The University of Texas at Austin
Civil, Architectural and Environmental Engineering
Cockrell School of Engineering

INTELLIGENT ENVIRONMENTS LABORATORY

Occupant-Centric Grid-Interactive Buildings
10. Calibration

CE 397
Spring 2024

Prof Dr Zoltan Nagy

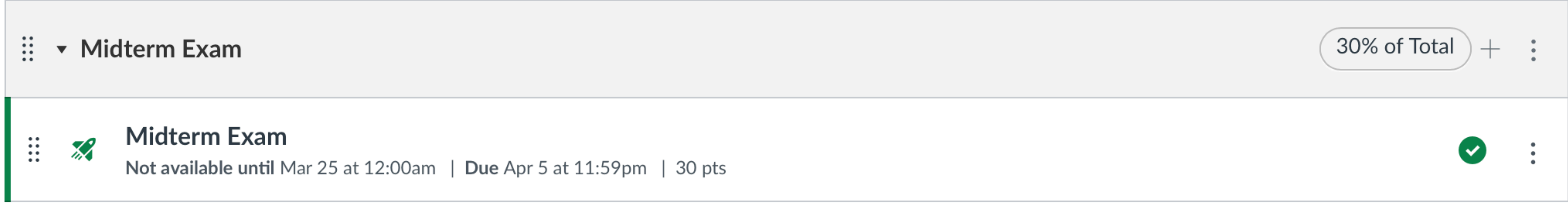
Plan for today

- Midterm reminder
- Project & Rest of the semester outlook
- Quick Recap: Modeling & Control of Buildings
- Main Course: Calibration

- Guest Lecture

Midterm Info

- Quiz on Canvas
- Open March 25
- Due April 5
- No extensions will be given

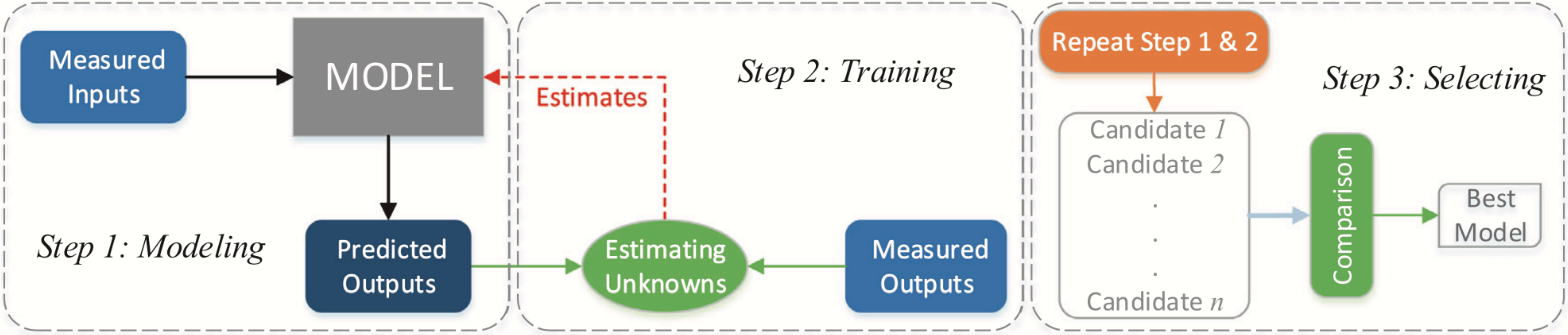


- There are 30 questions. Each question is 1 point.
- You have 60min once you started the exam
- The questions are either on Machine Learning, Building Performance Simulation or Python Programming
- Questions are based on the course material until spring break
- Each question has exactly one correct answer
- You can go back and forth between the questions
- You have only one submission (no resubmissions)
- Questions and answers are shuffled randomly

Tentative Course Outline / Schedule

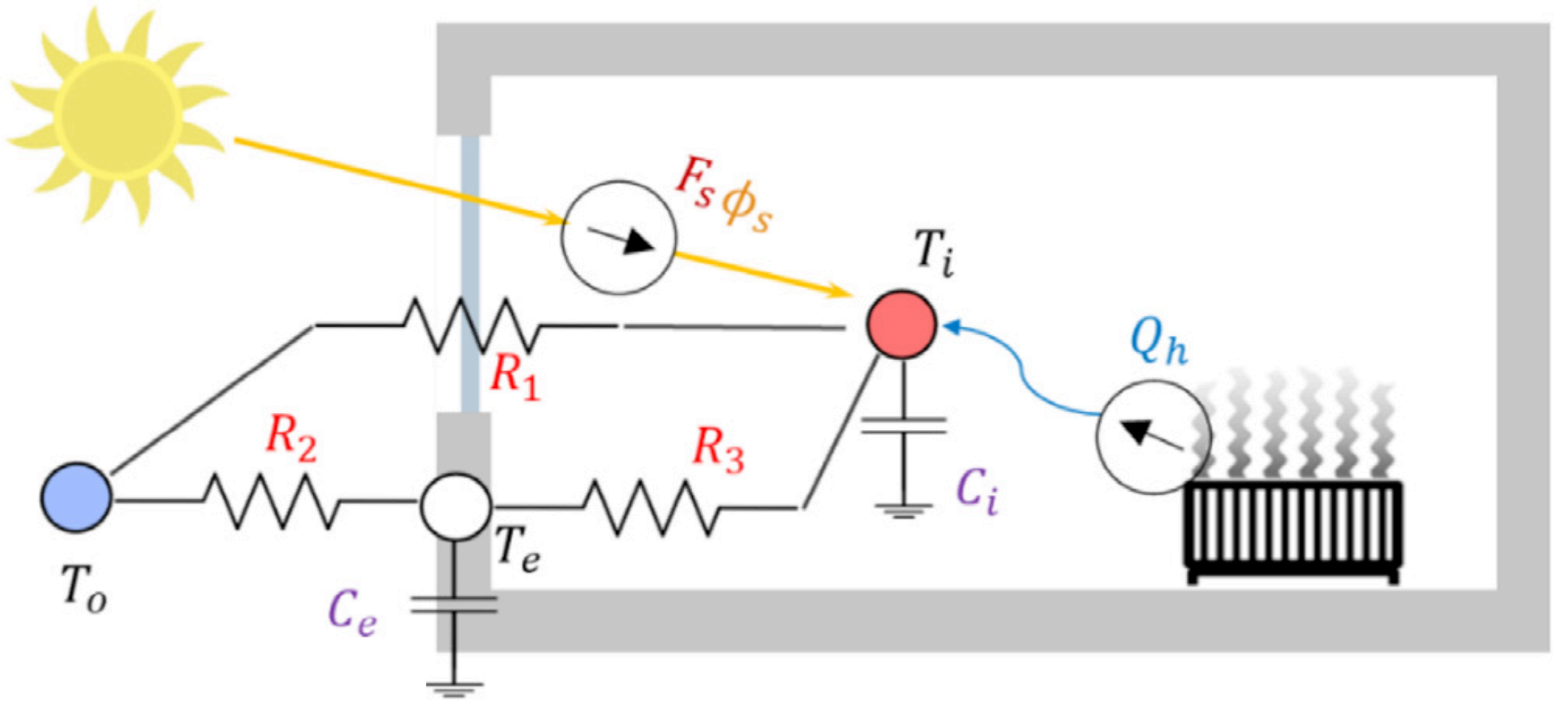
Week	Class	Topic	Guest Lecture
1	01/17	Introduction / Overview / Python	
2	01/24	Machine Learning I	
3	01/31	Machine Learning II	
4	02/07	Machine Learning III	Justin Hill (Southern)
5	02/14	Occupant Behavior Modeling	
6	02/21	Occupant Behavior Modeling	Tanya Barham (CEL)
7	02/28	Occupant Behavior Modeling	Jessica Granderson (LBNL)
8	03/06	Occupant Behavior Modeling	Hussain Kazmi (KU Leuven)
9	03/13	Spring Break	
10	03/20	Advanced Control & Calibration	Ankush Chakrabarty (MERL)
11	04/27	Calibration	Donghun Kim (LBNL)
12	04/03	Introduction to CityLearn	
13	04/10	Project Work	Siva Sankaranarayanan (EPRI)
14	04/17	Project work	
15	04/24	Project work	

Data-Driven Modeling of building thermal dynamics



1. **Modeling**: formulate mathematical model(s) with unknown parameters to predict system outputs using measured inputs
2. **Training**: estimate unknown parameters by matching measured outputs with predicted outputs
3. **Selecting**: choose best model

