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Towards Reliable Digital Twin Applications in Buildings: a Data Perspective

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Digital twins in the building industry

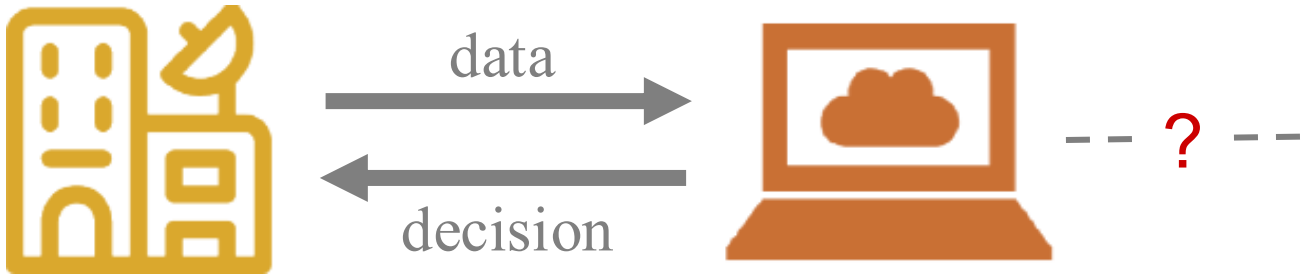
Existing digital twin solutions

- 3D BIM model
- Data acquisition
- Data visualization
- Energy prediction & evaluation

❖ Energy conservation services V.S. scalable solution/product

Digital twins in the building industry

Digital twins: Computational models that replicate the behaviour of real-world systems, conducting virtual experiments in unseen scenarios and supporting decision-making



How to guarantee the reliability before implementation?

