Technische Universität Braunschweig

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A Short Framework for Prototyping Nonlinear Model Predictive Control Loops

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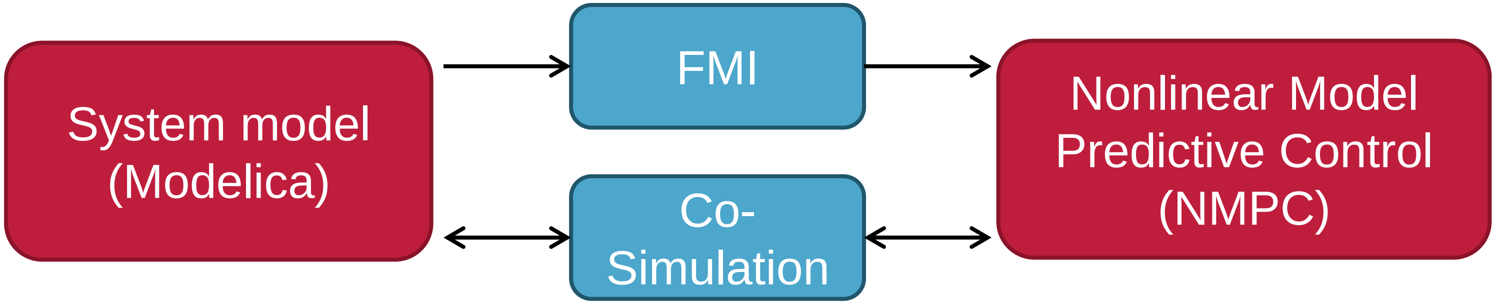
Introduction and Motivation



- Convenient tools for modeling and simulation
- Many different model libraries
- Mainly used for simulation

- Use system knowledge to improve control performance
- Highly efficient algorithms exist
- Designing and tuning is a complex task
- Very important: good system models

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Optimal Control Task and NMPC

Cost function

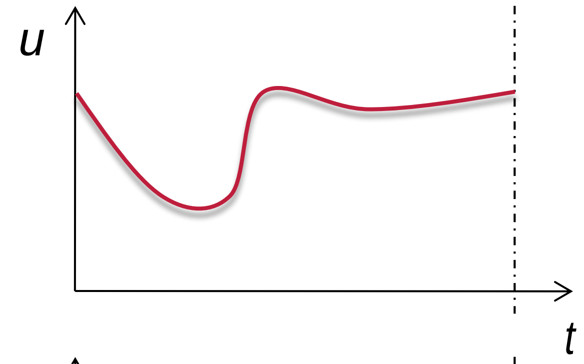
$$C = a\int_0^{\tau}(T - T_{\text{set}})^2\,\mathrm{d}t + b\int_0^{\tau} P\,\mathrm{d}t$$

Dynamic system model (ODE)

$$\dot{x}(t) = f(x(t), u(t))$$

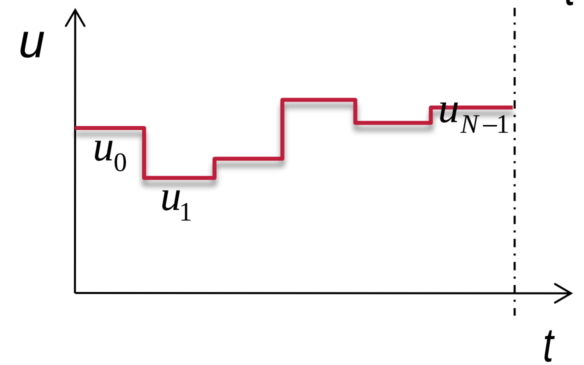
Optimal Control Problem (OCP)

$$\begin{aligned} \min_{x(\cdot),u(\cdot)} \; & C(x(\cdot),u(\cdot)) \\ \text{s.t.} \quad \dot{x}(t) = \; & f(x(t),u(t)) \\ 0 \le \; & c(x(t),u(t)) \\ x(0) = \; & x_0 \end{aligned}$$



Infinite dimensional problem (NLP)

$$\begin{aligned} \min_{\substack{s_0,\ldots,s_N \\ u_0,\ldots,u_{N-1}}} \; & \sum_{i=0}^{N} l_i(s_i,u_i) \\ \text{s.t.} \quad s_{i+1} = \; & x_i(\tau_{i+1}; s_i, u_i) \\ 0 \le \; & c(s_i,u_i) \\ s_0 = \; & x_0 \end{aligned}$$



