Karlsruher Institut für Technologie

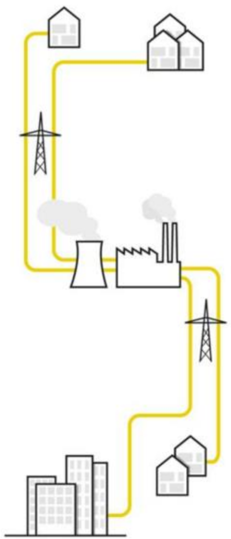
November, 12th, 2021

[Annex 79 ST 2] **PhD Forum, Moritz Frahm, KIT, Germany**

Model Predictive Control in Buildings: Accounting for Uncertainties of Weather and Occupancy Behavior Forecasts on Demand-Side-Management

Institut für Automation und angewandte Informatik

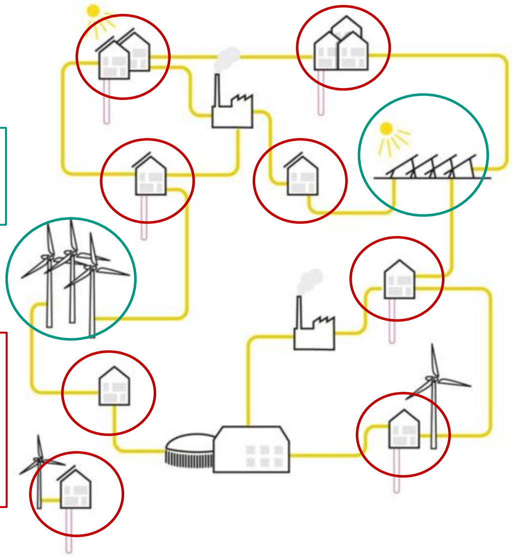
Introduction
Motivation for Demand-Side-Management (DSM)



Centralized energy system*

Including renew-able energies

More difficult to balance energy generation and demand



De-centralized energy system*

Energy consumption related to OB

40 % of primary energy consumed in buildings

Significant potential for load shifting

For future, more sustainable, but de-centralized energy systems, we need: (i) DSM in building control, and (ii) considering the occupants' demands

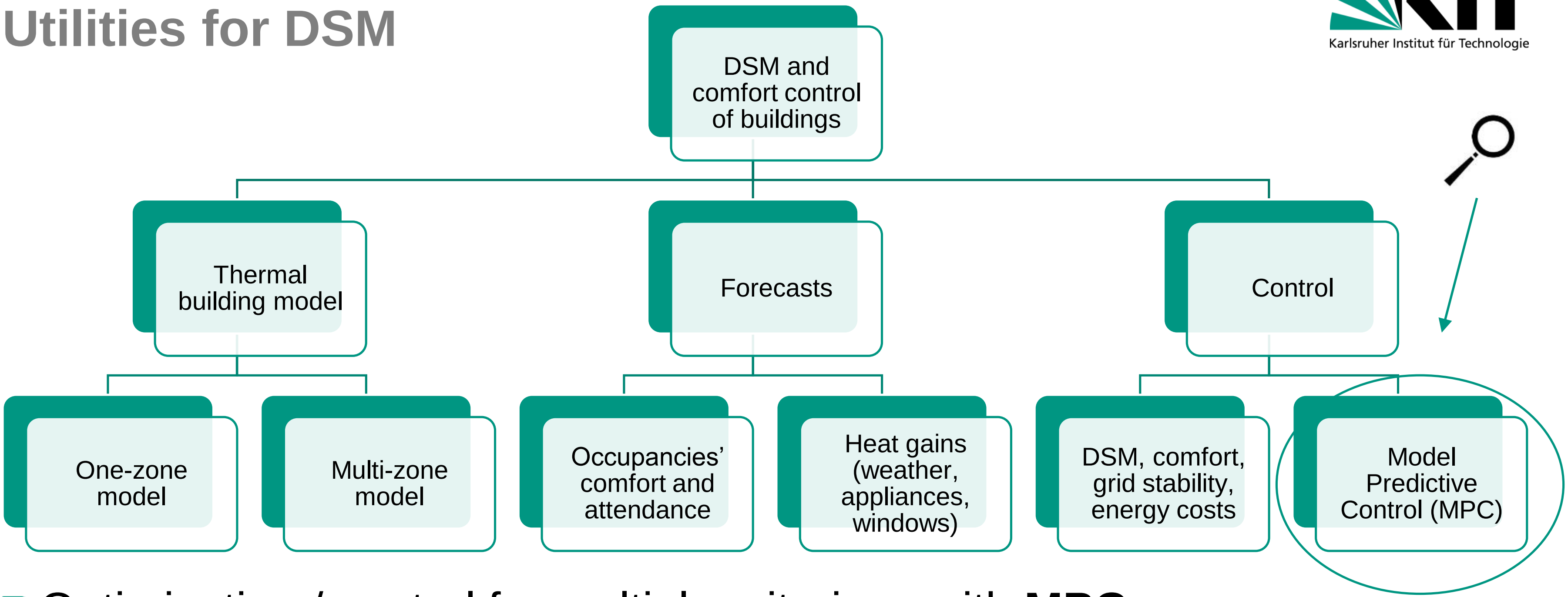
*Images for energy systems based on espazium and modified