Real-time data exchange

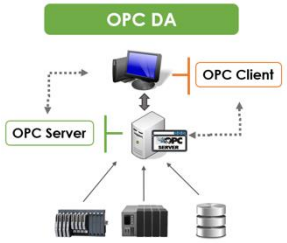
Web-based data acquisition and exchange

SIEMENS

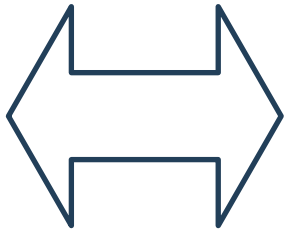
Honeywell

Schneider Electric

BOSCH

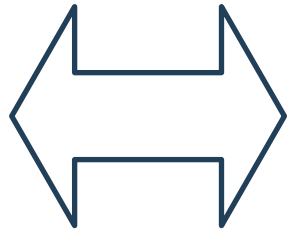


ASHRAE BACnet™

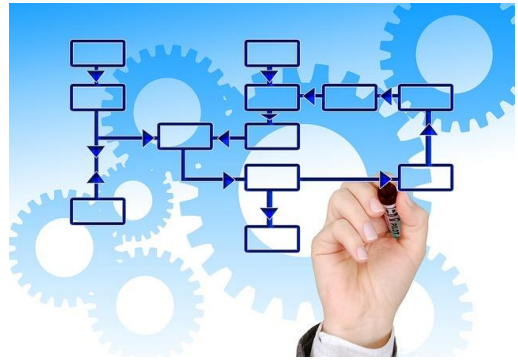


Interfaces

Central data server



Restful API

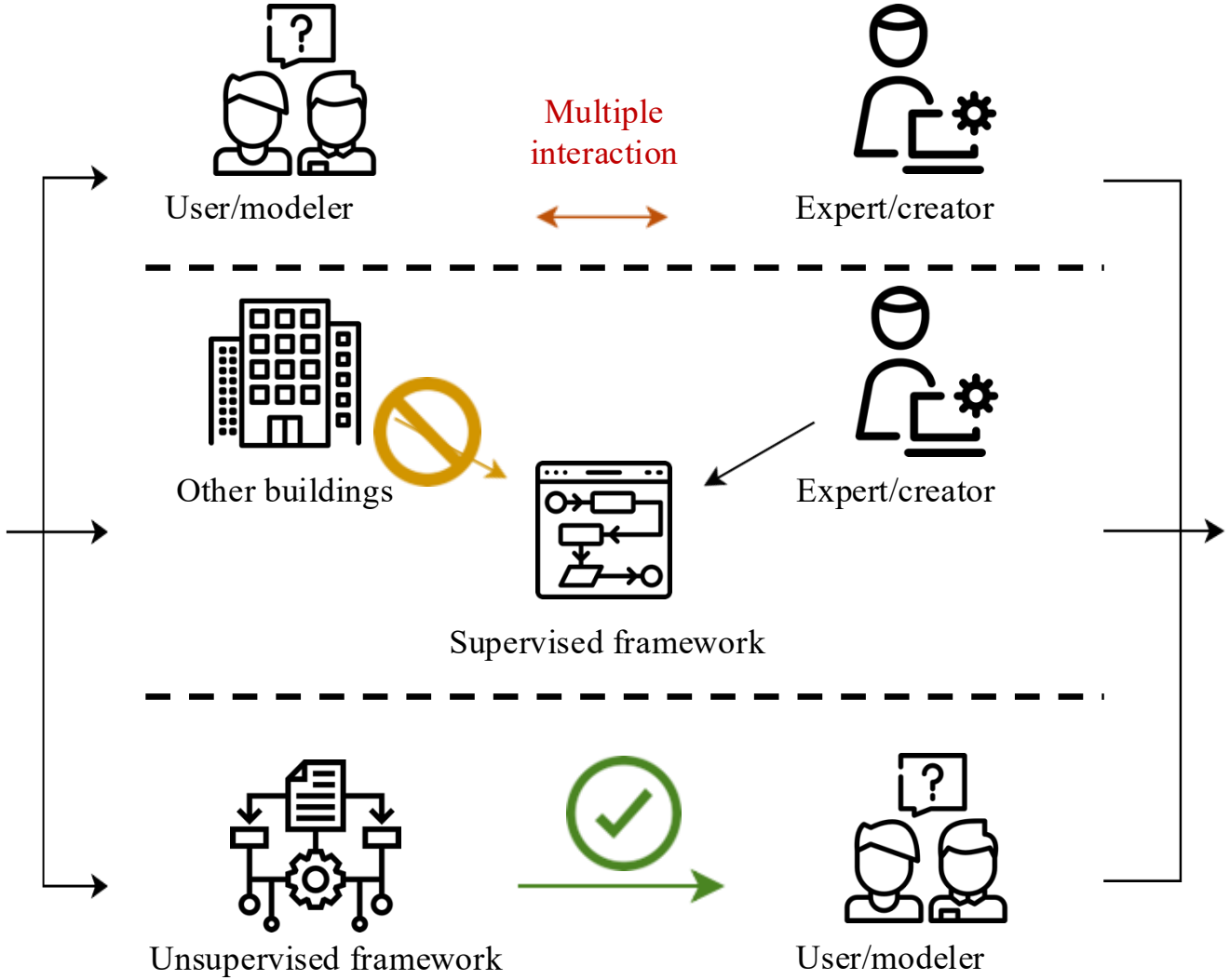


Applications

Buildings and building management systems

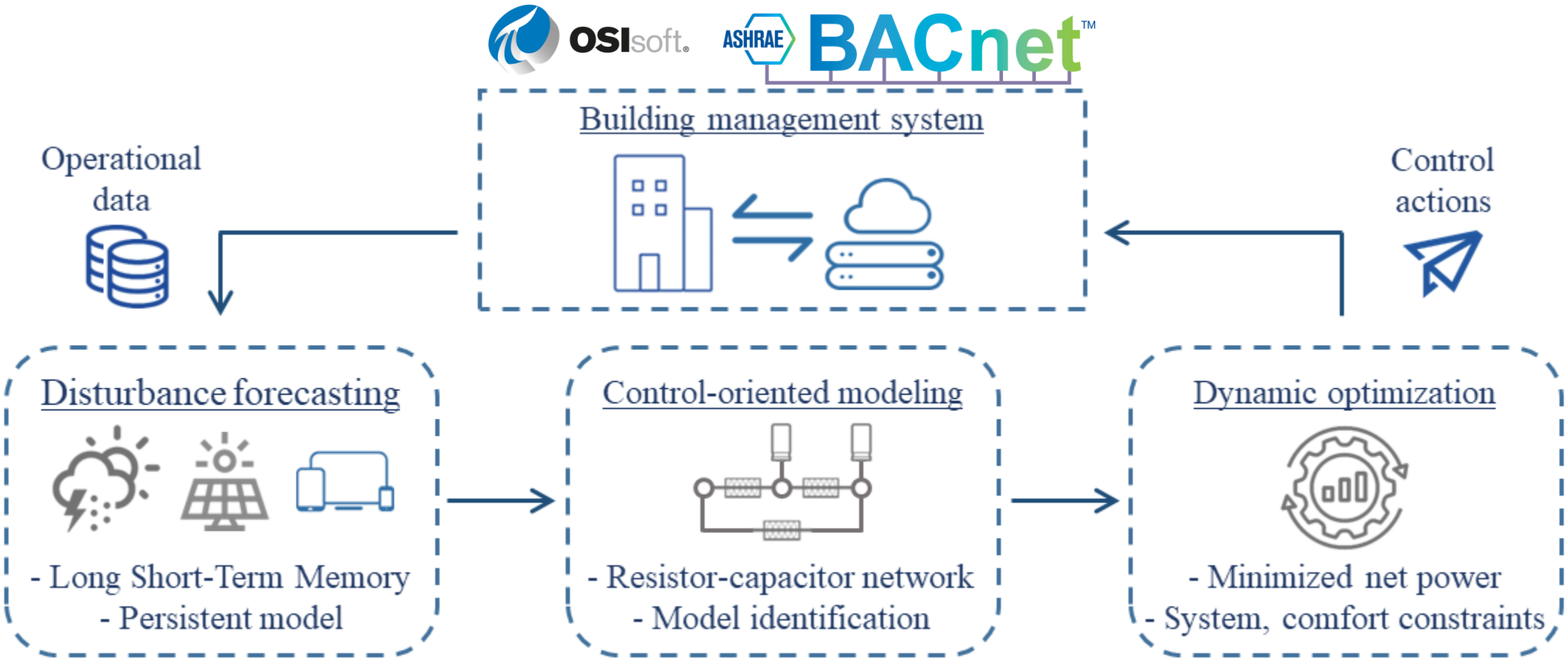
Automated tag recognition by unsupervised learning

Diversified point tags

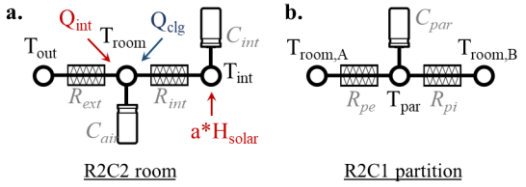


Machine/human-readable tags

Buildings as living labs



inputs: time, history
lookback: 120min
horizon: 60min



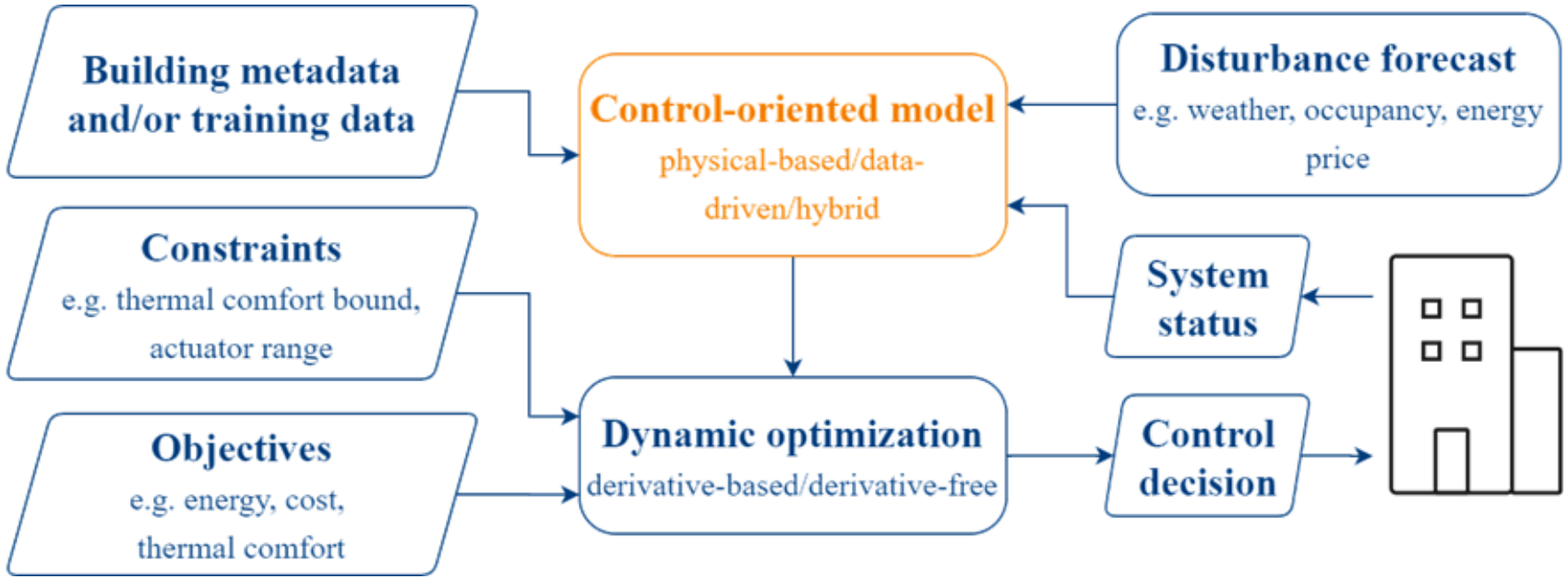
$$J = \int_{t_0}^{t_0+60min} (P_{PV} - P_{total})^2 + q_c \sum_{i}^{k} (T_{RM,i} - 26)^2$$

