Simulations of interactions between buildings and their outdoor conditions at multiple scales

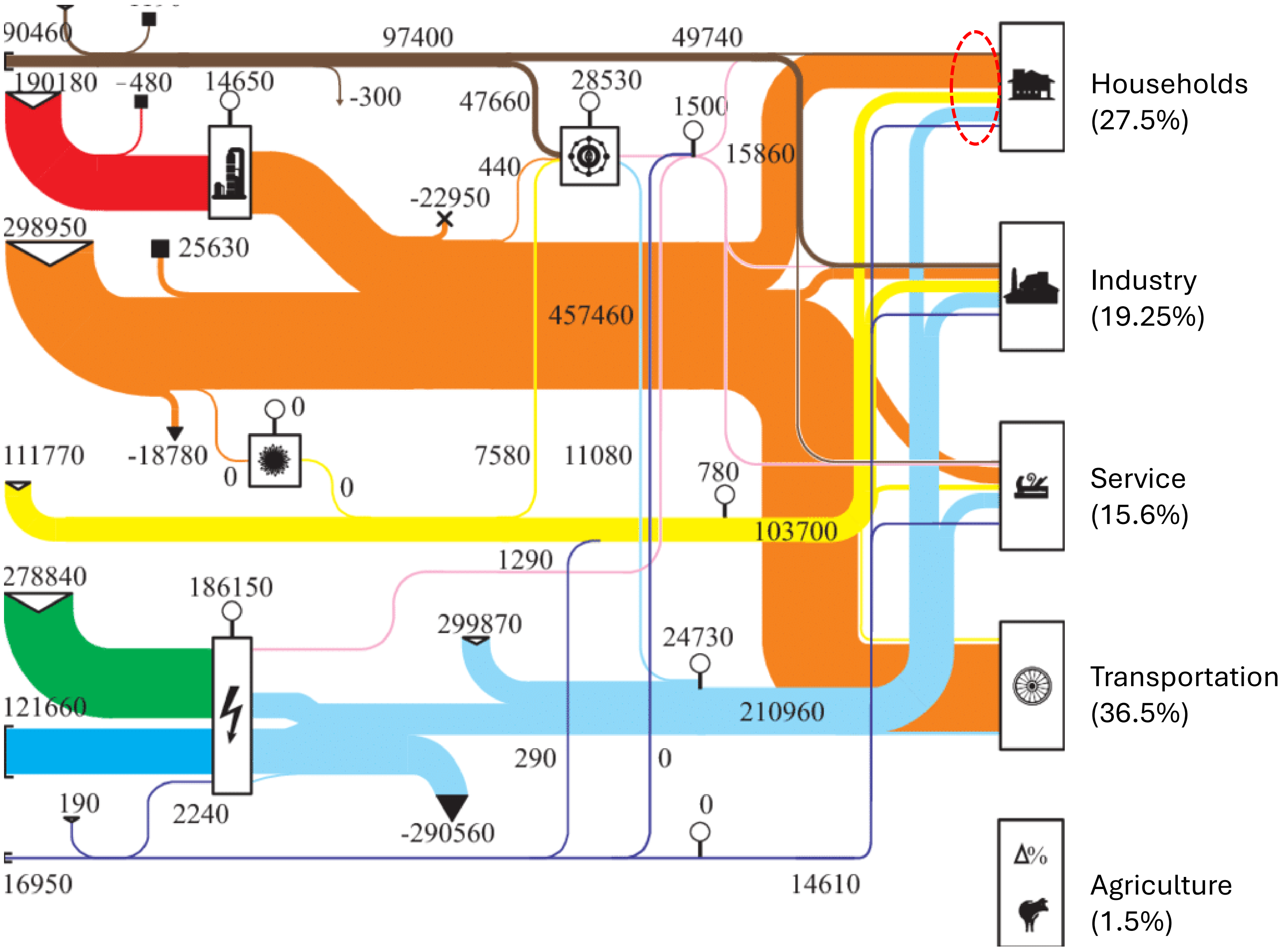
Dr. Miguel Martin

Agenda

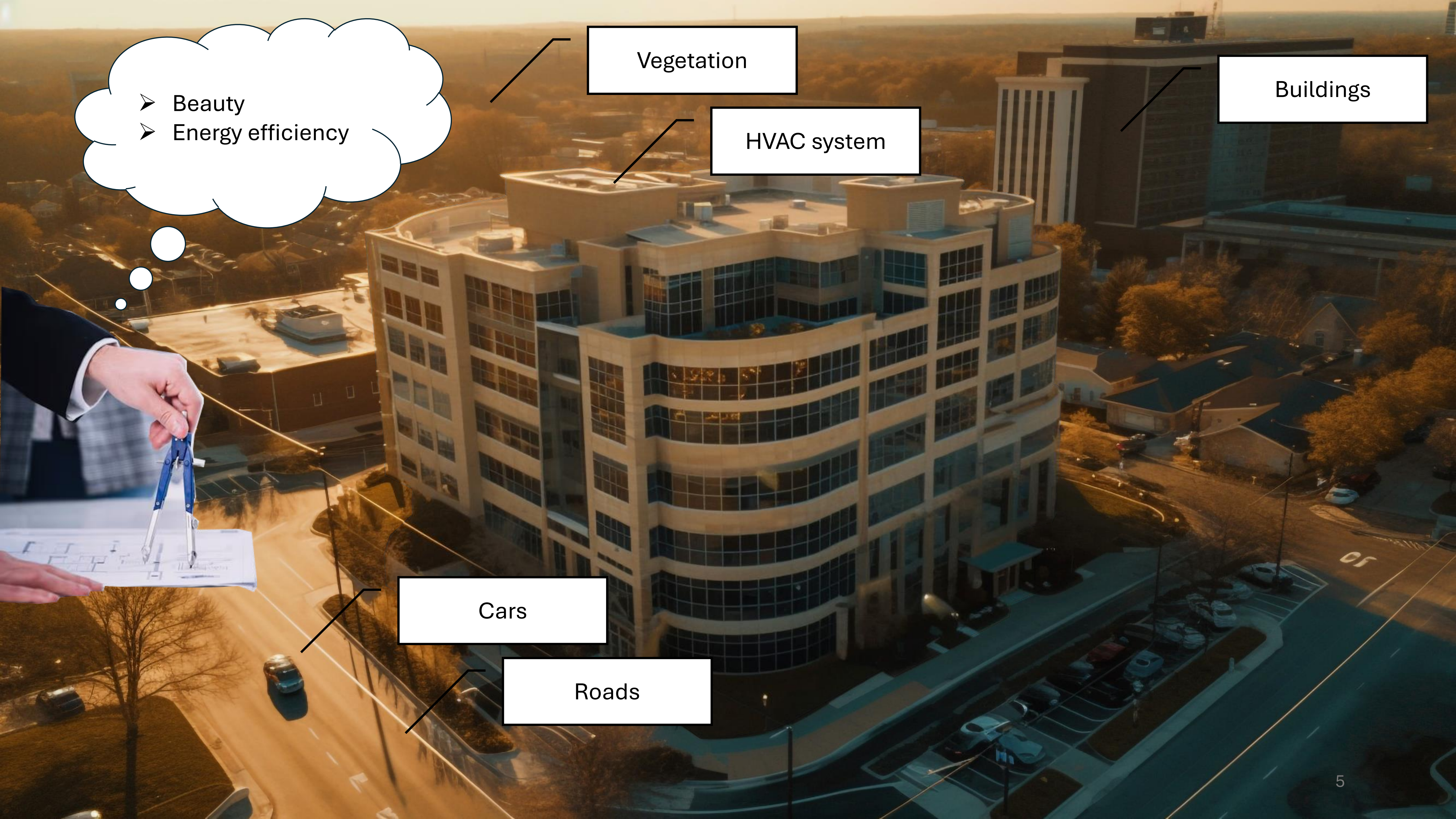
- Past research in simulations of interactions between one building and its outdoor conditions
- Overview of the SCIENCES project
- Coupling between detailed building energy models and a data driven urban canopy model for neighbourhood scale simulations
- Impact of interactions between buildings and their outdoor conditions on the calibration of an urban building energy model
- A full grey box model to simulate interactions between buildings and their outdoor conditions at the city scale

Past research in building energy and urban microclimate modelling

Energy Centre



Berger, M. (2012). Urban heat-balling-A review of measures on reducing heat in tropical and subtropical cities. *Sustainable future energy*, 445-451.


Beauty
Energy efficiency
Vegetation
HVAC system
Buildings
Cars
Roads


Temp.
Hum.
Heat
Vapour

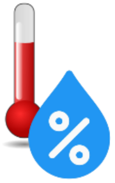
White box — Grey box — Black box

Building energy model

B.C. ↑ ↓ Outputs

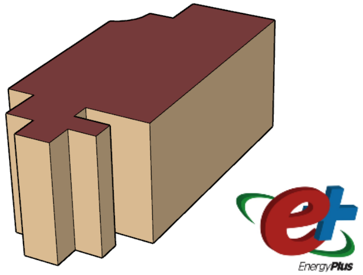
Coupled

Outputs ↑ ↓ Boundary Conditions (B.C.)

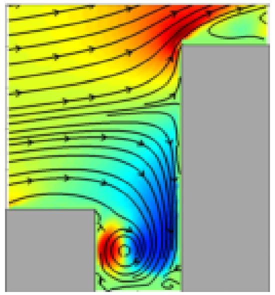


Urban microclimate model

Detailed model



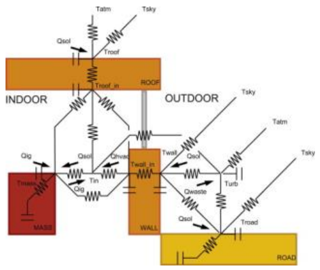
Computational fluid dynamics



Son et al. (2022)

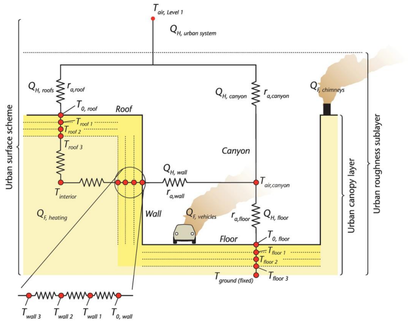
OpenFOAM

Lumped thermal model



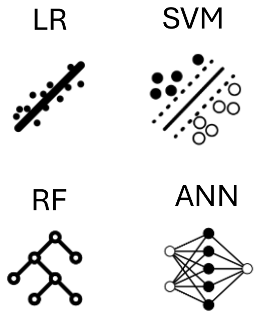
Bueno et al. (2012)

Lumped thermal model

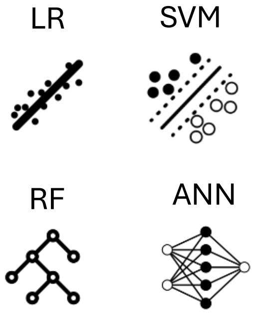


Oke et al. (2017)

