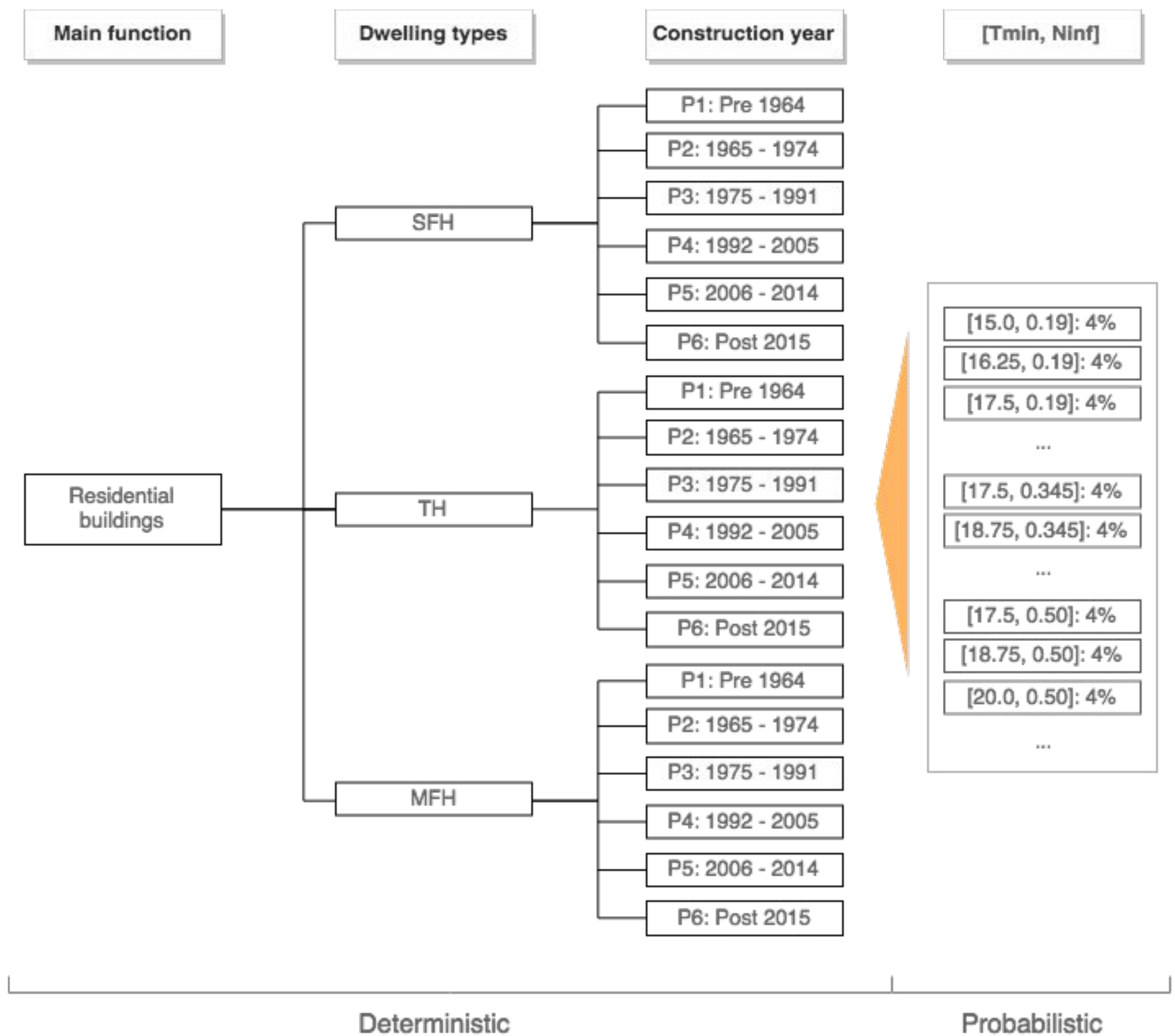


Archetype modeling - TABULA, National reference

- TABULA: 4 dwelling types, 6 construction periods: 24 archetypes
- National reference: 6 dwelling types, 6 construction periods: 36 archetypes



Archetype modeling



Bayesian inference
& model calibration

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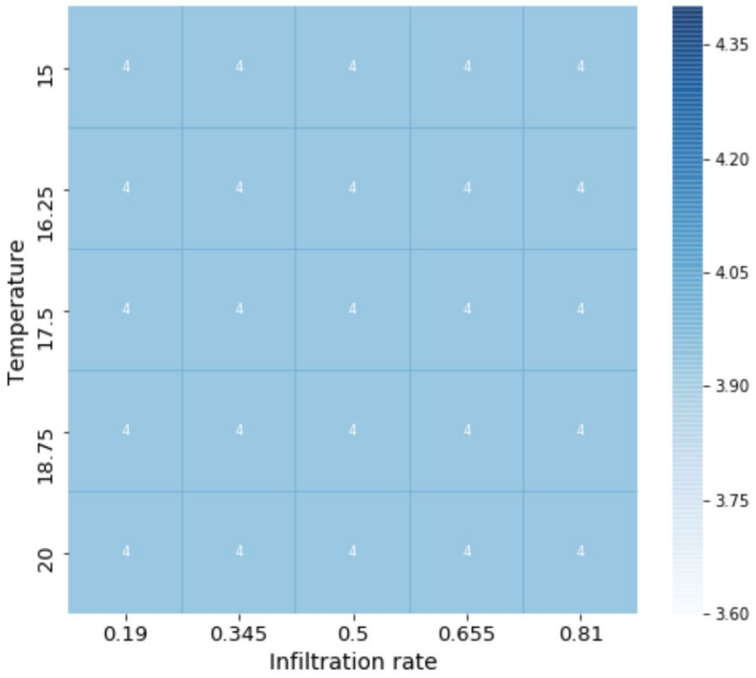
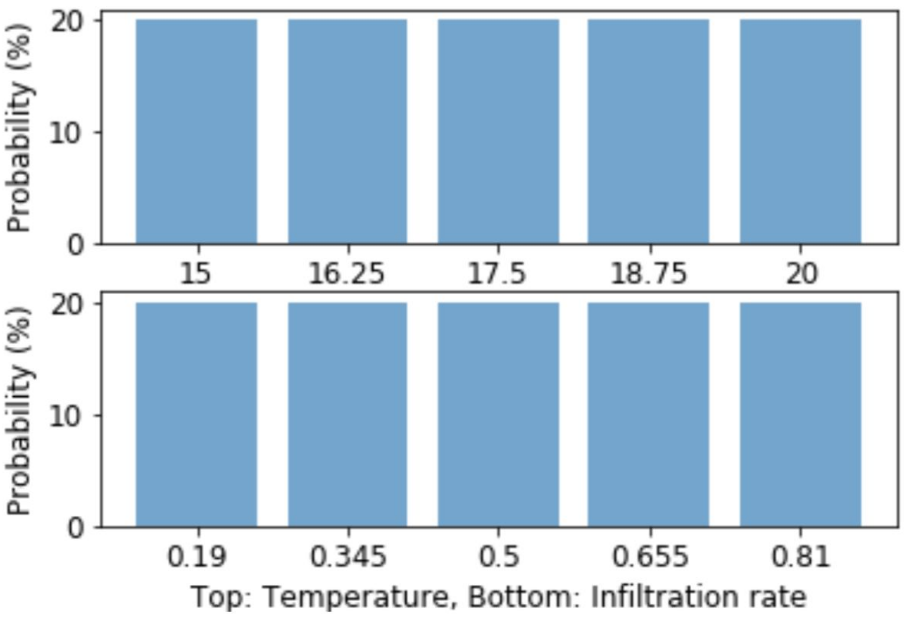
Prior $P(\theta)$

- Assuming each variable (Tmin, Ninf) is independent to each other
- Each variable is divided into 5 sections
- Initialize the prior to have an equal probability distribution
- Given enough prior knowledge, non-uniform prior distribution is possible