$$s.t. \quad \dot{V}_{SA,min,i} \le \dot{V}_{SA,i} \le \dot{V}_{SA,max,i}$$

$$25 \le T_{RM,i} \le 28$$

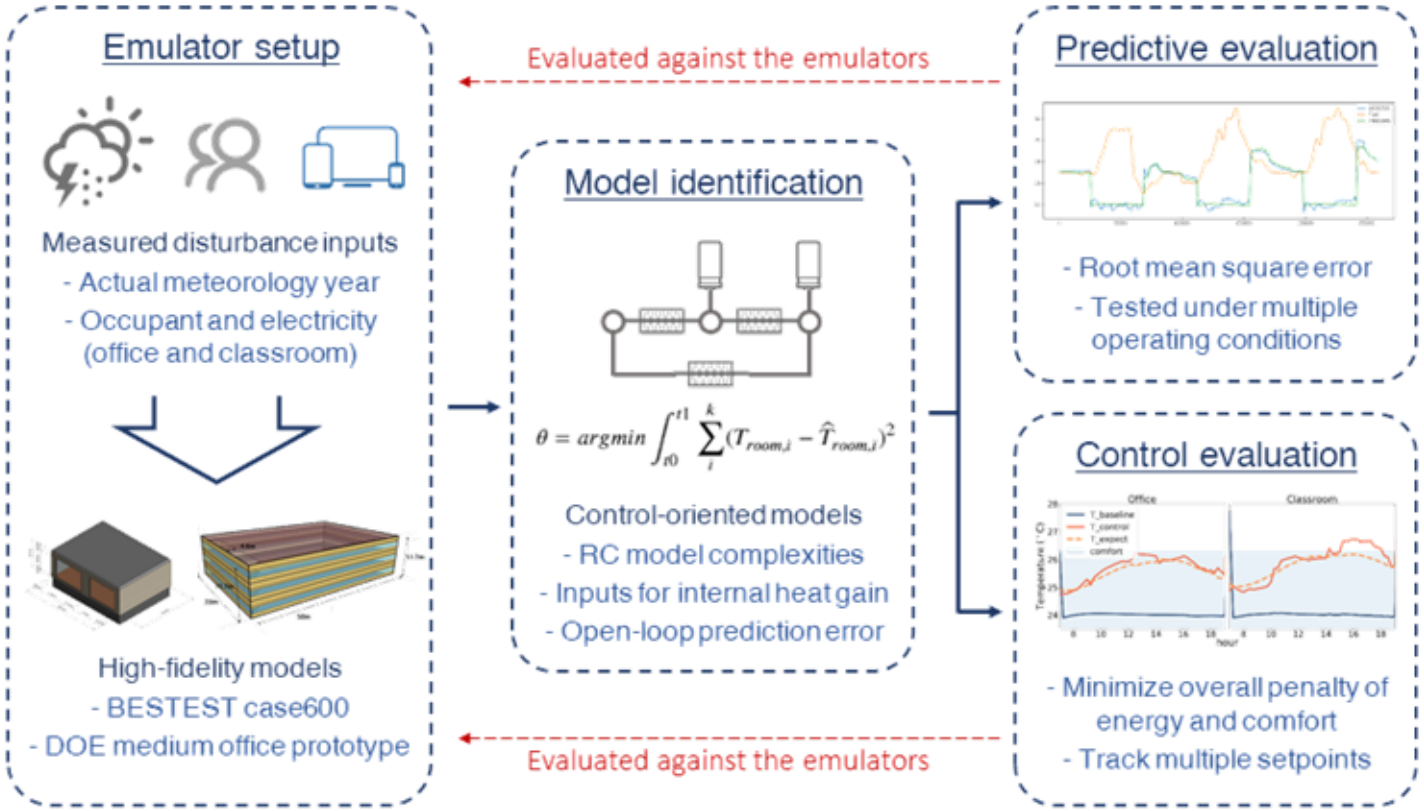
Impact of data on identification and optimization

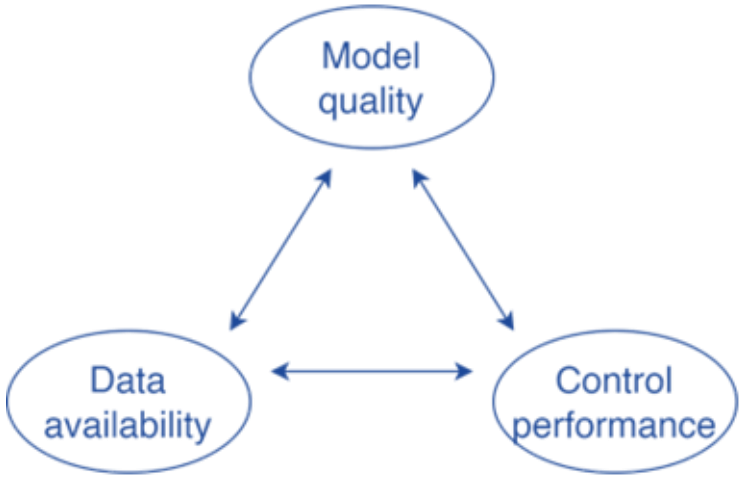
MPC as an example



- Three main processes: disturbance forecast, control-oriented model, dynamic optimization
- Control-oriented model is the cornerstone, data required for model establishment
- Up to 70% of total effort is attributed to model construction and calibration

Experimental design





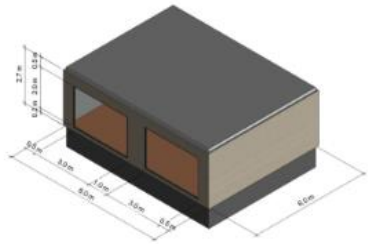
The relationship between data, model, and control?

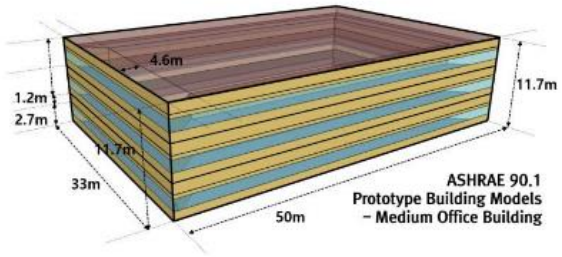
- Virtual and actual testbeds
- Series of factorial experiments
- Quantified relationship