Resistor-Capacitor (RC) Models

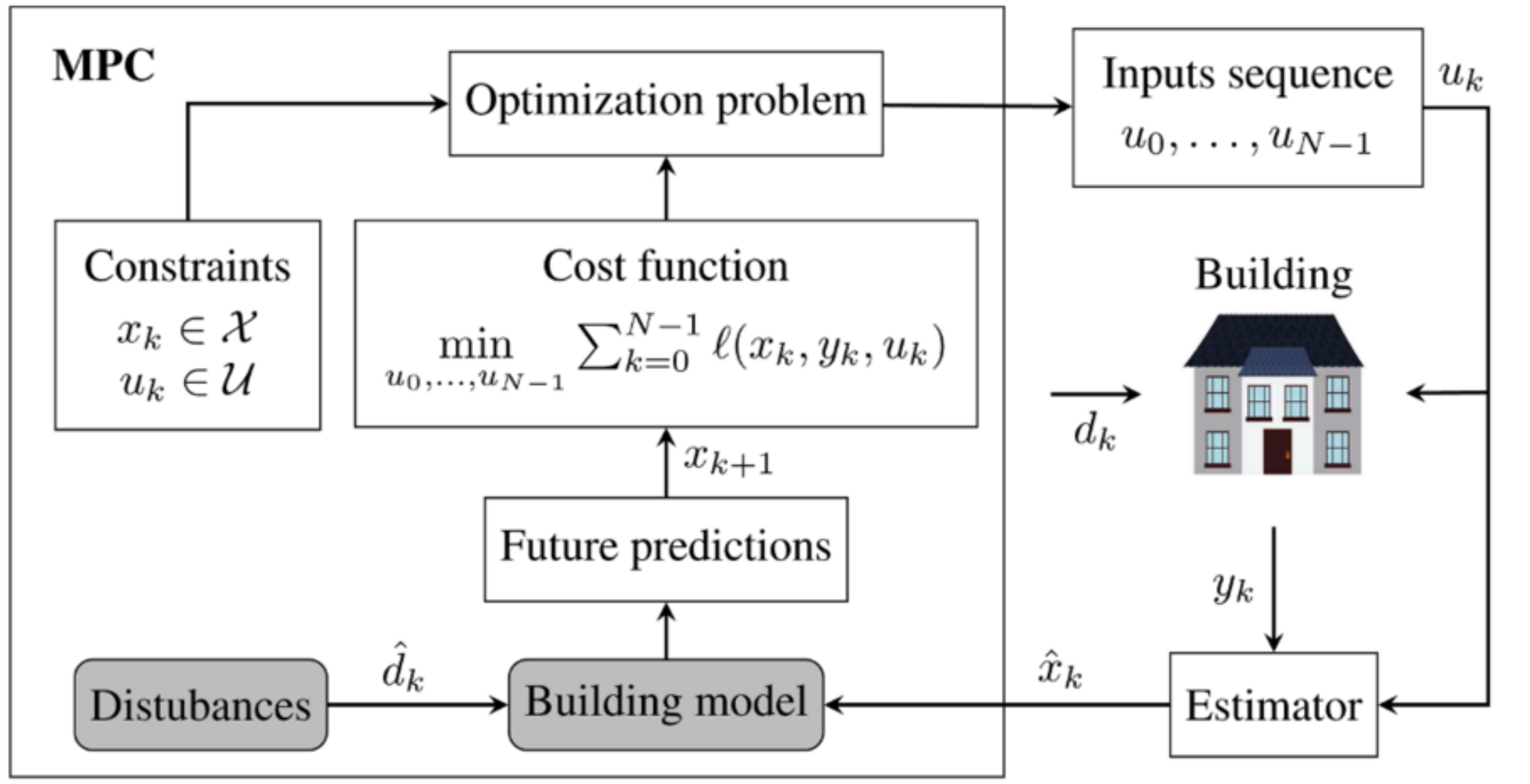


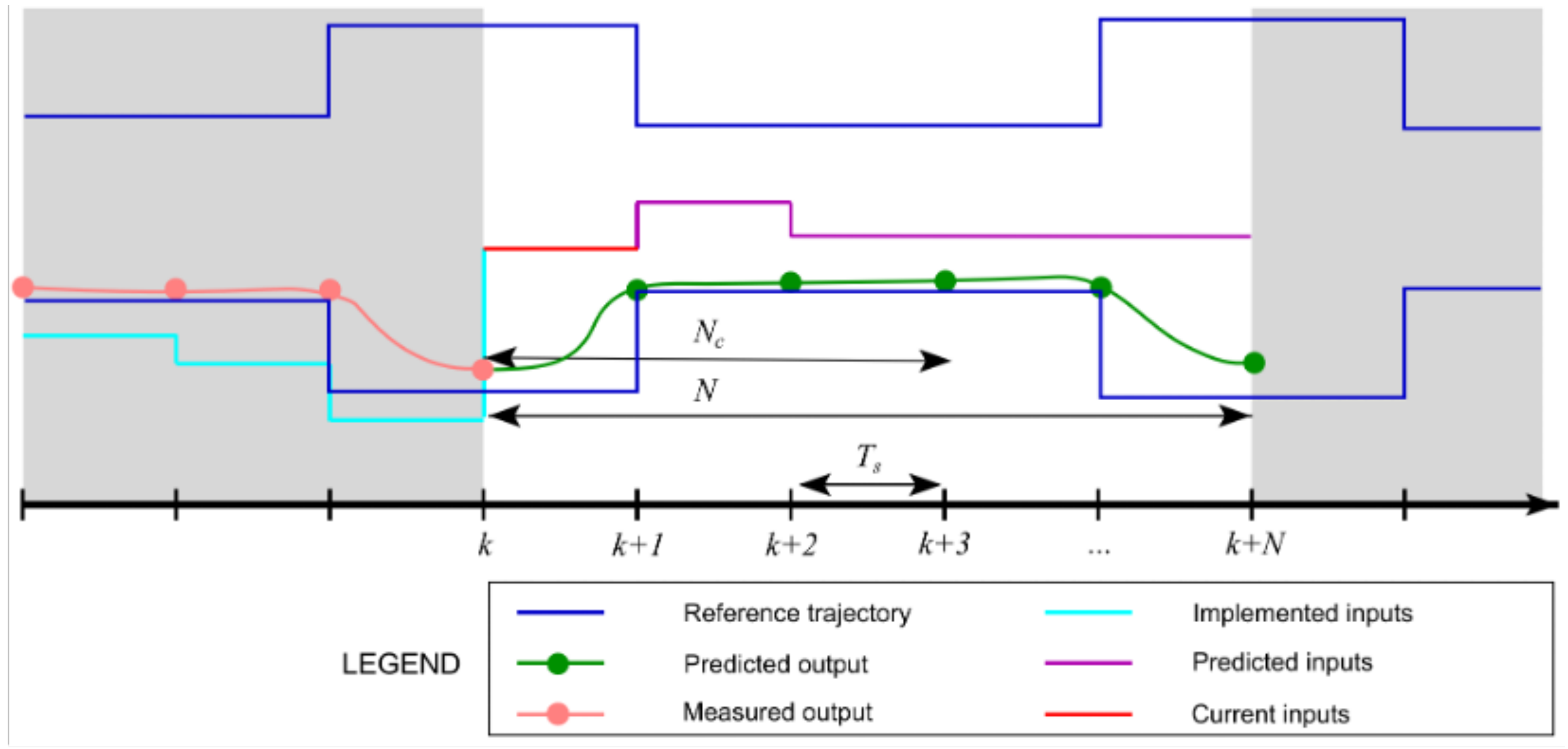
esentation of a room with a RC network (T_i: indoor air tem- e temperature of building envelop; T_o: outdoor air temper- er; ϕ_s: solar radiation on south façade; F_s: a ratio factor).

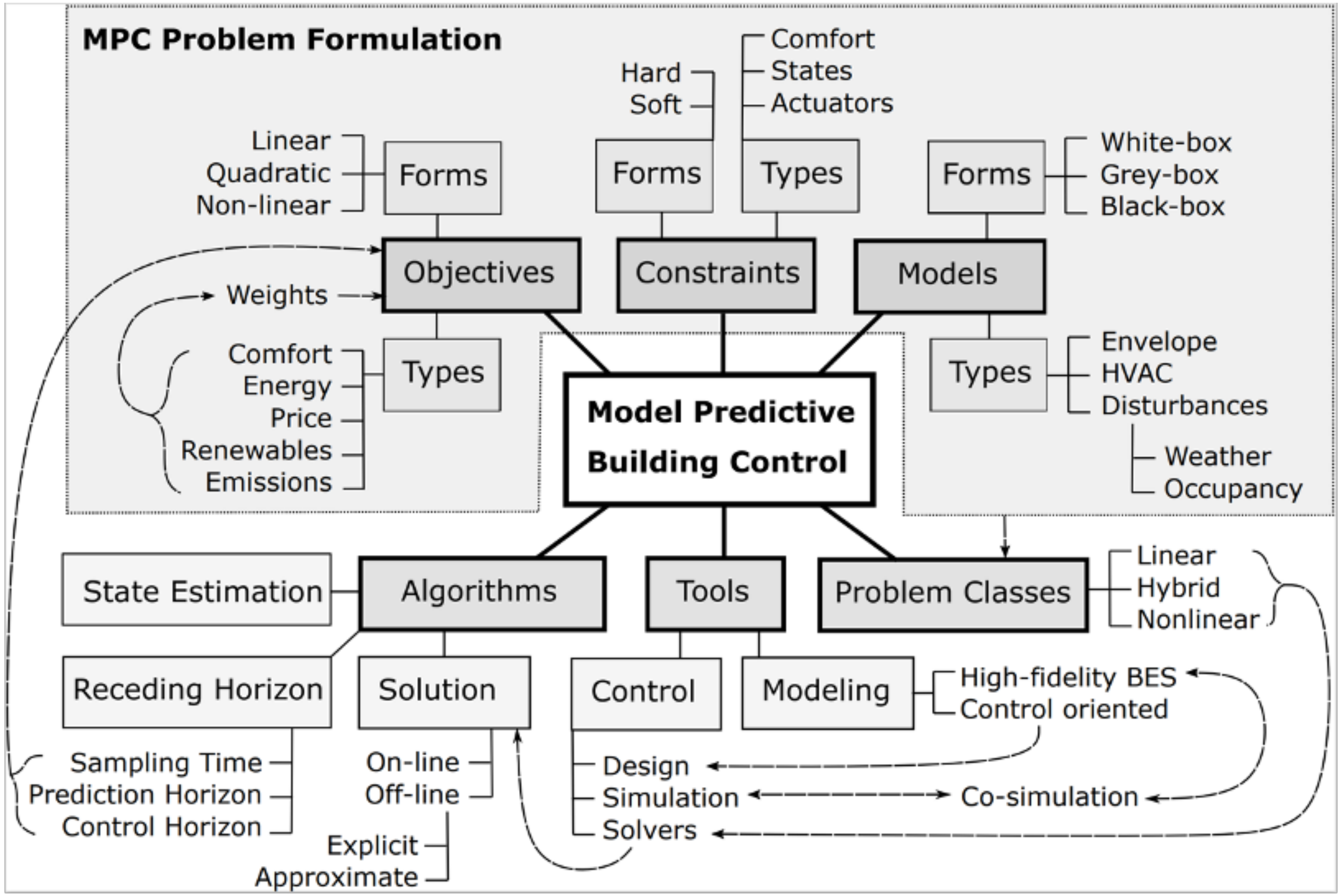
Table 1
An example of RC model formulation.

Model structure	RC network in Fig. 2
Variables	Input: $u = [T_o \quad \phi_s \quad Q_h]'$; Output: $y = T_i$; State: $x = [T_e \quad T_i]'$; Parameter: $\theta = [R_1 \quad R_2 \quad R_3 \quad C_e \quad C_i \quad F_s \quad F_h]'$
Ordinary differential equations	$C_e \frac{dT_e}{d\tilde{t}} = \frac{T_o - T_e}{R_2} + \frac{T_i - T_e}{R_3}$ $C_i \frac{dT_i}{d\tilde{t}} = \frac{T_o - T_i}{R_1} + \frac{T_e - T_i}{R_3} + F_s\phi_s + F_h Q_h \ (F_h = 1)$
State-space representation in continuous-time	$\frac{d}{d\tilde{t}}\begin{bmatrix} T_e \\ T_i \end{bmatrix} = \underbrace{\begin{bmatrix} -\frac{1}{C_eR_2} - \frac{1}{C_eR_3} & \frac{1}{C_eR_3} \\ \frac{1}{C_iR_3} & -\frac{1}{C_iR_1} - \frac{1}{C_iR_3} \end{bmatrix}}_{\tilde{A}} \begin{bmatrix} T_e \\ T_i \end{bmatrix} + \underbrace{\begin{bmatrix} \frac{1}{C_eR_2} & 0 & 0 \\ \frac{1}{C_iR_1} & \frac{F_s}{C_i} & \frac{1}{C_i} \end{bmatrix}}_{\tilde{B}} \begin{bmatrix} T_o \\ \phi_s \\ Q_h \end{bmatrix}$ $T_i = \underbrace{[0 \quad 1]}_{\tilde{C}} \begin{bmatrix} T_e \\ T_i \end{bmatrix} + \underbrace{0 \quad 0 \quad 0}_{\tilde{D}} \begin{bmatrix} T_o \\ \phi_s \\ Q_h \end{bmatrix}$

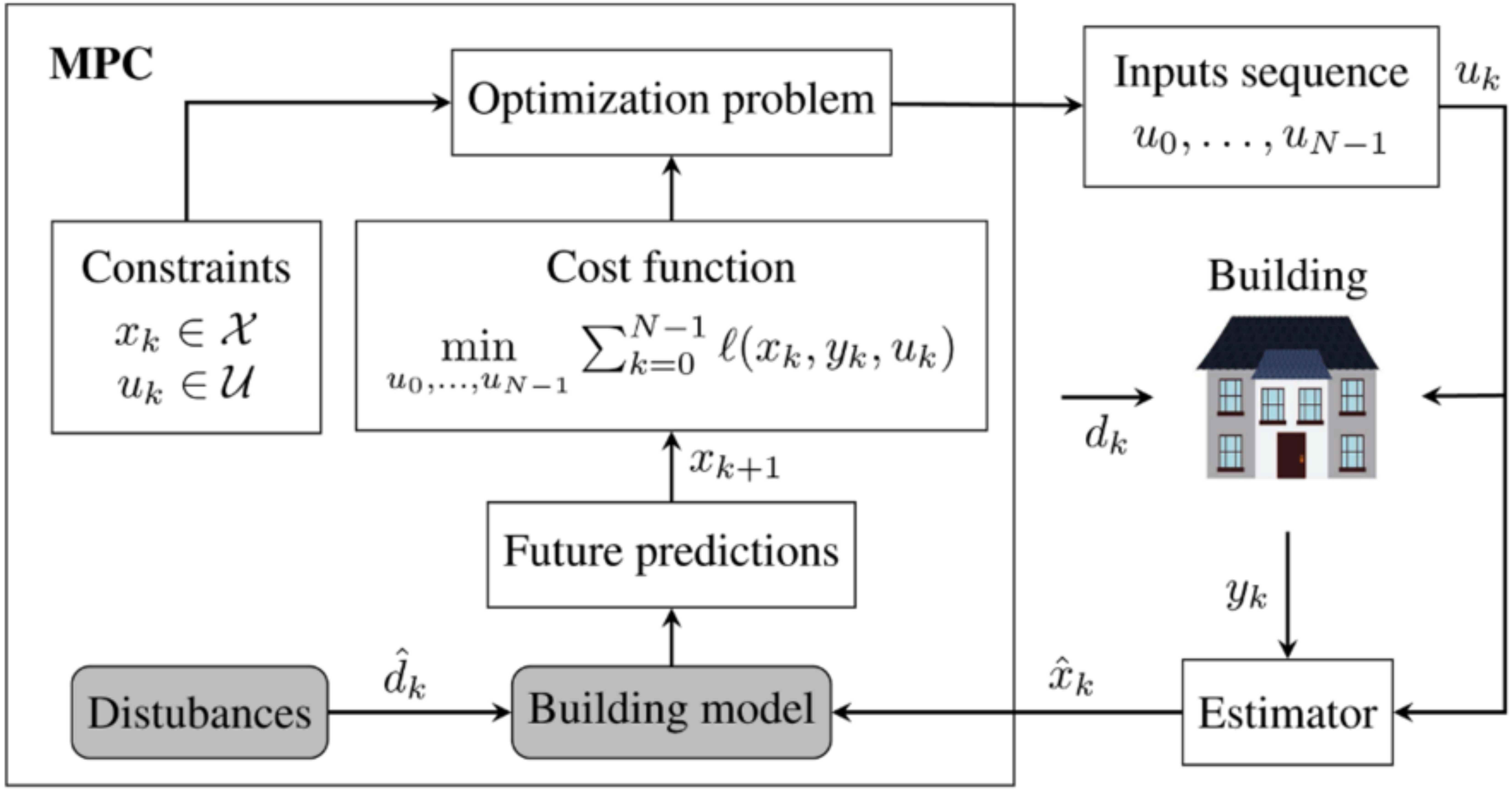
All you Need to Know About Model Predictive Control