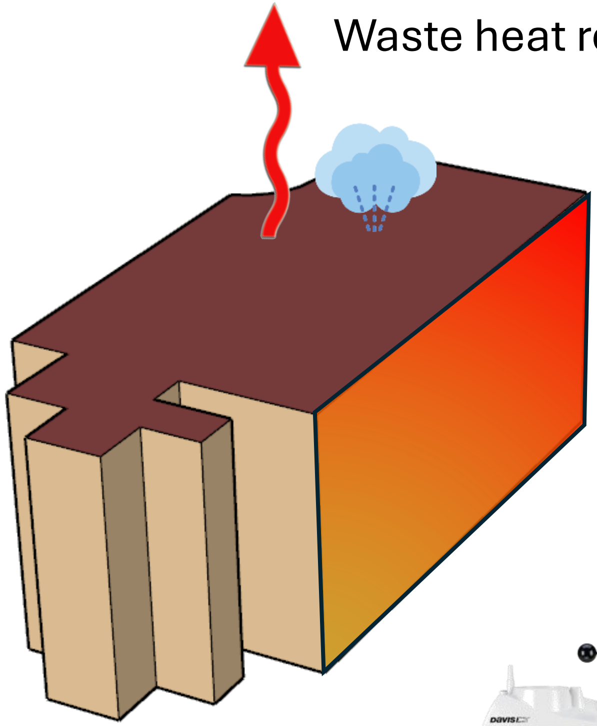
Statistical model



Statistical model

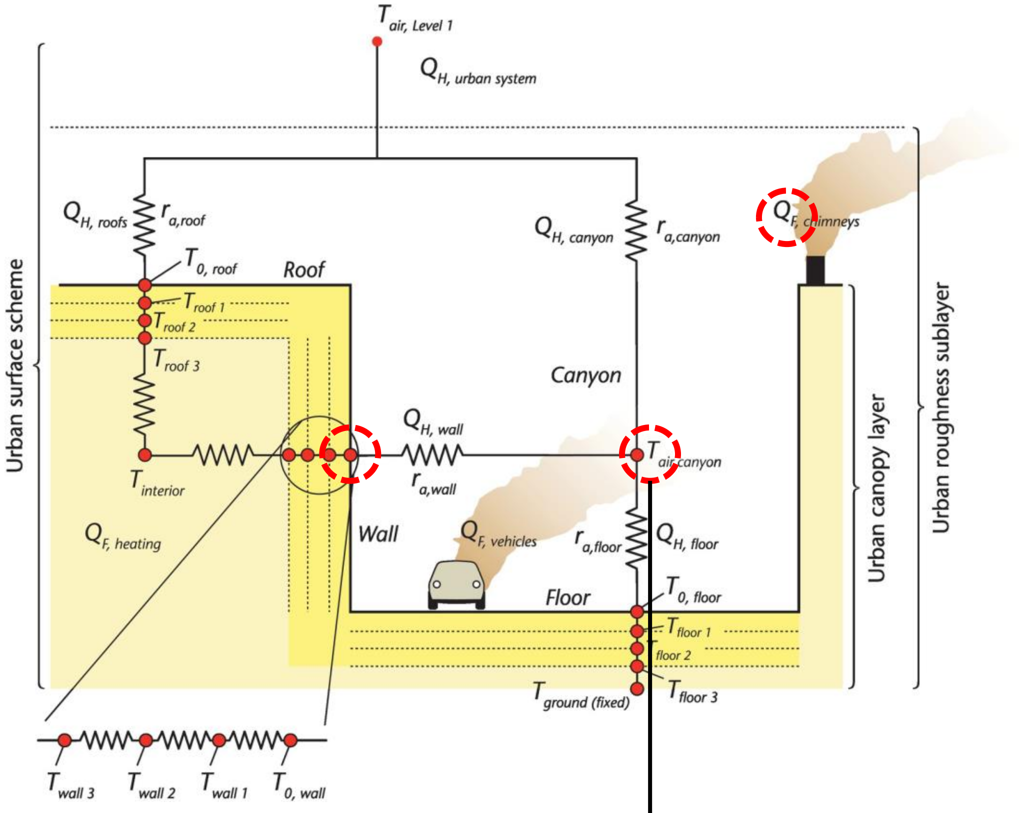


Waste heat releases



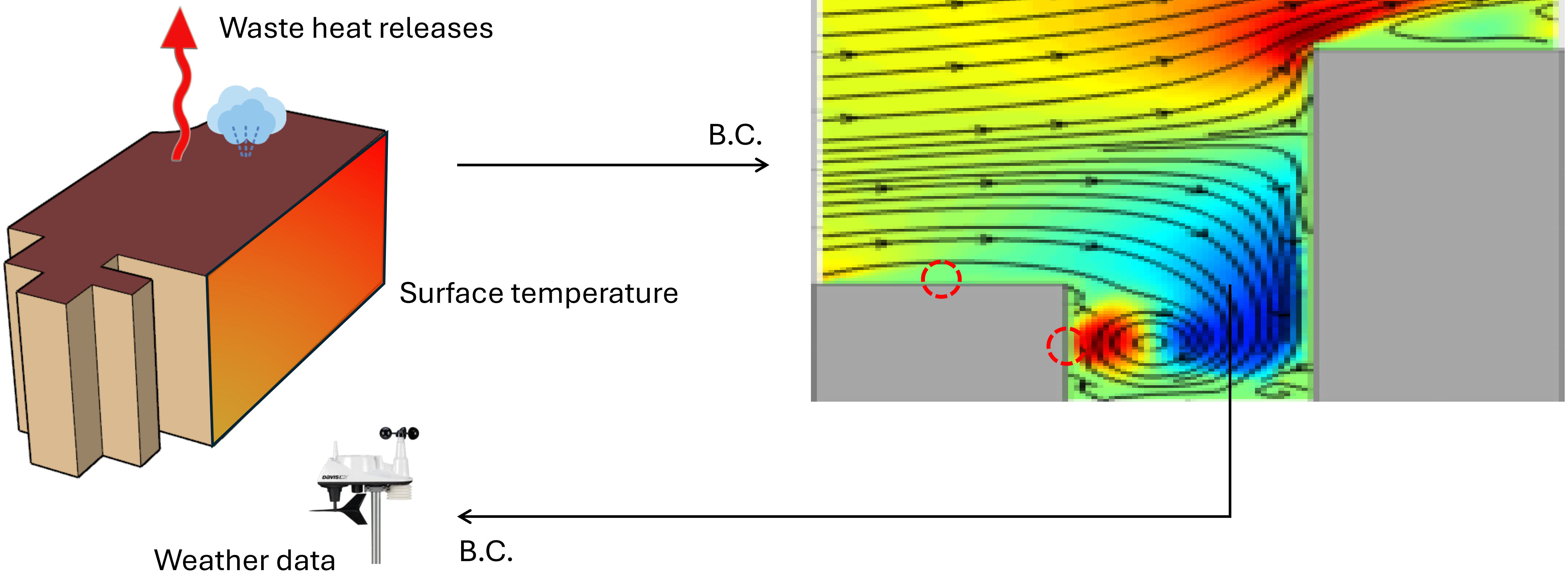
Surface temperature

B.C.

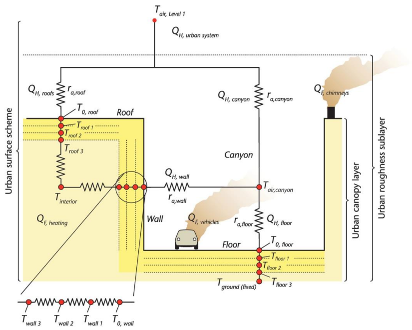


Weather data

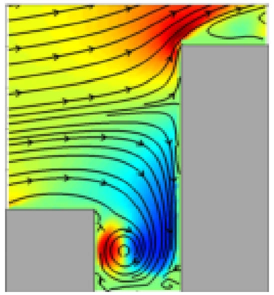
B.C.



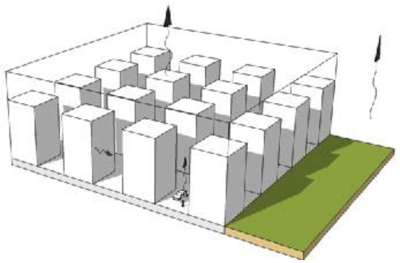
Waste heat releases
B.C.
Surface temperature
Weather data
B.C.

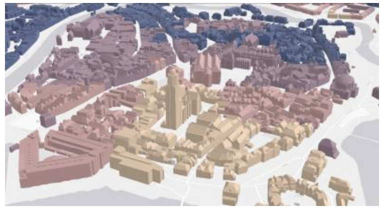


versus

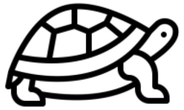


Urban morphology

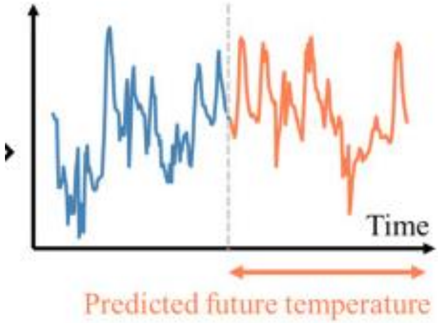




Computational efforts



Short- and long-term predictions



UHI mitigation strategies

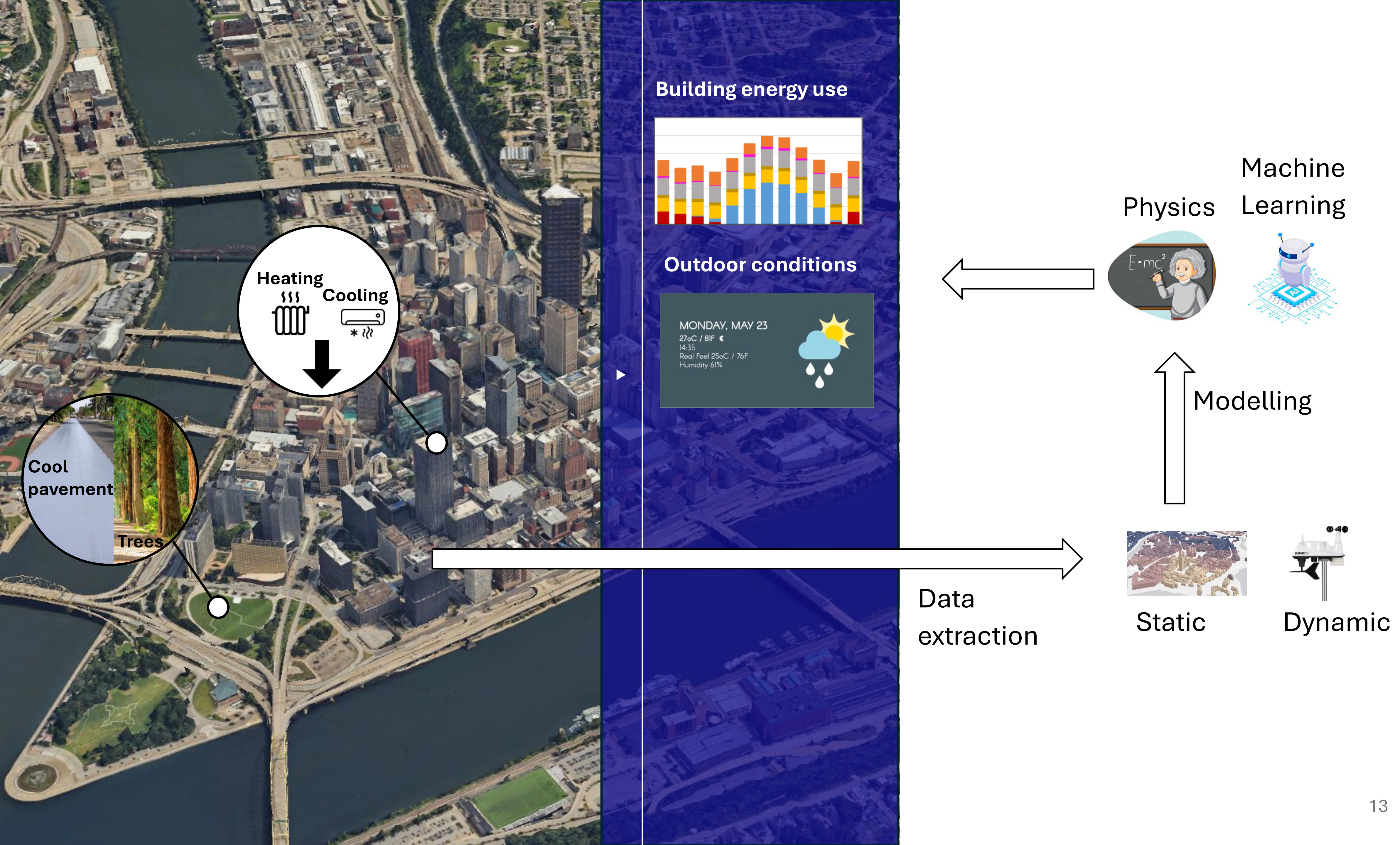
Bureau of Street Services LA

Perez et al. (2014)