Emulator configurations

Single-zone experiment

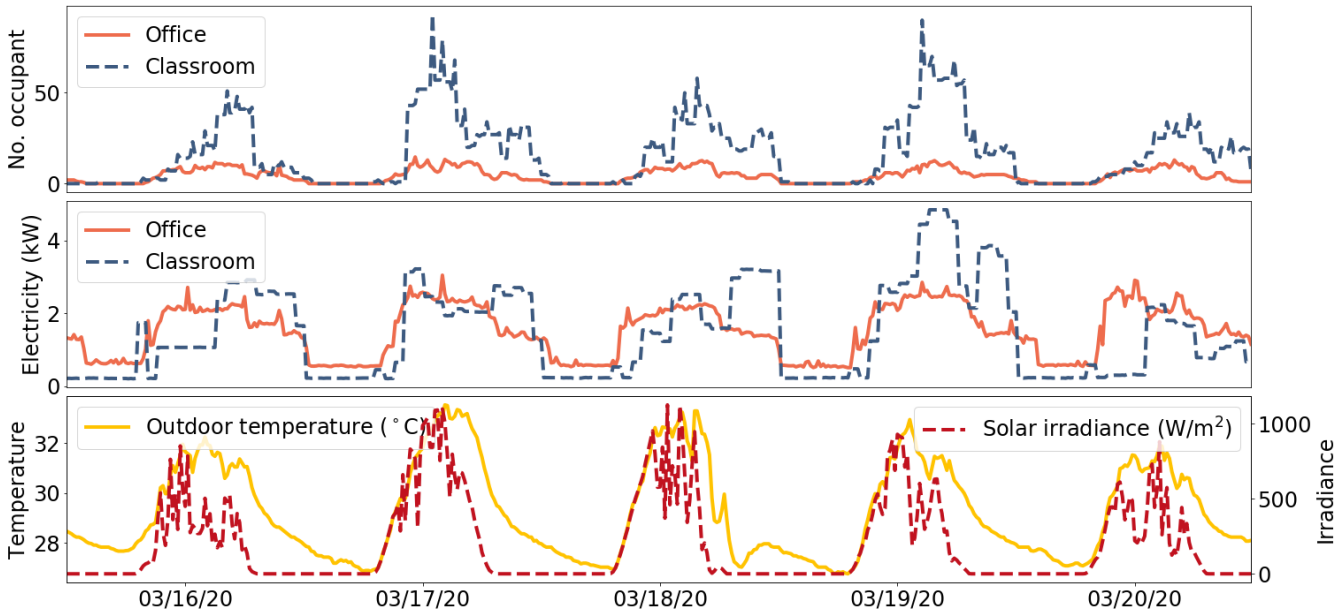
- BESTEST Case 600
- Fan coil unit with PI local control
- No. occupant and electricity load from an actual office and classroom



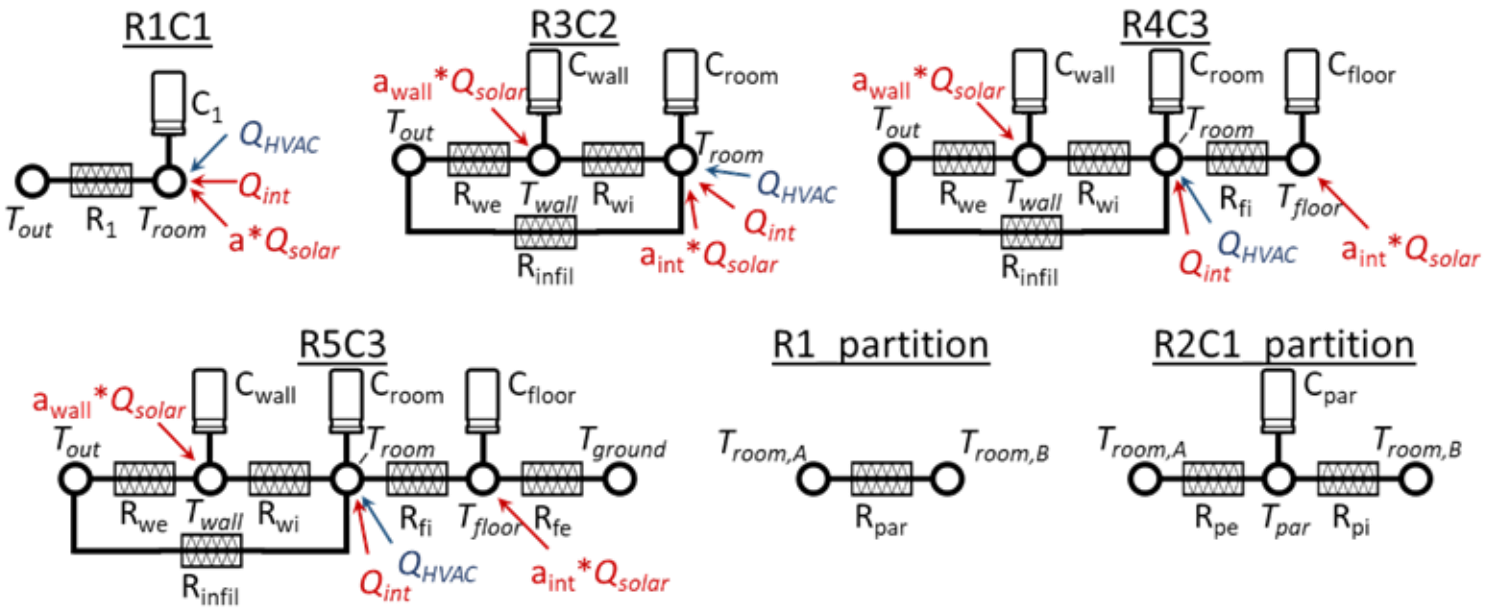


Multi-zone experiment

- A floor of DOE medium office
- Internal disturbance profiles randomly sampled for each room on each day



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

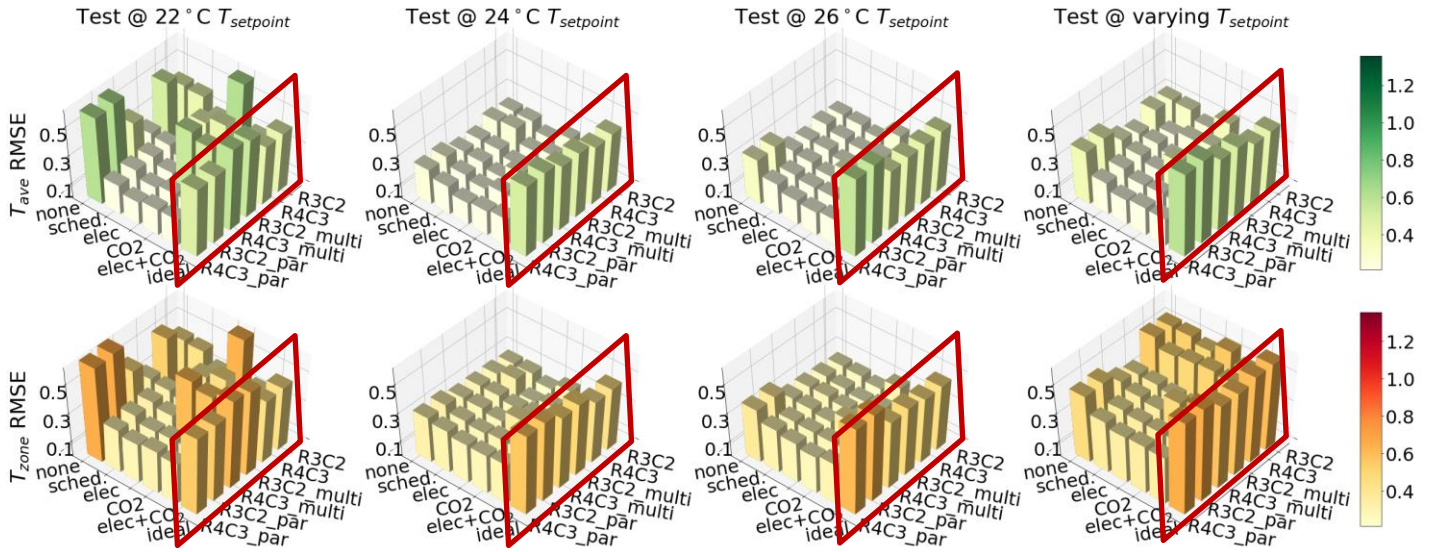
$$\theta = argmin \int_{t0}^{t1} \sum_{i}^{k} (T_{room,i} - \hat{T}_{room,i})^2 dt$$

