# Model Predictive Control in Buildings: from Model-Centric to Data-Centric

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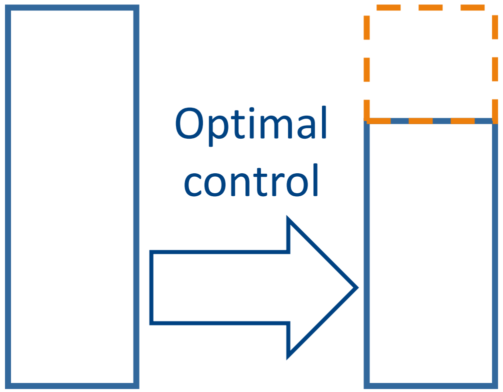
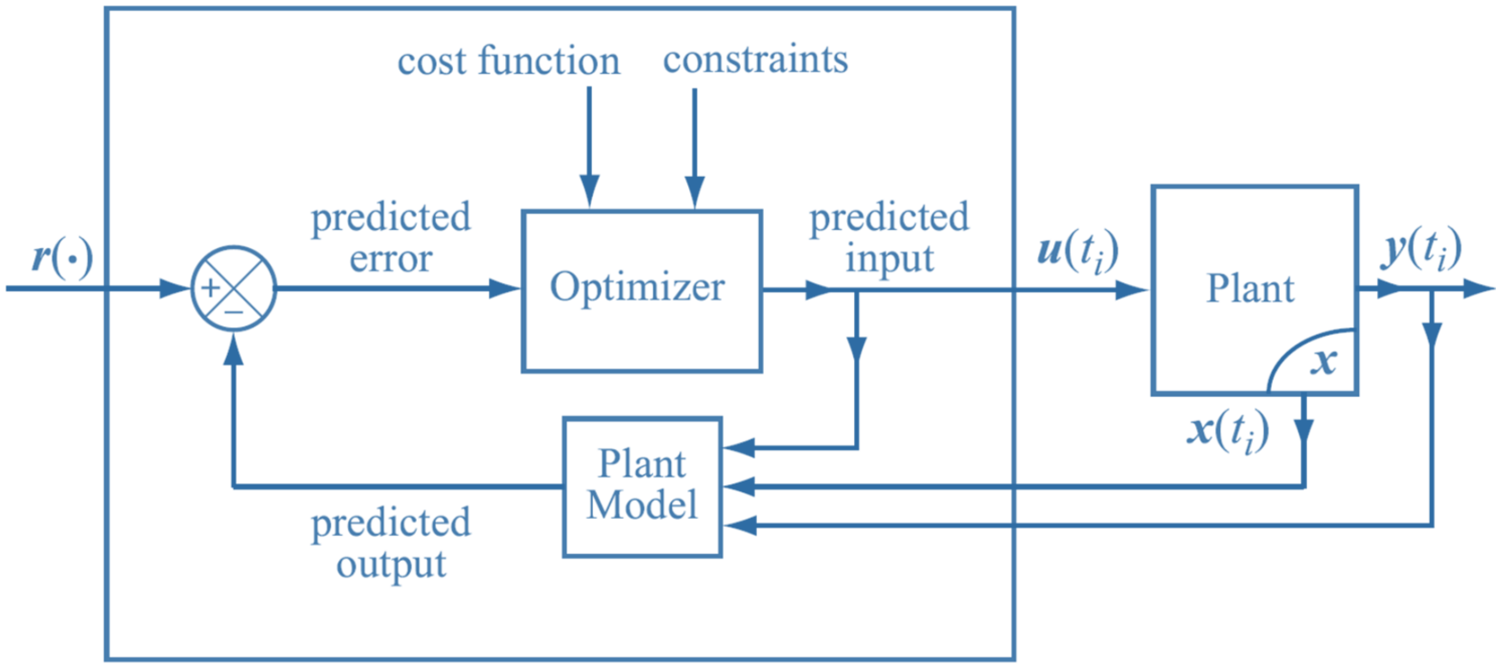
# The need of optimal control in buildings

Buildings contribute 30-40% global GHG emission and energy consumption, where ~90% is consumed in the operation phase

Buildings take up ~50% of electricity consumption in Singapore, where 50-70% goes to Air-conditioning & Mechanical Ventilation (ACMV) systems




Generally, ~30% of energy saving can be expected by applying optimal control (10-20% in the tropics)