Bayesian inference and calibration

- Training data: 2010, 2011, 2012, 2013, 2014, 2015
- Validation data: 2016, 2017
- Calibration parameters: **θ** (Tmin, Ninf)
- Calibrating each PC6 parameters ($\boldsymbol{\theta}_{pc6}$)

$$P(\boldsymbol{\theta}|g_{eui}) = \frac{P(g_{eui}|\boldsymbol{\theta})P(\boldsymbol{\theta})}{P(g_{eui})} \qquad P(g_{eui}) = \int_{\boldsymbol{\theta}} P(g_{eui}|\boldsymbol{\theta}) \times P(\boldsymbol{\theta})d(\boldsymbol{\theta})$$

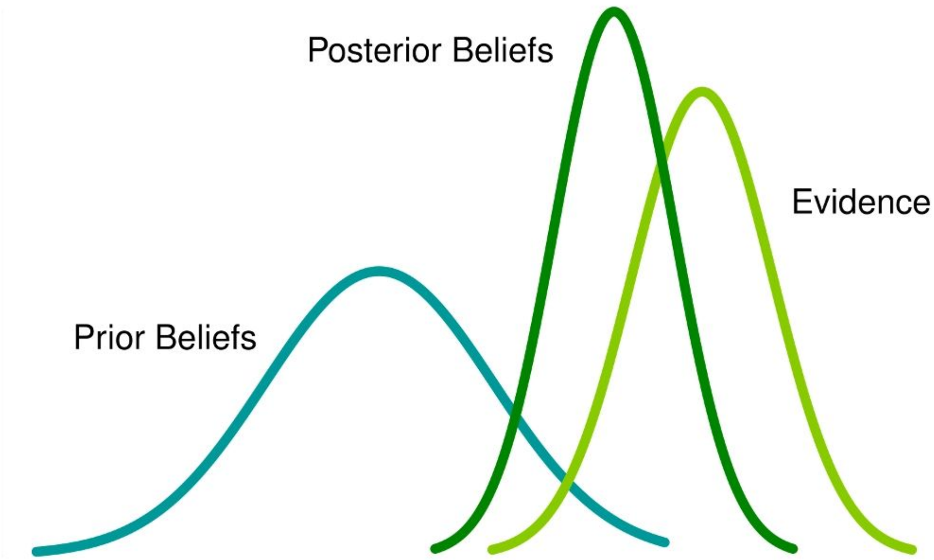


Image source: [10]

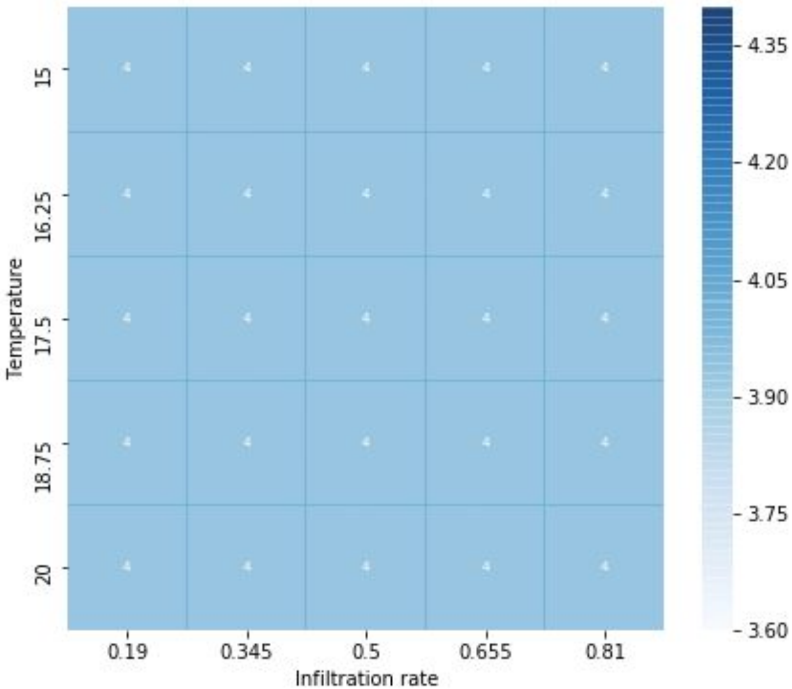
Likelihood $P(g_{eui}|\theta)$

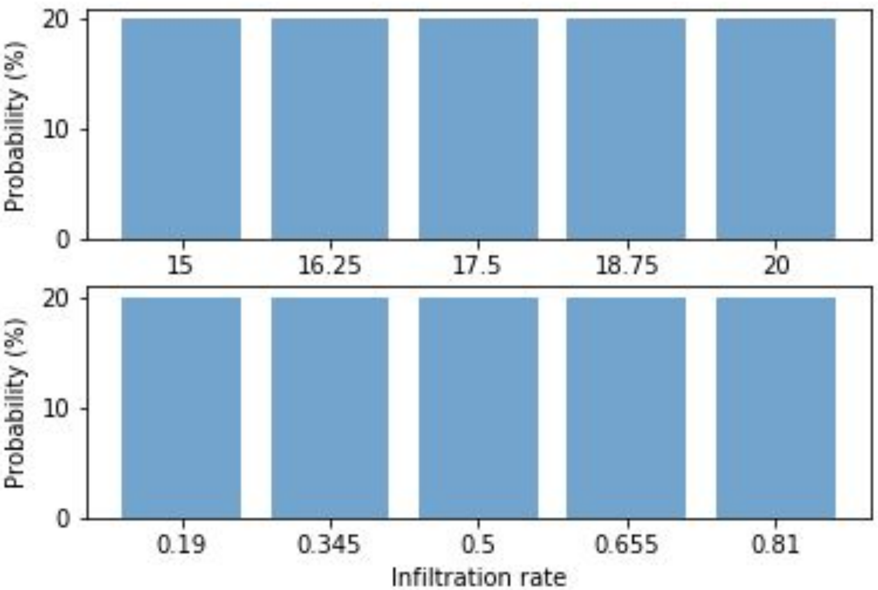
- Apply Gaussian to evaluate model n likelihood $P(d|\boldsymbol{\theta}_n)$
- g_{eui} = postcode 6 annual gas EUI
- μ = simulation EUI with the $\boldsymbol{\theta}_n$ input combination
- σ = standard deviation of the measured EUI distribution of the specific archetype group

$$P(g_{eui}|\boldsymbol{\theta}) \approx P(g_{eui};\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}}\exp(-\frac{(g_{eui}-\mu)^2}{2\sigma^2})$$