Introduction
Occupant-centric DSM

- Conflicting control goals
  - (i) Balancing energy demands in buildings with DSM
  - (ii) Maintaining thermal comfort
- Occupants want to feel good and comfortable
- Multi-criterion optimization required

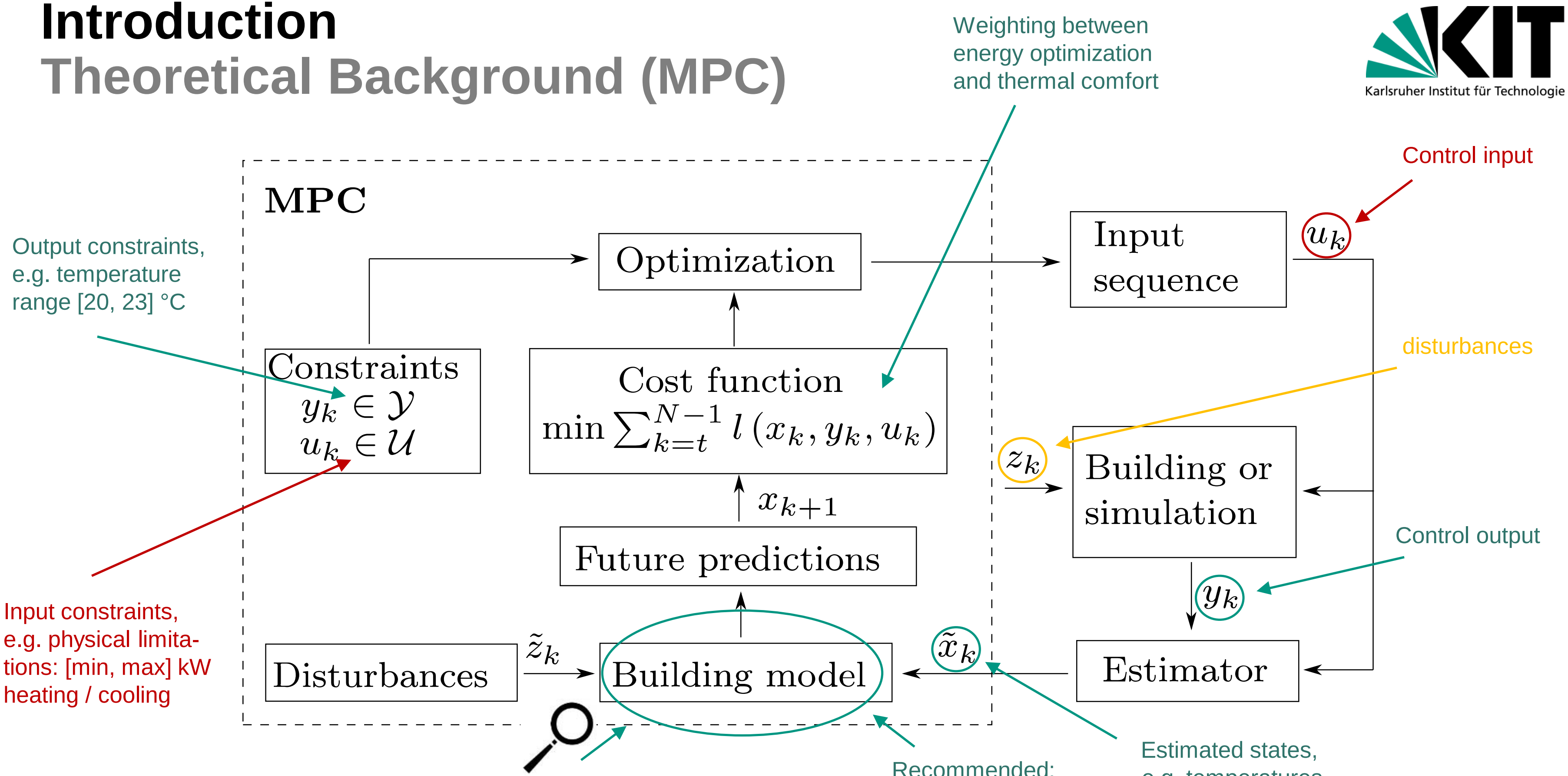
→ **Research Question:** How can we include OB into DSM and what impact do the OB models have on control metrics?