All you Need to Know About Model Predictive Control



$$\min_{u_0,\ldots,u_{N-1}} \ell_N(x_N) + \sum_{k=0}^{N-1} \ell_k(x_k, y_k, r_k, u_k, s_k)$$

$$\text{s.t. } x_{k+1} = f(x_k, u_k, d_k), k \in \mathbb{N}_0^{N-1}$$

$$y_k = g(x_k, u_k, d_k), k \in \mathbb{N}_0^{N-1}$$

$$u_k = f_{\text{HVAC}}(x_k, a_k, m_k), k \in \mathbb{N}_0^{N-1}$$

Calibration of Simulation Models

References for today

- Calibrating building energy simulation models: A review of the basics to guide future work

- How spatio-temporal resolution impacts urban energy calibration

Contents lists available at ScienceDirect
Energy & Buildings
journal homepage: www.elsevier.com/locate/enb

Calibrating building energy simulation models: A review of the basics to guide future work

Adrian Chong [a,*], Yaonan Gu [a], Hongyuan Jia [b,c]

[a] Department of the Built Environment, School of Design and Environment, National University of Singapore, 4 Architecture Drive, Singapore 117566, Singapore
[b] School of Civil Engineering and Architecture, Chongqing University of Science and Technology, Chongqing 401331, China
[c] SinBerBEST Program, Berkeley Education Alliance for Research in Singapore, Singapore 138602, Singapore

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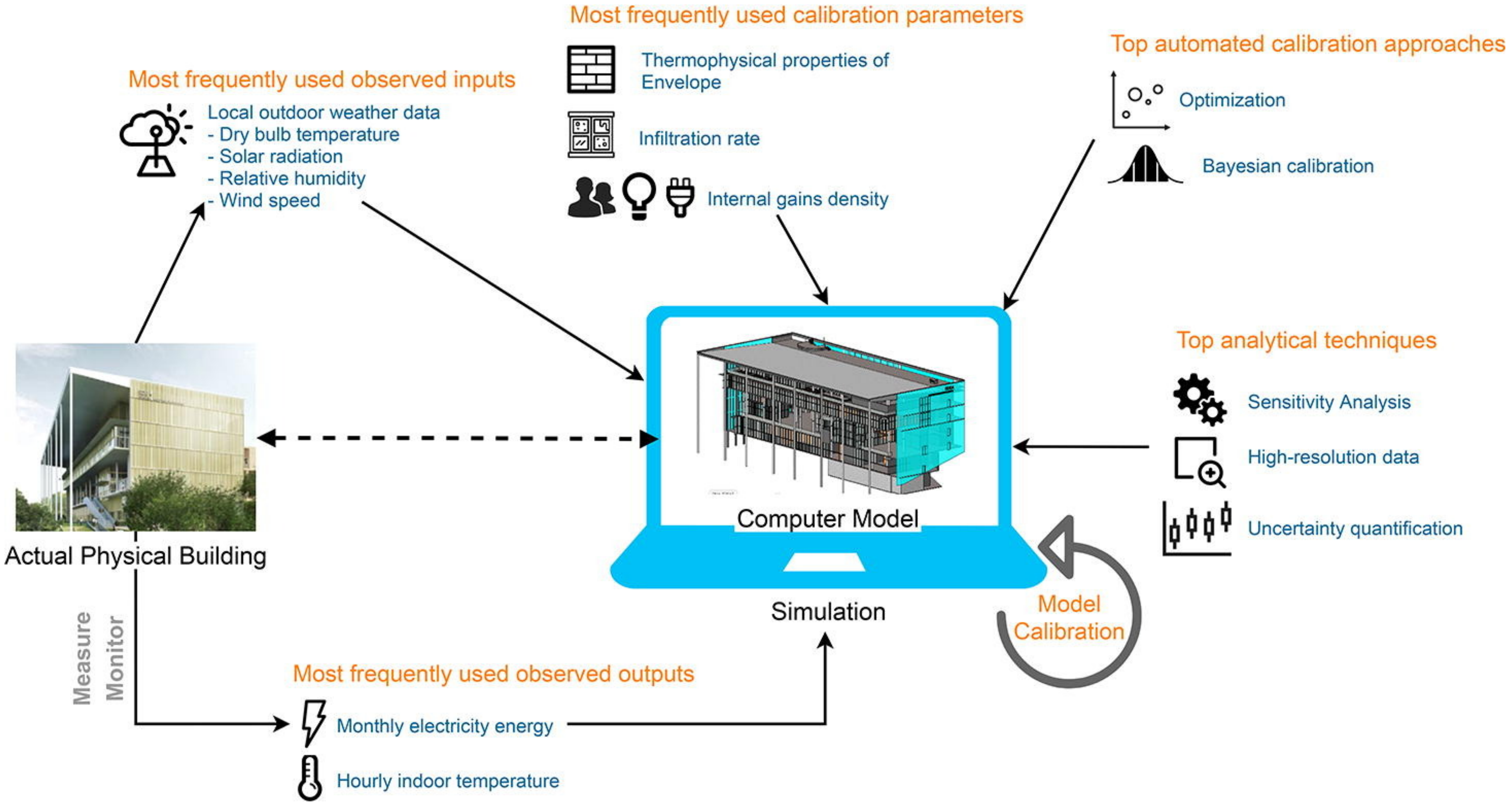
How spatio-temporal resolution impacts urban energy calibration

Aysegul Demir Dilsiz [a], Kingsley E. Nweye [b], Allen J. Wu [b], Jérôme H. Kämpf [c], Filip Biljecki [d], Zoltan Nagy [b]

What is calibration?

What is calibration?

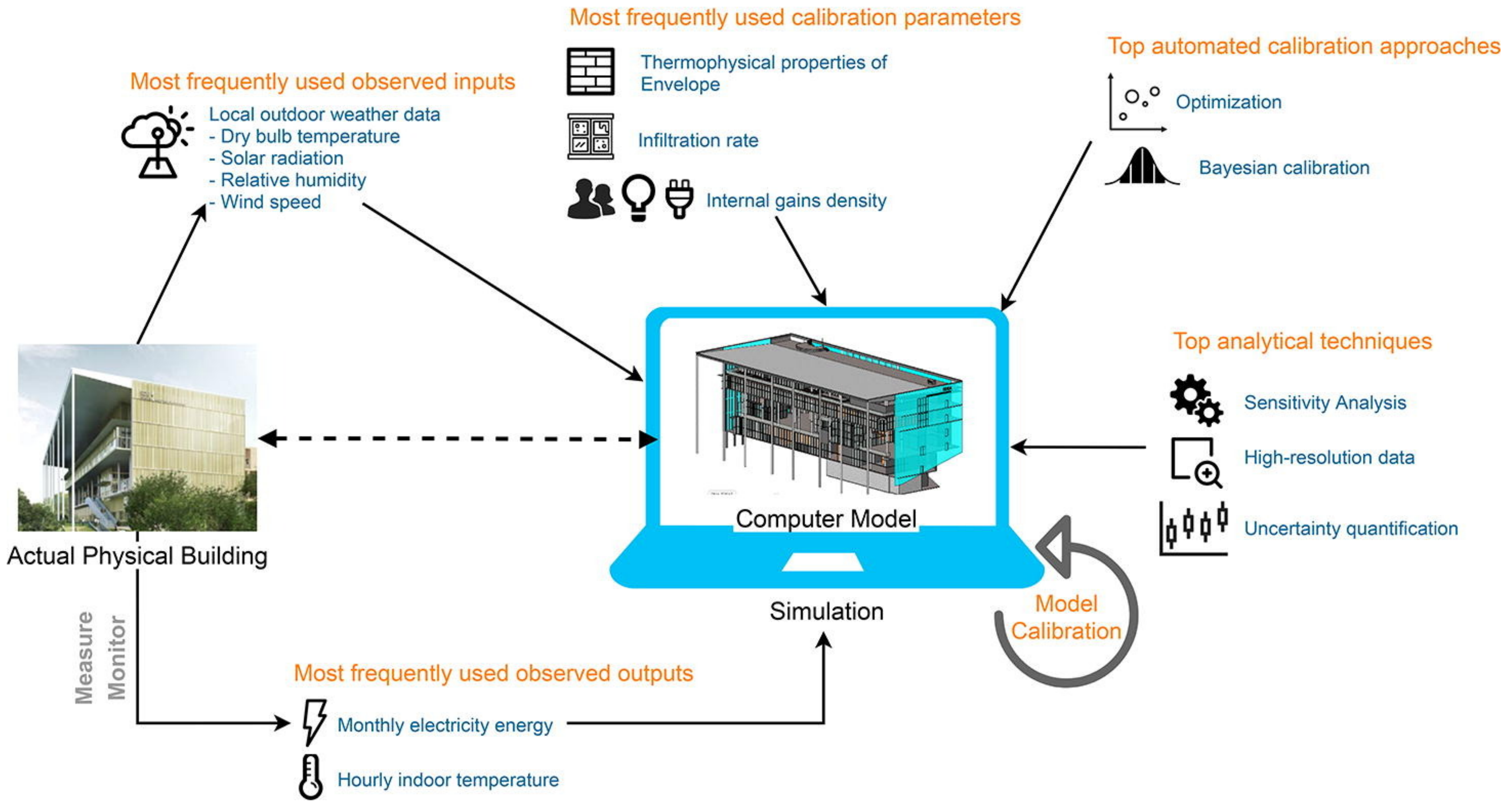
A review of the basics of model calibration to guide future work



What is calibration?

Calibration: The process of adjusting numerical or physical modeling parameters in the computational model for the purpose of improving agreement with experimental data.

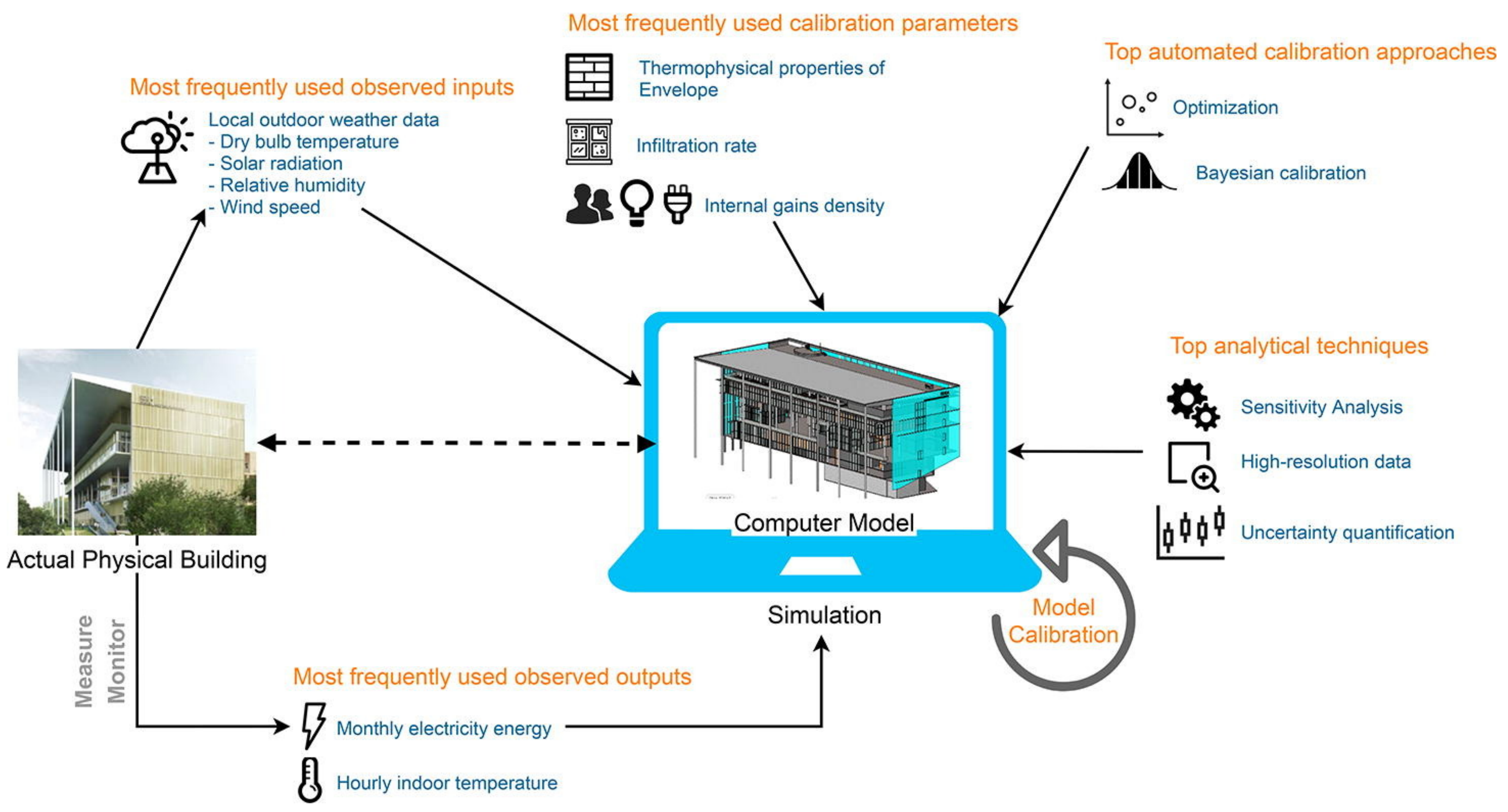
A review of the basics of model calibration to guide future work



What is calibration?