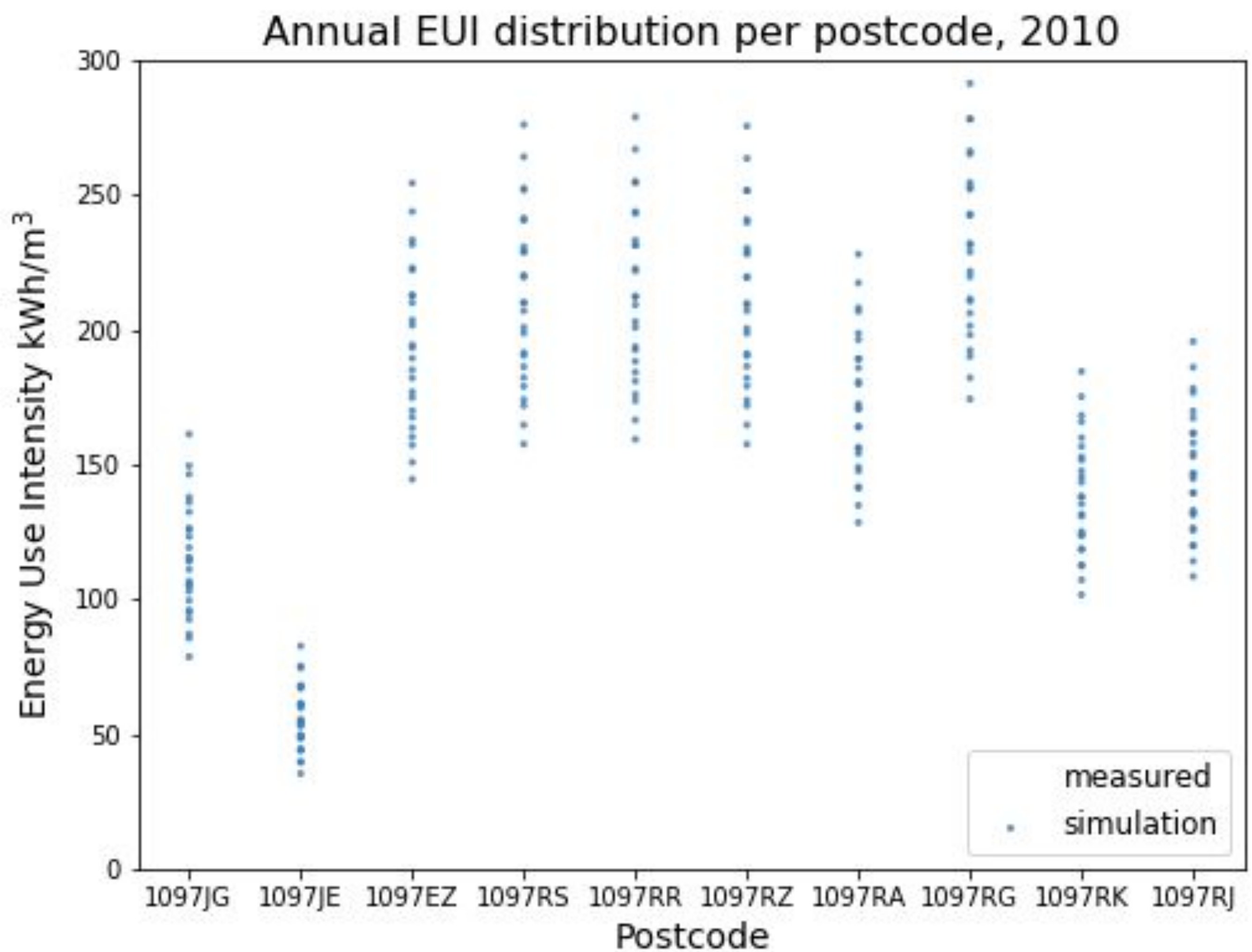
Posterior $P(\boldsymbol{\theta}|g_{eui})$

- When measurements come in…
- Starts with the 1st year having an equal Prior distribution
- The Posterior of the N year becomes a Prior of the N+1 year



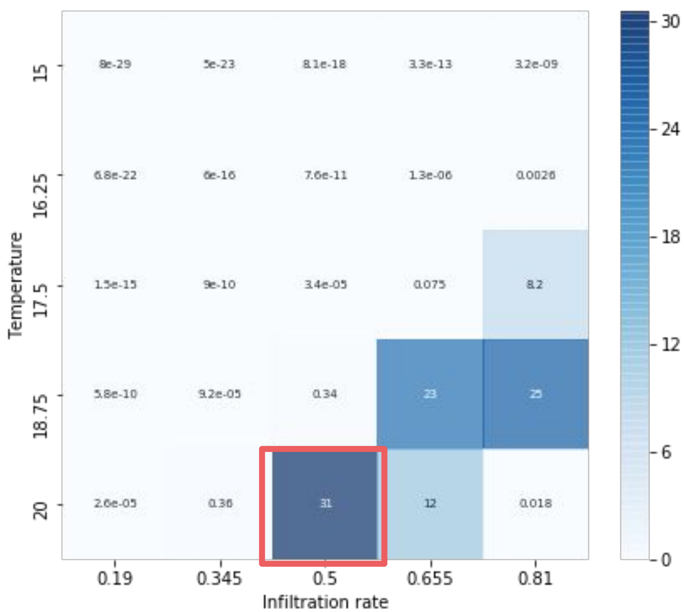


Bayesian calibration process



Validation

- Selecting optimal Posterior input combination of the final training year as calibrated inputs

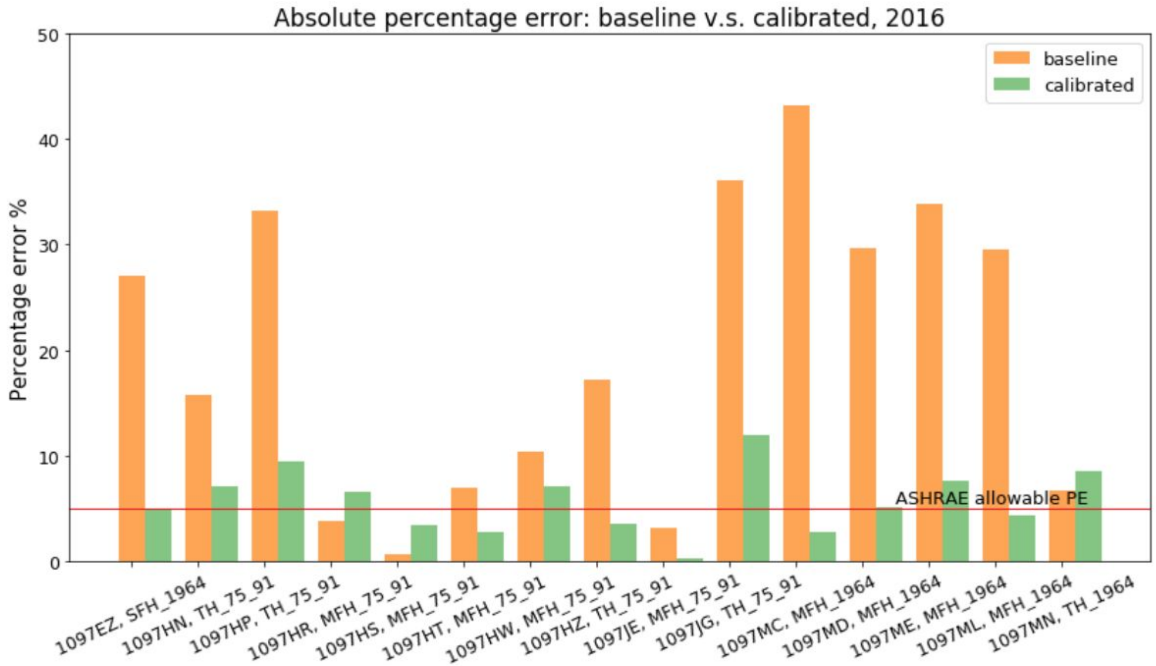


e.g. Calibrated parameters of (Tmin, Ninf) of postcode 6: 1094LW are (20, 0.5)