Introduction
Utilities for DSM



- Optimization / control for multiple criterions with **MPC**
- Predicts future system dynamics and can include occupancy behavior
- Requires models: thermal building and OB models

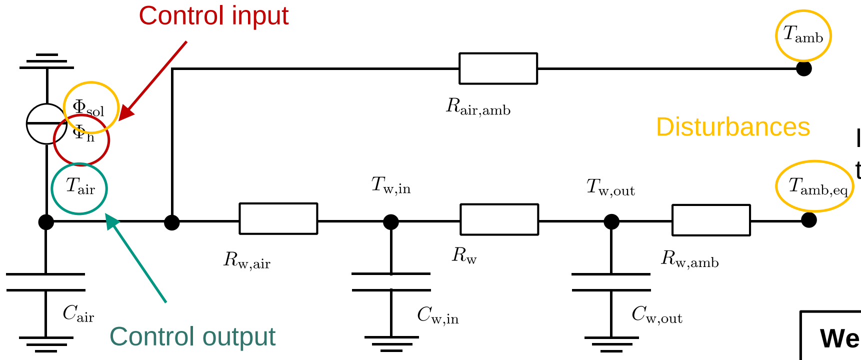
Introduction
Theoretical Background (MPC)



MPC image inspired by Drgoňa, J., Arroyo, J., Cupeiro Figueroa, I., et al., (2020). "All you need to know about model predictive control for buildings," Annual Reviews in Control, vol. 50, pp. 190–232

PART (I) APPLYING MPC FOR OCCUPANT-CENTRIC DSM

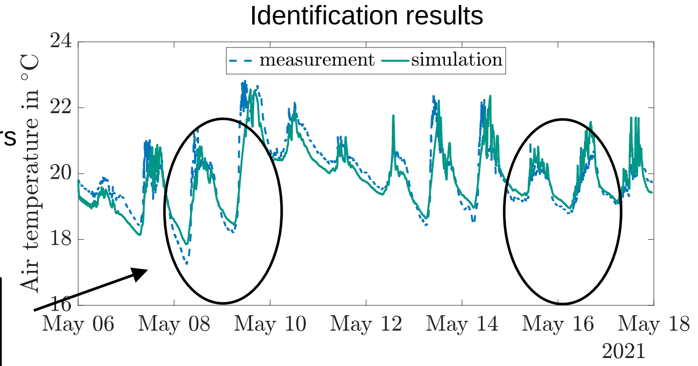
Methodology
Thermal Building Model for One Zone



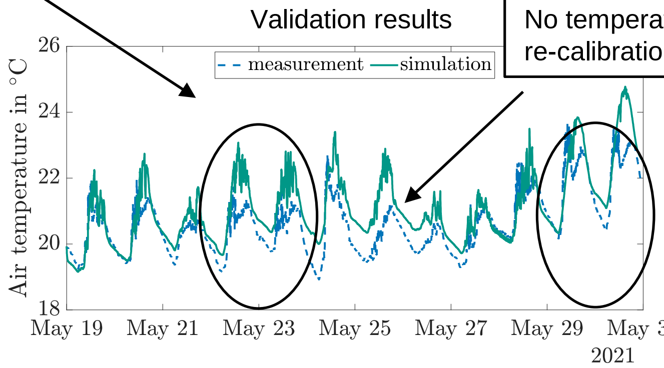
Thermal building model, inspired by [1]

[1]: Harb, H., Boyanov, N., Hernandez, L., Streblow, R., and Müller, D. (2016). Development and validation of grey-box models for forecasting the thermal response of occupied buildings. Energy and Buildings 117 (2016), 199–207.