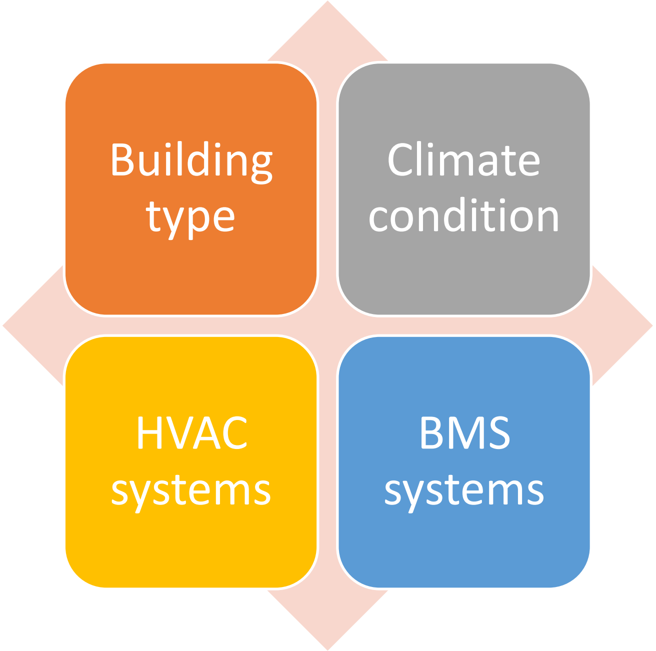


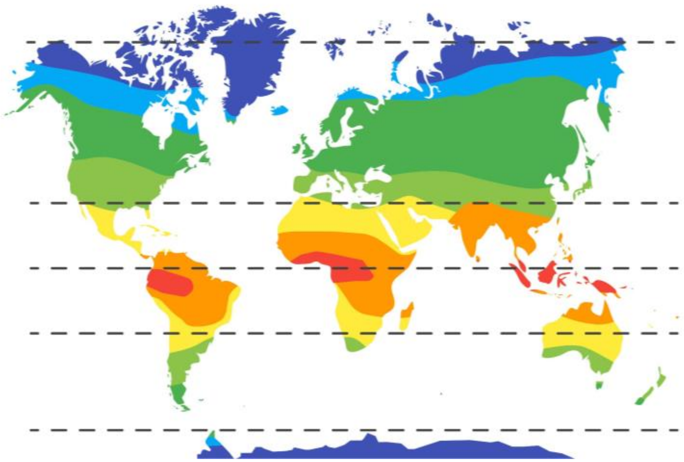

## Model predictive control ———— in buildings

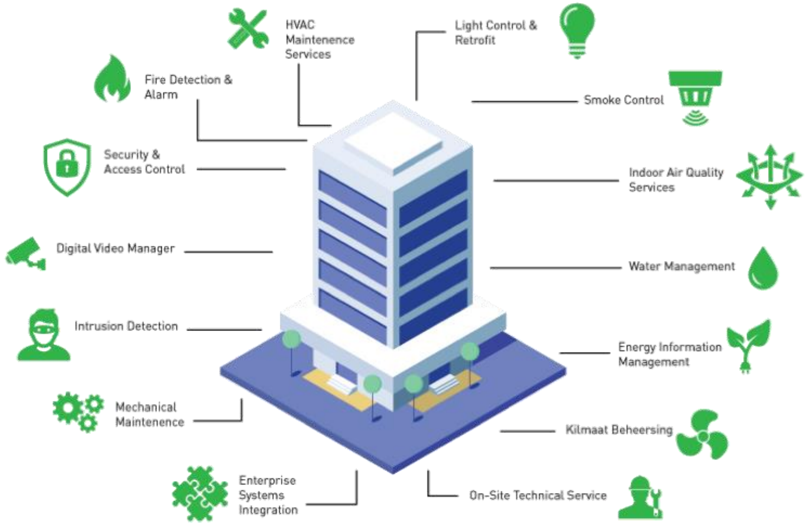
- ✓ Well-established optimal control framework
- ✓ Successfully implemented in places such as industrial process control

- Research since the 90s
- >70% studies were simulation
- >60% studies less than 5 zones
- Why?

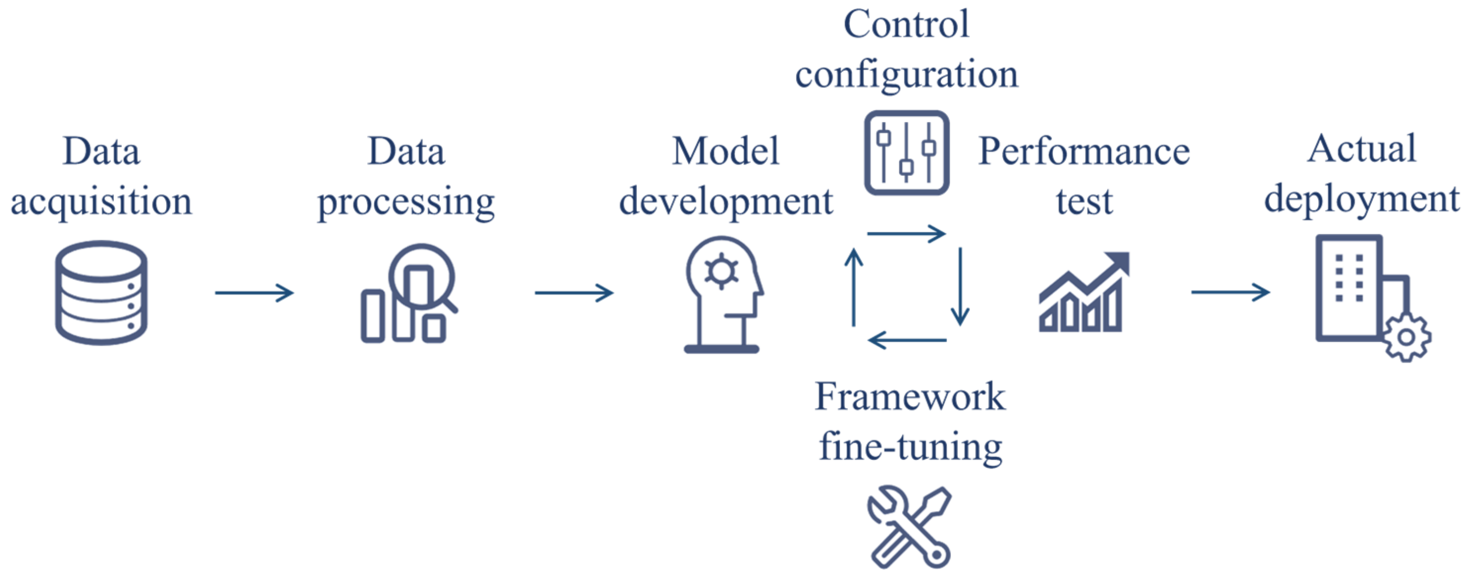
# Heterogeneity across buildings

# Model-centric/data-driven configuration procedure




- Work with the given data
- New models developed in each study
  - White/gray/black box models
- Expert-driven procedure to be repeated every time