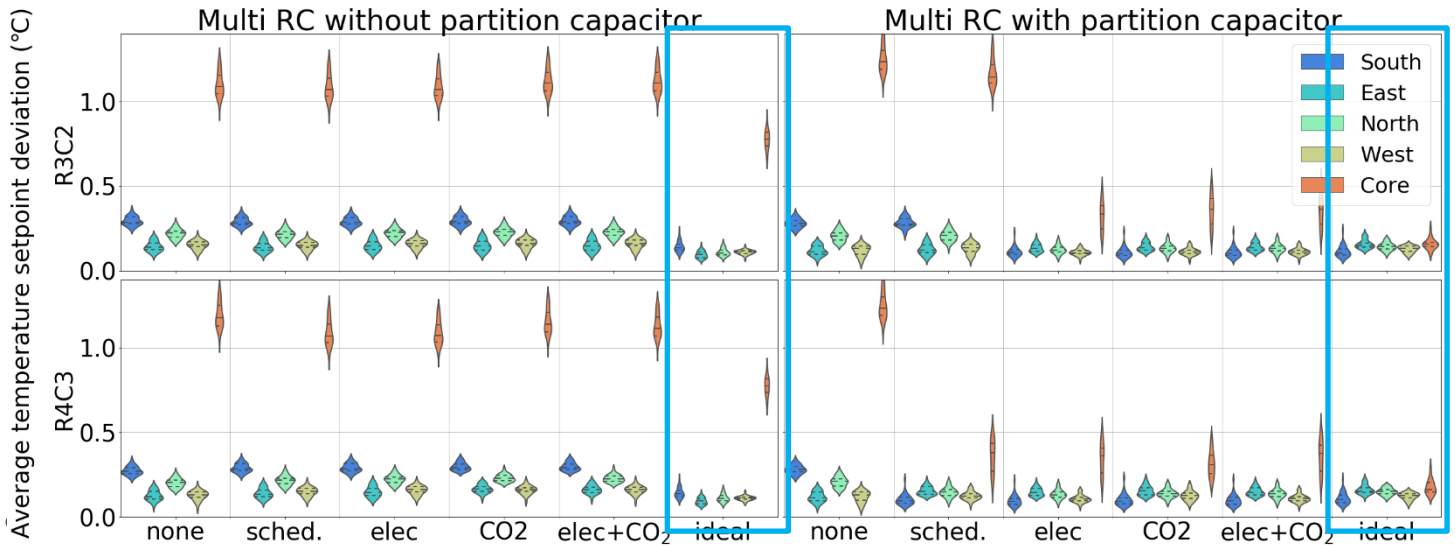
$$s.t. \quad \hat{T}_{room} = f(x, u, d, \theta)$$

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

- Tested under different conditions (extrapolation capability)

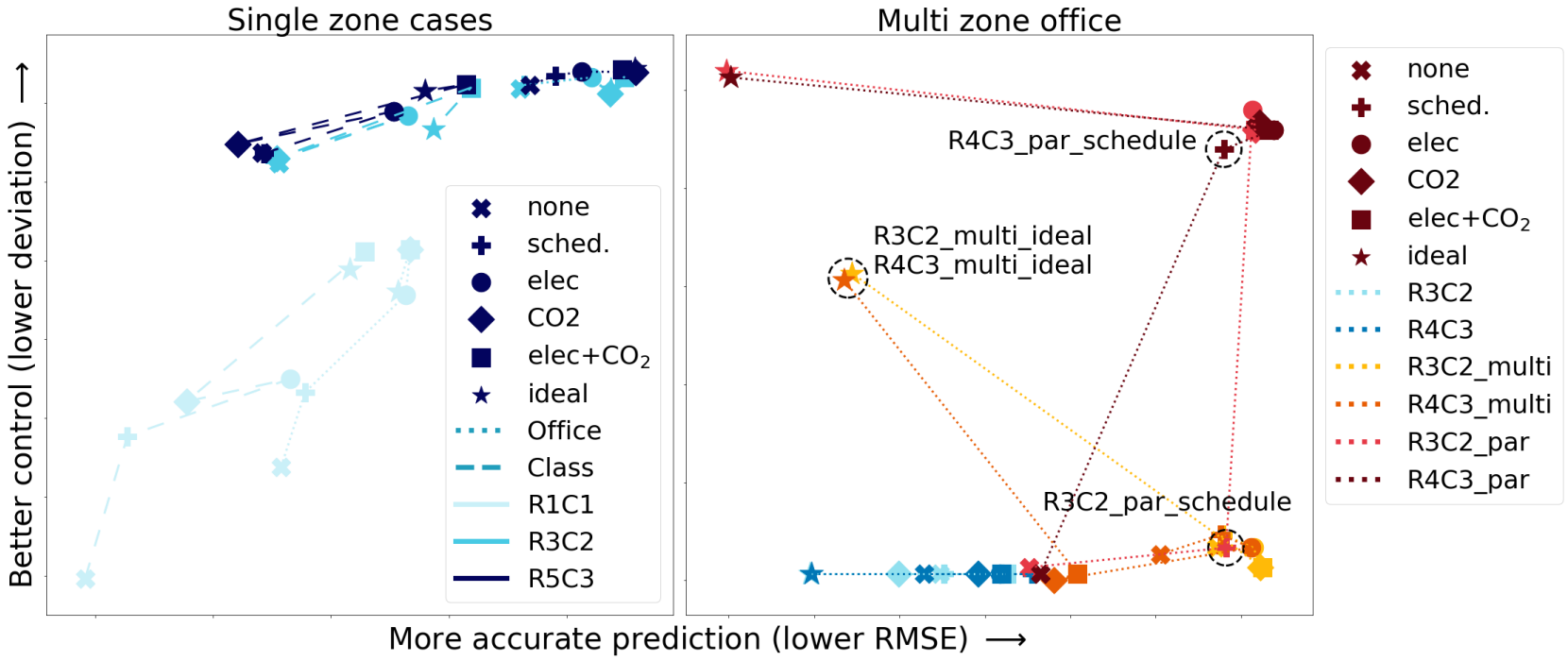
Multi-zone results





- The identification underestimate partition capacitor for lower RMSE
  - NOT detected by prediction tests
  - Yielded control deviations
- More representative input resulted in larger prediction error but better control