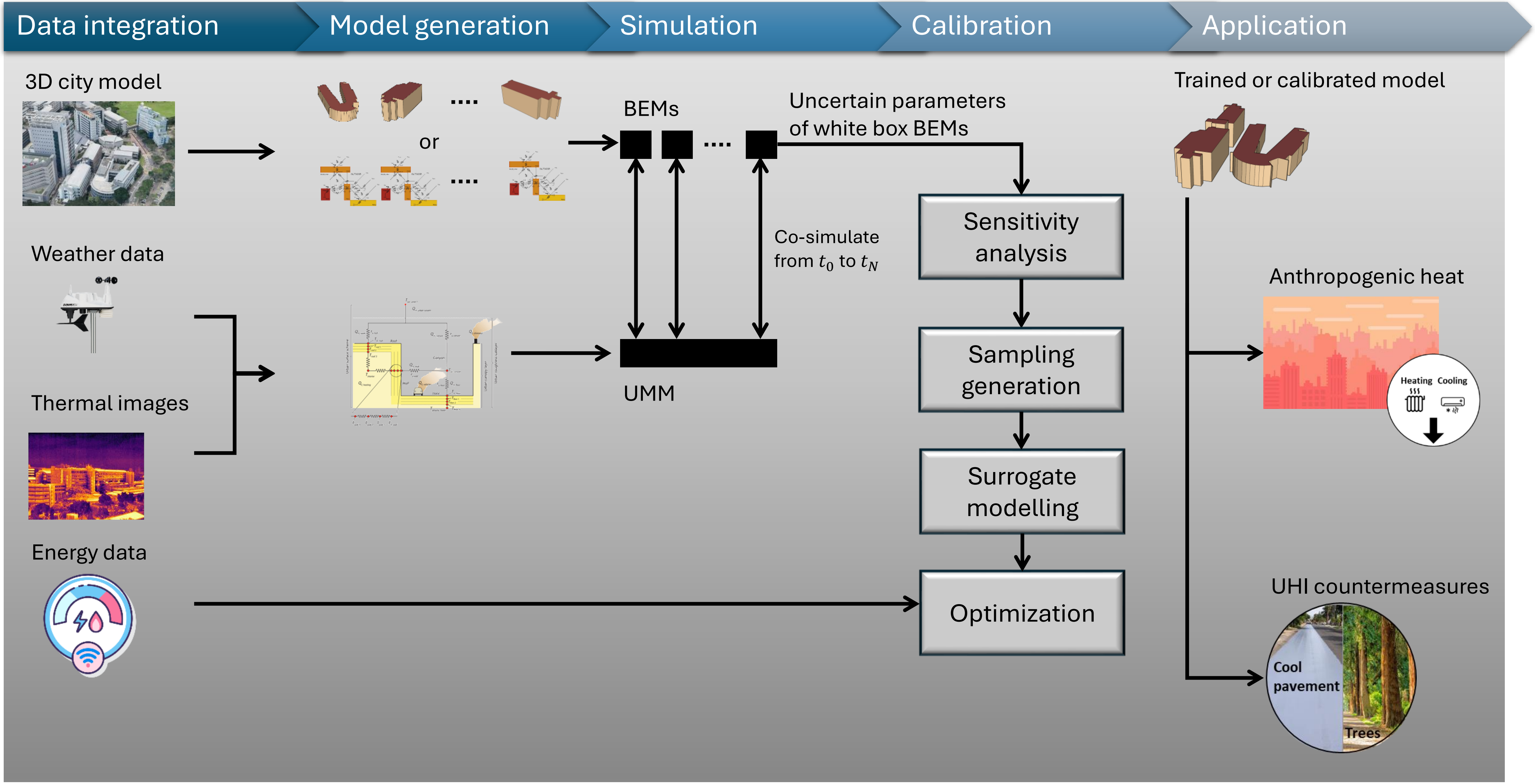
Overview SCIENCES project

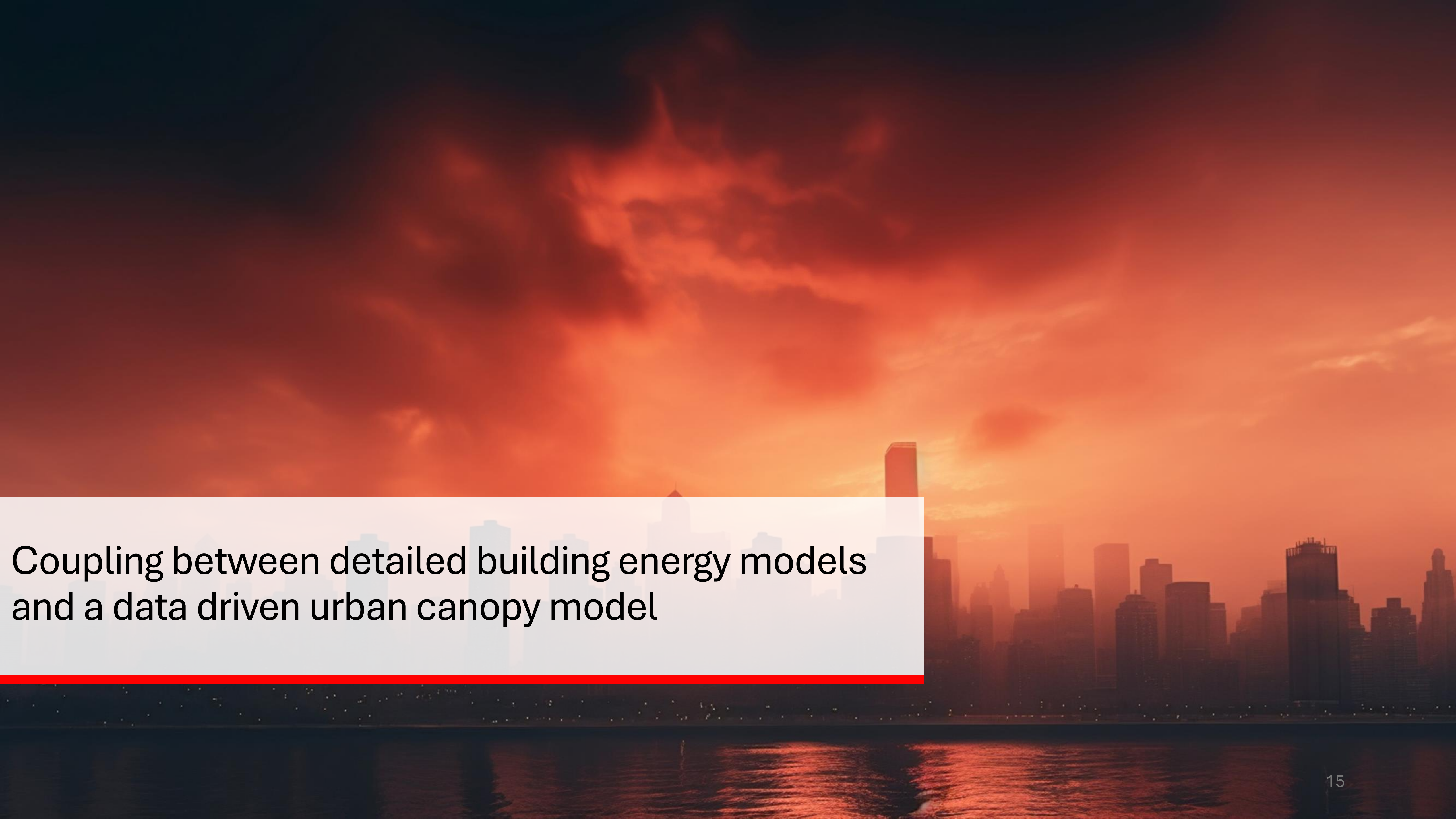

HORIZON
EUROPE


Now
2030
2050
100 cities
in Europe
All cities
in Europe



Heating
Cooling
Cool pavement
Trees
Building energy use
Outdoor conditions
MONDAY, MAY 23
27oC / 81F
14:35
Real Feel 25oC / 76F
Humidity 61%
Physics
Machine Learning
E=mc²
Modelling
Data extraction
Static
Dynamic

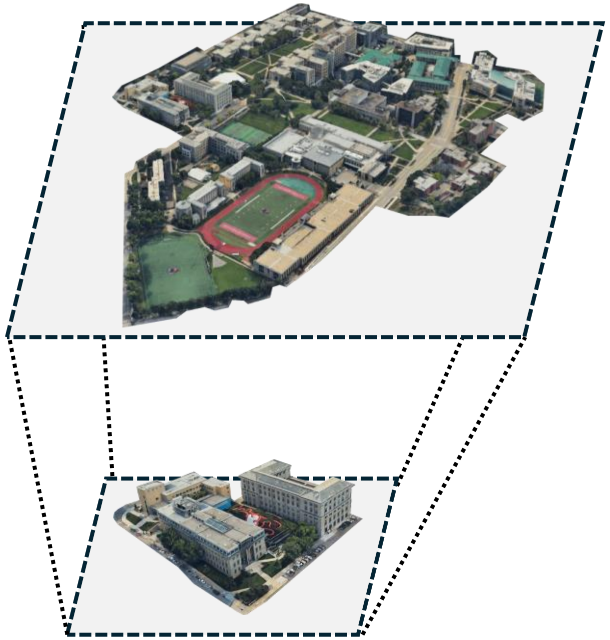

Data integration
Model generation
Simulation
Calibration
Application
3D city model
or
BEMs
Uncertain parameters
of white box BEMs
Trained or calibrated model
Weather data
Co-simulate
from t_0 to t_N
Sensitivity
analysis
Anthropogenic heat
Heating
Cooling
Sampling
generation
UMM
Thermal images
Surrogate
modelling
Energy data
UHI countermeasures
Optimization
Cool
pavement
Trees

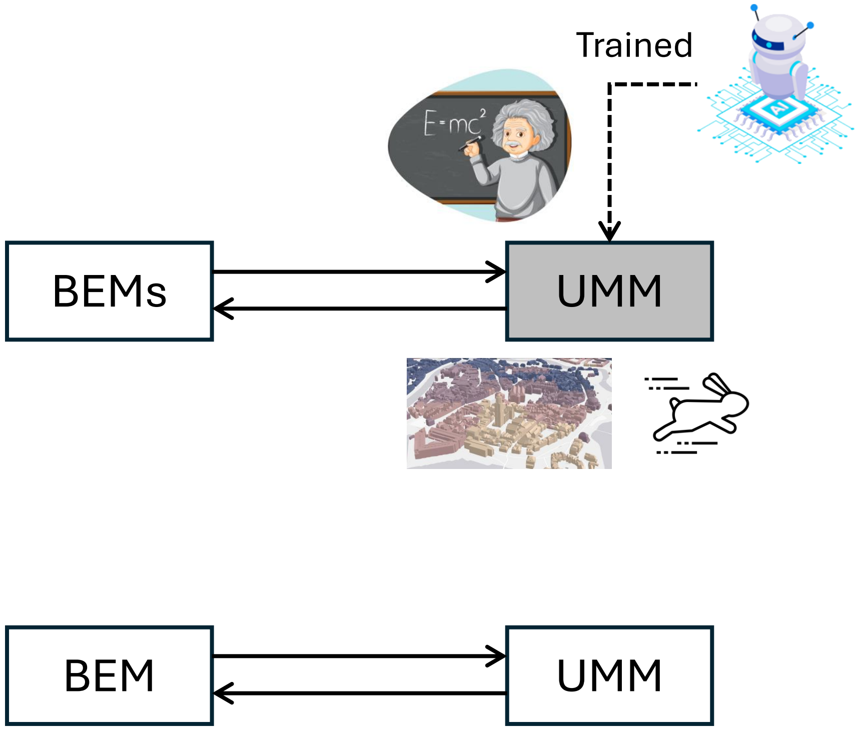


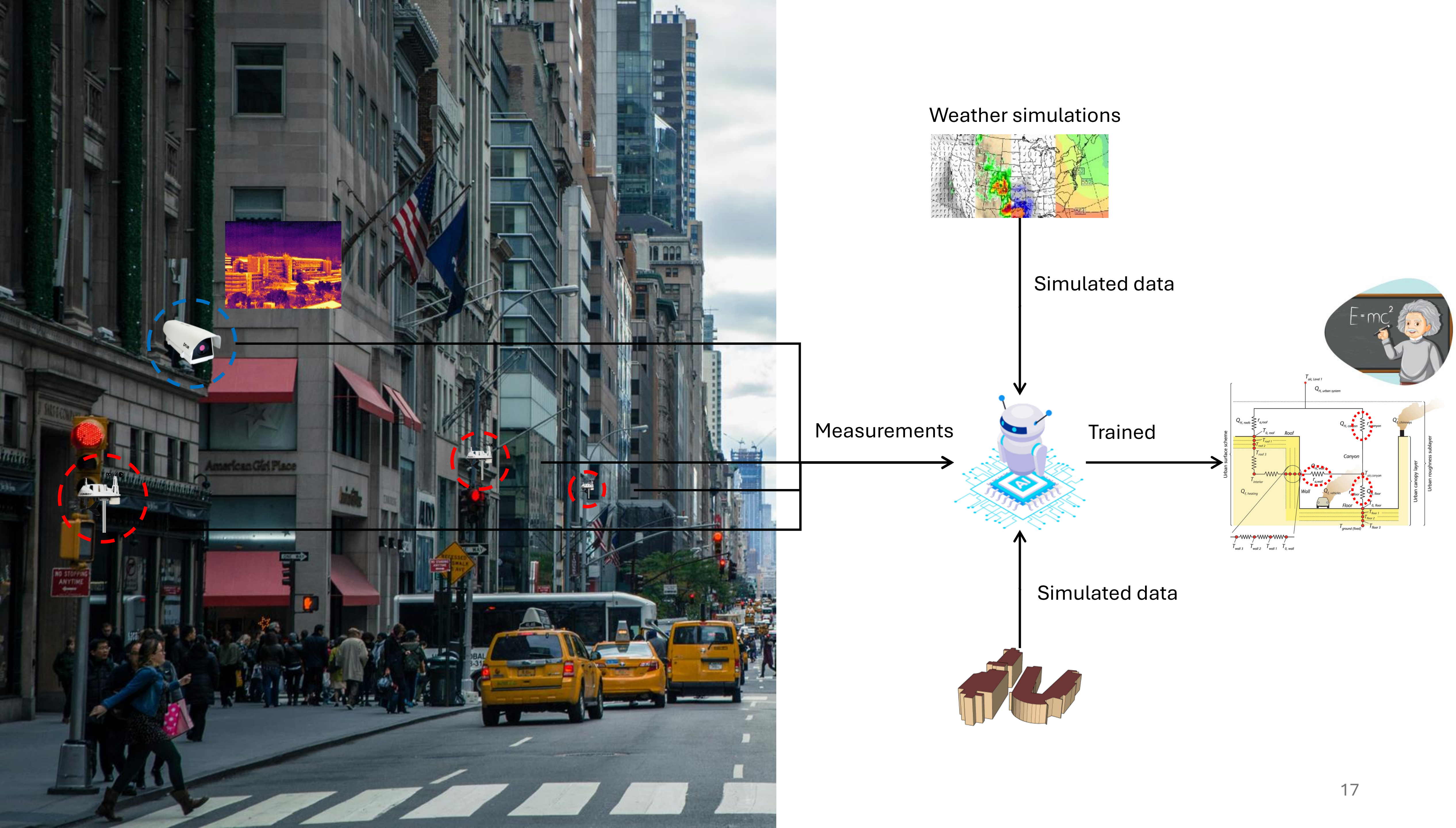
Coupling between detailed building energy models and a data driven urban canopy model