x Ungeneralizable experimental results

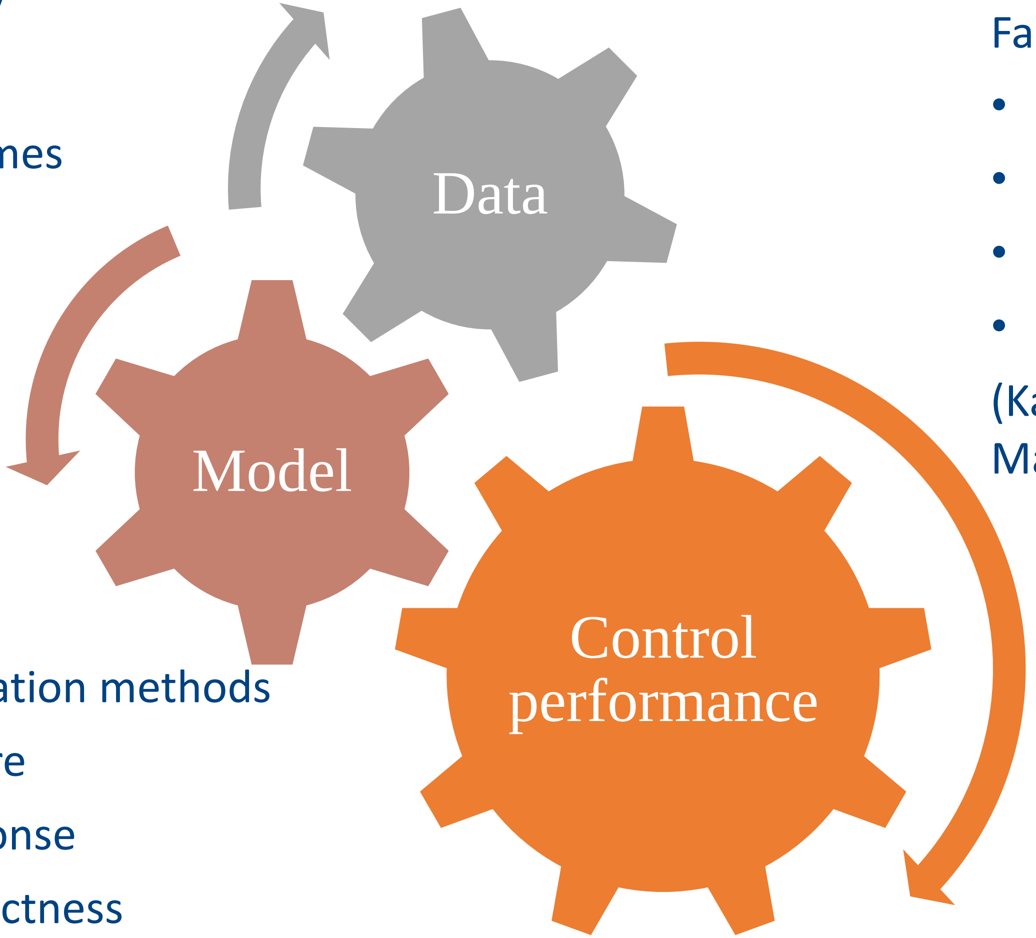
x Key data points missing, many unused

x Unpredictable implementation cost and control performance

# Unclear relationships between data, model, and control

Prediction accuracy

- Metrics
- Prediction schemes
- Testing data




Other model evaluation methods

- Physical structure
- Frequency response
- Parameter correctness

(Picard et al. 2017, Lin et al. 2012 , Reynders et al. 2014)

Unknown before implementation

Factors affecting the control performance

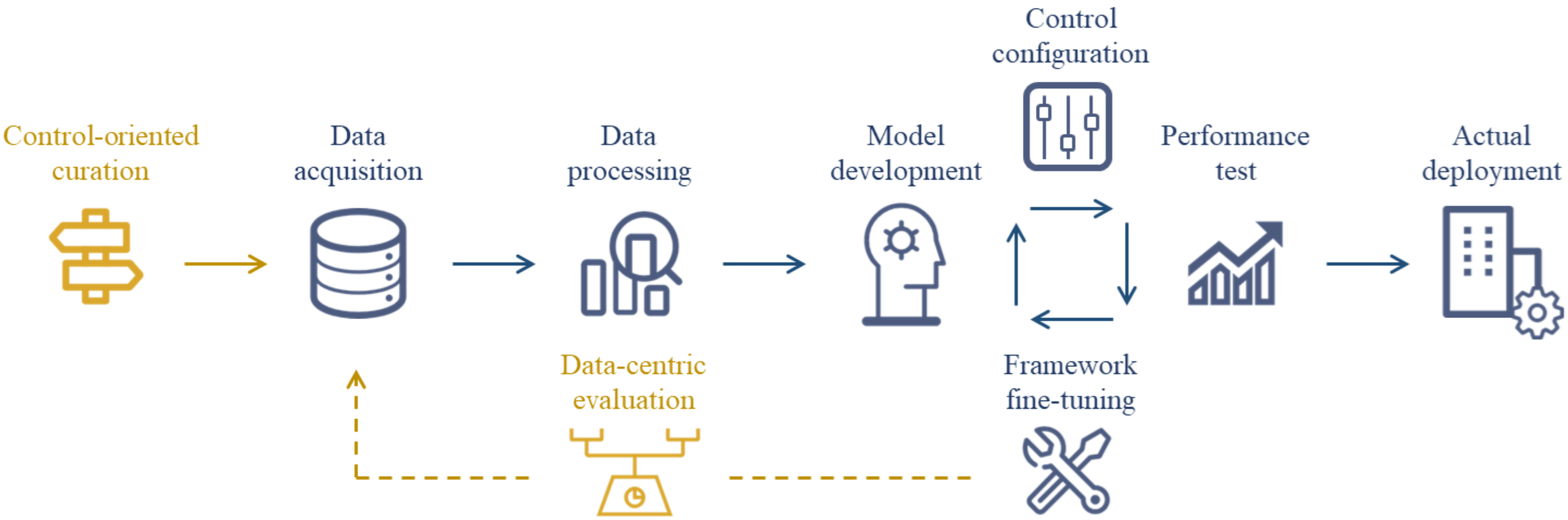
- Model quality
- Building characteristics
- Ambient conditions
- Control formulation

(Kavgic et al. 2015, Sturzenegger et al. 2015, Maasoumy et al. 2014, Ma et al. 2014)

Interrelated factors require explicit experiments to isolate the effect of data and model

*Buildings have potential, and data decides how much can be realized.*

# Data-centric MPC research framework




Control-oriented curation

- Data acquisition based on the need of control scenario

Data-centric evaluation

- Well-designed experiments conducted to support control-oriented curation for one kind of control scenario