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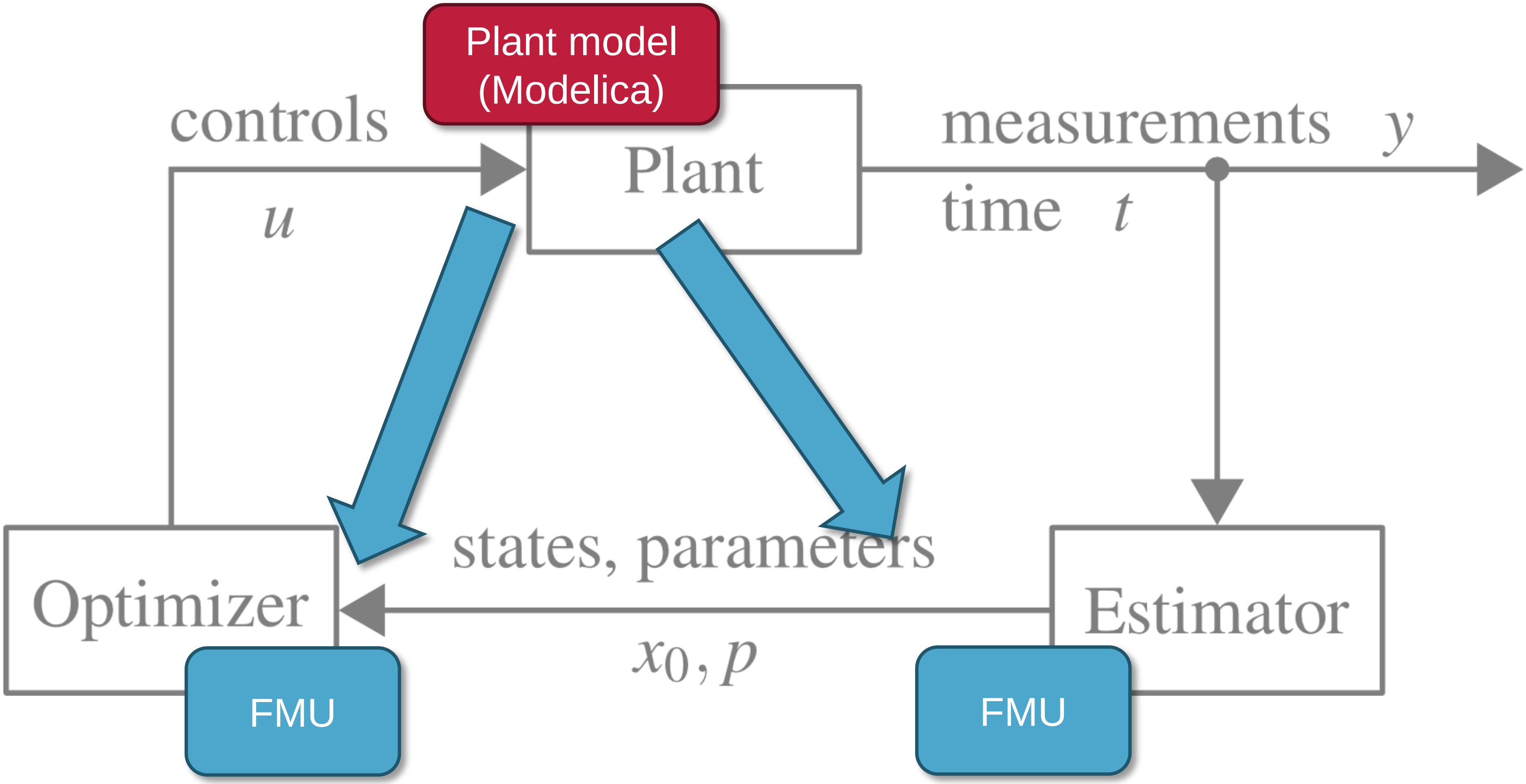
- Optimal Control Task and NMPC
- Used Software
- Simulation of Vapour Compression Cycle
- Simulation of Thermoactive Ceiling
- Conclusion

Used Software



Used Software

Co-Simulation Master