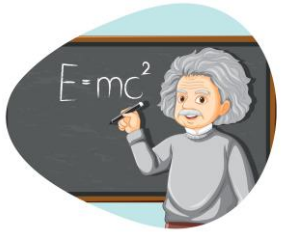
Neighbourhood scale

Building scale






Weather simulations
Simulated data
Measurements
Trained
Simulated data
E=mc²
American Girl Place
NO STOPPING ANYTIME



Heat and water mass stored by the street canyon

Convective heat and mass transfer between surfaces and the air volume

Sensible and latent heat releases by buildings and traffic

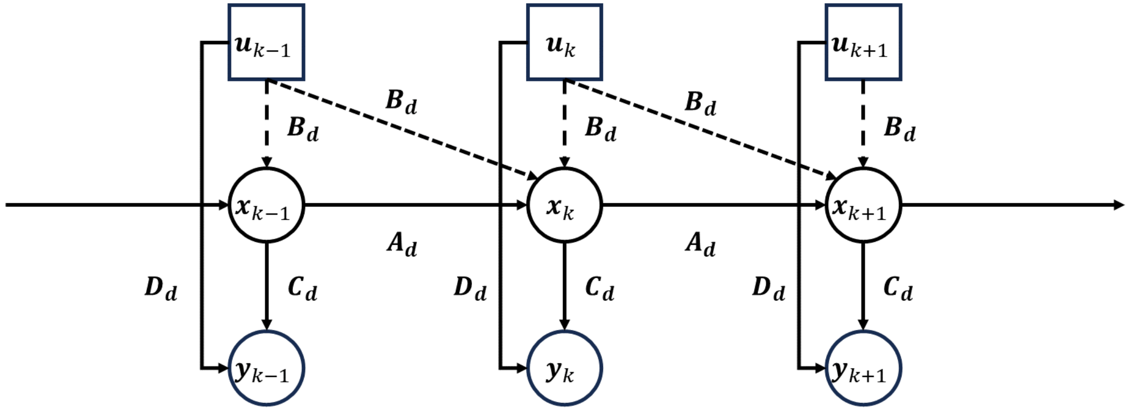
$$C\frac{d\bar{T}_{can}}{dt} = \sum_{m=1}^{M} h_m A_m(\bar{T}_m - \bar{T}_{can}) + \sum_{n=1}^{N} H_n$$

$$C\frac{d\bar{q}_{can}}{dt} = \sum_{p=1}^{P} h_p A_p(\bar{q}_m - \bar{q}_{can}) + \frac{c_p}{L}\sum_{q=1}^{Q} LE_q$$

Linear state space

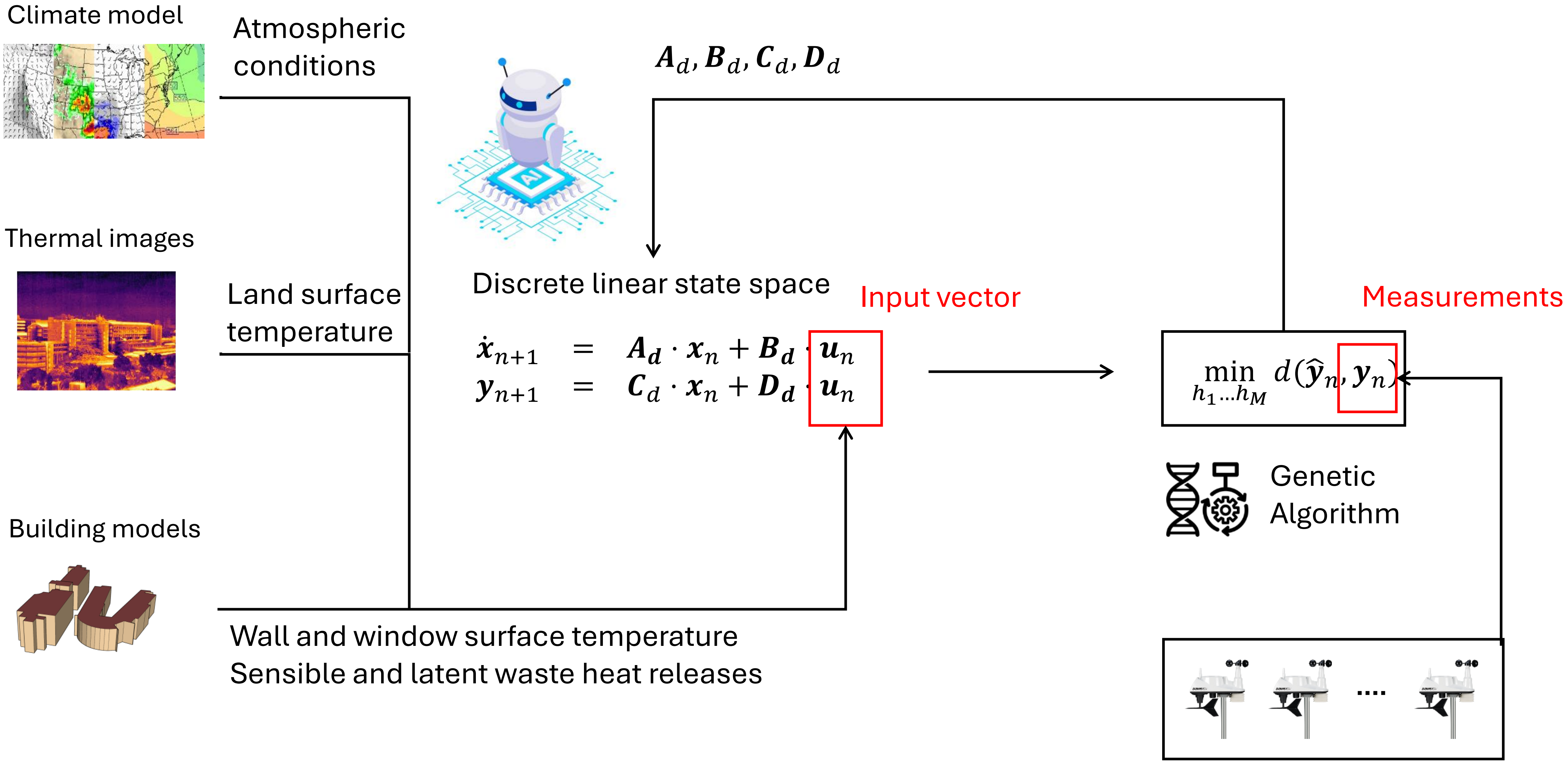
$$\begin{aligned} \dot{\boldsymbol{x}} &= \boldsymbol{A}\cdot\boldsymbol{x} + \boldsymbol{B}\cdot\boldsymbol{u} \\ \boldsymbol{y} &= \boldsymbol{C}\cdot\boldsymbol{x} + \boldsymbol{D}\cdot\boldsymbol{u} \end{aligned}$$