# Virtual and actual testbed

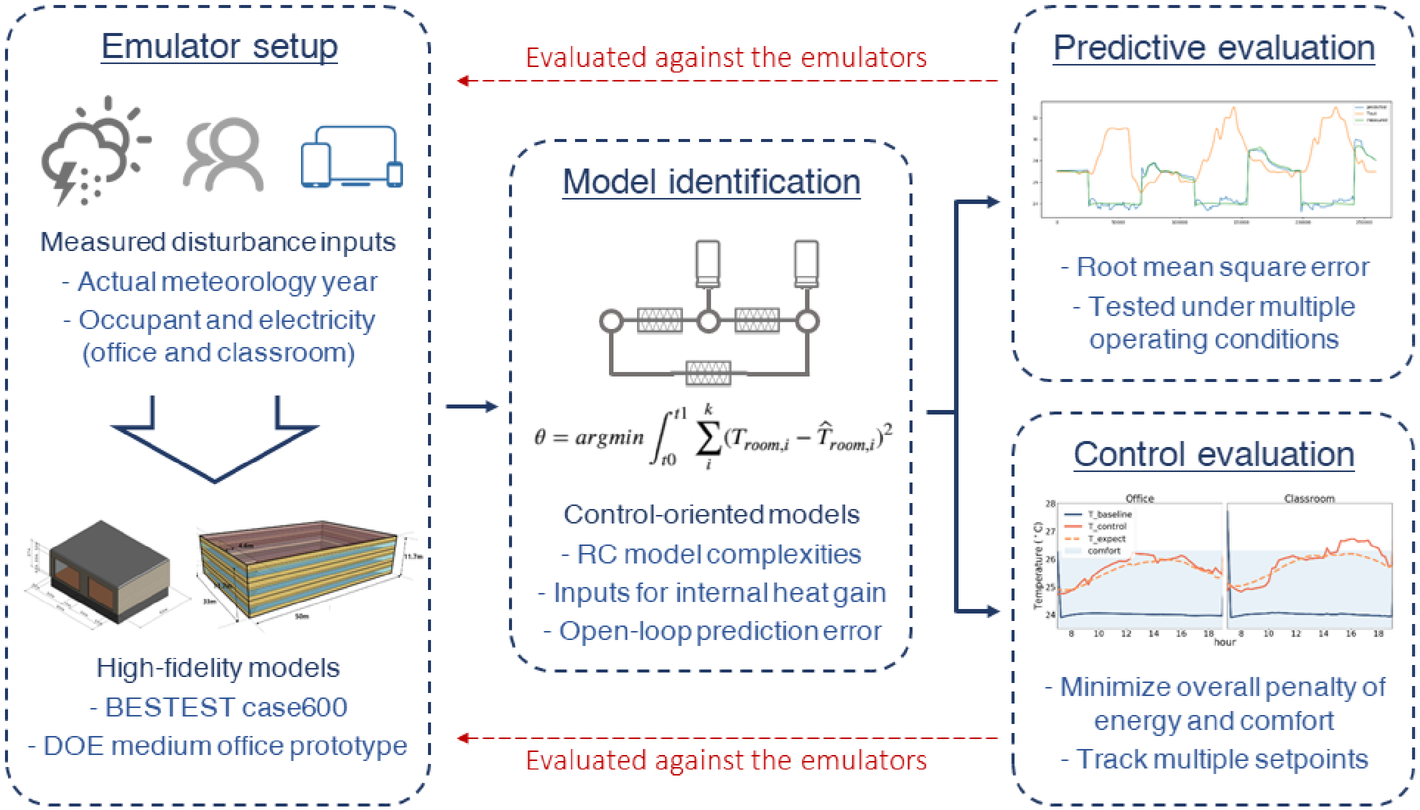
## Emulation model

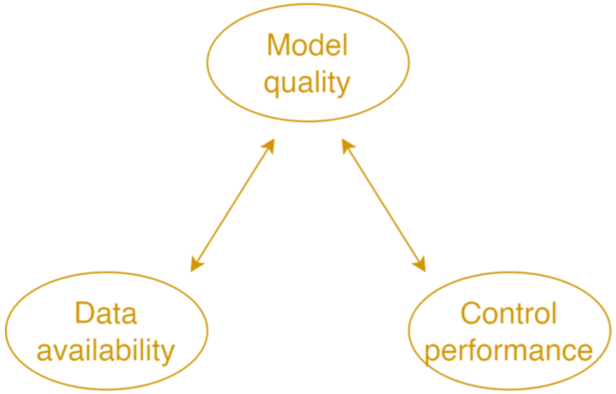
- Lower experimental costs
- Full flexibility of experimental design
- All variables attainable

## Actual building

- Real-world implementation
- Realistic disturbances
- Occupant in the loop

# Impact of occupant-related data




- How data inputs interact with model complexity and affect the performance through identification
- Occupant-related data as the primary focus