TISC

Simulated Plant

NATIONAL INSTRUMENTS LabVIEW

Real-World Plant

MUSCOD II

Optimizer

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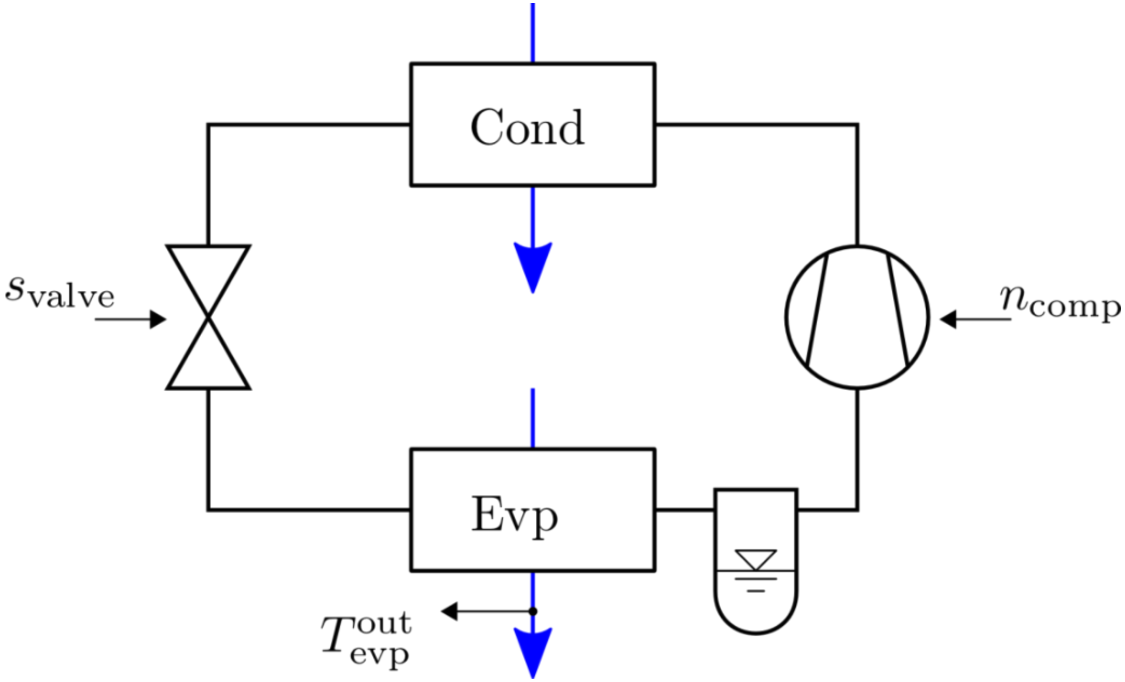
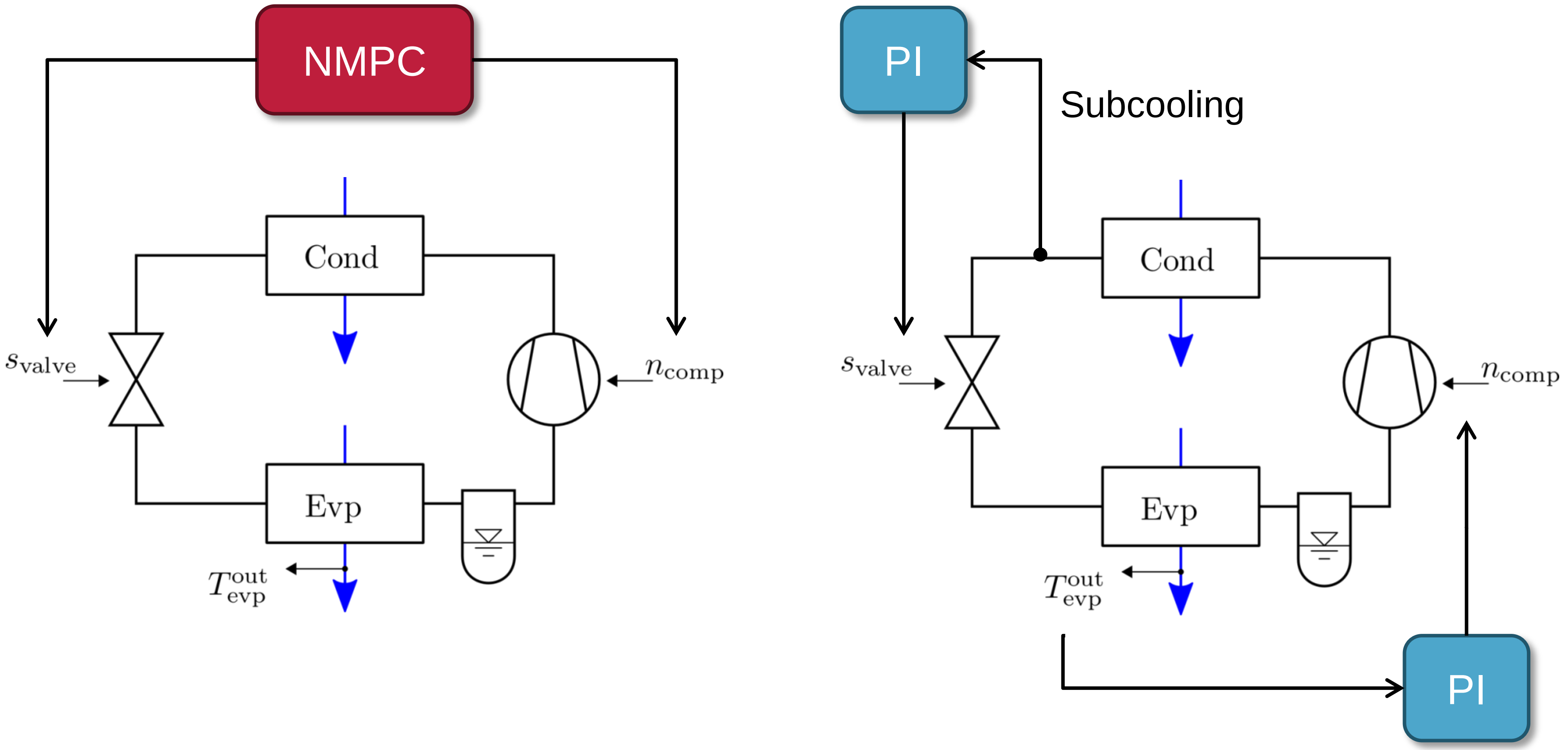
Simulation of Vapour Compression Cycle