Summary of results

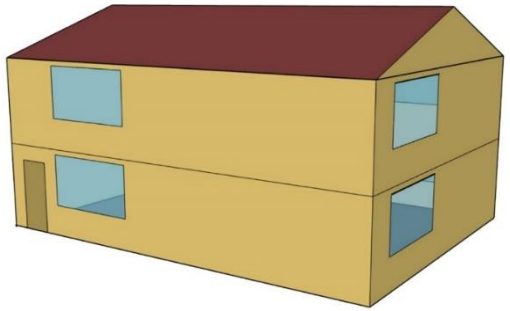


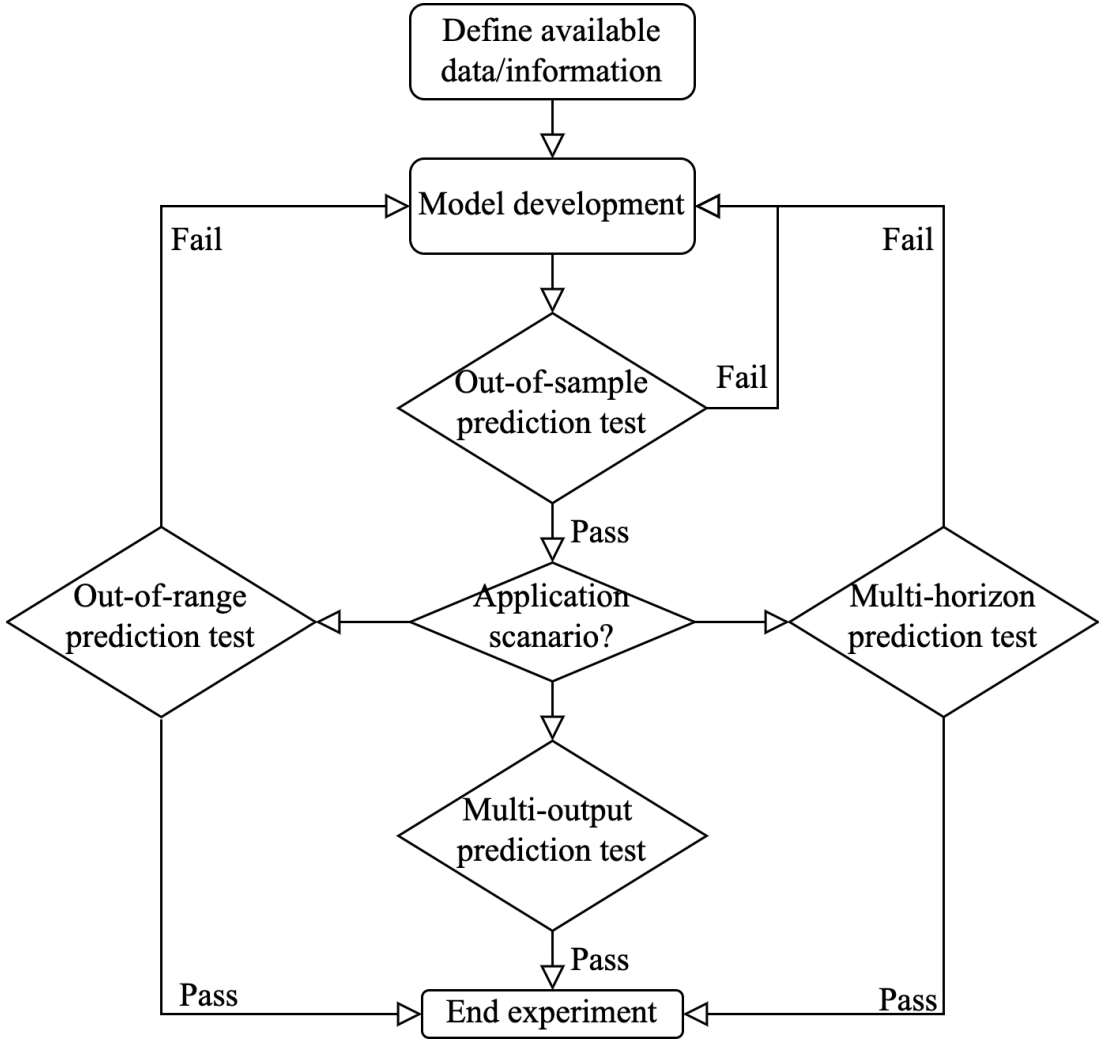
- Lower prediction error means better control for simple dynamics
- For complex buildings, only led to better control with adequate model
- Critical physical component should be preserved (partition capacitor here)

Co-simulation for every building is impractical

Prediction/extrapolation capability is the key

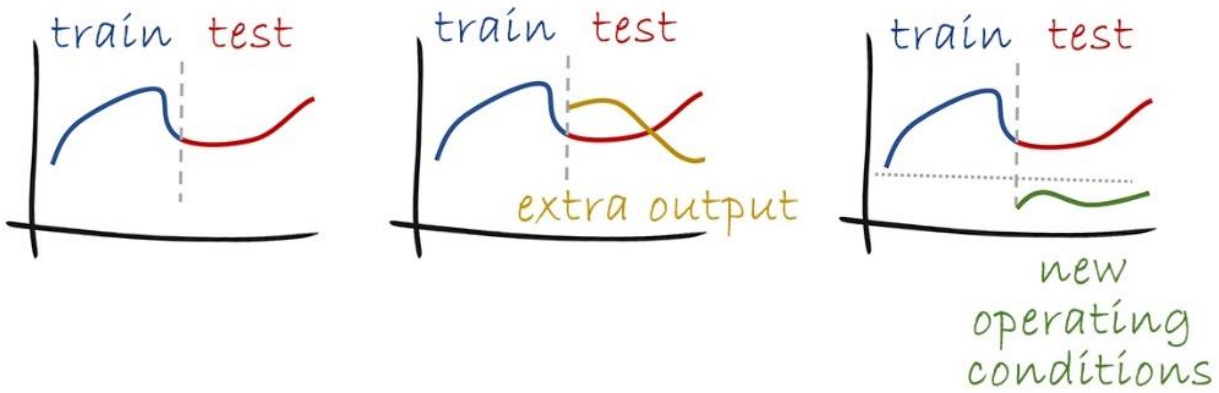
- A testing framework for digital twins
  - Based on a virtual testbed
  - Emulator as the actual building, higher-fidelity than its twins
  - Reproducibility
    - Single-family house/small office
    - Different climate zone (IECC envelope)