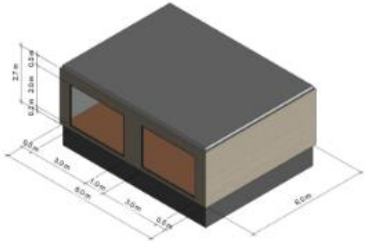
# Emulator configurations

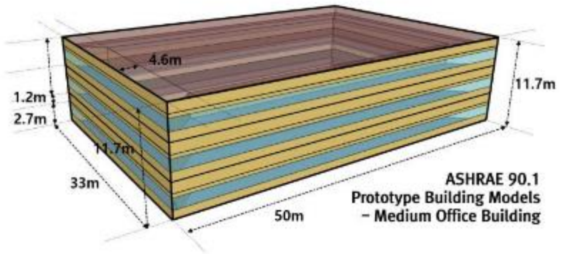
**Single-zone experiment**

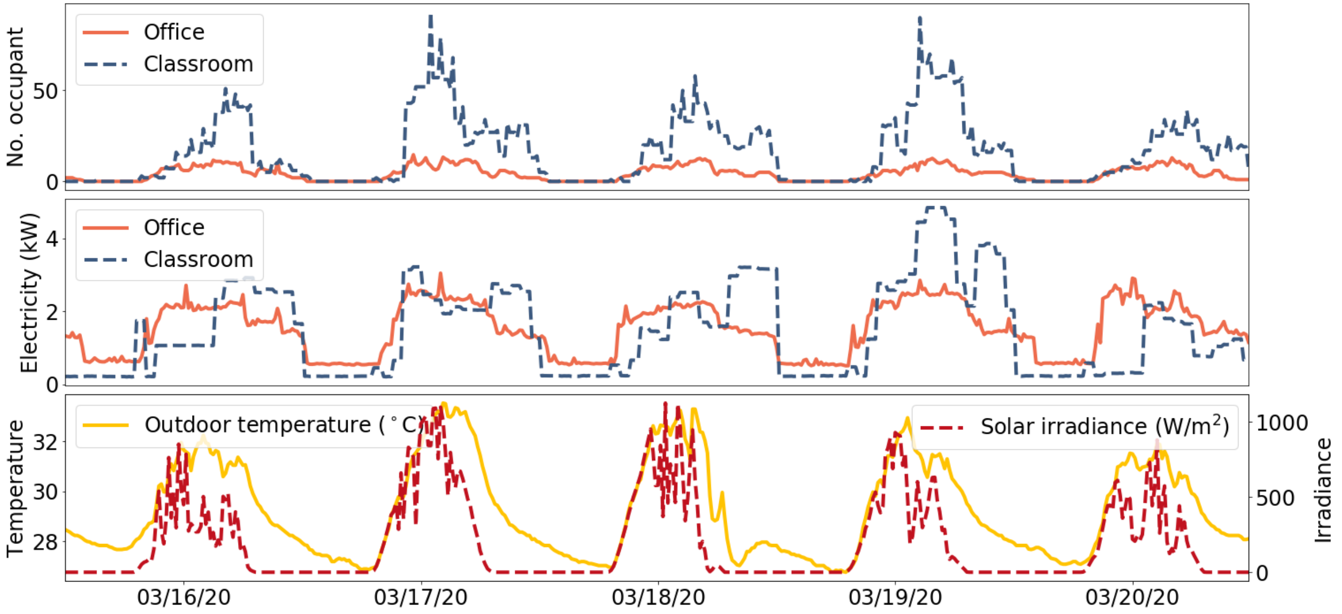
- BESTEST Case 600
- Fan coil unit with PI local control
- No. occupant and electricity load from an actual office and classroom

**Multi-zone experiment**

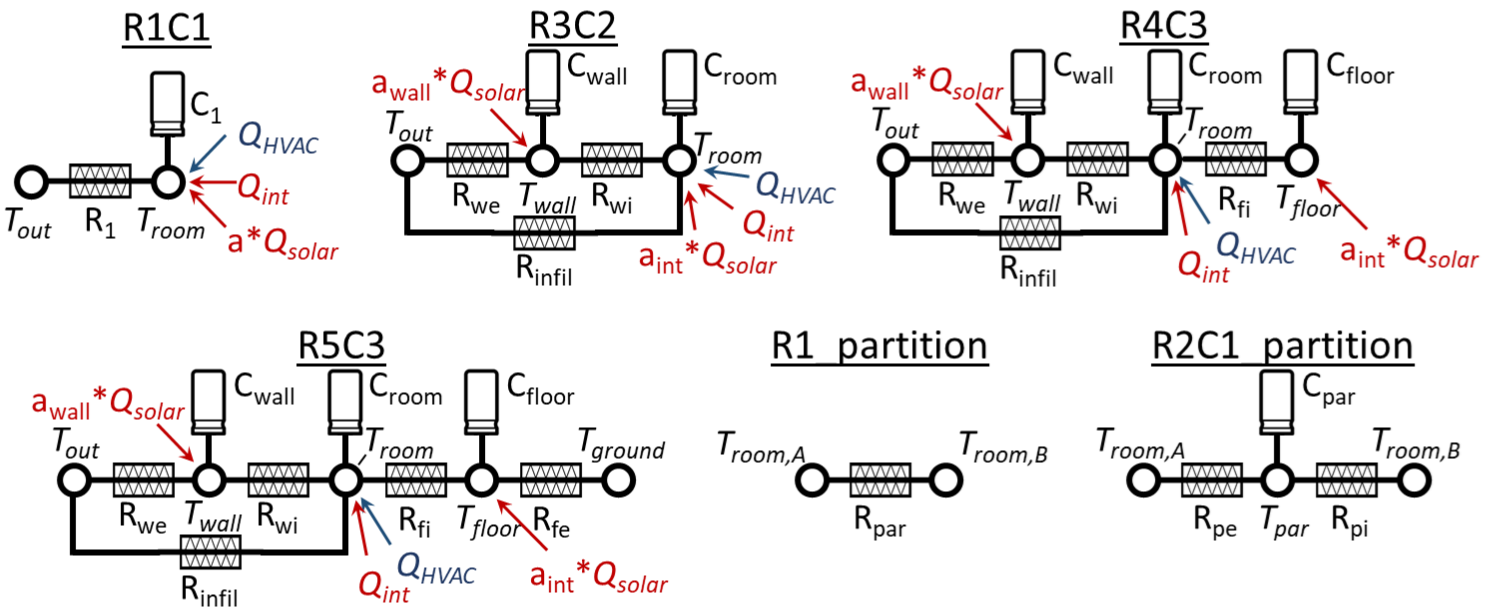
- A floor of DOE medium office (5 zones, VAV)
- Internal disturbance profiles randomly sampled for each room on each day





# RC model identification




- Increasing RC model complexity
- 6 alternative inputs for occupant-related disturbances
  - none, schedule, plug, $CO_2$, plug+$CO_2$, ideal
- Identified with the same dataset through non-linear programming

$$\theta = argmin \int_{t0}^{t1} \sum_{i}^{k} (T_{room,i} - \hat{T}_{room,i})^2 dt$$

$$s.t. \quad \hat{T}_{room} = f(x, u, d, \theta)$$

$$\theta^{lb} \leq \theta \leq \theta^{ub}$$

- Tested under different conditions (extrapolation capability)