Identification of thermal parameters



Weekends: different occupancy behavior in office



No temperature re-calibration

$$\frac{\mathrm{d}T_{air}}{\mathrm{d}t} = \frac{1}{C_{air}} \cdot \left(\frac{T_{w,in} - T_{air}}{R_{air,wall}} + \frac{T_{amb} - T_{air}}{R_{air,amb}} + \Phi_{sol} + \Phi_{h,air} \right)$$

$$\frac{\mathrm{d}T_{w,in}}{\mathrm{d}t} = \frac{1}{C_{w,in}} \cdot \left(\frac{T_{air} - T_{w,in}}{R_{w,air}} + \frac{T_{w,out} - T_{w,in}}{R_w} + \Phi_{h,wall} \right)$$

$$\frac{\mathrm{d}T_{w,out}}{\mathrm{d}t} = \frac{1}{C_{w,out}} \cdot \left(\frac{T_{w,in} - T_{w,out}}{R_w} + \frac{T_{amb,eq} - T_{w,out}}{R_{w,amb}} \right)$$

Corresponding differential equations

$$\Phi_{h,air} = (1 - f_{heat,rad})\,\Phi_h$$

$$\Phi_{h,wall} = f_{heat,rad}\Phi_h$$

$$\Phi_{sol} = f_{sol}\phi_{global}$$

$$T_{amb,eq} = T_{amb} + \phi_{global}\frac{a_f}{\alpha_A}$$

Model inputs

Source: Fahm, M., Langner, F., Zwickel, P., Matthes, J., Mikut, R., and Hagenmeyer, V. (2021). How to Derive and Implement a Minimalistic RC Model from Thermodynamics for the Control of Thermal Parameters for Assuring Thermal Comfort. https://easychair.org/publications/preprint/WQXD

Results

MPC for DSM: Utilizing Thermal Storage for Cooling

Optimization of cost function $l(k,y,u)$

Time-discrete state-space representation of linear, time-invariant building model

$$\min_{u(\cdot|t)} \sum_{k=t}^{N-1} l\left(k, y(k|t), u(k|t)\right)$$

subject to $\forall k \in [0, N-1]$:

$$x(k+1|t) = A_{\mathrm{d}} x(k|t) + B_{\mathrm{d}} u(k|t) + B_{\mathrm{zd}} z(k|t)$$

$$y(k|t) = C_{\mathrm{d}} x(k|t)$$

$$x(0|t) = x(t),\ u(k|t) \in \mathcal{U},\ y(k|t) \in \mathcal{Y}$$

$$l(k,y,u) = \lambda (y-\tilde{y})^T (y-\tilde{y}) + (1-\lambda) p(k)^T u,$$

Weight factor

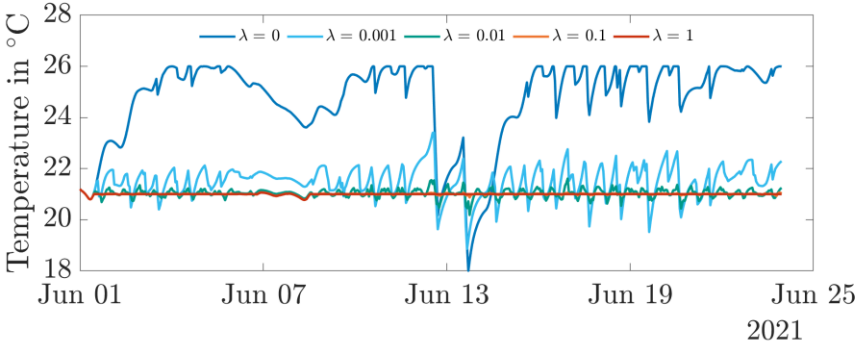
Model-predictive optimal-control algorithm, based on [2]