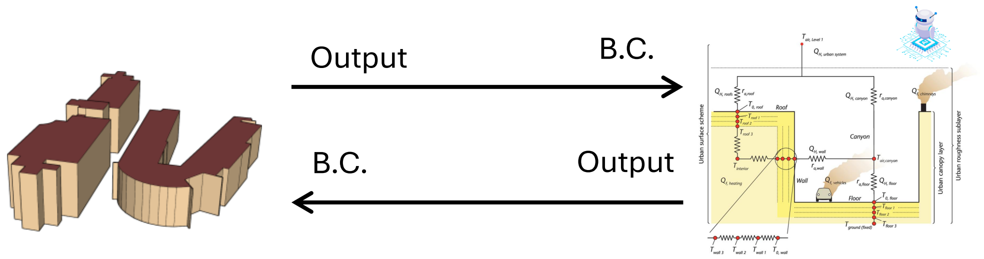
Discrete linear state space

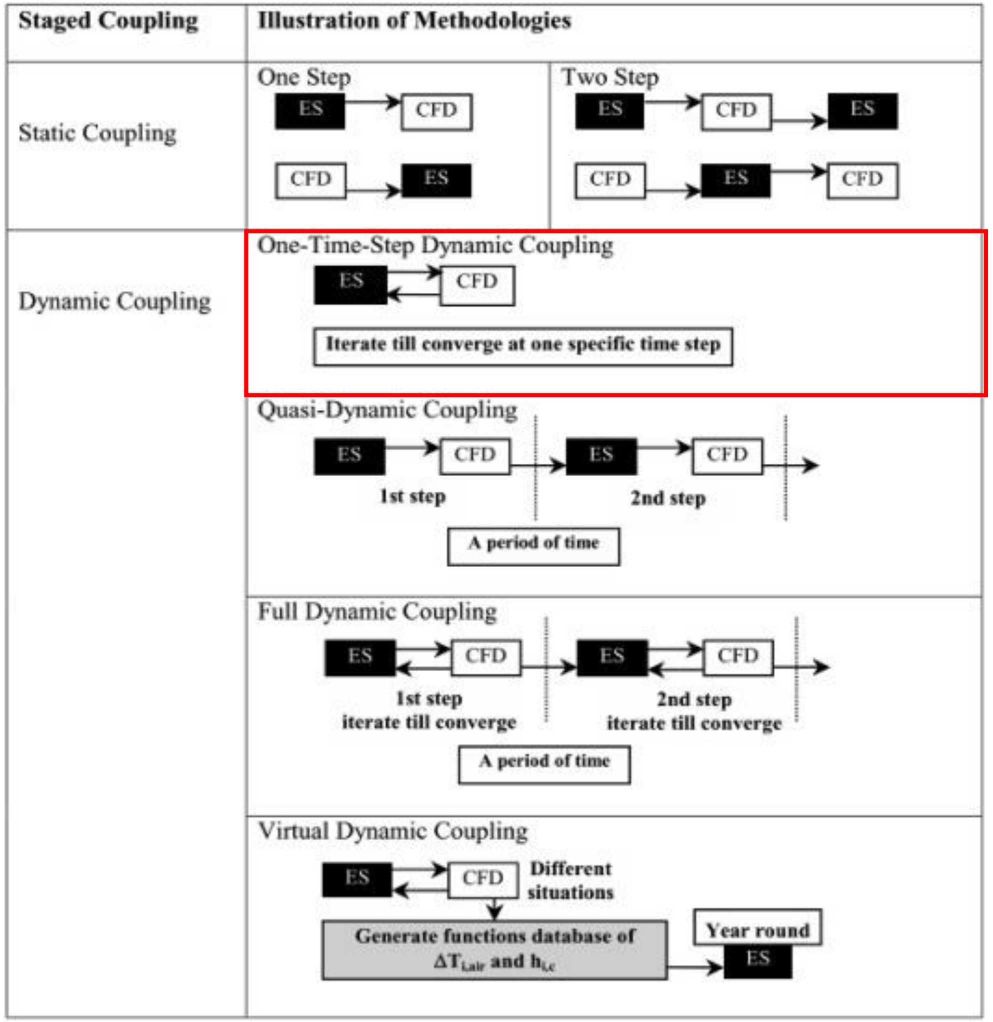


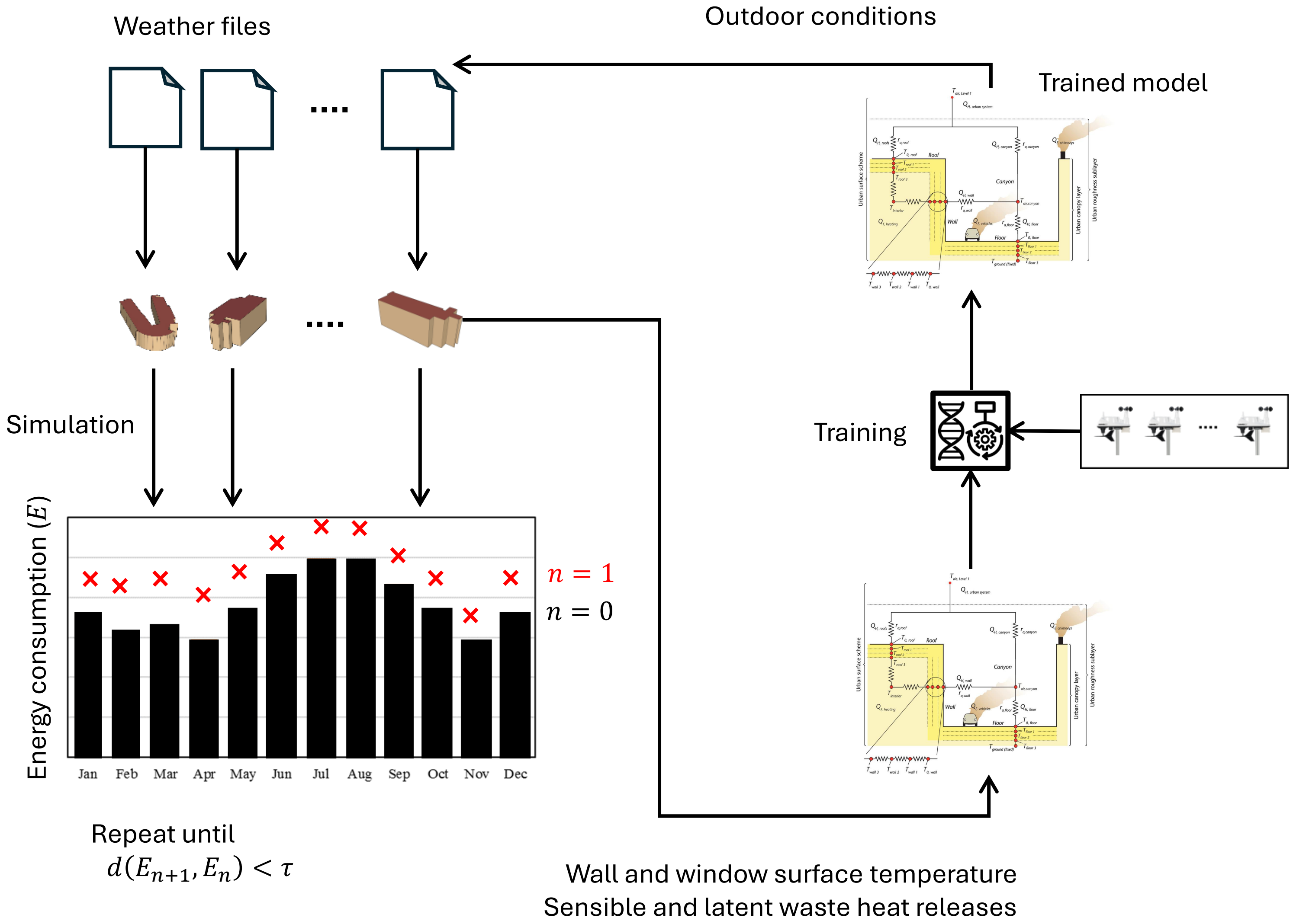
Implicit discretization scheme

Explicit discretization scheme

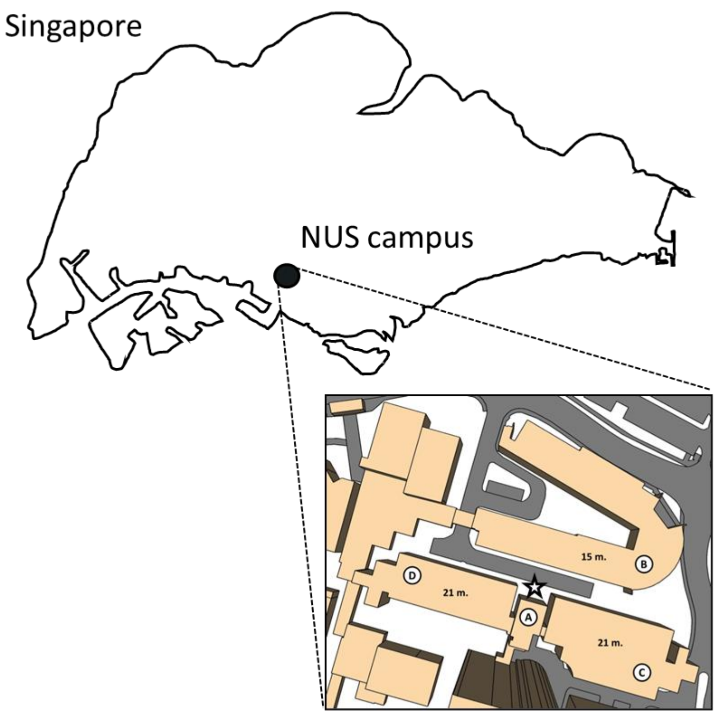

Climate model
Atmospheric conditions
Thermal images
Land surface temperature
Building models
Wall and window surface temperature
Sensible and latent waste heat releases
A_d, B_d, C_d, D_d
Discrete linear state space
$\dot{x}_{n+1} = A_d \cdot x_n + B_d \cdot u_n$
$y_{n+1} = C_d \cdot x_n + D_d \cdot u_n$
Input vector
Measurements
$\min_{h_1 \dots h_M} d(\hat{y}_n, y_n)$
Genetic Algorithm
....

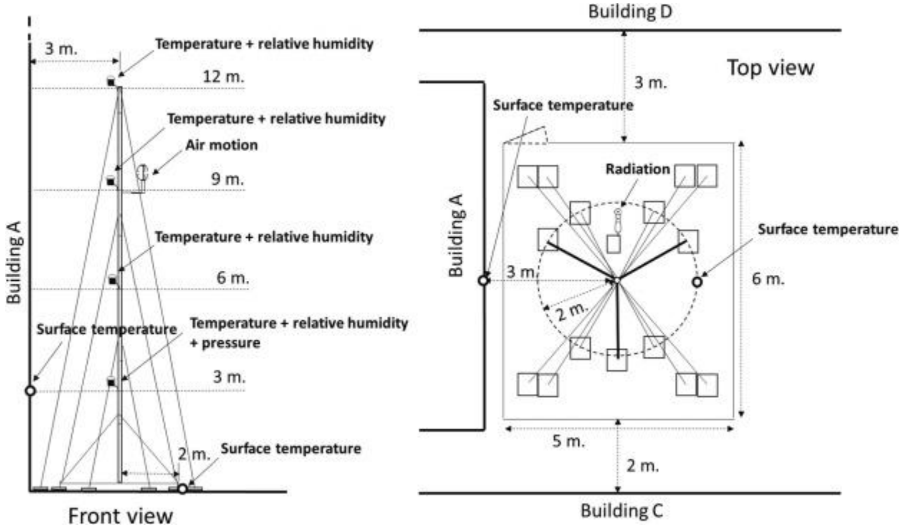




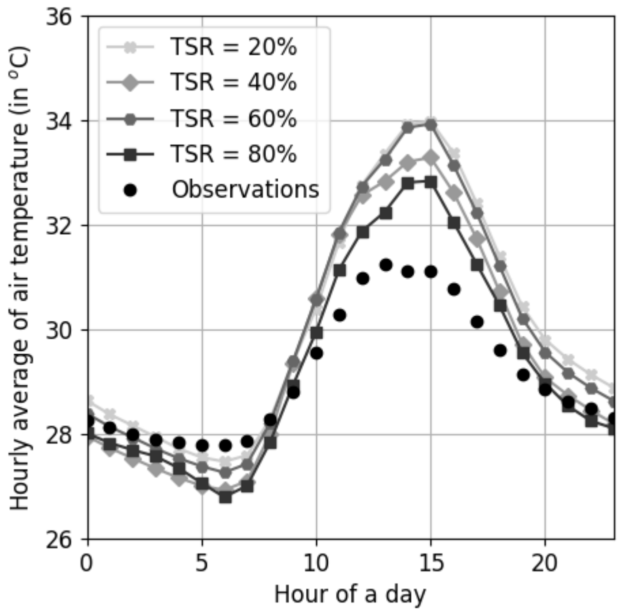


Zhang, R., Mirzaei, P. A., & Jones, B. (2018). Development of a dynamic external CFD and BES coupling framework for application of urban neighbourhoods energy modelling. *Building and Environment*, *146*, 37-49.