# Control performance evaluation

Two control tasks designed for comprehensive evaluation

1. Typical MPC task of balancing energy and thermal comfort
2. Simpler setpoint tracking to examine the control capability of RC models

$$J = \int_{t_0}^{t_0+30min} \sum_{i}^{k} \left( q_u (m_{flow,i})^2 + q_t (PMV_i)^2 \right) dt$$

$$\begin{aligned} s.t. \quad & 0 \leq m_{flow,i} \leq m_{flow,norm} \\ & -0.5 \leq PMV_i \leq 0.5 \end{aligned}$$


$$J = \int_{t_0}^{t_0+30min} \sum_{i}^{k} (T_{room,i} - T_{setpoint,i})^2 dt$$

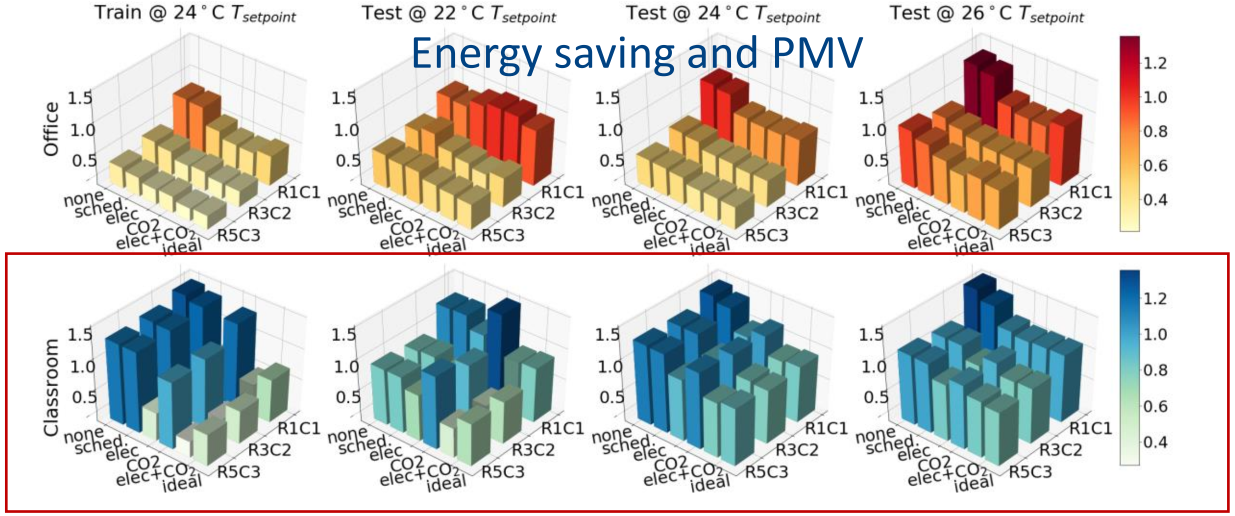
$$s.t. \quad 0 \leq m_{flow,i} \leq m_{flow,cap}$$

# Impact of internal disturbance data

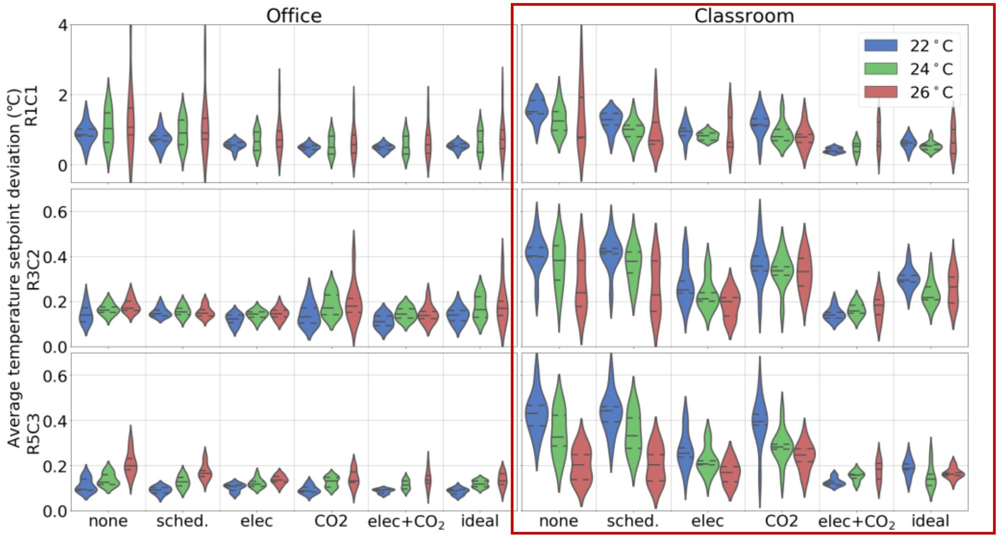
- More impactful in the classroom scenarios than in offices
    - Larger portion of internal gain, higher variability, and more irregular patterns
- The performance of balancing energy and comfort not affected
    - Deviations corrected every step by the state feedback
- Design schedule is typically sufficient for offices
    - Model complexity as a more important factor