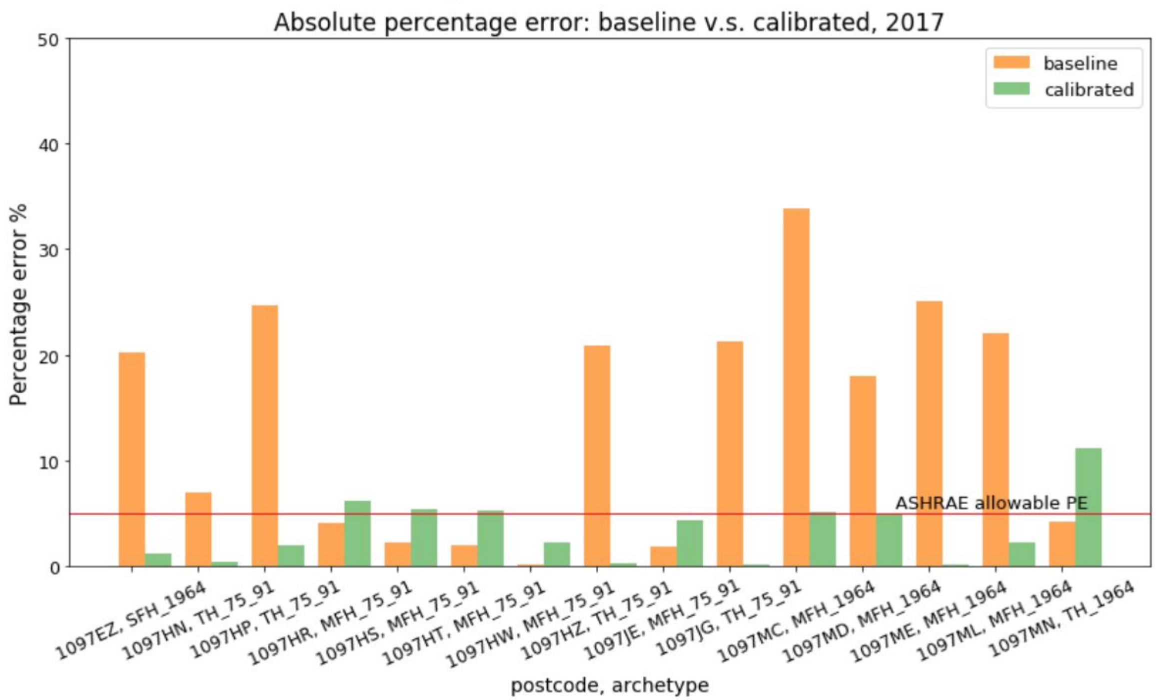
Absolute percentage error:

$$PE = \left| \frac{EUI_{metered} - EUI_{sim}}{EUI_{metered}} \right| \times 100\%$$

2016
2017

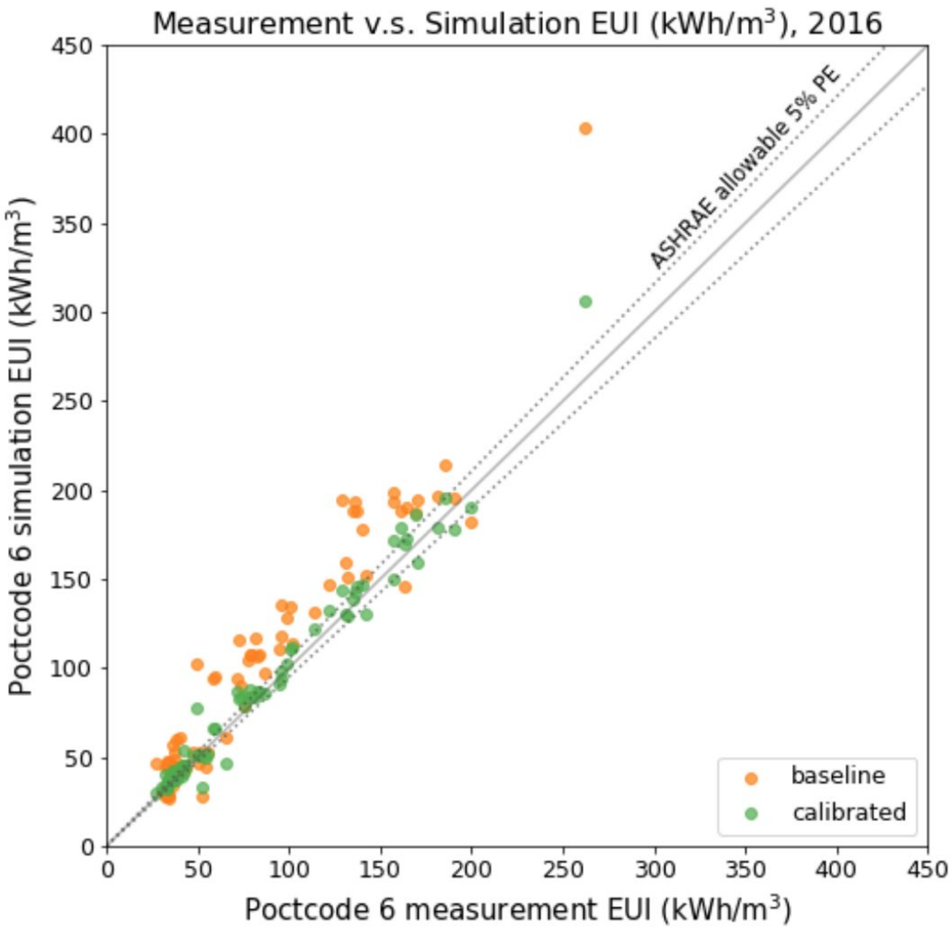


Absolute percentage error: baseline v.s. calibrated, 2016
baseline
calibrated
ASHRAE allowable PE
Percentage error %
0
10
20
30
40
50
1097EZ, SFH_1964
1097HN, TH_75_91
1097HP, TH_75_91
1097HR, MFH_75_91
1097HS, MFH_75_91
1097HT, MFH_75_91
1097HW, MFH_75_91
1097HZ, TH_75_91
1097JE, MFH_75_91
1097JG, TH_75_91
1097MC, MFH_1964
1097MD, MFH_1964
1097ME, MFH_1964
1097ML, MFH_1964
1097MN, TH_1964

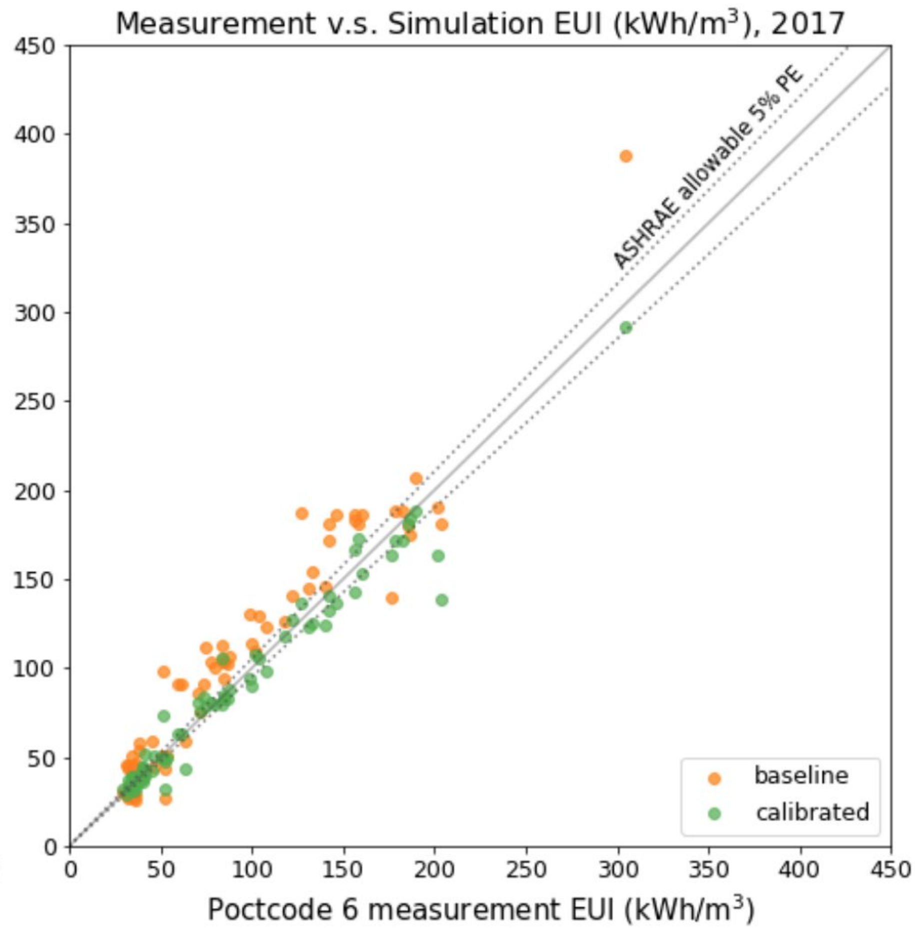


Absolute percentage error: baseline v.s. calibrated, 2017
baseline
calibrated
ASHRAE allowable PE
Percentage error %
0
10
20
30
40
50
1097EZ, SFH_1964
1097HN, TH_75_91
1097HP, TH_75_91
1097HR, MFH_75_91
1097HS, MFH_75_91
1097HT, MFH_75_91
1097HW, MFH_75_91
1097HZ, TH_75_91
1097JE, MFH_75_91
1097JG, TH_75_91
1097MC, MFH_1964
1097MD, MFH_1964
1097ME, MFH_1964
1097ML, MFH_1964
1097MN, TH_1964
postcode, archetype