Calibration is not essential for BES research and practice, but it increases the model’s credibility.

A review of the basics of model calibration to guide future work

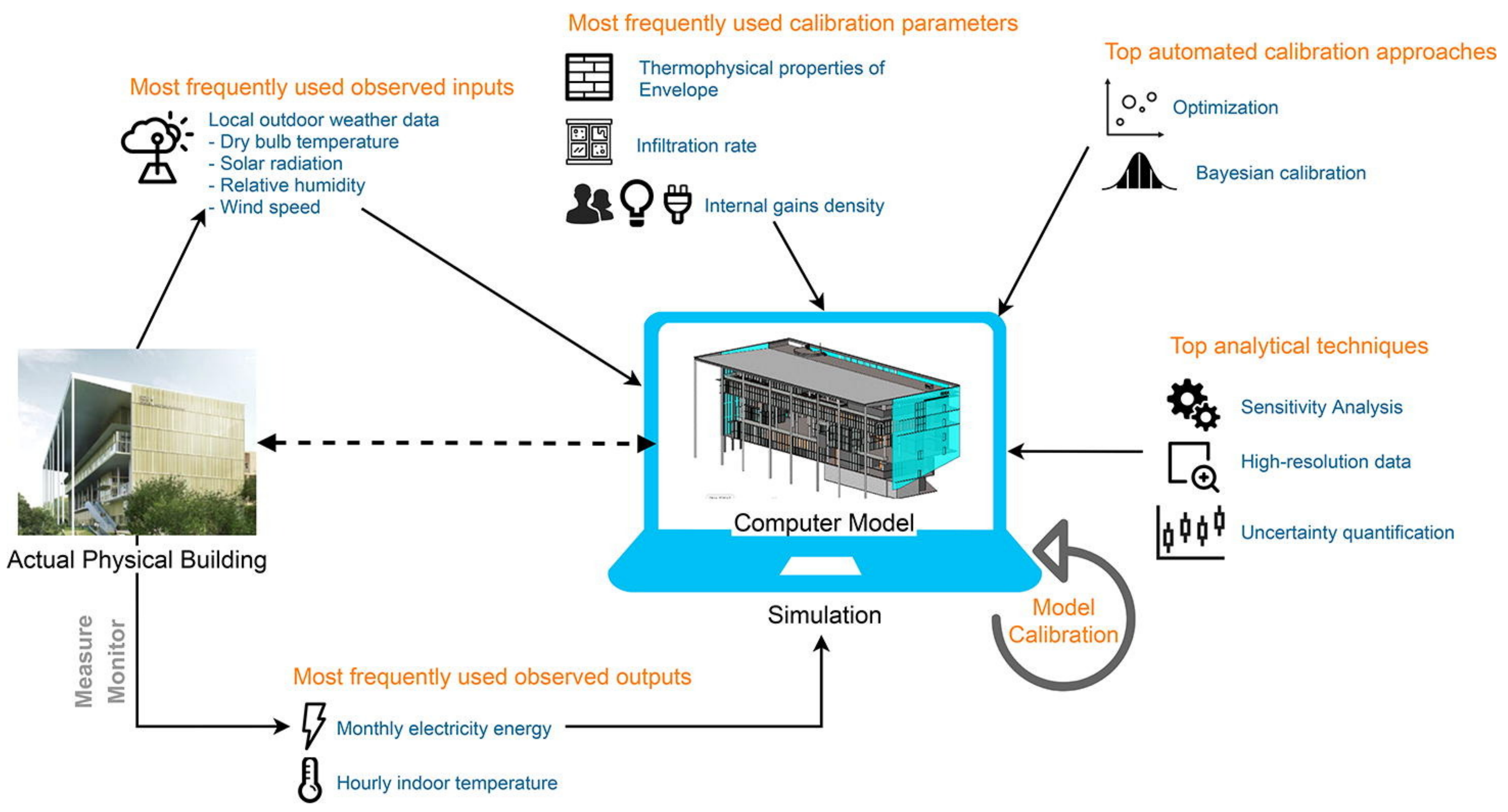


Why Calibration ?

Simulating an experiment without knowledge of its results or prior to its execution.

e.g., retrofit analysis that compares the cost-effectiveness of different energy conservation measures (ECMs).

A review of the basics of model calibration to guide future work

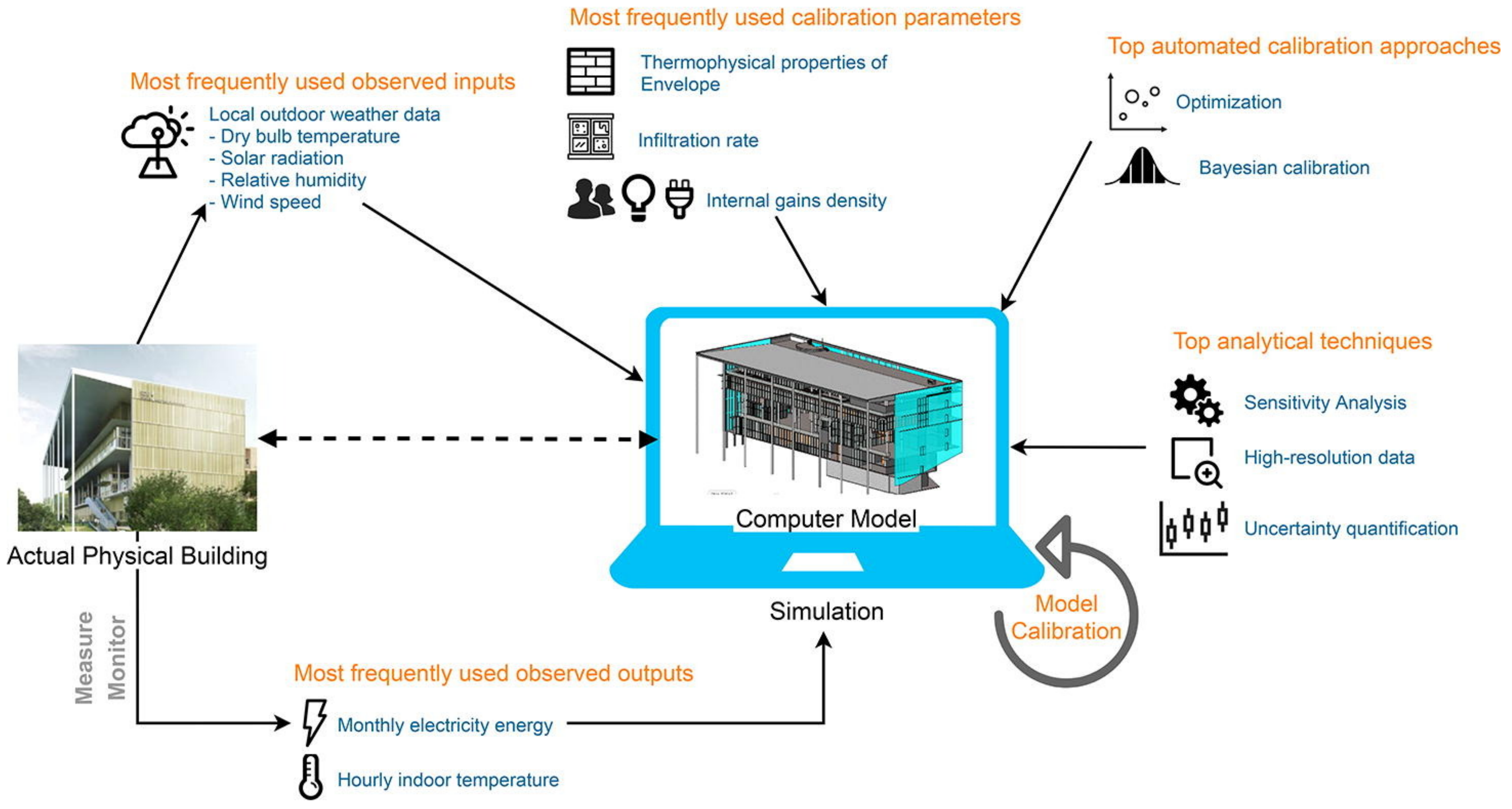


Why Calibration ?

Making scientific pronouncements about phenomena that **cannot currently be studied experimentally.**

e.g., Observing changes in building energy performance considering different climate change scenarios or a scenario where occupancy and building usage can become sporadic in the event of a pandemic.

A review of the basics of model calibration to guide future work

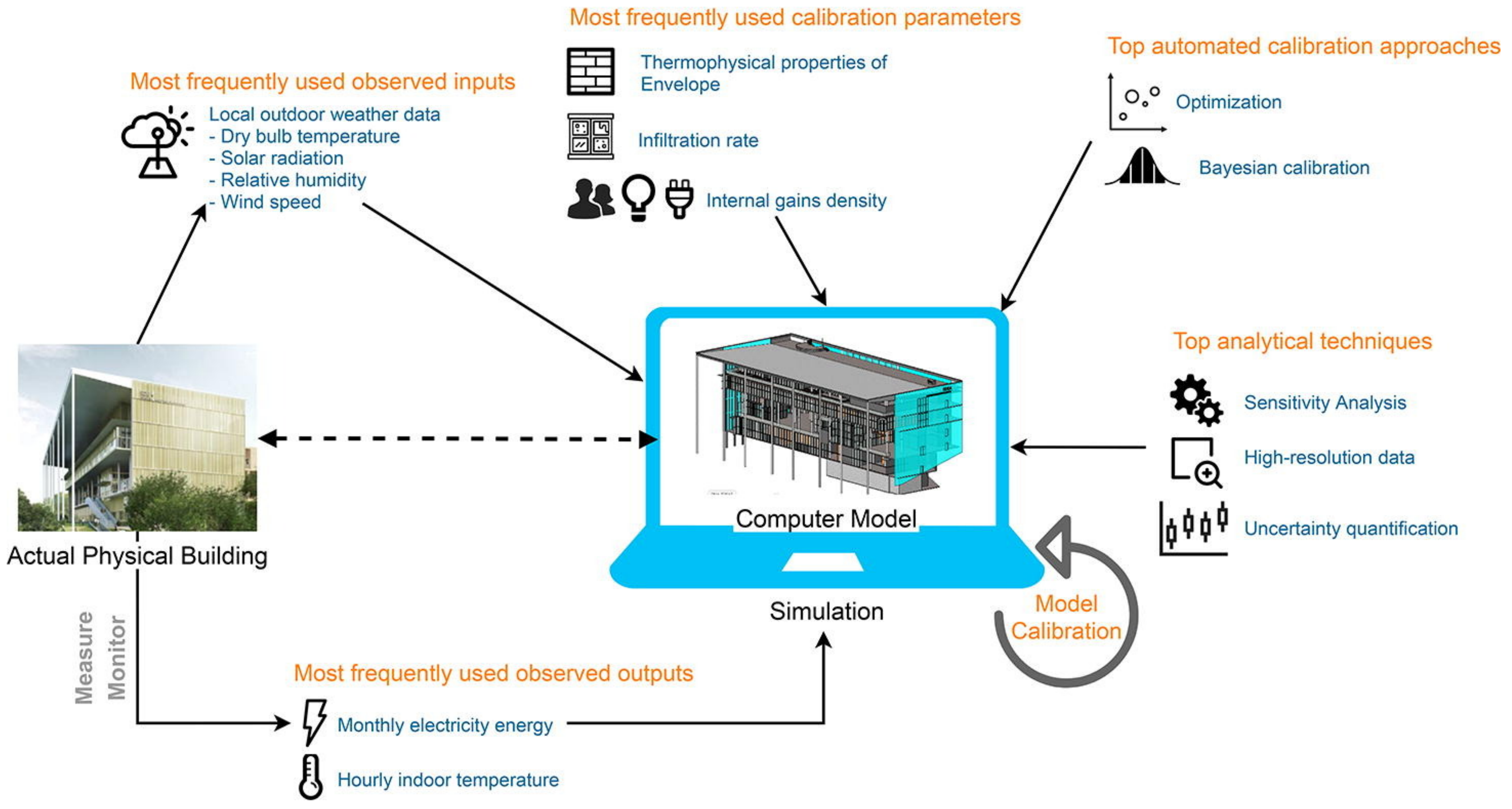


Why Calibration ?

Using computation to extrapolate existing understanding into **experimentally unexplored regimes**.

e.g., using BES to create a baseline for quantifying energy savings for buildings with multiple interactive ECMs.