- Control inputs: expansion valve opening, compressor speed
- Goal 1: constant outlet temperature
- Goal 2: as less electrical energy as possible

Simulation Experiment – Vapour Compression Cycle

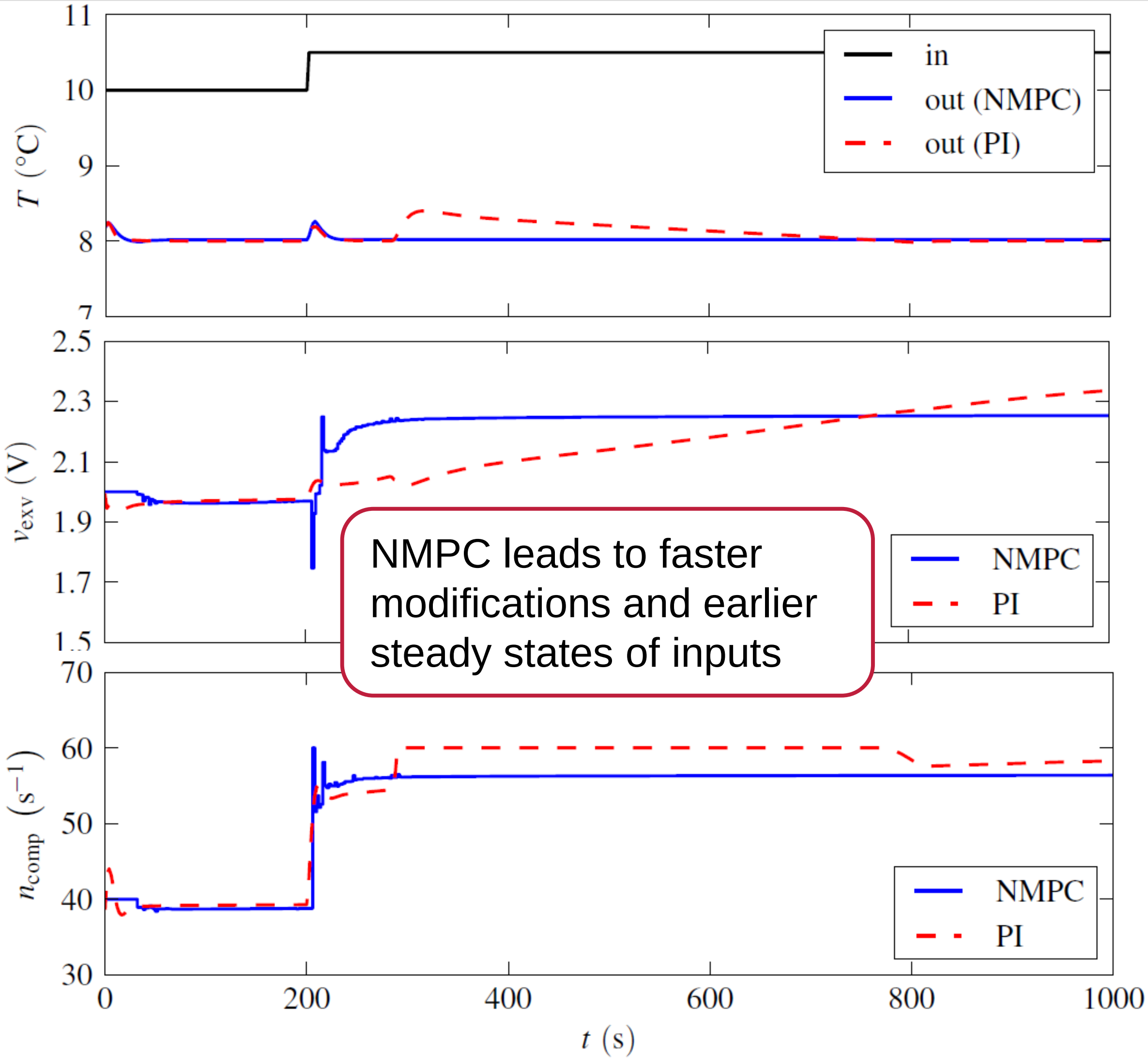


Simulation Results - Compression Cycle

Inlet and outlet
Chilled water temperatures

Control input
Expansion valve opening

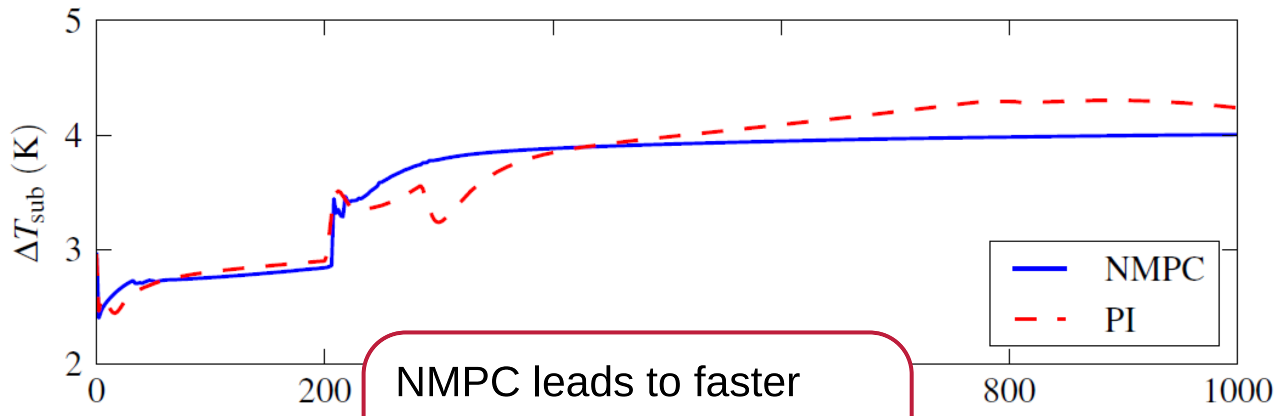
Control input
Compressor speed



NMPC leads to faster modifications and earlier steady states of inputs

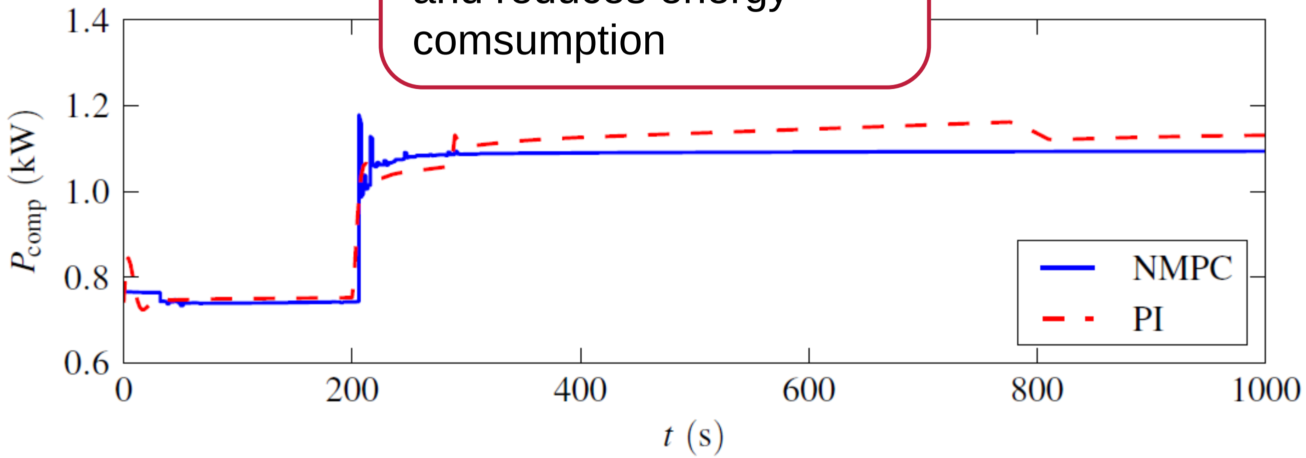
Simulation Results – Vapour Compression Cycle

Output
Refrigerant subcooling



NMPC leads to faster steady state of ouputs and reduces energy comsumption

Output
Compressor power



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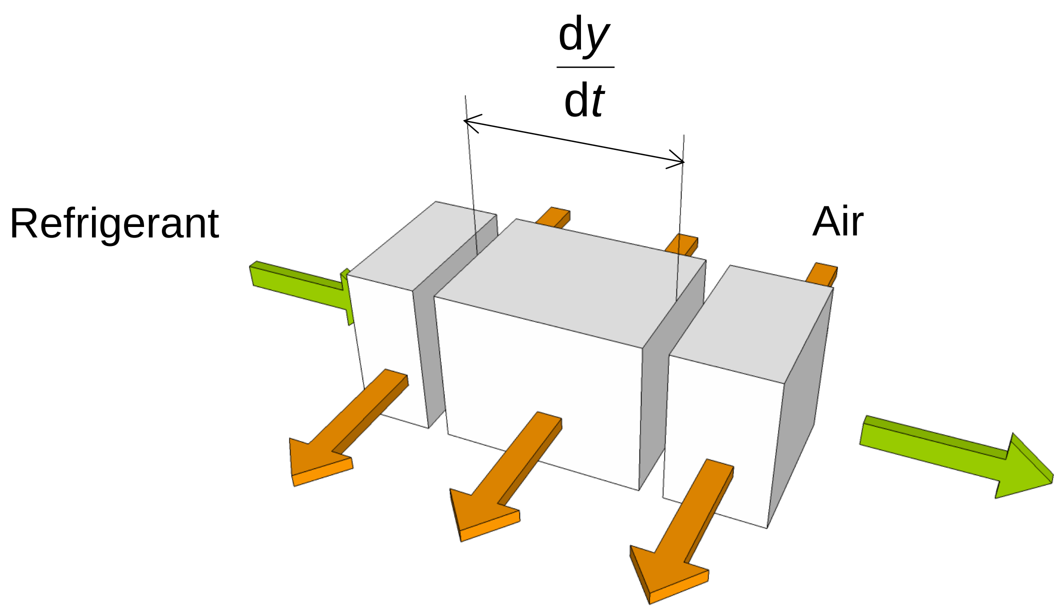
Steps to Speed Up Optimization - Heat Exchanger Model



- Dynamic control volumes
- Boundaries always at 1-phase / 2-phase transition point
- Mass and energy balance equations for each volume