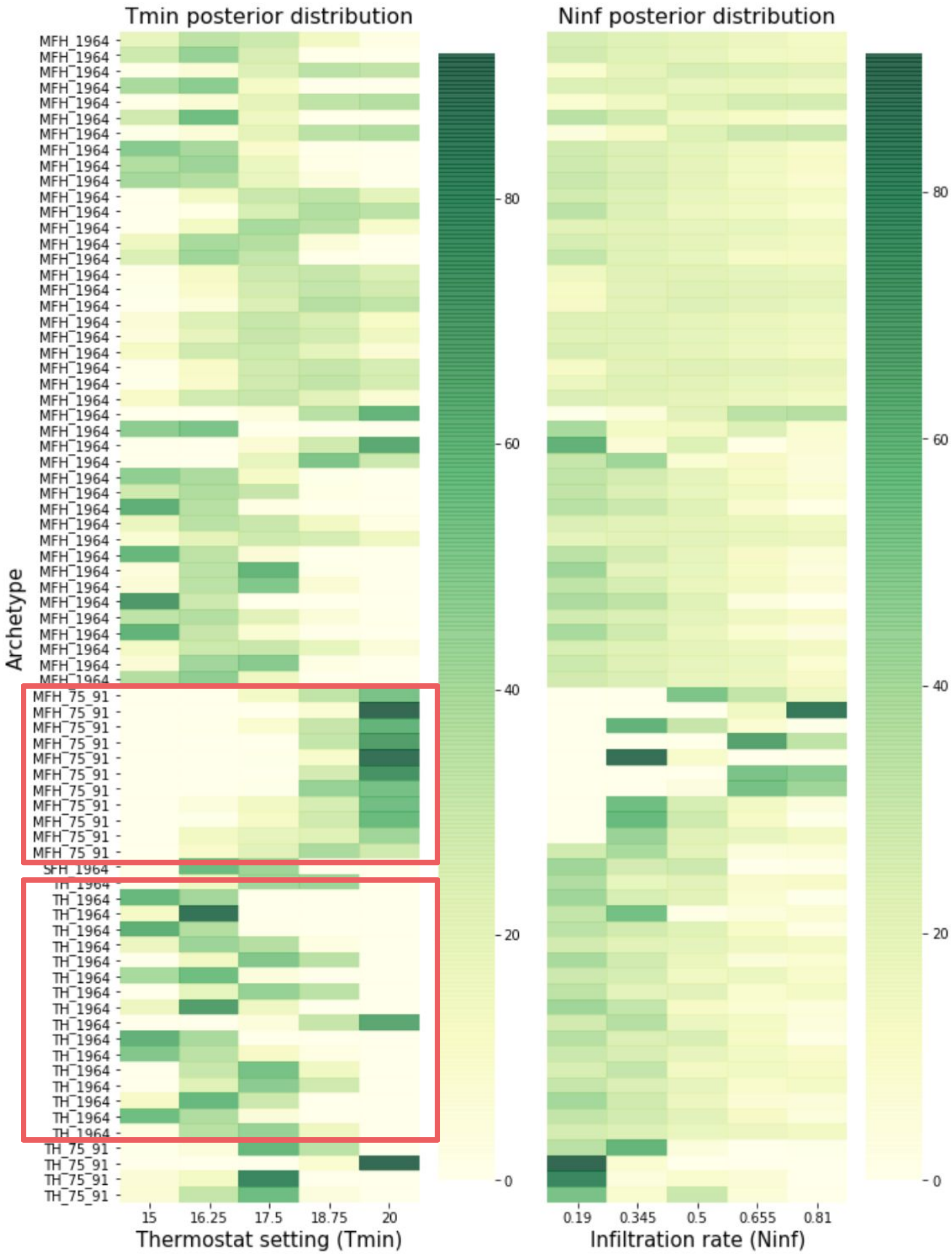
2016, 2017



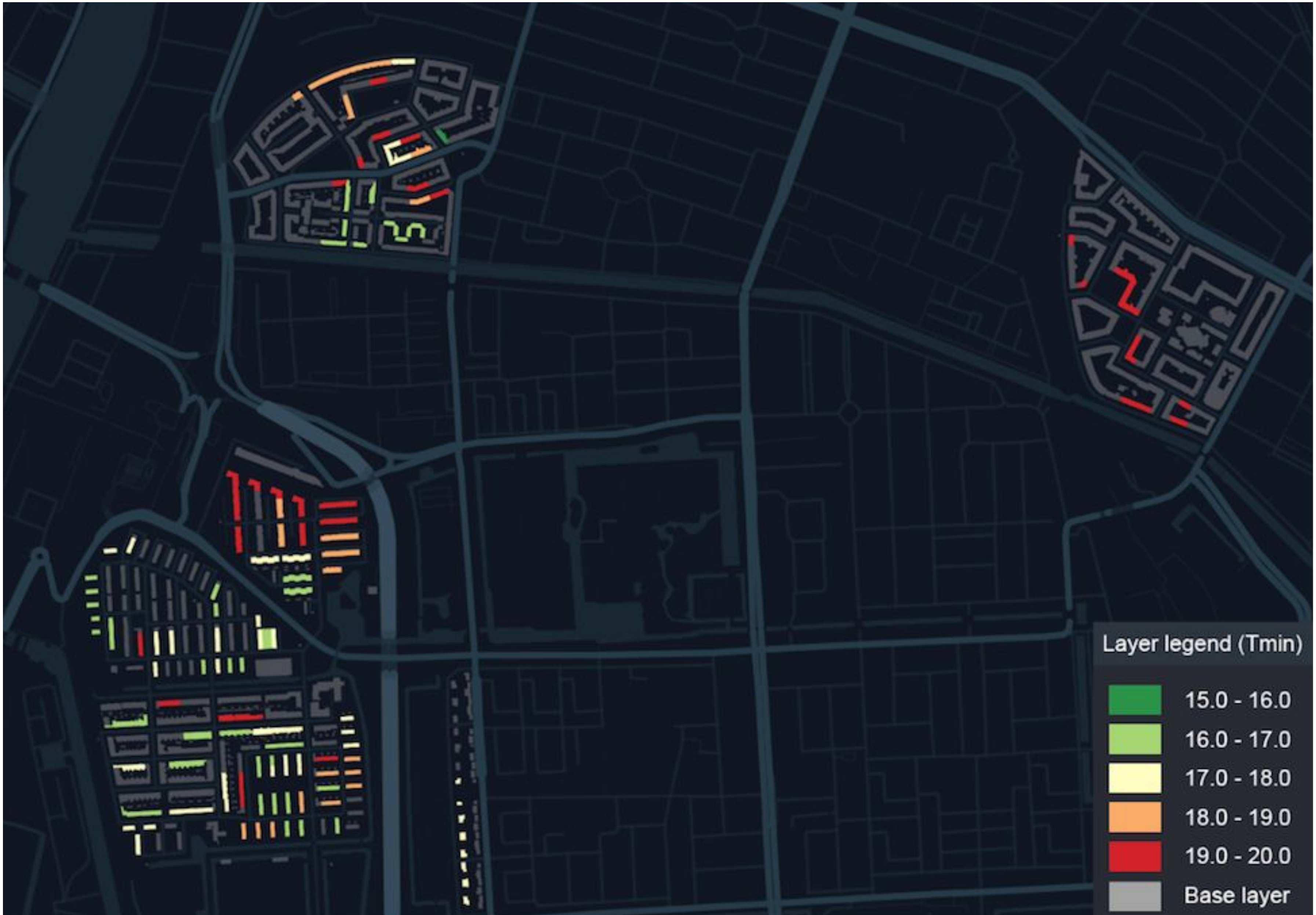
Measurement v.s. Simulation EUI (kWh/m3), 2016
Poctcode 6 simulation EUI (kWh/m3)
Poctcode 6 measurement EUI (kWh/m3)
ASHRAE allowable 5% PE
baseline
calibrated
0
50
100
150
200
250
300
350
400
450