A review of the basics of model calibration to guide future work

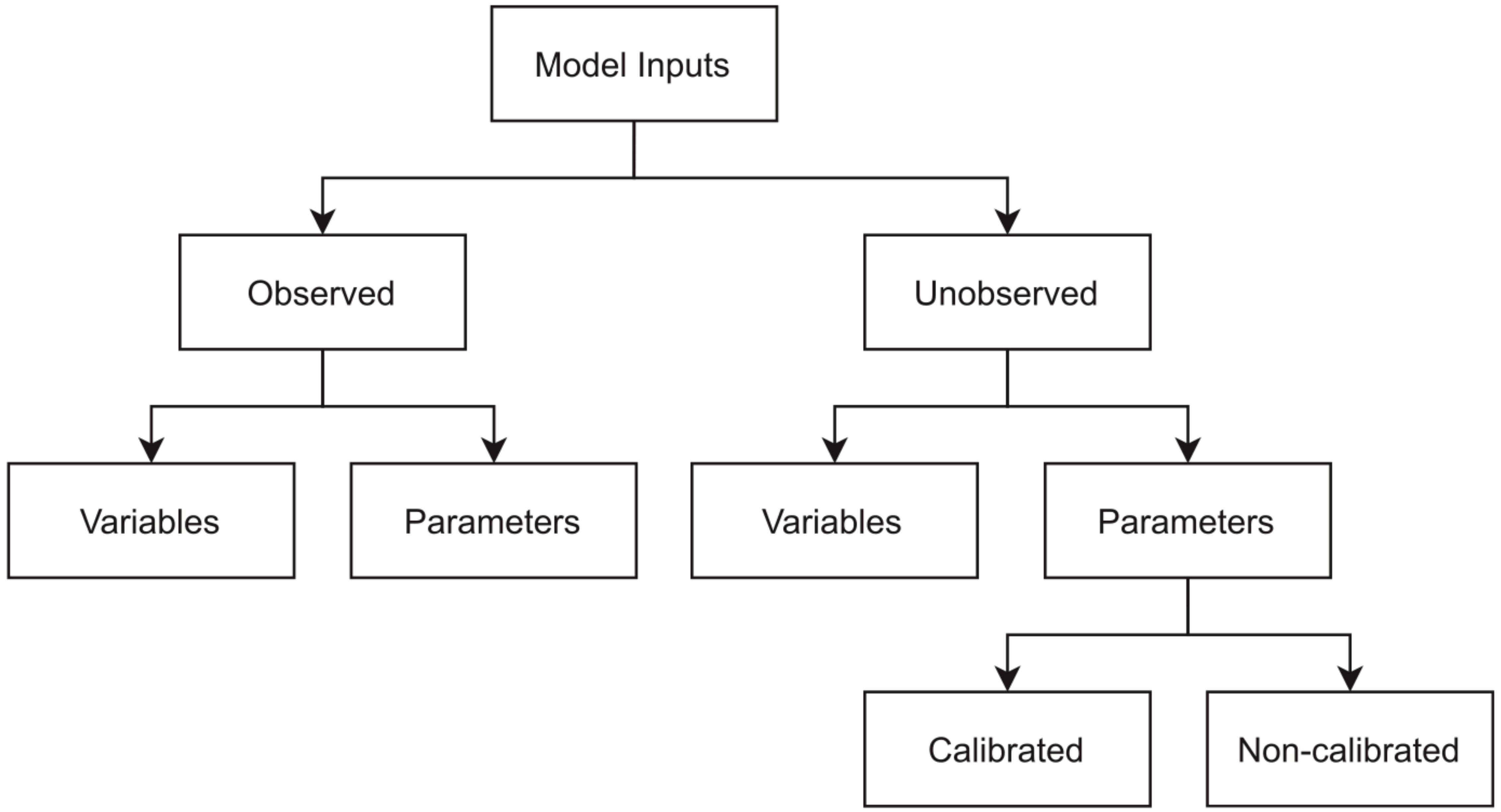


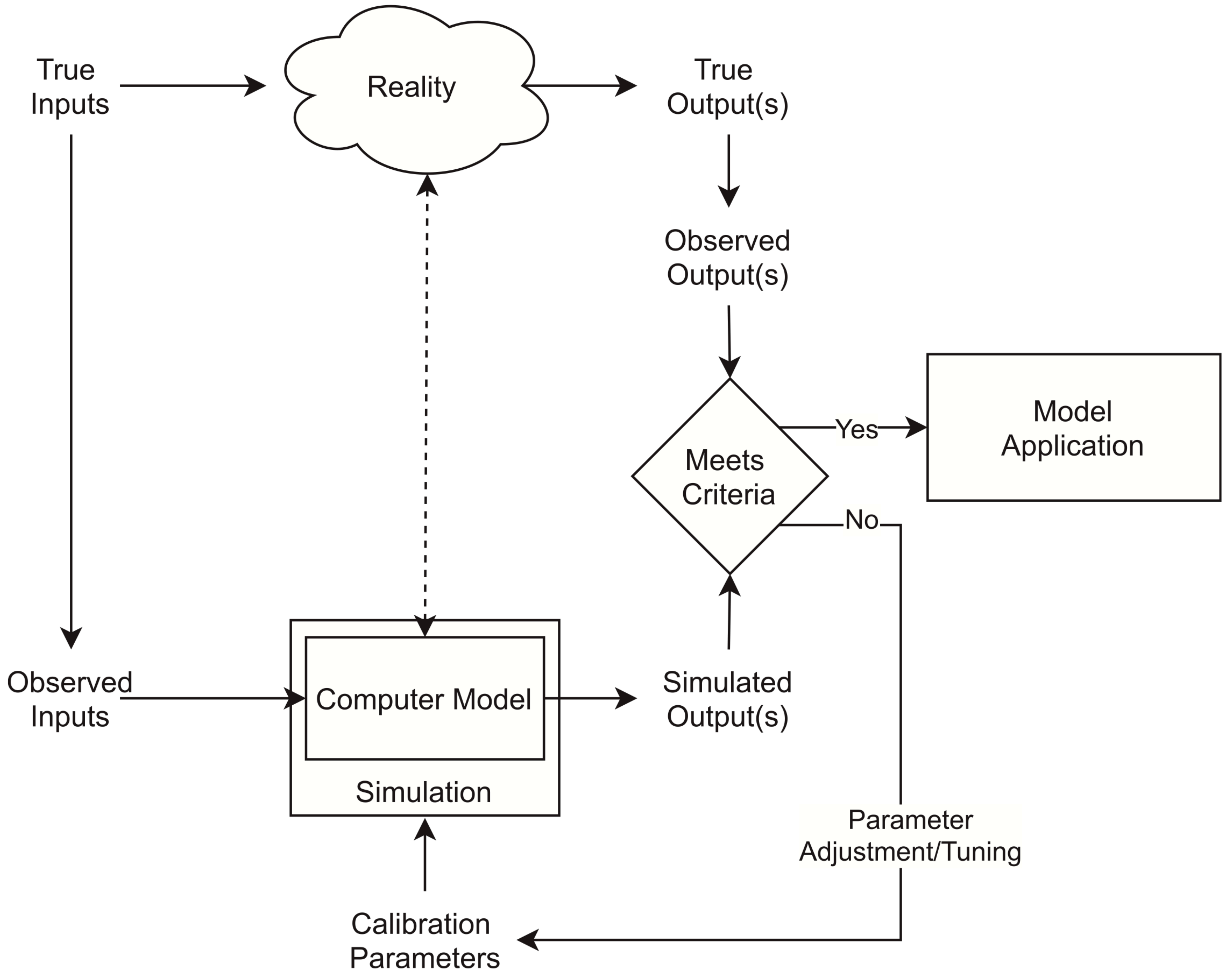
Key Calibration Approaches

Calibration: The process of adjusting numerical or physical modeling parameters in the computational model for the purpose of improving agreement with experimental data.

- Manual vs Automated
- Automated calibration
  - mathematical optimization
    - genetic algorithms, particle swarm optimization
  - bayesian calibration
    - ability to naturally incorporate uncertainty and combine prior information with measured data to derive posterior estimates of the model parameters

Calibration Schematic





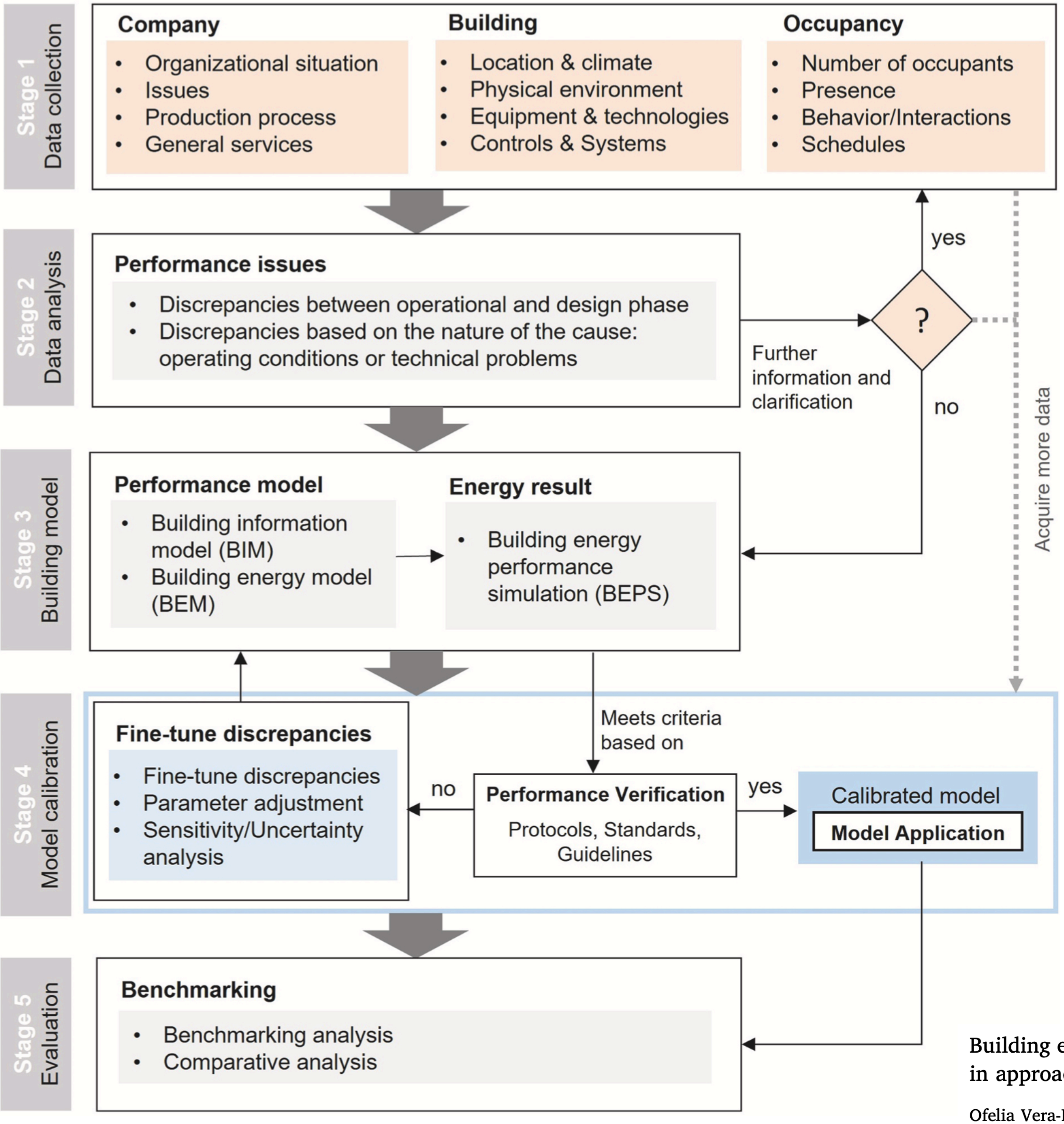
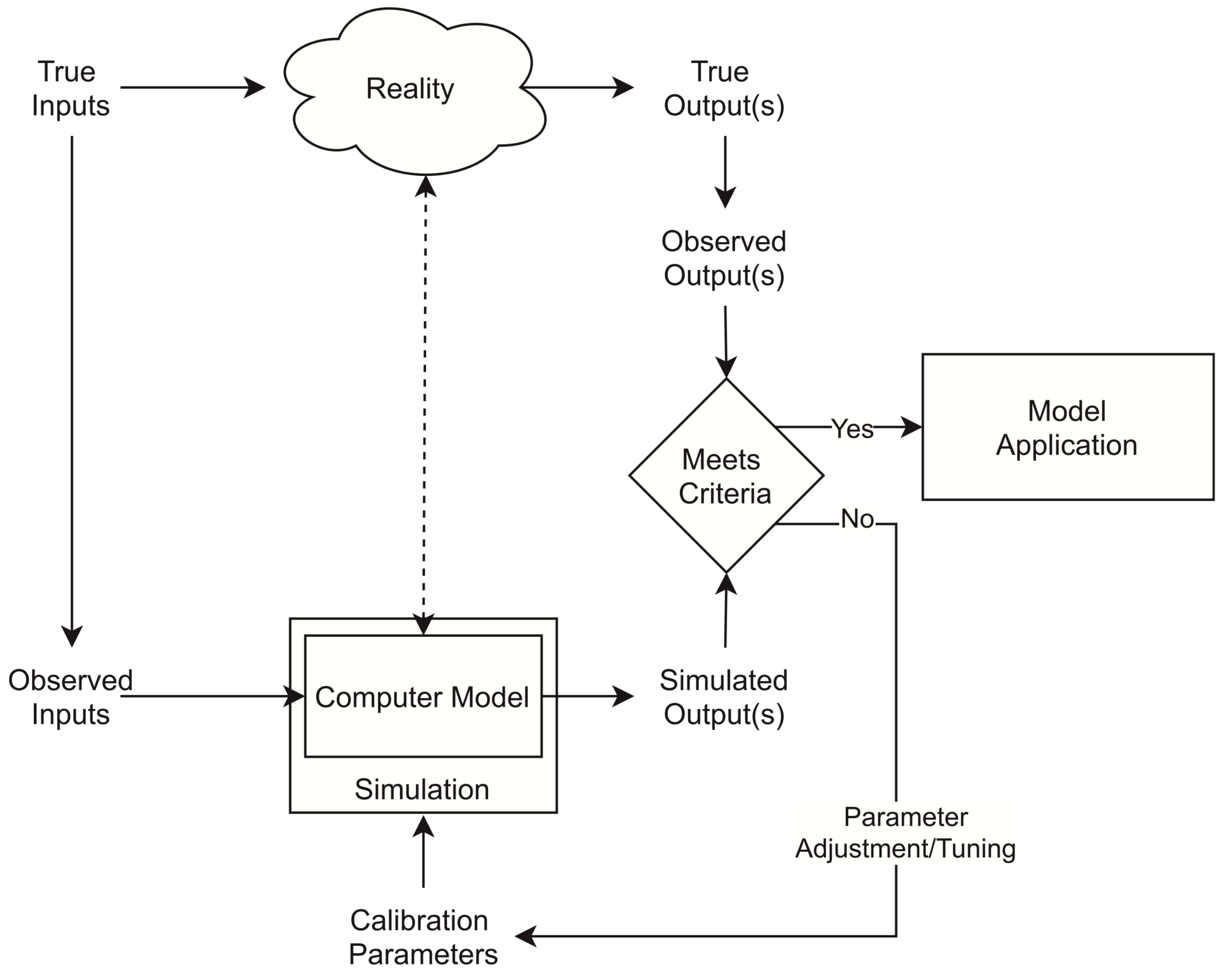