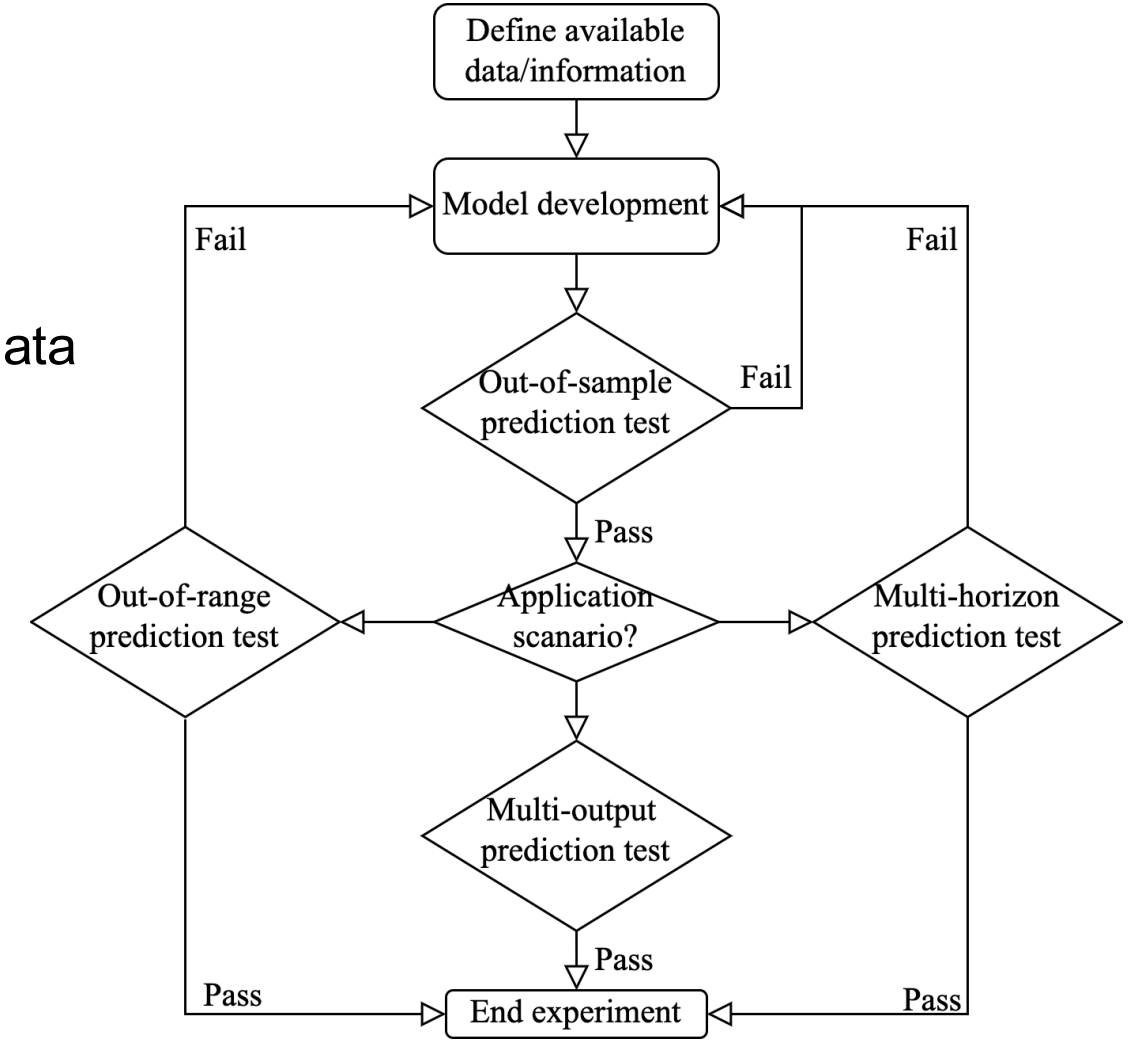




Prediction/extrapolation capability is the key

- Out of sample as a must
- Optional more demanding tests, e.g. multi-horizon/resolution
- Ability to generate application-oriented testing data (python script)