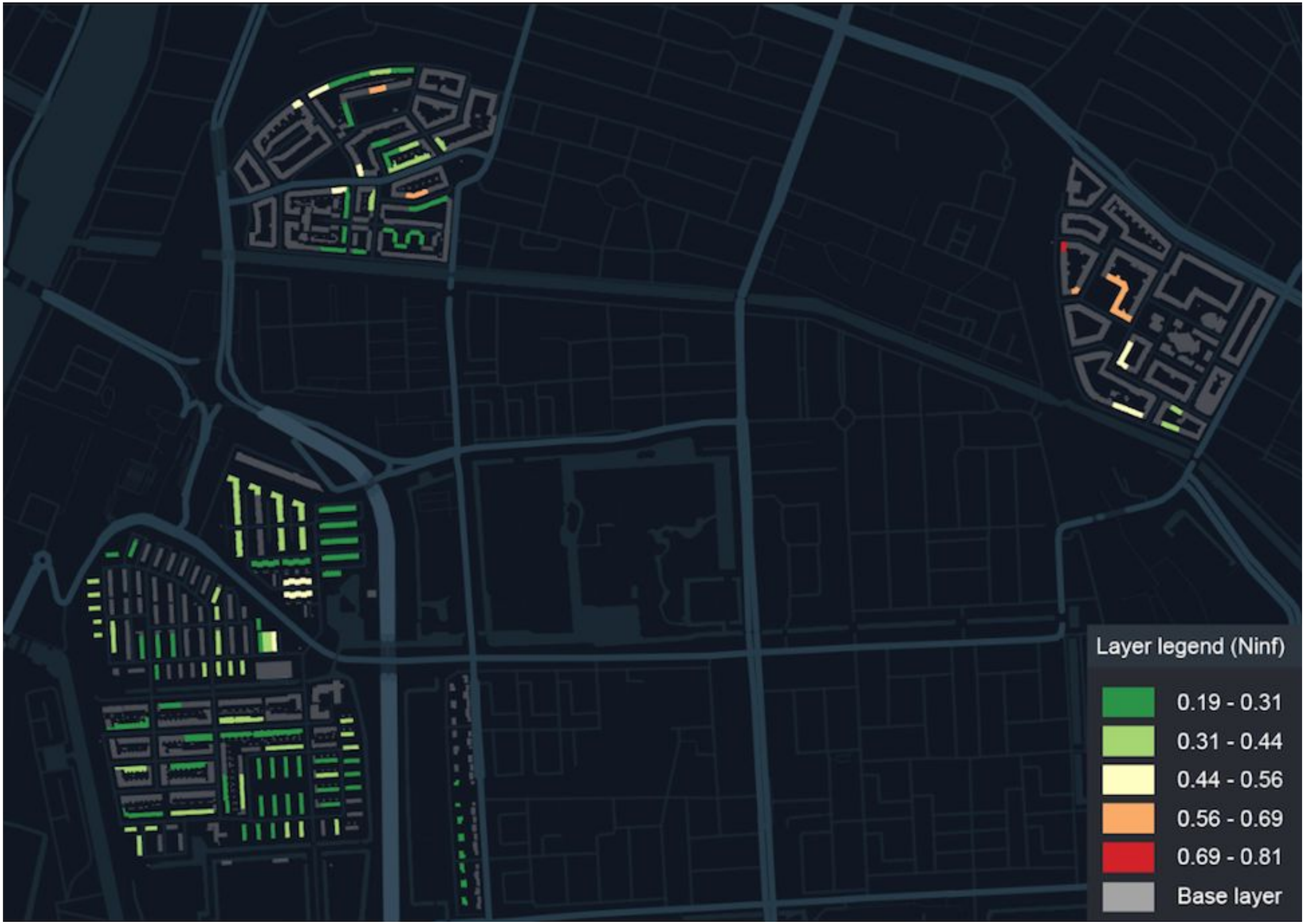


Measurement v.s. Simulation EUI (kWh/m3), 2017
Poctcode 6 measurement EUI (kWh/m3)
ASHRAE allowable 5% PE
baseline
calibrated
0
50
100
150
200
250
300
350
400
450



MFH: Multi family house
SFH: Single family house
TH: Terrace house

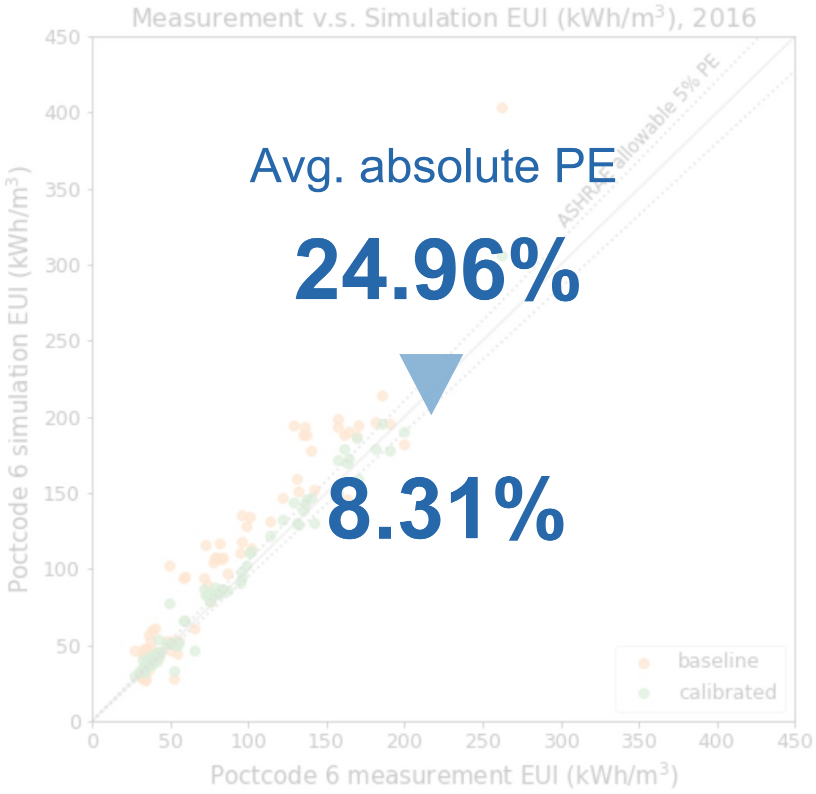

Layer legend (Tmin)
15.0 - 16.0
16.0 - 17.0
17.0 - 18.0
18.0 - 19.0
19.0 - 20.0
Base layer