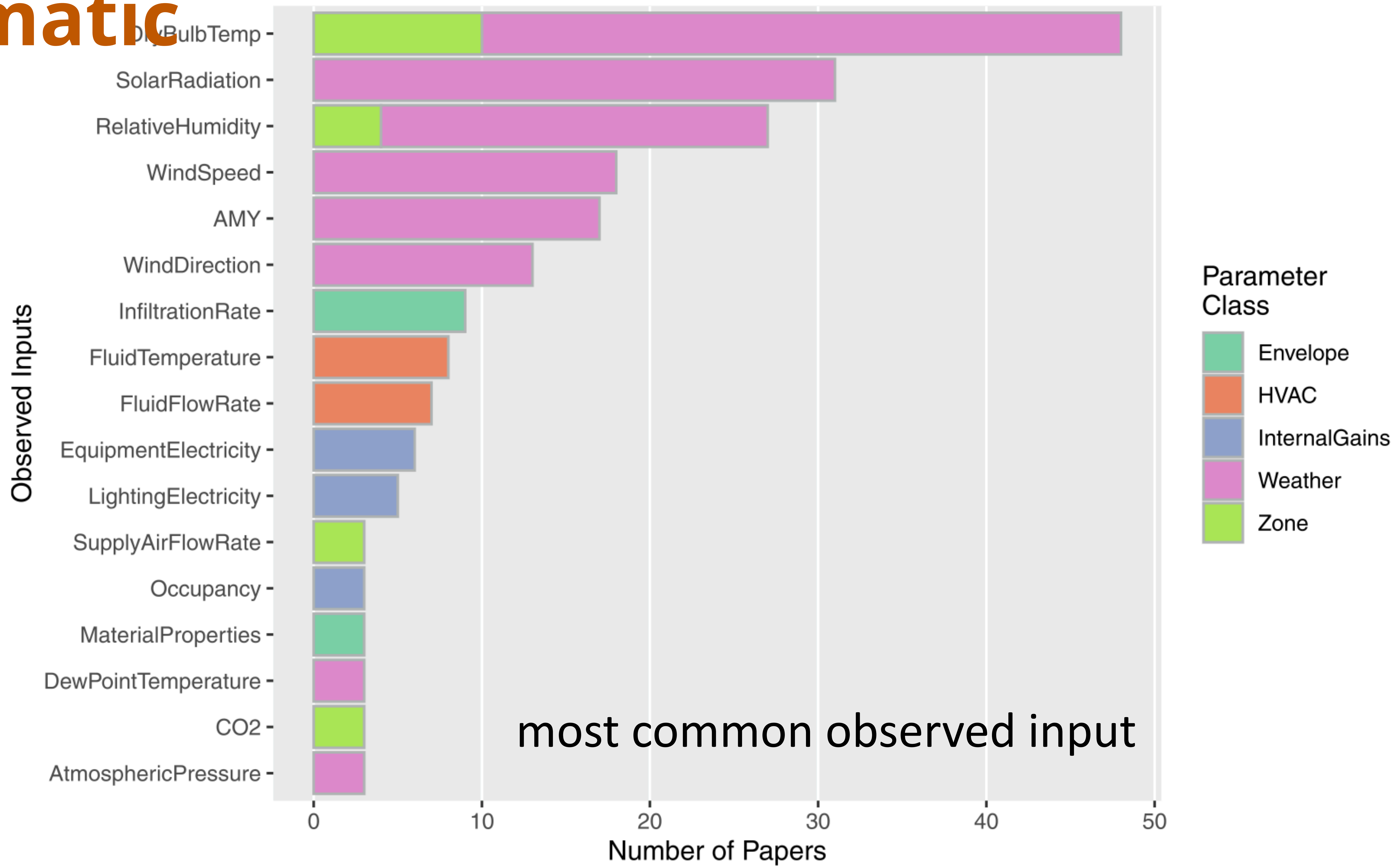
Fig. 12. Generalized model calibration process based on the reviewed literature.

Building energy model calibration: A review of the state of the art in approaches, methods, and tools

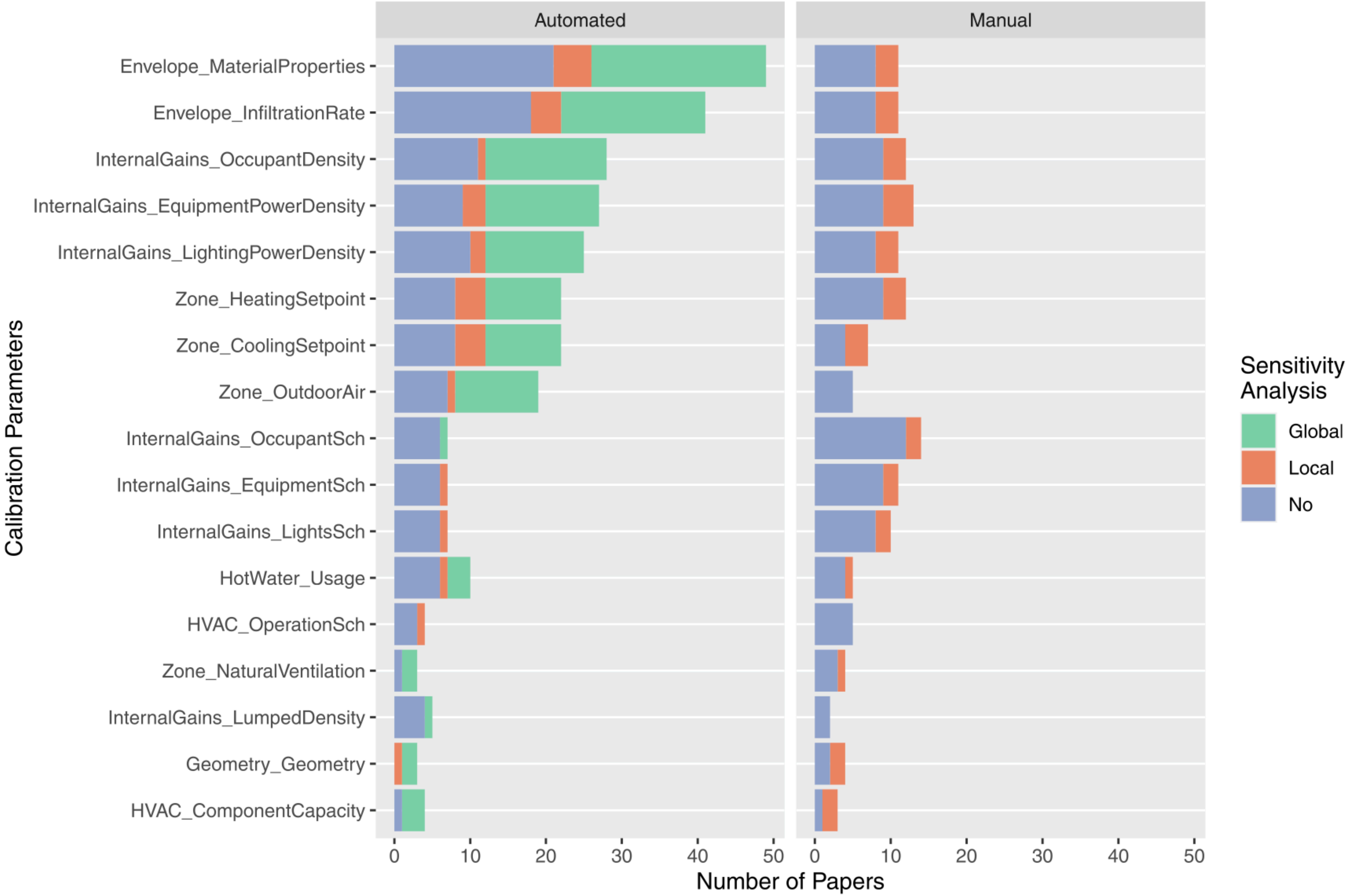
Ofelia Vera-Piazzini [a,*], Massimiliano Scarpa [b]

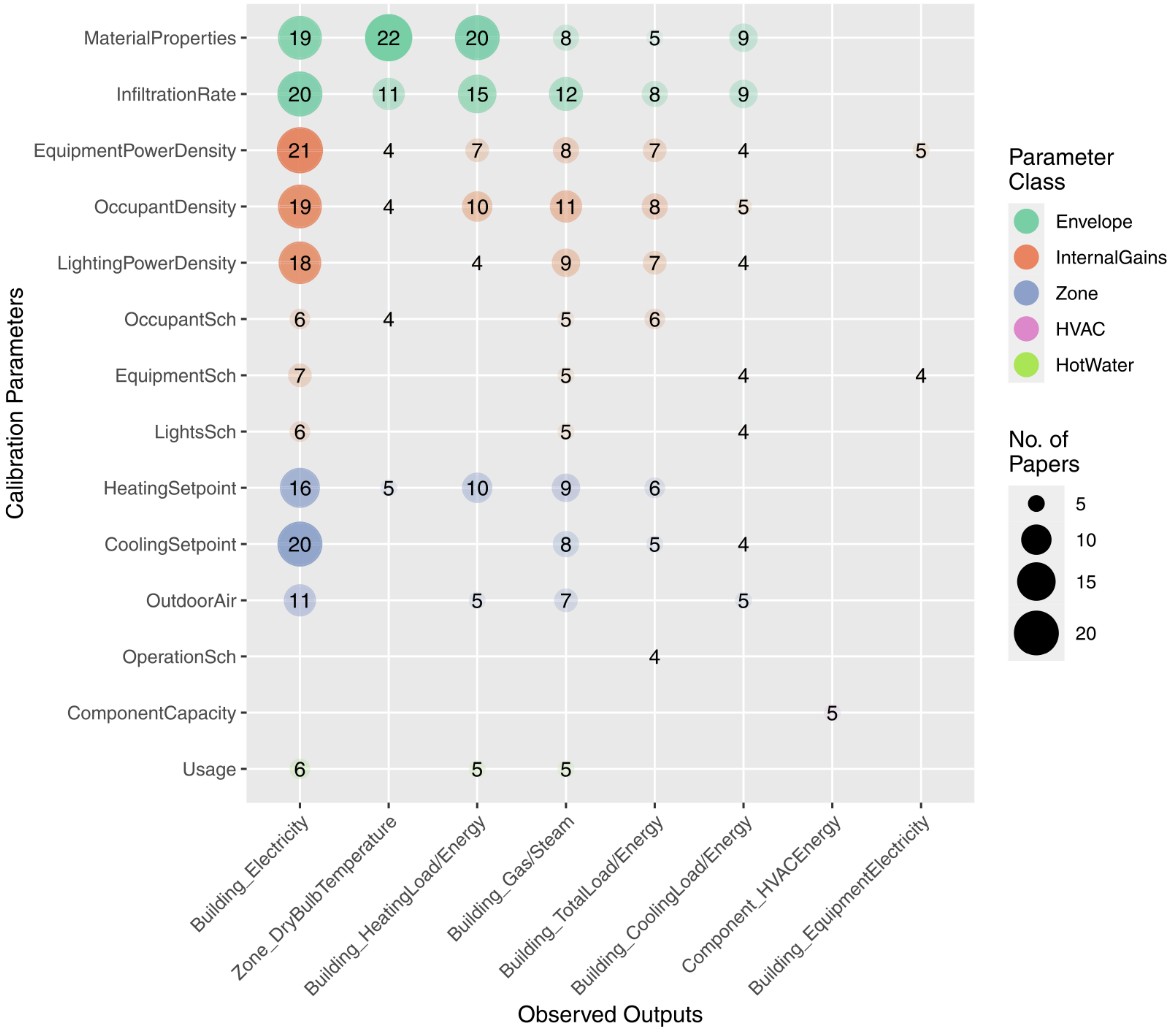
Calibration Schematic





most common observed input


Automated
Manual
Envelope_MaterialProperties
Envelope_InfiltrationRate
InternalGains_OccupantDensity
InternalGains_EquipmentPowerDensity
InternalGains_LightingPowerDensity
Zone_HeatingSetpoint
Zone_CoolingSetpoint
Zone_OutdoorAir
InternalGains_OccupantSch
InternalGains_EquipmentSch
InternalGains_LightsSch
HotWater_Usage
HVAC_OperationSch
Zone_NaturalVentilation
InternalGains_LumpedDensity
Geometry_Geometry
HVAC_ComponentCapacity
Calibration Parameters
0
10
20
30
40
50
Number of Papers
Sensitivity Analysis
Global
Local
No