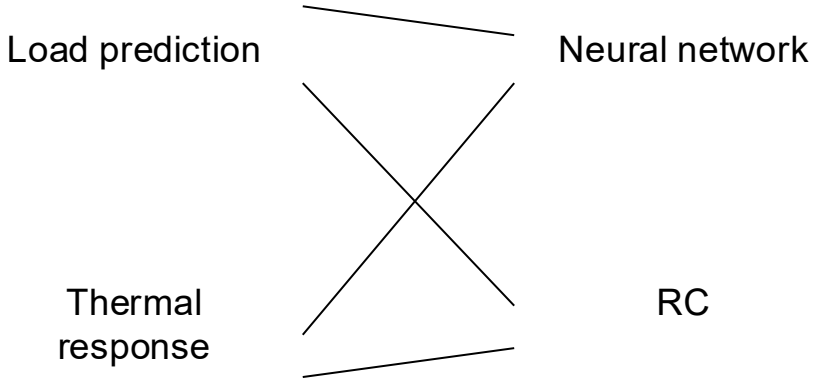


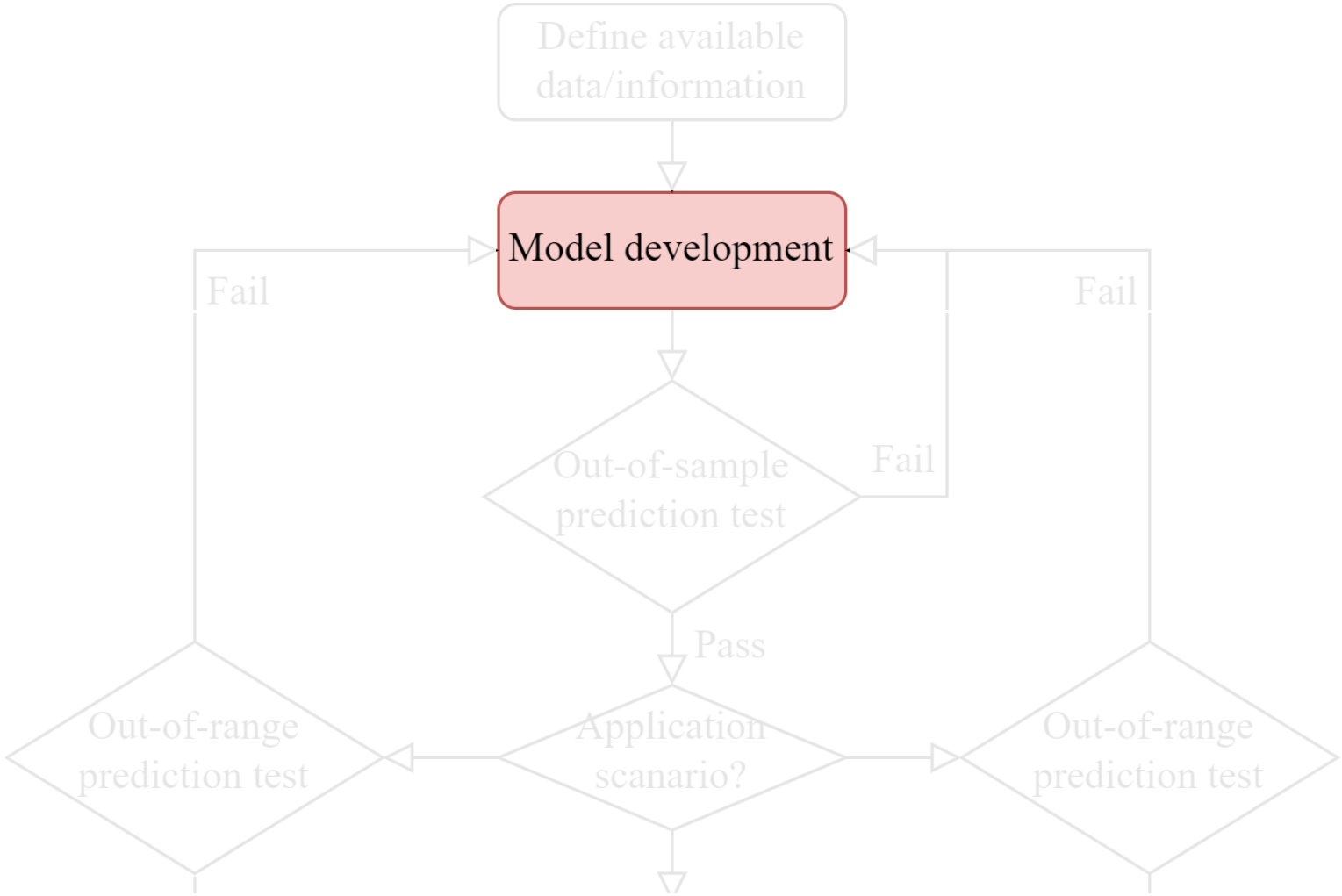


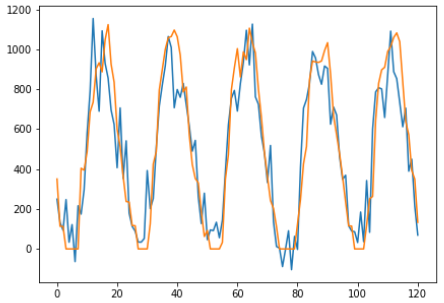
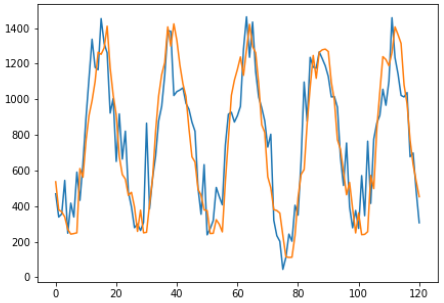
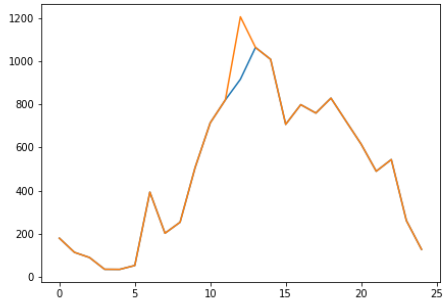
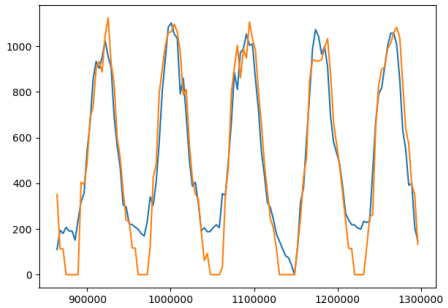
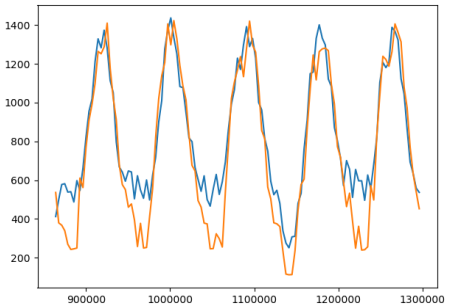
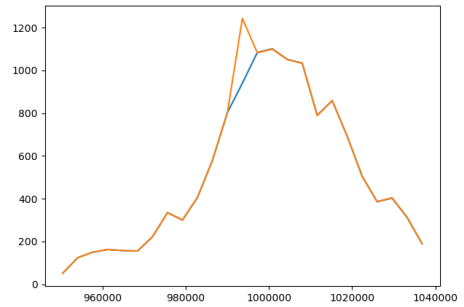
How “physical” does the model need to be?

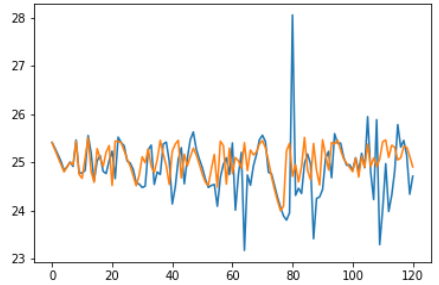
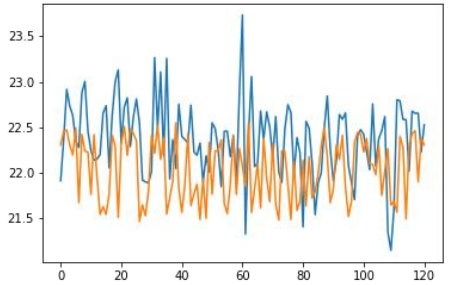
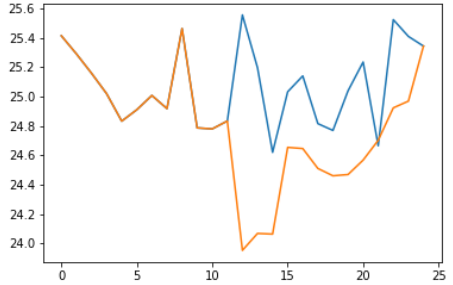
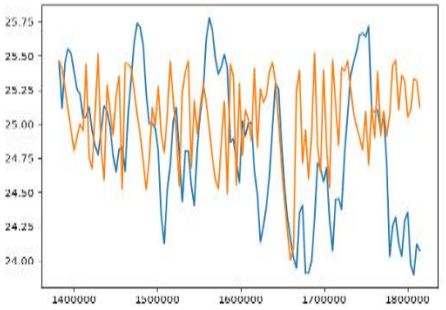
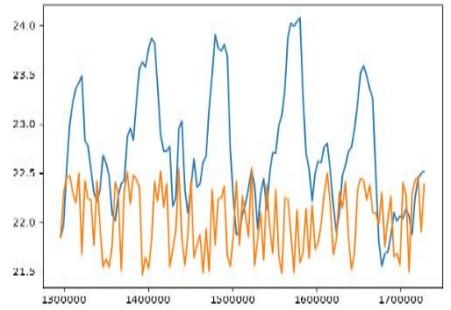
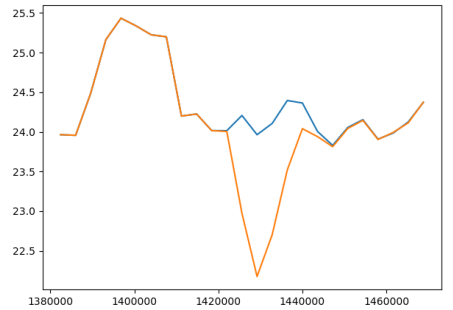
White/grey/black box

An example of pre-cooling





Load prediction	Out of sample test	Out of range test	Physical test
Neural network	 30.6%	 23.5%	 Failed
RC	 23.9%	 20.2%	 Failed

Thermal response	Out of sample test	Out of range test	Physical test
Neural network	 2.57%	 2.81%	 Failed
RC	 2.55%	 4.47%	 Passed

Discussion

- Physical systems set the upper bound of energy performance, data availability determines the actual performance
- Traditional error-based evaluation could be misleading
- Data as the fuel: towards data-centric digital twins (strategic data acquisition for training and testing)
- Model developments need to cater for the downstream application (predictive scenario)

Thank you!

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