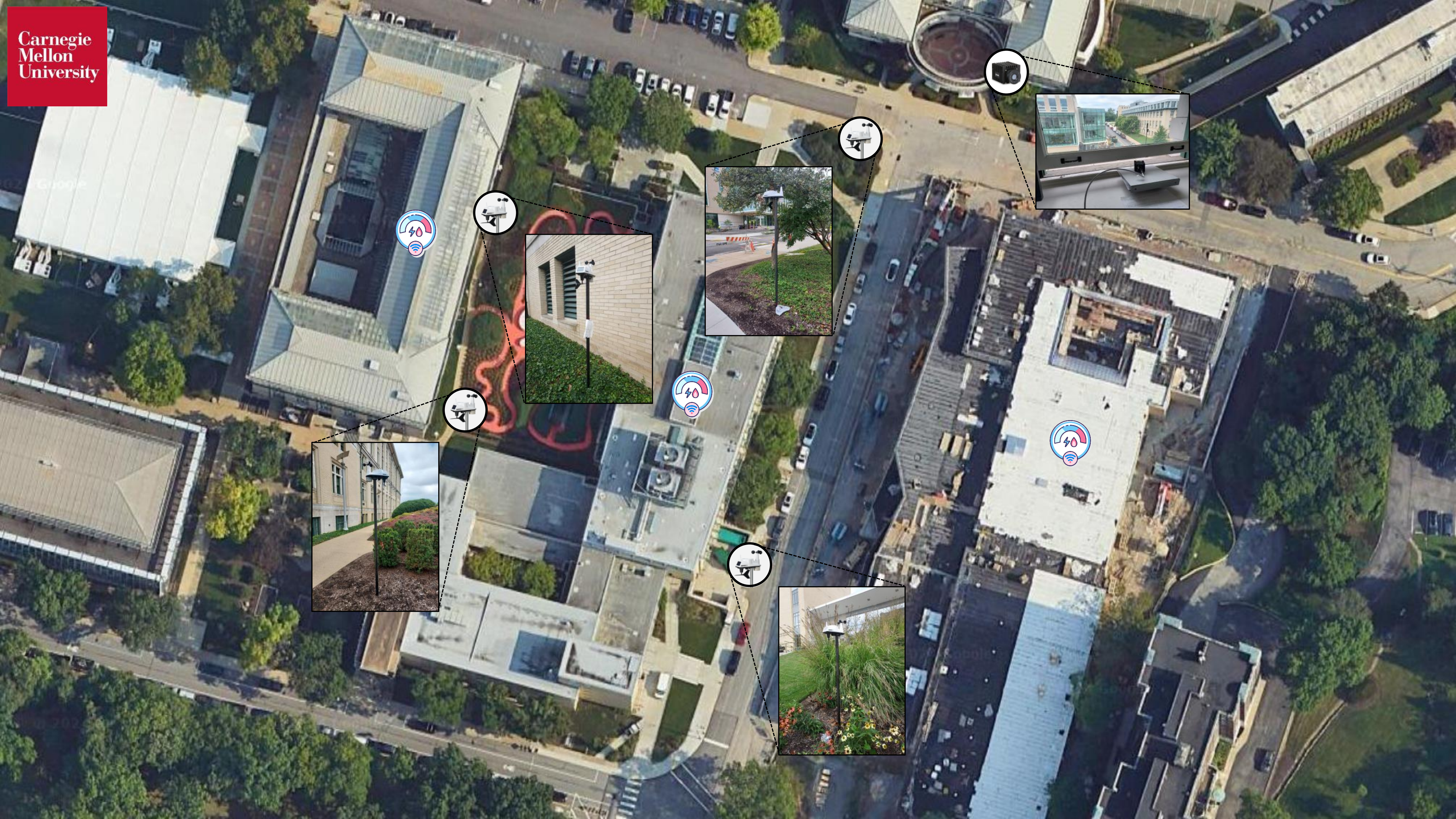




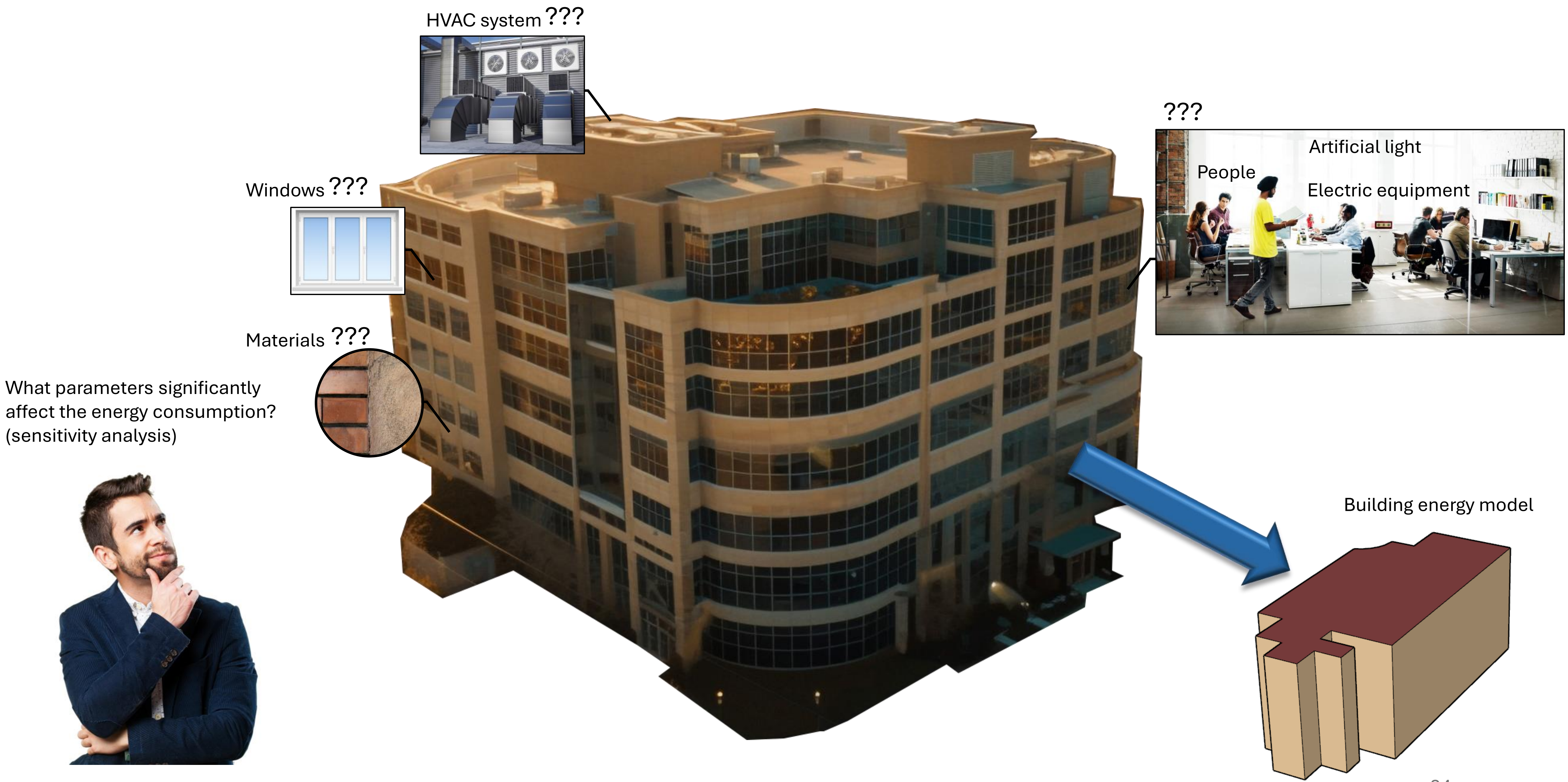
TSR = Training Sampling Ratio

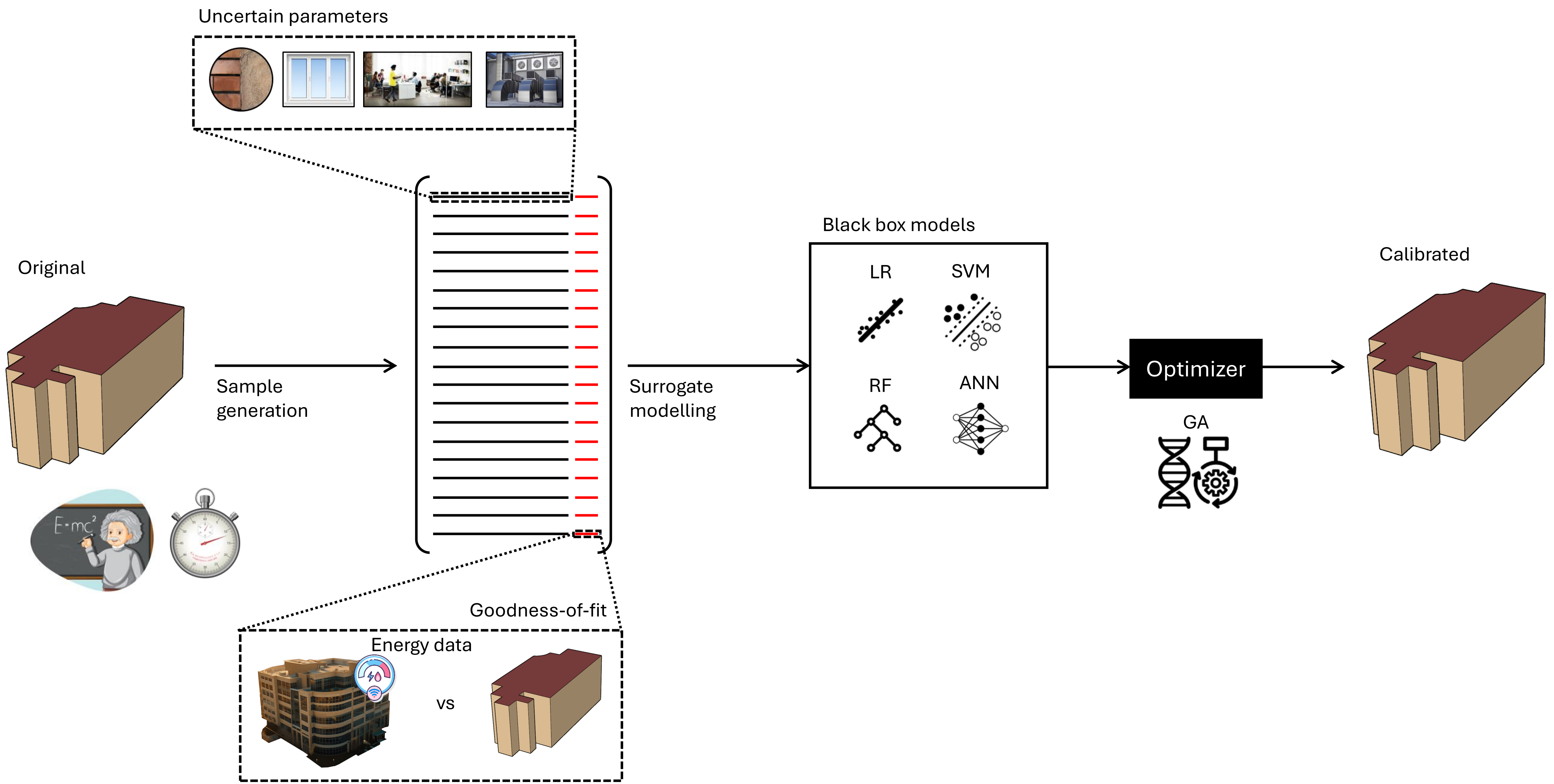


TSR	Temperature		Humidity		Size test samples
	RMSE (K)	MBE (K)	RMSE (g/kg)	MAE (g/kg)	
20%	2.24	0.93	6.80	5.90	8291
40%	2.24	0.39	4.19	3.67	6219
60%	2.31	0.80	5.46	4.76	4146
80%	2.16	0.23	4.42	3.82	2074


Carnegie Mellon University

Calibration of an urban building energy model


HVAC system ???
Windows ???
Materials ???
What parameters significantly affect the energy consumption? (sensitivity analysis)
???
Artificial light
People
Electric equipment
Building energy model


Uncertain parameters
Original
Sample
generation
E=mc²
Goodness-of-fit
Energy data
vs
Surrogate
modelling
Black box models
LR
SVM
RF
ANN
Optimizer
GA
Calibrated

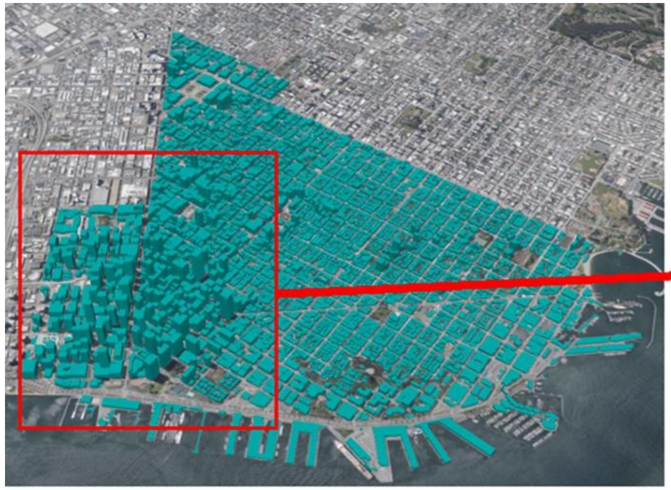
Sensitivity analysis

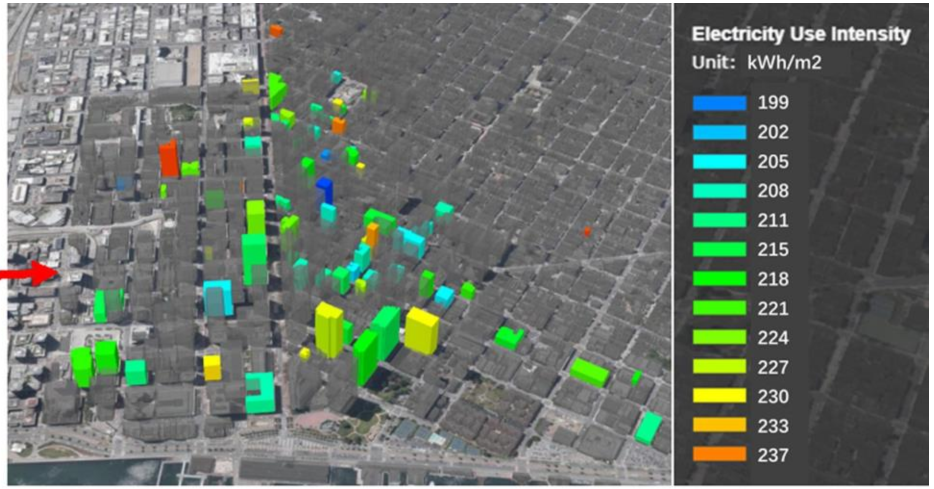
Sampling generation

Surrogate modelling

Optimization

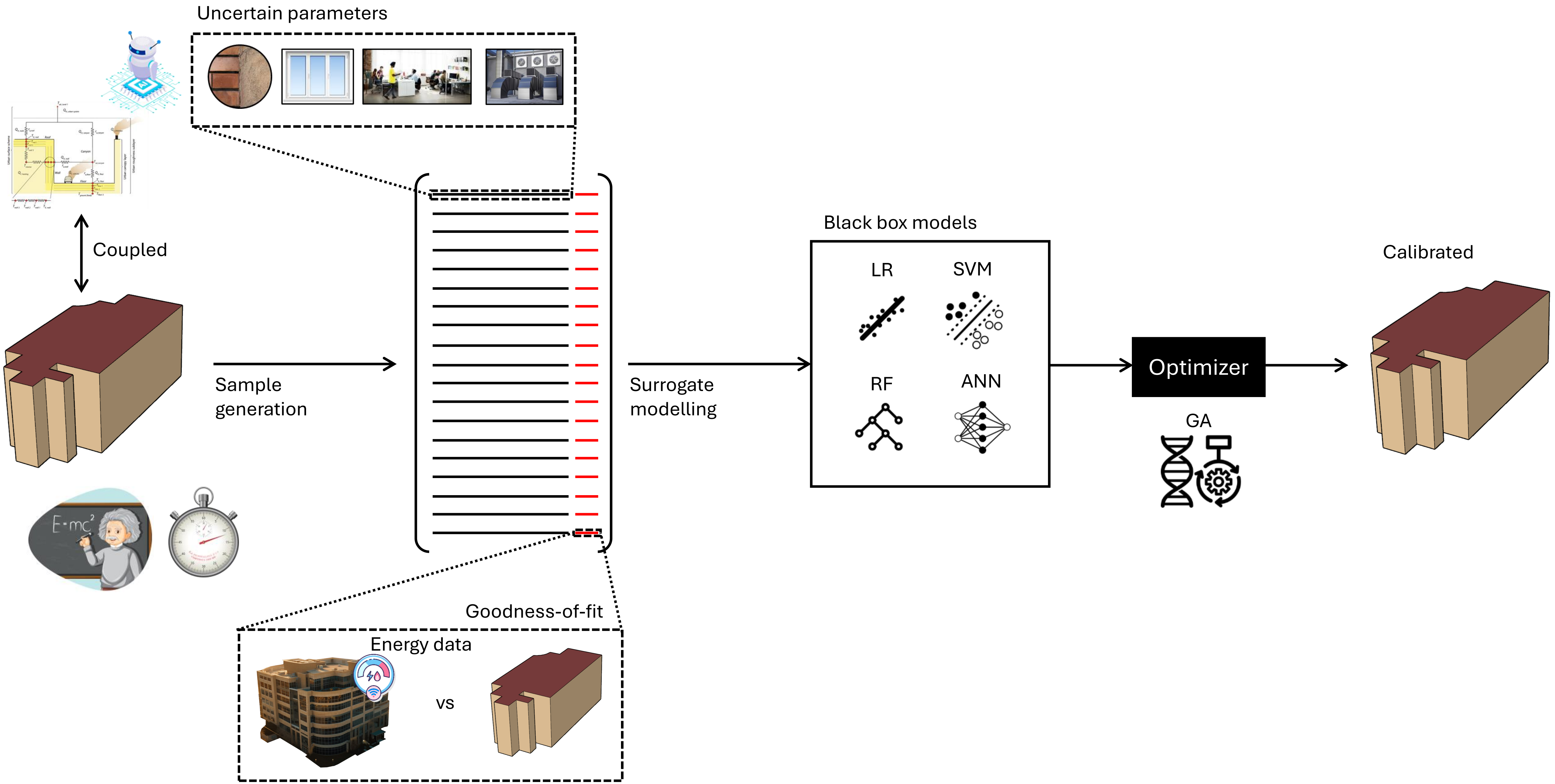
Urban building energy model





Chen et al. (2020) (a) (b)

Why are interactions between buildings and their outdoor conditions being ignored in most urban building energy models?