Calibration Parameters
MaterialProperties
InfiltrationRate
EquipmentPowerDensity
OccupantDensity
LightingPowerDensity
OccupantSch
EquipmentSch
LightsSch
HeatingSetpoint
CoolingSetpoint
OutdoorAir
OperationSch
ComponentCapacity
Usage
Building_Electricity
Zone_DryBulbTemperature
Building_HeatingLoad/Energy
Building_Gas/Steam
Building_TotalLoad/Energy
Building_CoolingLoad/Energy
Component_HVACEnergy
Building_EquipmentElectricity
Observed Outputs
Parameter Class
Envelope
InternalGains
Zone
HVAC
HotWater
No. of Papers
5
10
15
20

Calibration Evaluation

$$CV(RMSE) = \frac{1}{\bar{m}} \cdot \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n-p}} \times 100$$

$$NMBE(\%) = \frac{1}{\bar{m}} \cdot \frac{\sum_{i=1}^{n}(m_i - s_i)}{n-p} \times 100$$

Table 6
Error limits specified by various guidelines and protocols for a building energy simulation model to be deemed calibrated.

Guideline/ Protocol	Monthly Criteria (%)		Hourly Criteria (%)	
	NMBE	CV(RMSE)	NMBE	CV(RMSE)
ASHRAE Guideline 14 [59]	±5	15	±10	30
IPMVP [60]	–	–	±5	20
FEMP [61]	±5	15	±10	30

Example - Calibrating the UT campus energy model

Example - Calibrating the UT campus energy model

> UT Energy Dashboard

Creating the model

1. BUILDING GEOMETRY

Open Street Map
- Area Footprints

University of Texas, at Austin
- Window-to-wall ratio for each orientation
- Floor Heights

2. BUILDING CHARACTERISTIC

University of Texas, at Austin
- Construction year
- Primary Use Type
- Occupancy Load

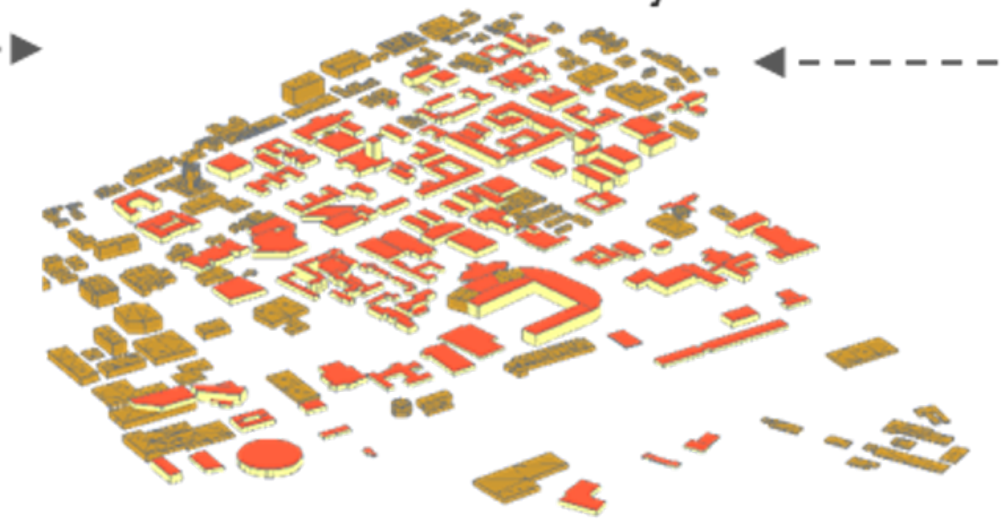
3. TEMPORAL RESOLUTION OF METERED DATA

University of Texas, at Austin
- Campus Metered Cooling Consumption Data [Wh/m^2]
- Monthly and Annually

3D Campus Environment
Created in Rhino

Hourly Climatic Data
Meteonorm

Urban Energy Modeling
Created in CitySIM



Baseline Simulated
Cooling Consumption [Wh/m^2]

BAYESIAN CALIBRATION OF UNKNOWN FIVE PARAMETERS

Updated Unknown Parameters
assigned to each building
Rerun Simulations

1. BUILDING GEOMETRY
Open Street Map
Area Footprints
University of Texas, at Austin
Window-to-wall ratio for each orientation
Floor Heights
2. BUILDING CHARACTERISTIC
University of Texas, at Austin
Construction year
Primary Use Type
Occupancy Load
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Campus Metered Cooling Consumption Data [Wh/m2]
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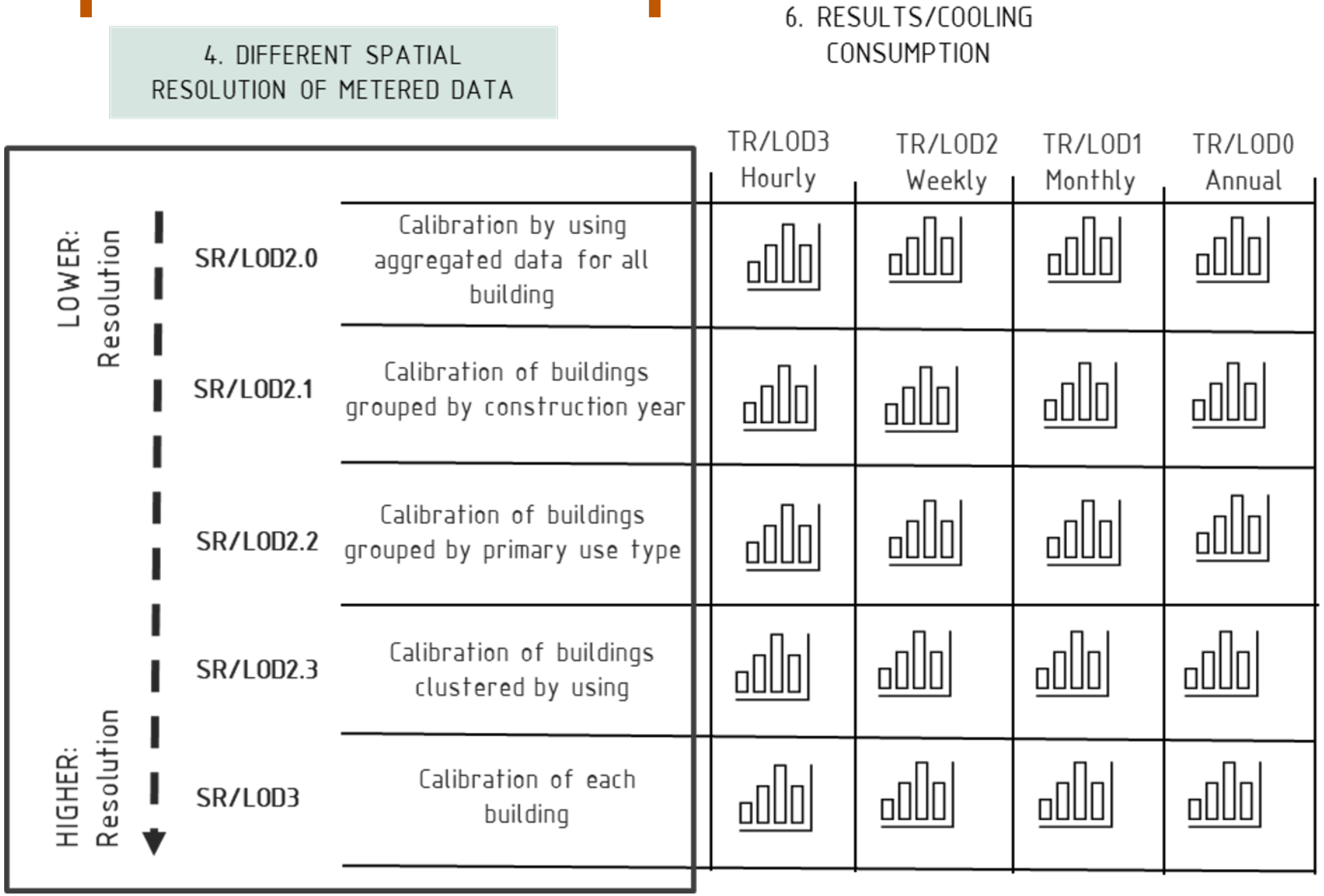
Baseline Simulated Cooling Consumption [Wh/m2]
BAYESIAN CALIBRATION OF UNKNOWN FIVE PARAMETERS
Updated Unknown Parameters assigned to each building
Rerun Simulations
4. DIFFERENT SPATIAL RESOLUTION OF METERED DATA
6. RESULTS/COOLING CONSUMPTION
TR/LOD3 Hourly
TR/LOD2 Weekly
TR/LOD1 Monthly
TR/LOD0 Annual
LOWER: Resolution
HIGHER: Resolution
SR/LOD2.0
Calibration by using aggregated data for all building
SR/LOD2.1
Calibration of buildings grouped by construction year
SR/LOD2.2
Calibration of buildings grouped by primary use type
SR/LOD2.3
Calibration of buildings clustered by using
SR/LOD3
Calibration of each building
Results

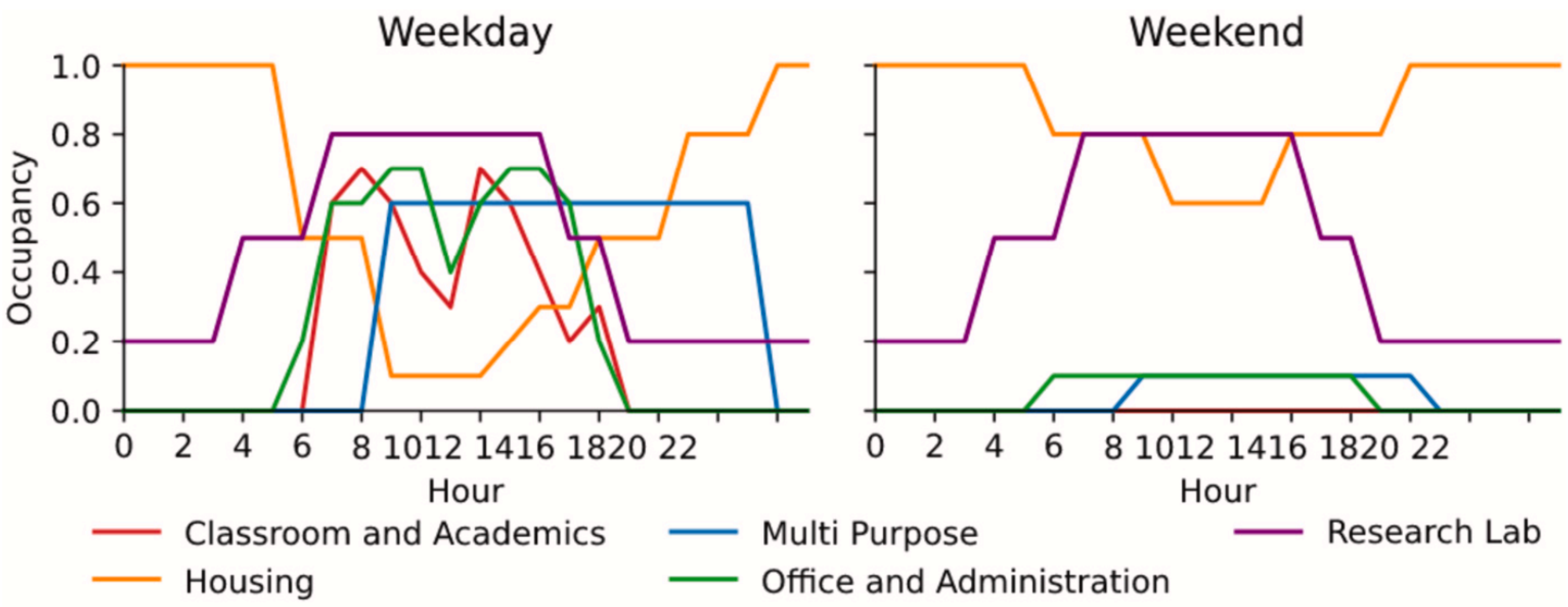
Spatial and temporal data resolutions



Characteristic of each spatial resolution.