Steps to Speed Up Optimization - Real-Time Iteration

- Only one Sequential Quadratic Programming (SQP) iteration per NMPC sample

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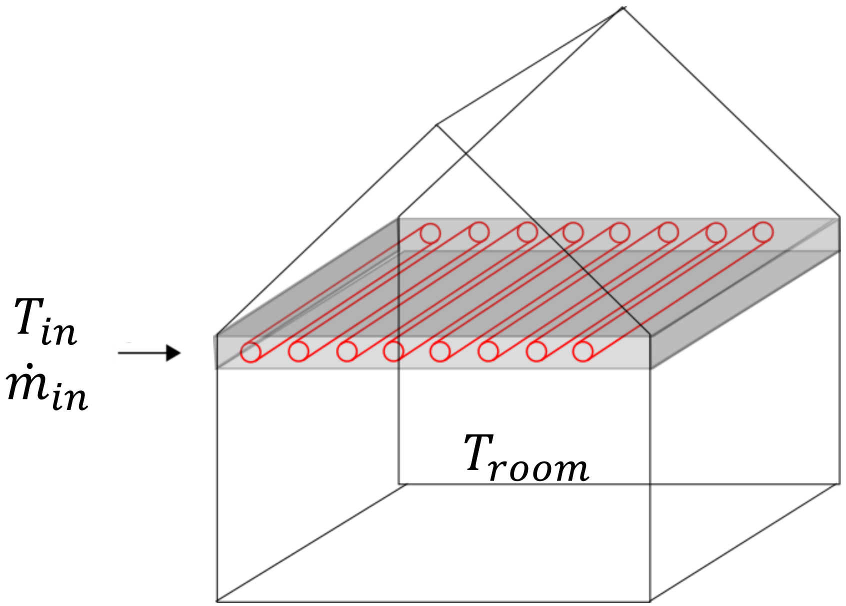
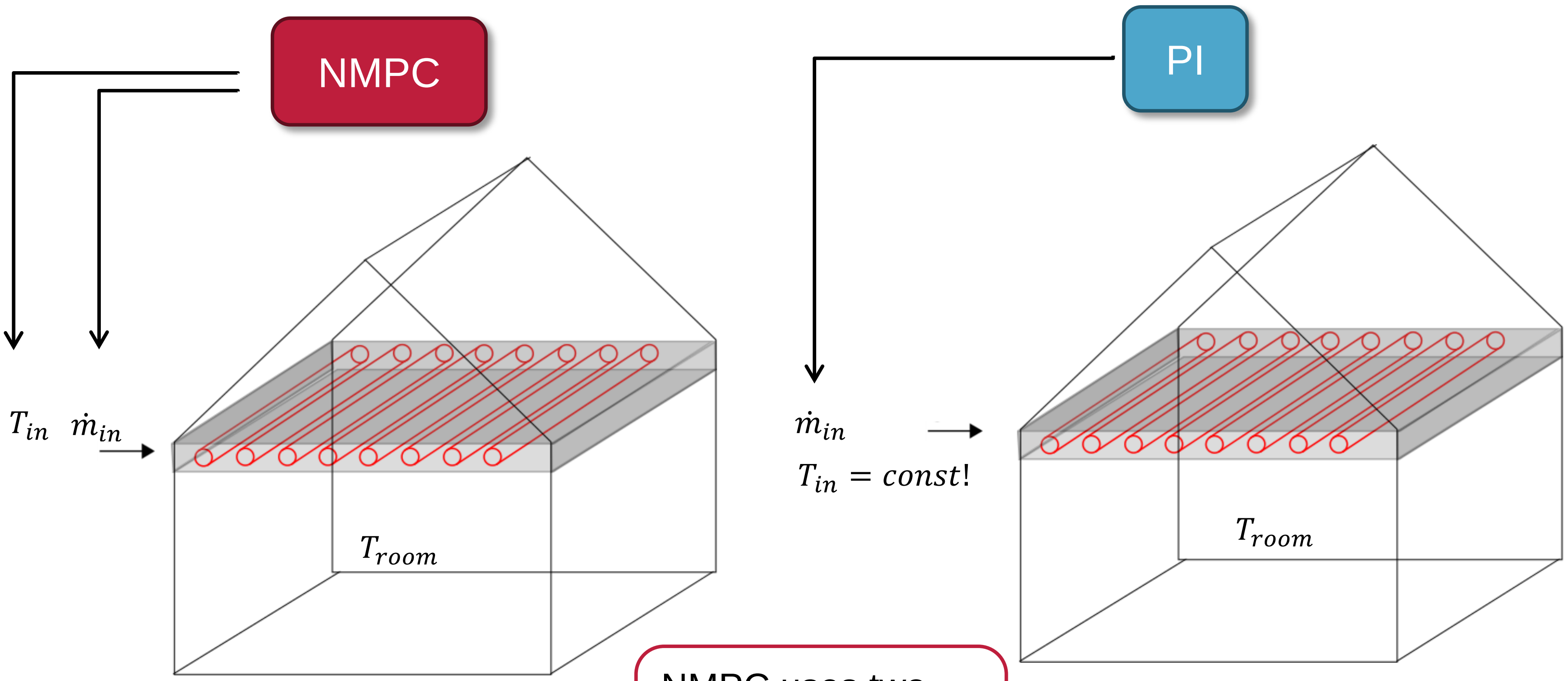
Simulation of Thermoactive Ceiling



- Control inputs: inlet temperature, inlet massflow
- Goal 1: constant room temperature
- Goal 2: as less heating energy as possible