Average RMSE of alternative RC models

Energy saving and PMV

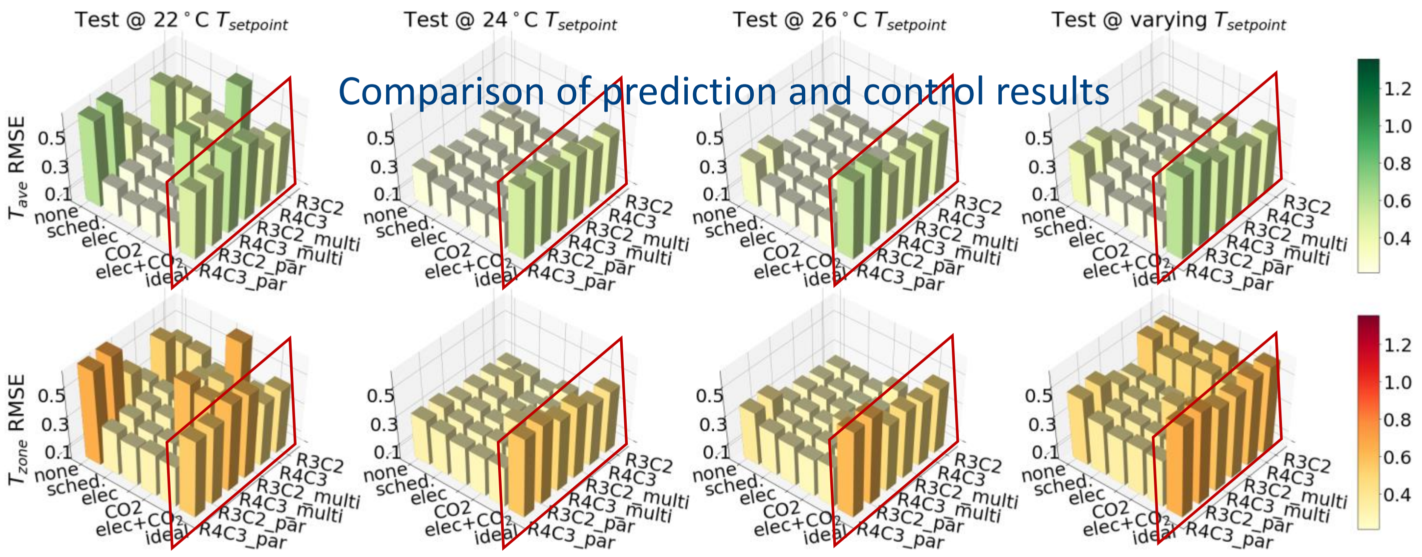


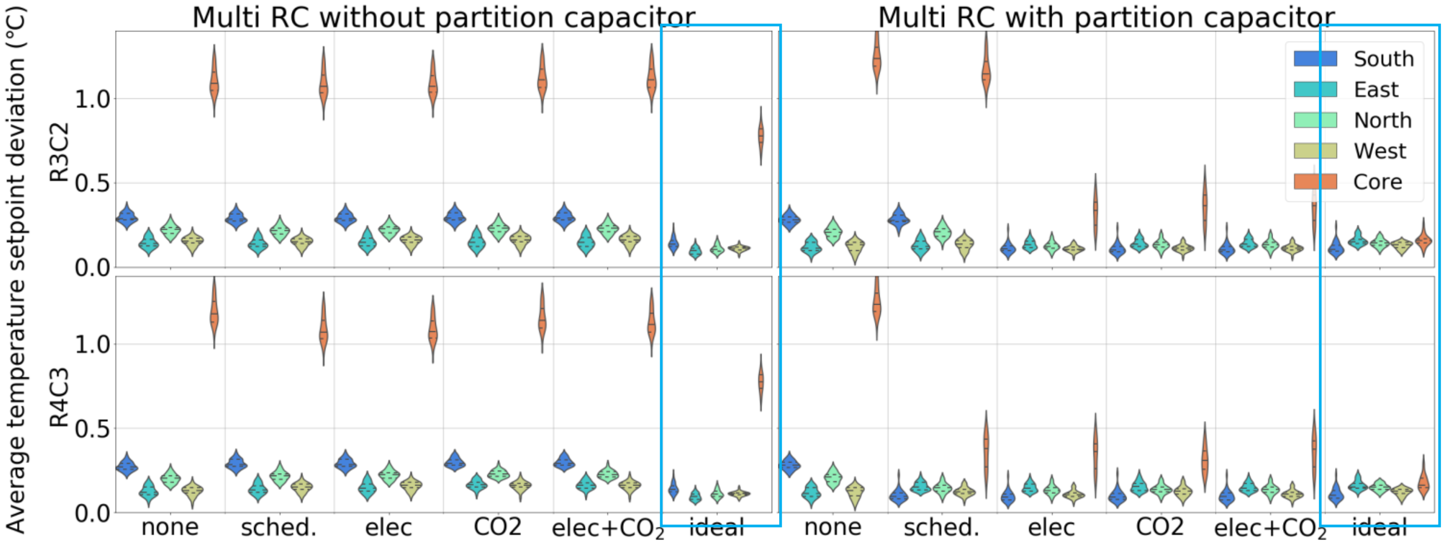

Temperature deviations in control



# Mismatch between model and control performance

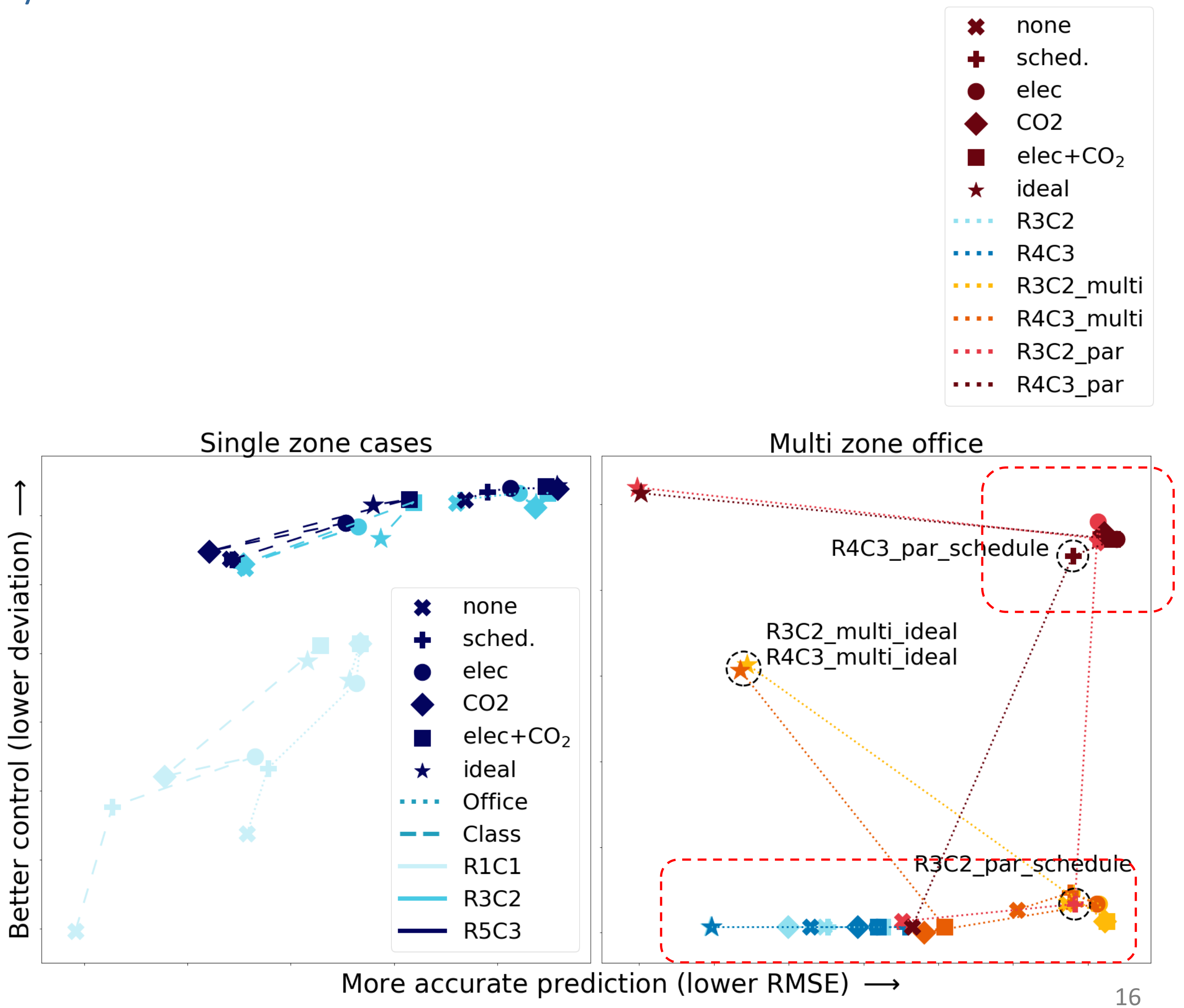
- Different story about the quality of RC model with ideal input
  - Same conclusion with other evaluation metrics tested
- The identification underestimate partition capacitor for lower RMSE
  - Not detected by prediction tests
  - Prevented by the ideal input as a constraint of optimization
- The predictive and control capability of control-oriented models should be carefully examined