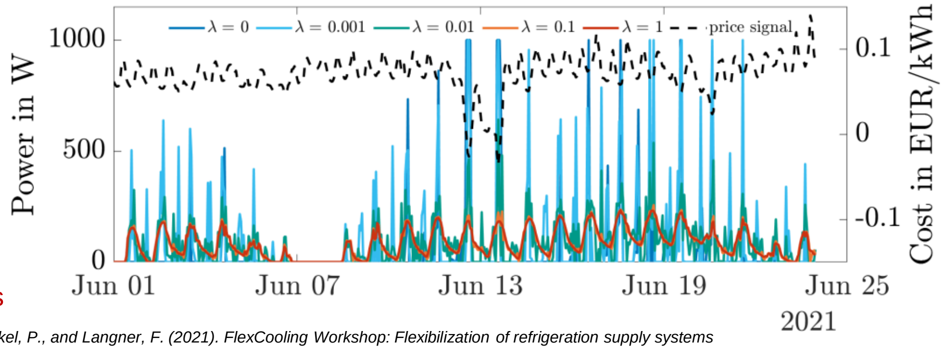
Temperature tracking $\tilde{y} = 21°C$

$u_{min} = 0\ kW$
$u_{max} = 1\ kW$

$y_{min} = 18°C$
$y_{max} = 26°C$

Energy costs





Source: Frahm, M., Zwickel, P., and Langner, F. (2021). FlexCooling Workshop: Flexibilization of refrigeration supply systems (orig.: FlexKälte-Workshop: Flexibilisierung von Kälteversorgungssystemen). https://doi.org/10.5445/IR/1000137324

[2]: Zwickel, P., Engelmann, A., Gröll, L., Hagenmeyer, V., Sauer, D., and Faulwasser, T. (2019). A Comparison of Economic MPC Formulations for Thermal Building Control. In 2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe). IEEE, 1–5.

Discussion
Summary of Results

- Easily applicable tools for occupant-centric DSM
  - application on various buildings
  - sufficient accuracy of model for control (feedback / closed loop)

- Direct consideration of measure-able and predict-able signals
  - weather
  - energy price
  - occupancy

- Limitations
  - simulation-based results
  - linear-time-invariant (LTI) model
  - simplified solar signal

- Future work
  - real-world application
  - including occupancy behavior models (OBM)