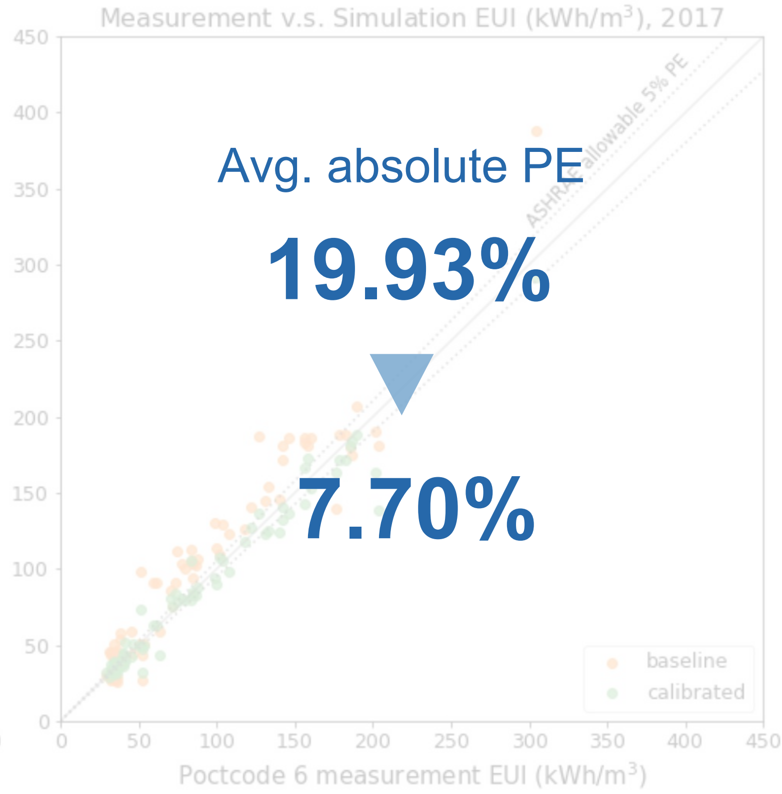

Layer legend (Ninf)
0.19 - 0.31
0.31 - 0.44
0.44 - 0.56
0.56 - 0.69
0.69 - 0.81
Base layer

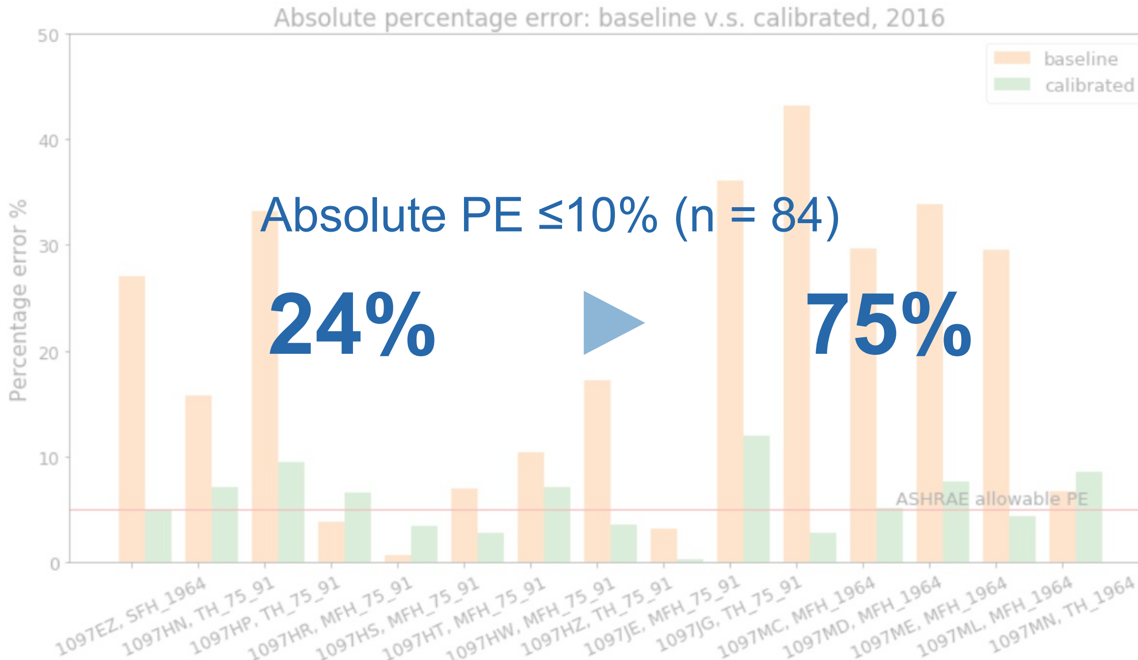
Discussion and conclusion

https://www.wallpapervortex.com

Discussion and conclusion

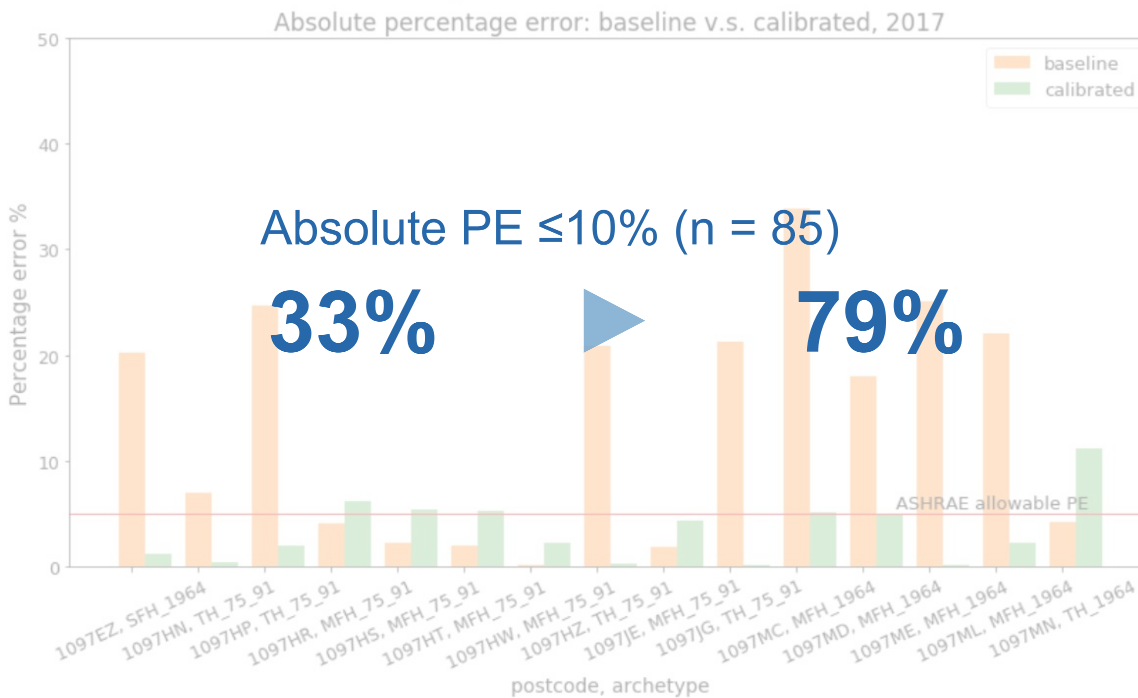






Absolute PE ≤10% (n = 84)