Spatial resolution	Aggregation	Buildings
SR/LOD2.0	All Buildings	70
SR/LOD2.1	Before 1980	55
	1980-2004	8
	2004-2007	3
	2007-2013	4
SR/LOD2.2	RL	11
	H	9
	OA	4
	CA	24
	PA	22
SR/LOD2.3	Class 1	13
	Class 2	29
	Class 3	28

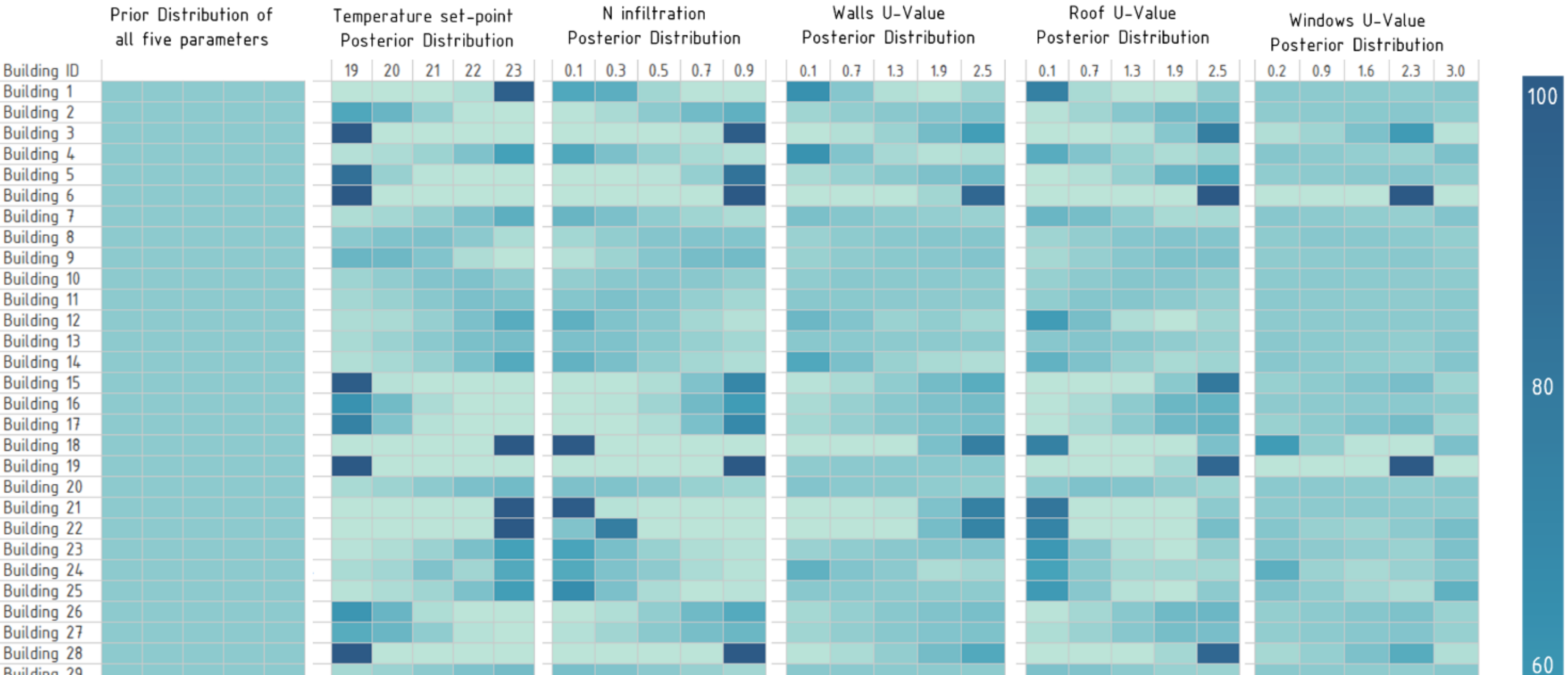
Occupancy Assumptions



Occupancy density used to calculate occupancy for each building [47].

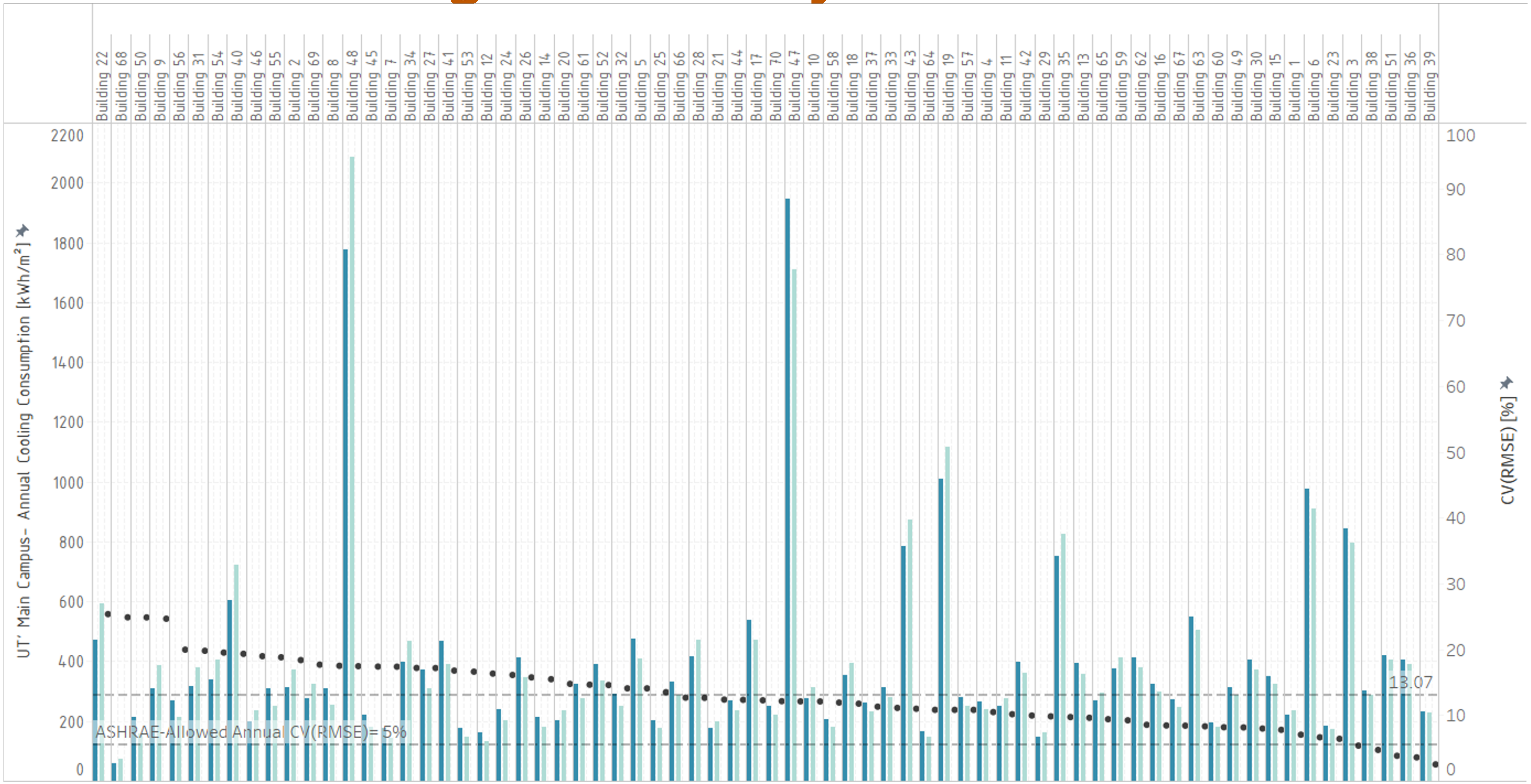
List of space definitions used at UT campus	Person / 100 m^2	List of space definitions used at UT campus	Person / 100 m^2
Office Space	5	Public Restroom	1
Conference Room	50	General-Purpose Classroom	65
Library	10	Laboratories	25
Study Sleep/Dormitory Bedroom	10	Athletic Service and Recreation facility	7
Daycare	25	Assembly Facilities (Conference, dining, gym)	100
Multi-use Cafeteria/Dining	100	Lounge-Public Assembly Lobbies	150
Exhibition Facilities (museum)	40	Storage	-
Locker room	2	Radio	25
Data Processing	1	Shop Facilities	15
Nurses Station, Surgery, Healthcare	200		

Bayesian Calibration of 5 parameters



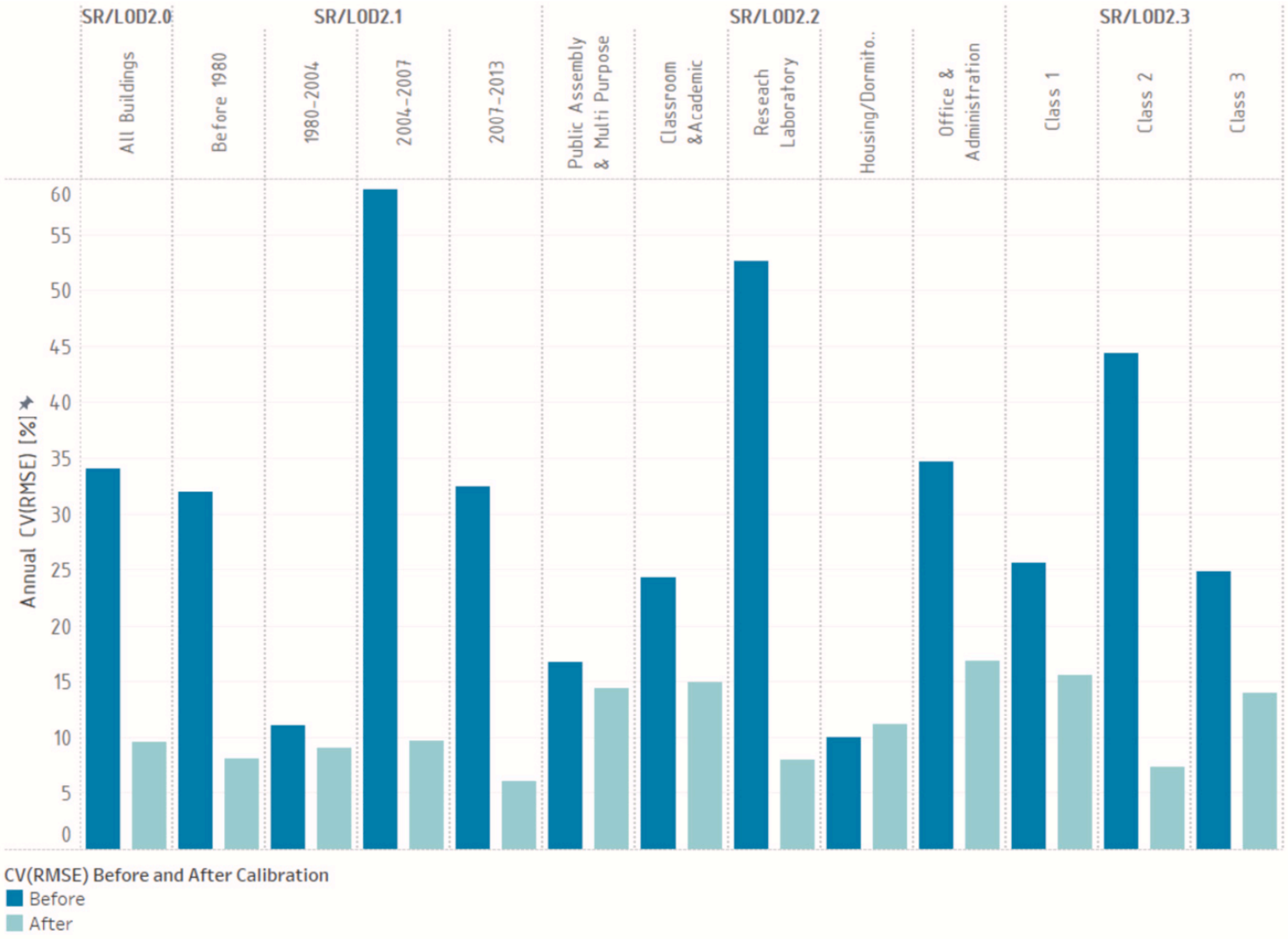
Bayesian Calibration of 5 parameters

Example for all buildings individually calibrated on annual data



Calibration generally improves the error

Overall building level calibration with annual data yielded the best results.



Use calibrated model in the UT Digital Twin to estimate impact of climate change —>
www.tinyurl.com/utwin

Break