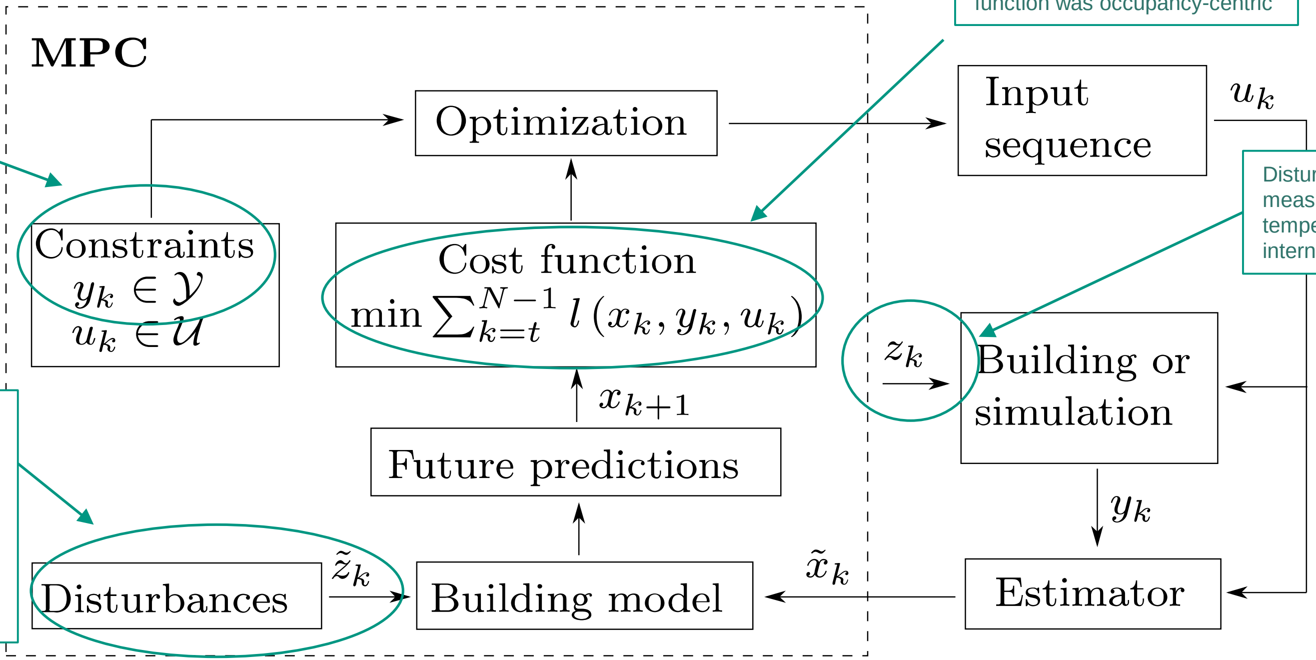
PART (II) INCLUDING OBM INTO MPC

Methodology
Occupancy Behavior Models (OBM) for MPC

Previously, only the cost function was occupancy-centric

Prediction of required set-point temperature

OBM:
- thermostat adjustment
- occupancy prediction



Disturbances can often be measured, e.g. ambient temperature, solar radiation, or internal heat gains

Estimate disturbances for future predictions

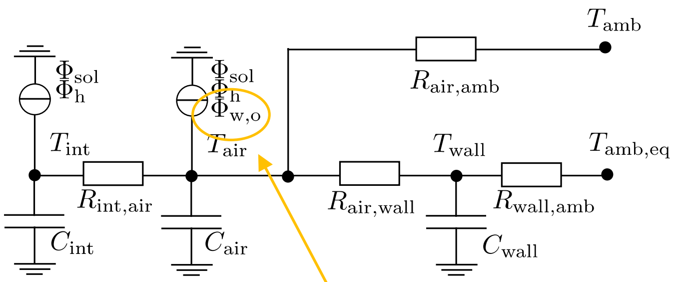
External forecast:
- weather forecast

OBM:
- windows operation
- shading operation
- appliance use

MPC image inspired by Drgoňa, J., Arroyo, J., Cupeiro Figueroa, I., et al., (2020). “All you need to know about model predictive control for buildings,” Annual Reviews in Control, vol. 50, pp. 190–232

Results
Example: Including Windows Openings into MPC

Similar model like before, inspired by [1] and modified



Including heat flow through windows

From OBM: Windows state (1/0 for open/closed)

$$\frac{dT_{air}}{dt} = \frac{1}{C_{air}} \cdot \left(\frac{T_{int} - T_{air}}{R_{int,air}} + \frac{T_{wall} - T_{air}}{R_{air,wall}} + \frac{T_{amb} - T_{air}}{R_{air,amb}} + f_{conv}\Phi_{sol} + \Phi_{h,air} + \Phi_{w,o} \cdot z_{w,o} \right)$$

$$\frac{dT_{int}}{dt} = \frac{1}{C_{int}} \cdot \left(\frac{T_{air} - T_{int}}{R_{int,air}} + \Phi_{h,int} + (1 - f_{conv}) \cdot \Phi_{sol} \right)$$

$$\frac{dT_{wall}}{dt} = \frac{1}{C_{wall}} \cdot \left(\frac{T_{air} - T_{wall}}{R_{air,wall}} + \frac{T_{amb,eq} - T_{wall}}{R_{wall,amb}} + \Phi_{h,wall} \right)$$

For MPC: Windows state can be modeled as a
(i) disturbance or
(ii) time-variable system parameter
to be included into the MPC

Source: Markovic, R., Frahm, M., Zwickel, P., Hoxha, M., Pham, N. S.H., Drgona, J., Hagenmeyer, V., and Wagner, A. (2021). Data-Driven Predictive Occupant Behavior Models for Model-Based Control of Buildings.

[1]: Harb, H., Boyanov, N., Hernandez, L., Streblow, R., and Müller, D. (2016). Development and validation of grey-box models for forecasting the thermal response of occupied buildings. Energy and Buildings 117 (2016), 199–207.

Discussion
Outlook

Impact of OBM in DSM/MPC

- How significant do OBM improve the control metrics?
- How to include OBM into DSM/MPC?
  (Related to the ST2 guidance / review paper)
- Accounting for uncertainties: evaluation of indirect (control) metrics, e.g. energy costs, DSM flexibility, thermal comfort

Thank you for your attention!

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image source: https://www.pngfind.com

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