Uncertain parameters
Coupled
Sample generation
Surrogate modelling
Black box models
LR
SVM
RF
ANN
Optimizer
GA
Calibrated
Goodness-of-fit
Energy data
vs

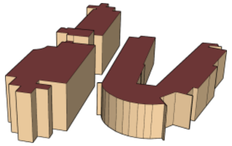
Sensitivity analysis

Sampling generation

Surrogate modelling

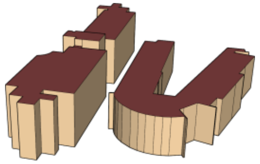
Optimization

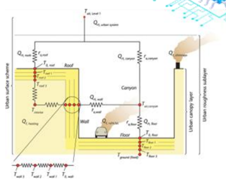
Uncoupled



versus

Coupled

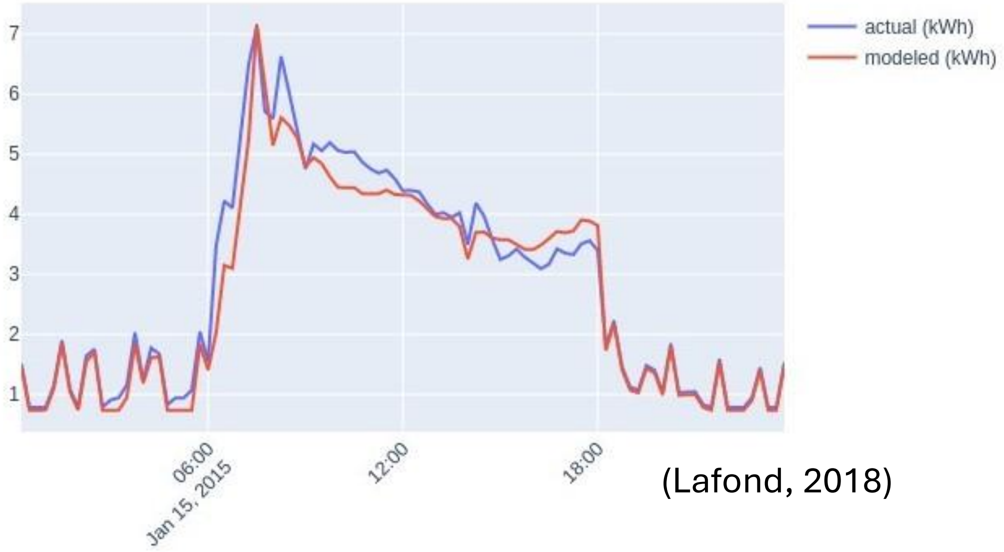




Goodness-of-fit

$$\mathrm{CV(RMSE)} = \frac{1}{\bar{Y}} \sqrt{\frac{\sum_{i=1}^{N} (Y_i - \hat{Y}_i)^2}{N}}$$

Total heating/cooling load



(Lafond, 2018)

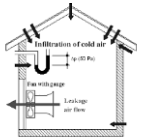
Sensitivity analysis

Sampling generation

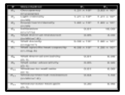
Surrogate modelling

Optimization

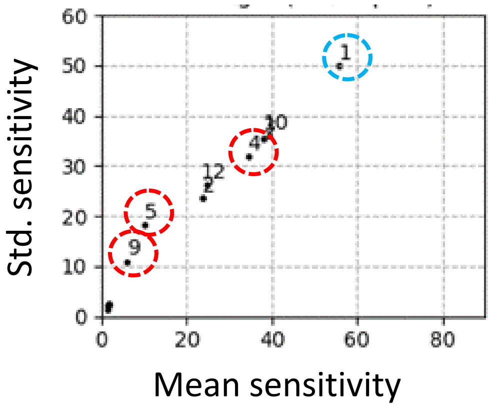
$$S(\theta_i) = \Delta CV(RMSE)/\Delta\theta_i$$

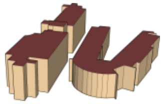


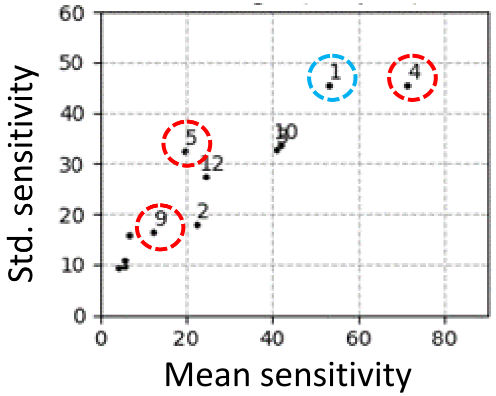
INIVE EEIG (2004)

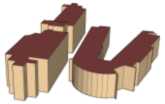


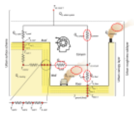
θ	Description	θ_l	θ_u
θ_1	Occupancy (in people)	1.21×10^2	3.03×10^3
θ_2	Light intensity (in W)	1.21×10^4	1.21×10^5
θ_3	Equipment intensity (in W)	1.82×10^4	1.82×10^5
θ_4	Infiltration (in m^3/s)	0.01	10.00
θ_5	Wall thermal resistance (in W/m^2-K)	0.05	3.00
θ_6	Wall density (in kg/m^3)	3.00×10^2	1.80×10^3
θ_7	Wall specific heat capacity (in J/kg-K)	4.00×10^2	1.50×10^3
θ_8	Wall thermal emissivity (0-1)	0.01	0.98
θ_9	Wall solar absorptivity (0-1)	0.05	0.90
θ_{10}	Window-to-wall ratio (0-1)	0.01	0.90
θ_{11}	Window thermal resistance (in W/m^2-K)	0.04	1.50
θ_{12}	Window solar heat gain (0-1)	0.20	0.90