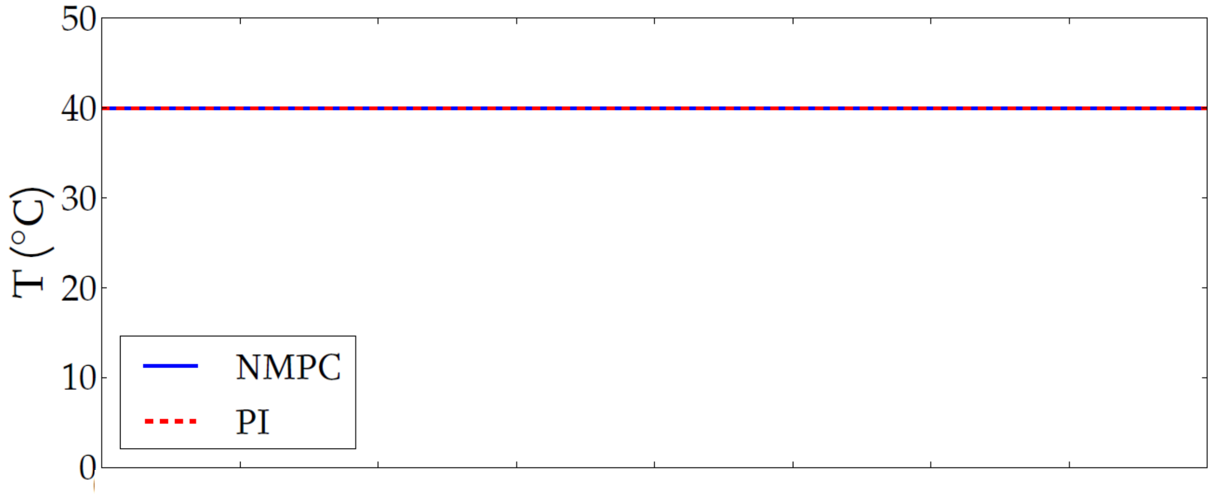
Simulation Experiment - Thermoactive Ceiling



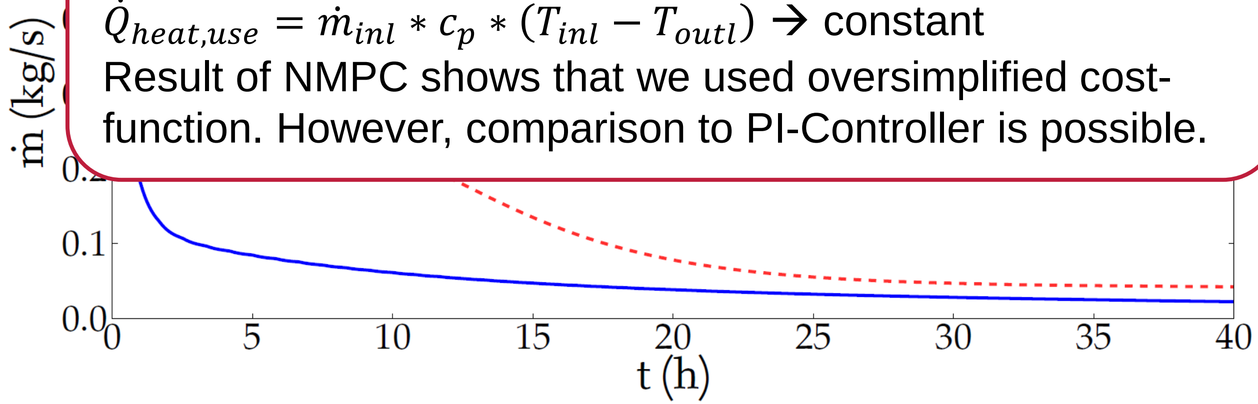
NMPC uses two, PI-Controller only one variable.

Simulation Results – Thermoactive Ceiling

Control input
Inlet temperature



Control input
Inlet massflow



NMPC „shows“ to always use maximum inlet temperature.

$\dot{Q}_{heat,pay} = \dot{m}_{inl} * c_p * \left(T_{inl} - T_{ref}\right)$ → minimize

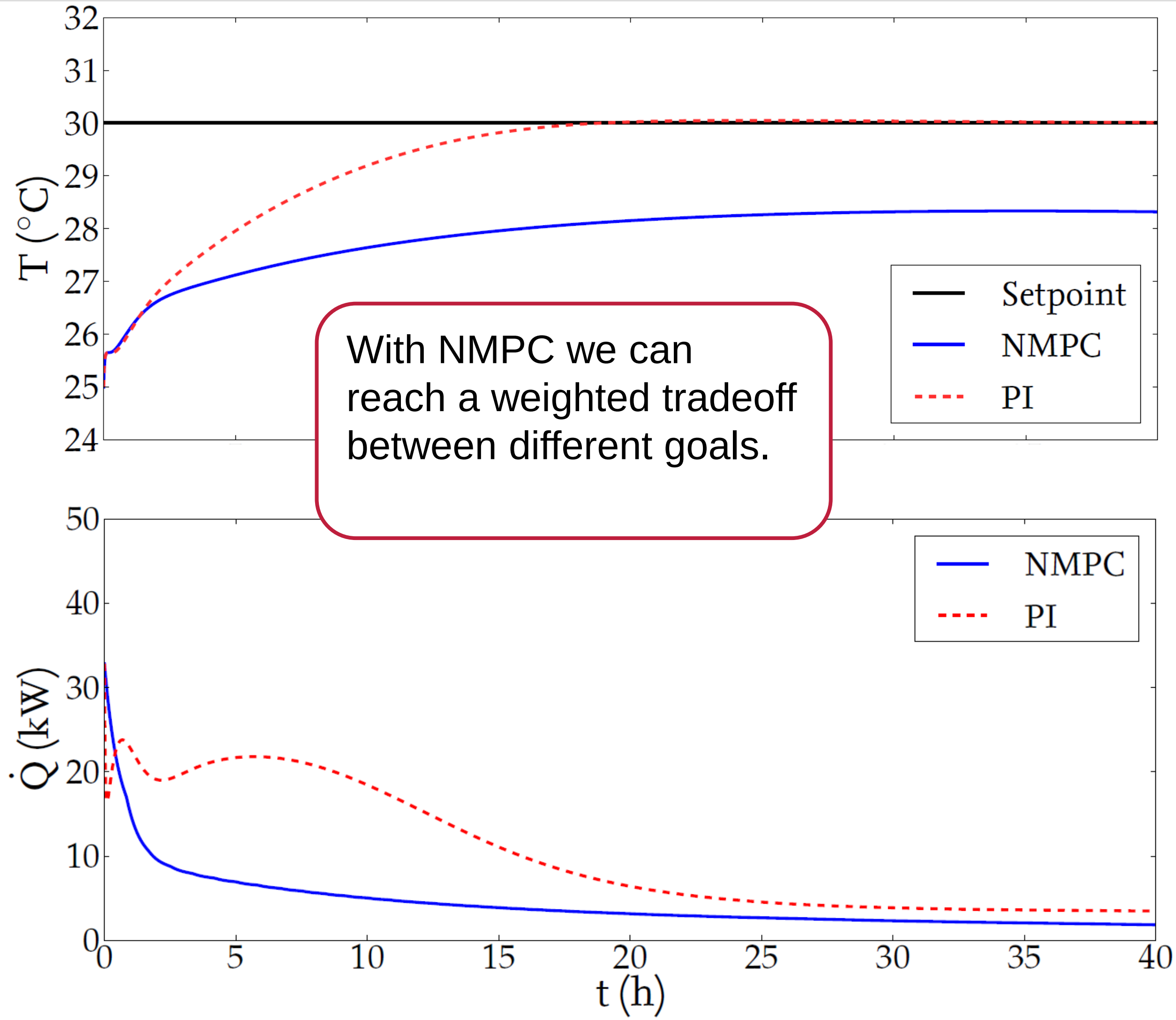
$\dot{Q}_{heat,use} = \dot{m}_{inl} * c_p * (T_{inl} - T_{outl})$ → constant

Result of NMPC shows that we used oversimplified cost-function. However, comparison to PI-Controller is possible.