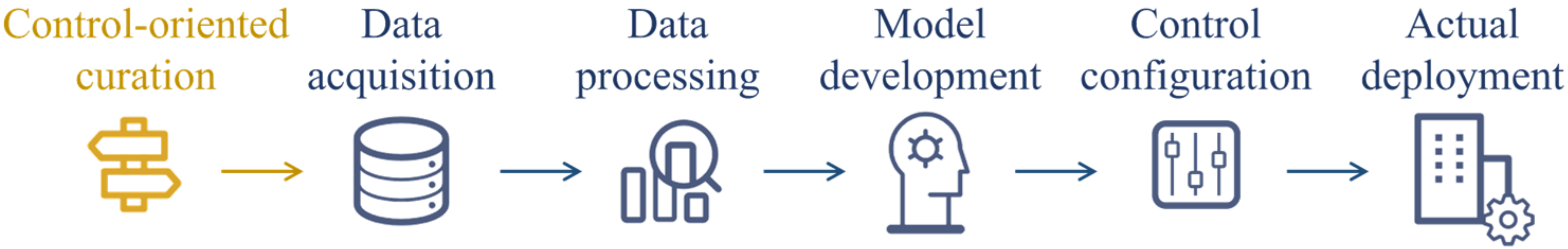



# Model adequacy and data informativeness

- Better control is the ultimate goal
  - Unknown in practice until field implementation
  - Lack of robust indicator
- Model adequacy and data informativeness are both essential
  - More informative data generally reduce prediction error
  - Only led to better control with adequate model
  - Critical physical component should be preserved (partition capacitor here)



# Data-centric configuration procedure



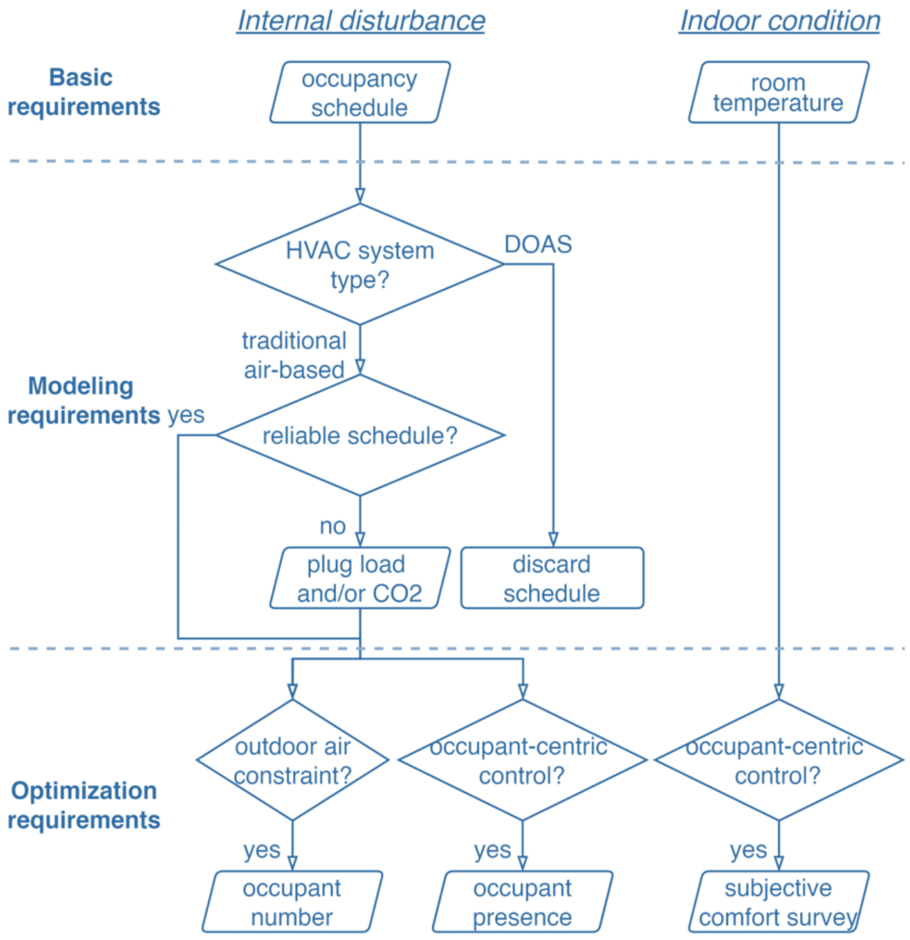

- Systematically acquire data according to the control scenario
- Performance decided by data availability
- Smoother model and control configuration
- Reproducible for a certain type of buildings

# Control-oriented data curation

Control-oriented curation

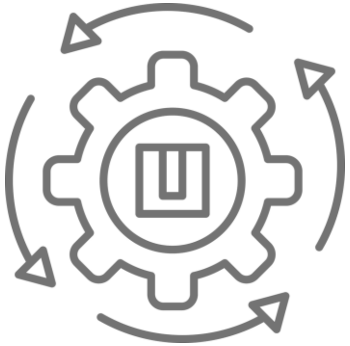
- Data acquisition based on the need of control scenario

- Established relationship between data and performance



# Ongoing work

Absolute quantification of data informativeness



Automation of active data acquisition

*Thank you!*