24% ▶ **75%**



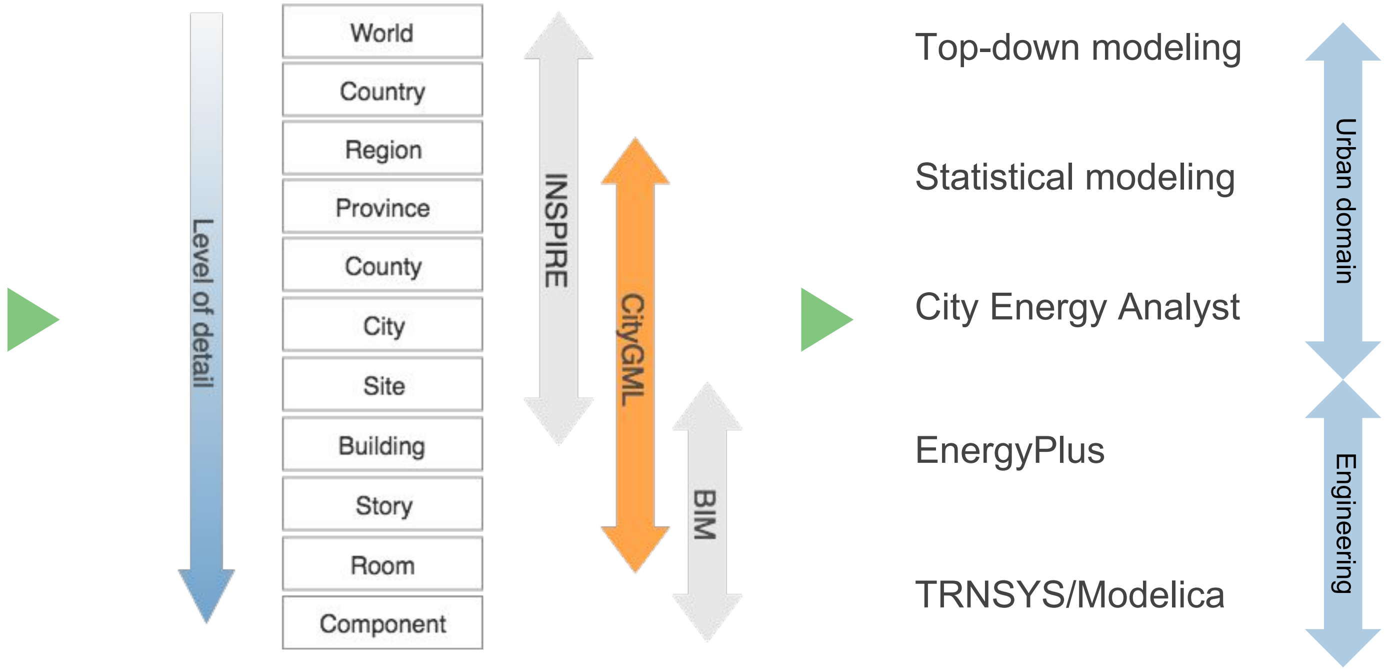
Absolute PE ≤10% (n = 85)

33% ▶ **79%**

Discussion and conclusion

- Data preparation
  - Preparing and harmonizing data is time-consuming and challenging. An appropriate data model such as CityGML might alleviate this process and facilitate data interoperability

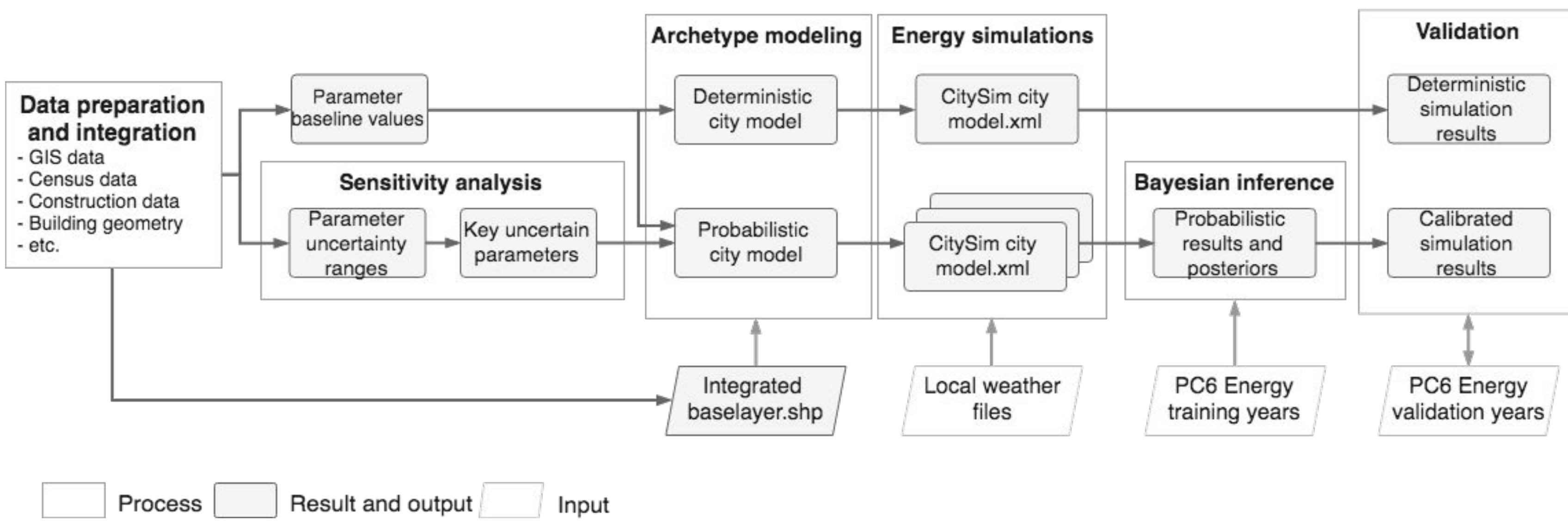
CitySim.XML



Adapted from Agugiaro et al., 2018

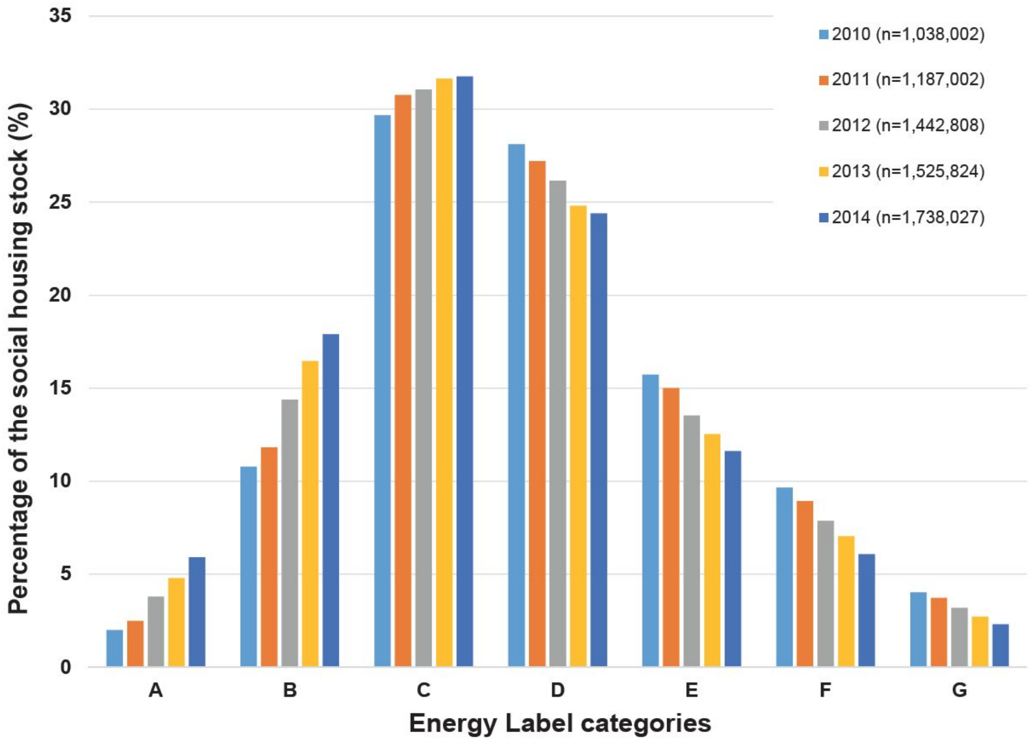
Discussion and conclusion

- UBEM in general
    - Calibrating with higher spatial-temporal resolution energy data might help to reduce more parameter uncertainties in UBEM.
    - Following the same methodology, developing the UBEM for other cities based on same or different simulation engines is possible.



UBEM in practice

“Base on the renovation rates achieved since 2010, attaining the short term goals of achieving an average energy label B in the non-profit Dutch housing stock by the end of 2020 is not probable...” (Filippidou, 2018)



Energy label distribution in the non-profit housing stock 2010-2014 (Filippidou, 2018)


Questions?
https://www.wallpapervortex.com

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