Simulation Results - Thermoactive Ceiling

Output
Room Temperature

Output
Heating energy



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Conclusion

Summary

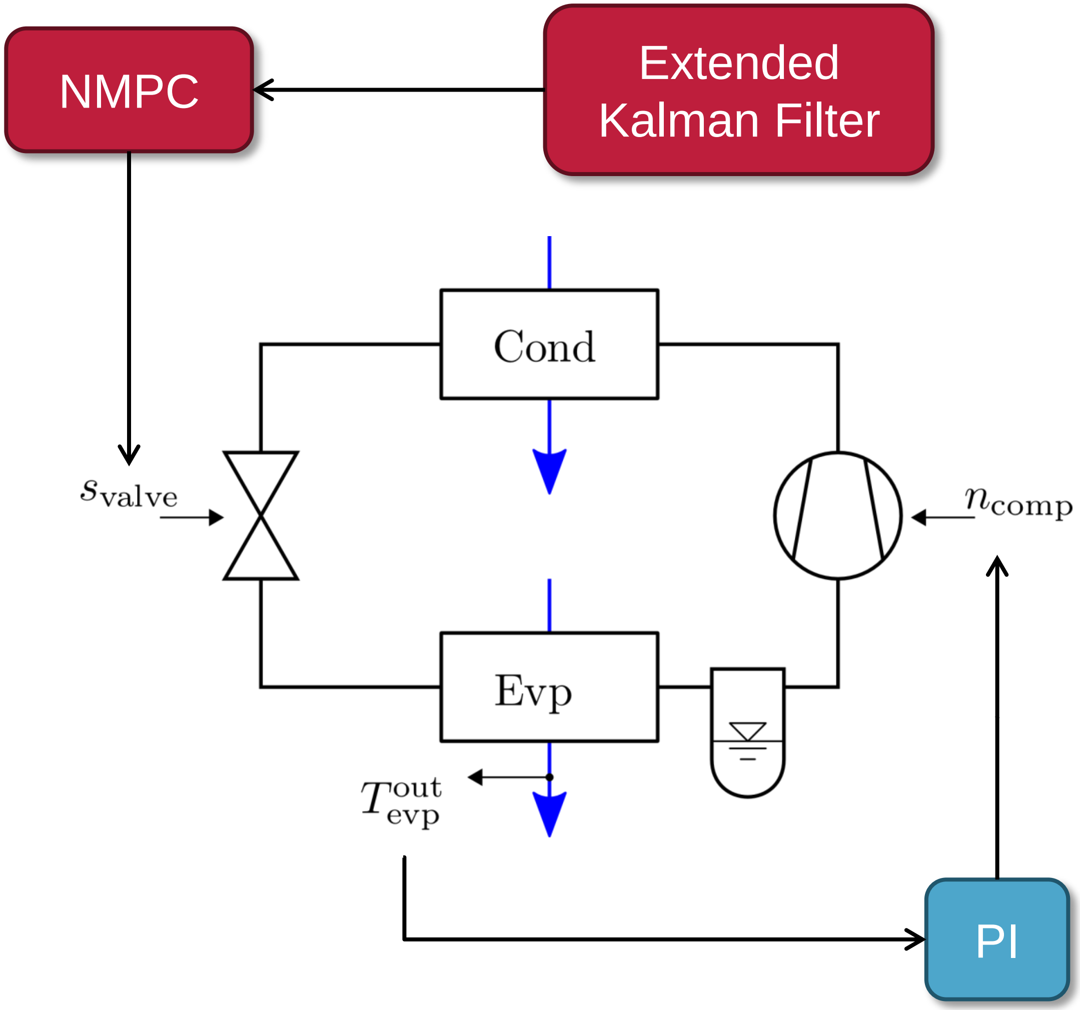
- FMI successfully used in NMPC applications
- Control method for vapor compression presented
- Simulation and measurement results (not presented) show feasibility
- (Oversimplified) control method for climate control of buildings presented