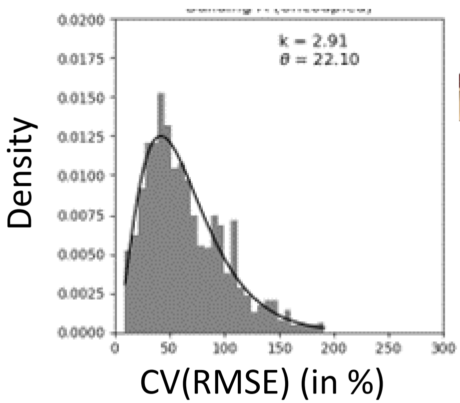


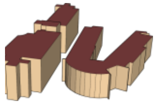
Sensitivity analysis

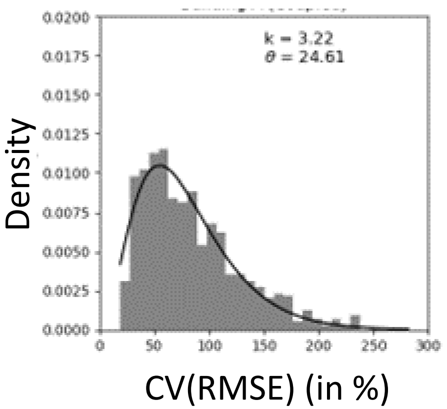
Sampling generation

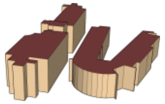
Surrogate modelling

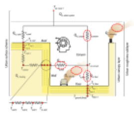
Optimization









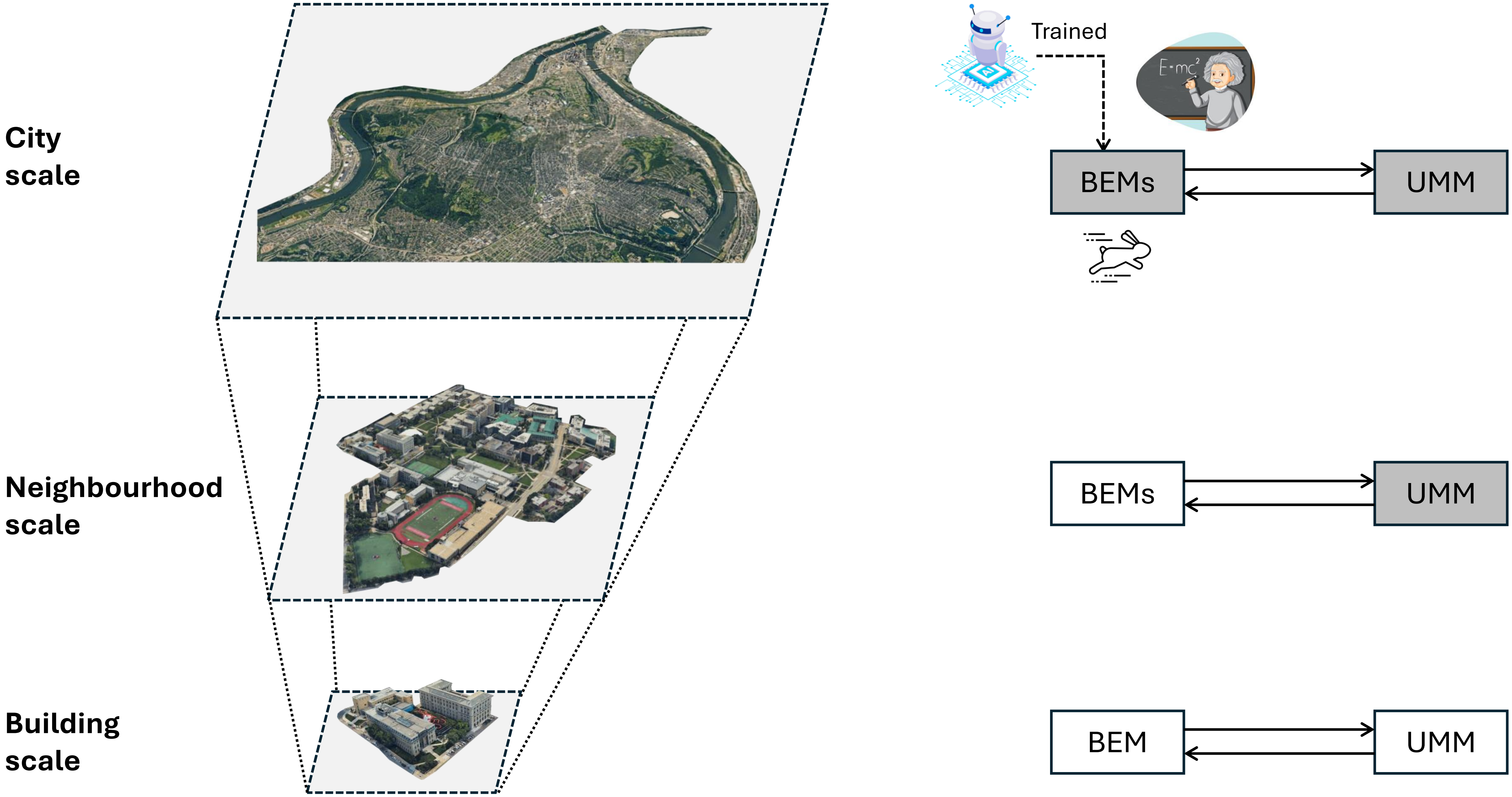


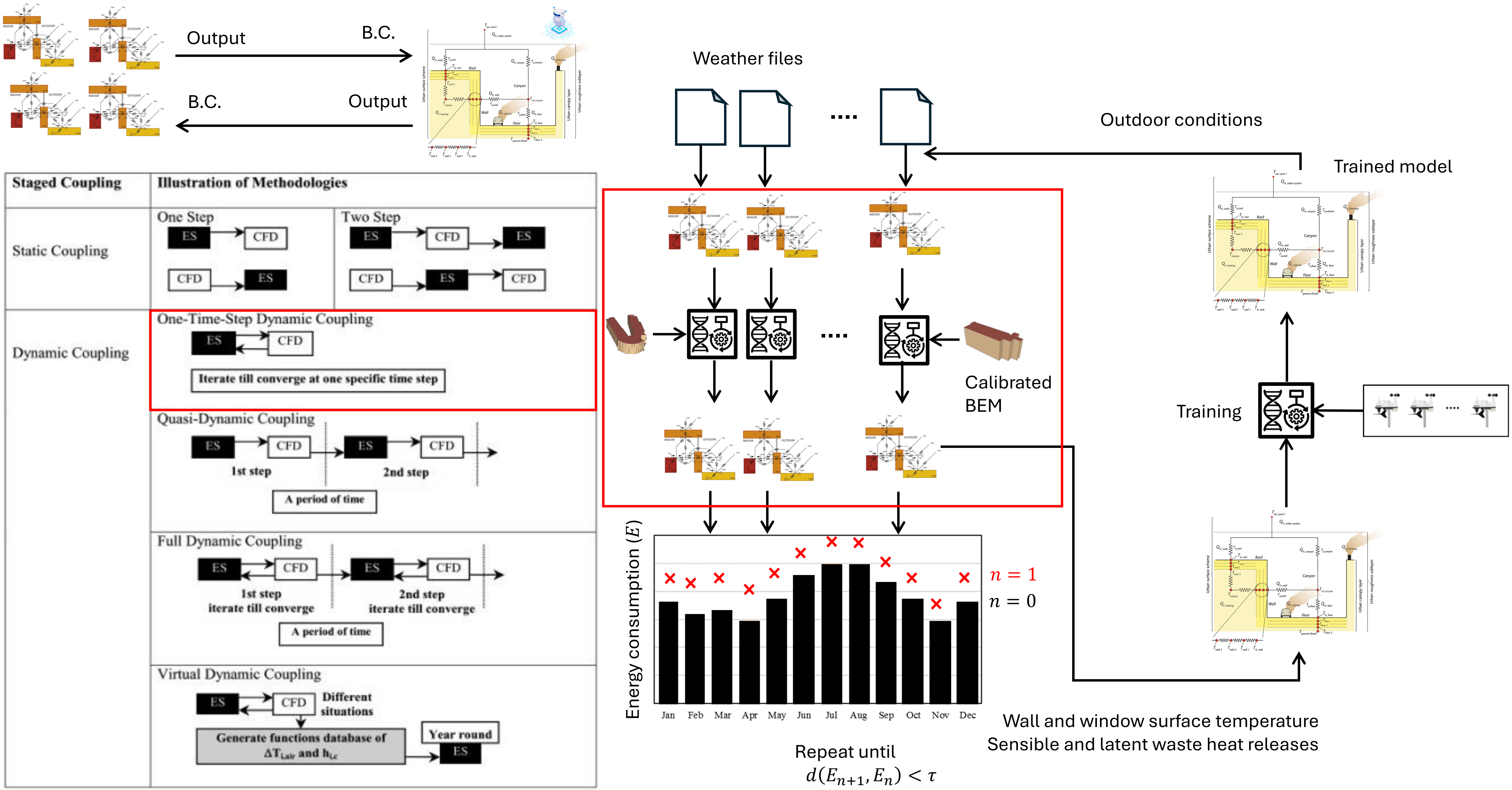
ASHRAE

	Building A		Building B		Building C	
	20%	30%	20%	30%	20%	30%
Uncoupled	7.2	17.2	3.9	13.5	4.4	13.0
Coupled	3.5	9.6	3.7	9.6	3.0	8.6

θ	Building A coeff.	Building A t	Building B coeff.	Building B t	Building C coeff.	Building C t
θ_1	0.0141	27.1	0.0156	35.4	0.0140	28.8
θ_2	0.0001	10.0	0.0001	11.1	0.0001	8.9
θ_3	0.0001	14.7	0.0002	21.3	0.0002	18.4
θ_4	4.1065	27.0	4.7787	37.6	4.2432	29.8
θ_5	-1.6943	-3.4	-1.2795	-2.9	0.0304	0.1
θ_6	-0.0012	-1.1	-0.0007	-0.7	-0.0006	-0.6
θ_7	-0.0052	-3.6	-0.0020	-1.7	-0.0011	-0.8
θ_8	-3.9092	-2.8	-2.3606	-1.7	-0.9580	-0.6
θ_9	3.6317	2.0	11.7867	7.8	14.0499	8.0
θ_{10}	41.6530	24.5	28.1425	20.1	24.8345	16.3
θ_{11}	2.7882	2.7	2.4681	-2.9	3.7907	3.7
θ_{12}	33.4358	15.7	22.3531	12.6	20.9123	10.2
C	20.8267	17.4	21.8236	21.8	18.2139	16.3

A full grey box model to simulate interactions between buildings and their outdoor conditions


City scale
Neighbourhood scale
Building scale
Trained
E=mc²
BEMs
UMM
BEMs
UMM
BEM
UMM



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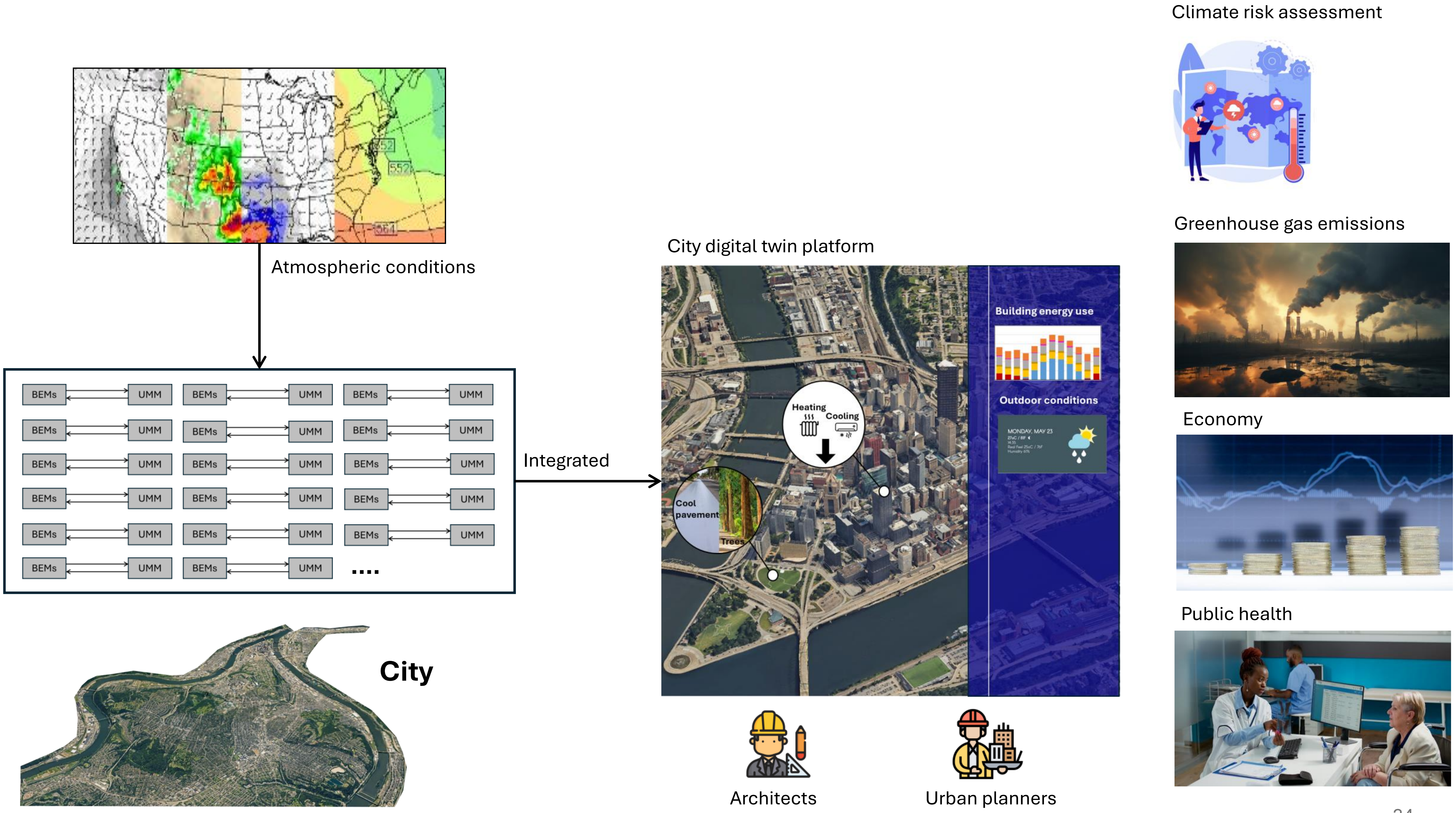
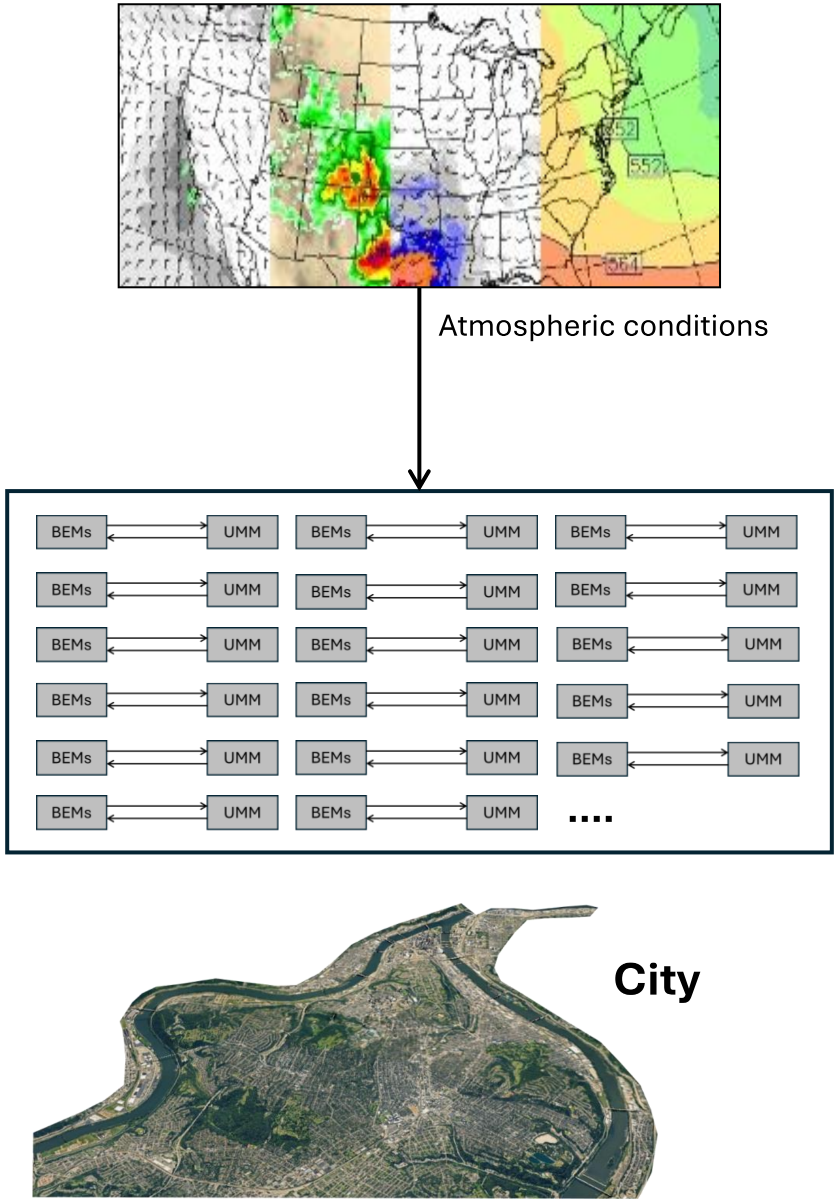
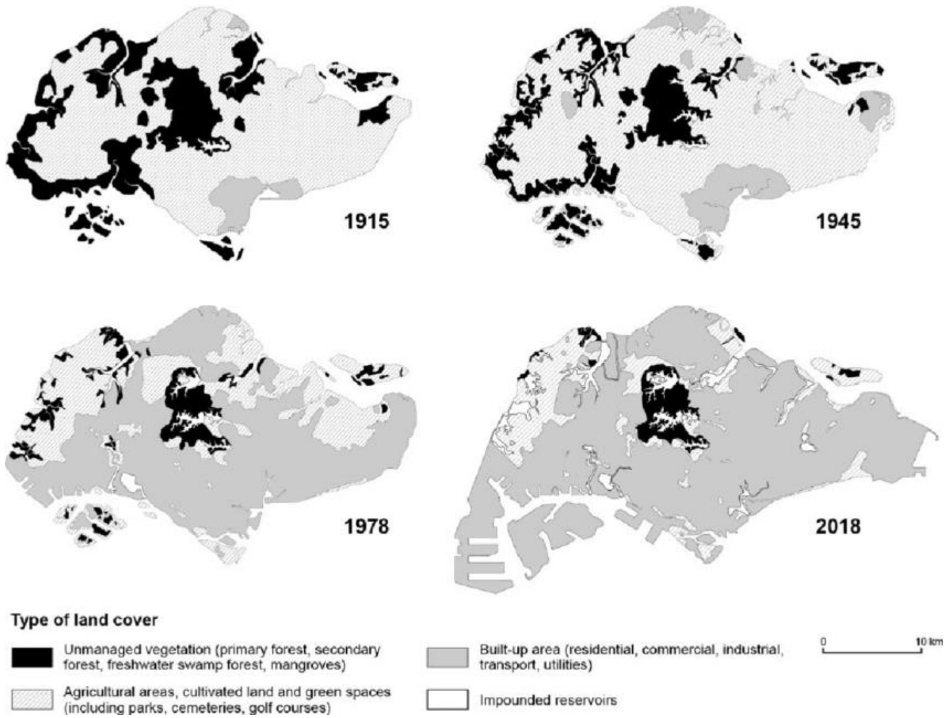

Atmospheric conditions
BEMs
UMM
....
Integrated
City
City digital twin platform
Heating
Cooling
Cool pavement
Trees
Building energy use
Outdoor conditions
MONDAY, MAY 23
Architects
Urban planners
Climate risk assessment
Greenhouse gas emissions
Economy
Public health



Urban expansion



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Q&A session