Future work

- Include Jacobian information (FMI 2.0)
- Extend model interface to hybrid DAE

Additional Slides

Real-World Application

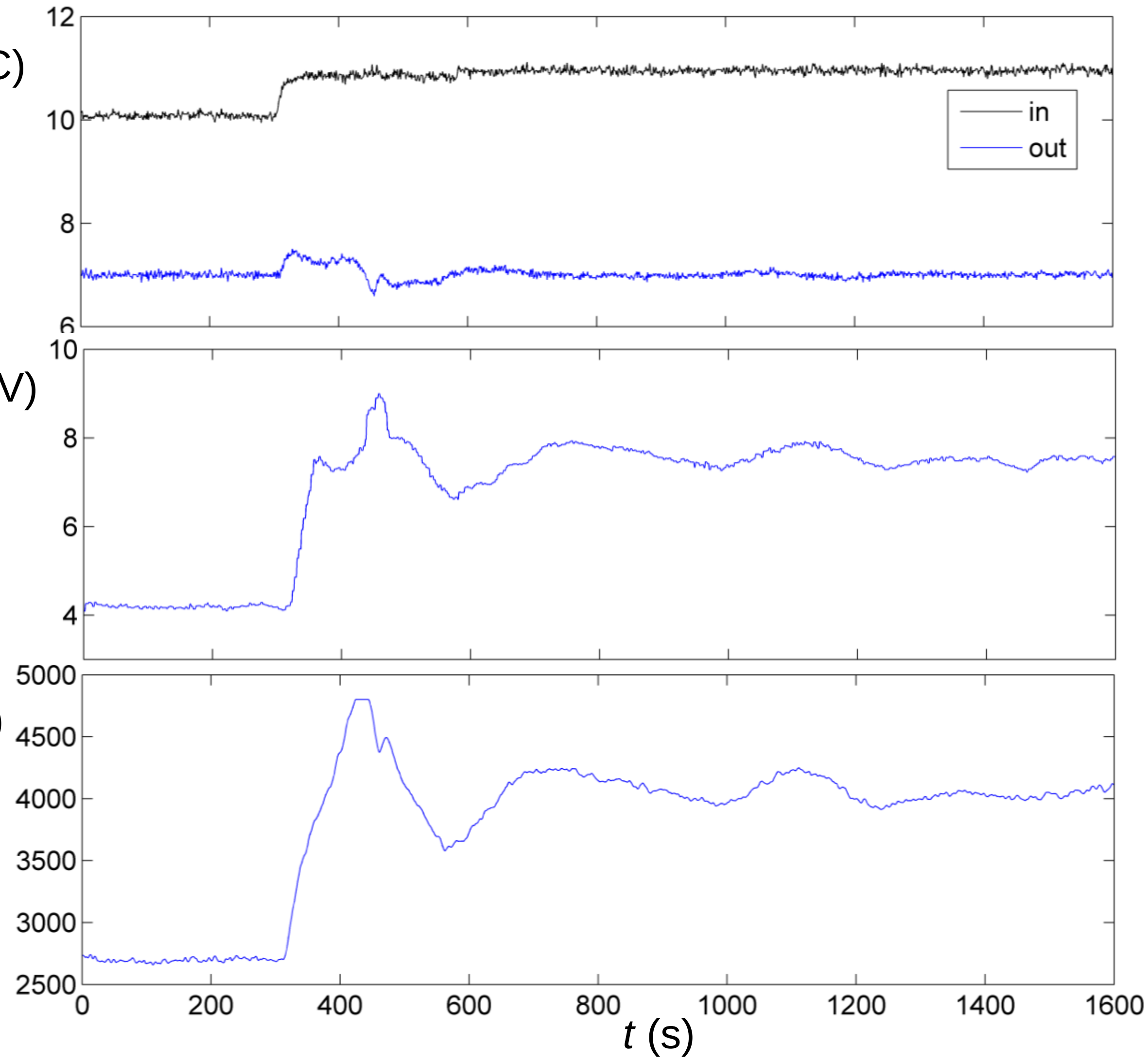


Measurement Results

Inlet and outlet
Chilled water temperatures

Control input
Expansion valve opening

Control input
Compressor speed

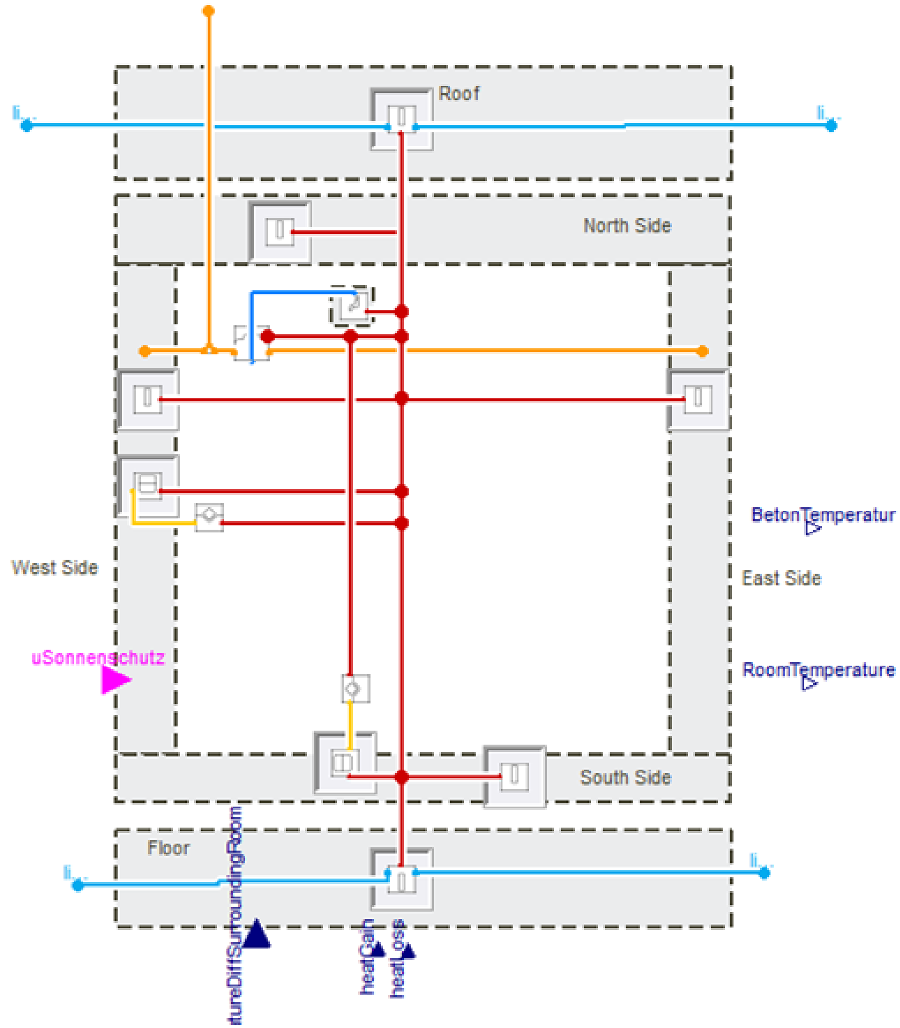


Modell of Buildling – Thermoactive Ceiling

- Temperature of room regulated with water between 15°C and 35°C

- Modelling of significant heatflows

- Model reduction leads to ODE with about 25 states



Fluid Properties Calculation

- Many fluid properties (e.g. heat capacity) are discontinuous at saturation curve

New approach:

- Inputs: *p, h*
- Calculate superheated, subcooled *h*:

$$h^{+} := h - h^{\text{vap}}(p)$$
$$h^{-} := h - h^{\text{liq}}(p)$$

- Coordinate transformation

$$(p,h) \to \begin{cases} (p,h^{+}) & \text{if } h \geq h^{\text{vap}} \\ (p,h^{-}) & \text{if } h \leq h^{\text{liq}} \end{cases}$$

- Evaluate tabulated bicubic splines on transformed coordinates