Maximizing operational efficiency of heat pumps with Model Predictive Control: An experimental case study for residential application

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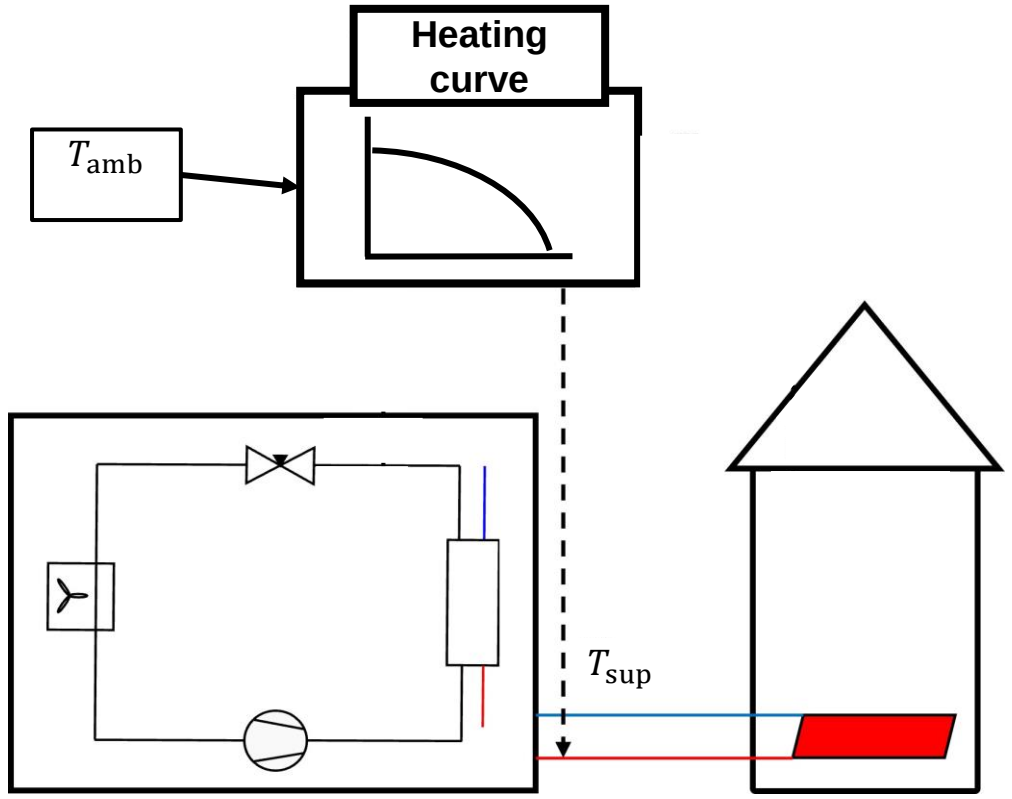
Supported by:
Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag

State of the Art vs. MPC

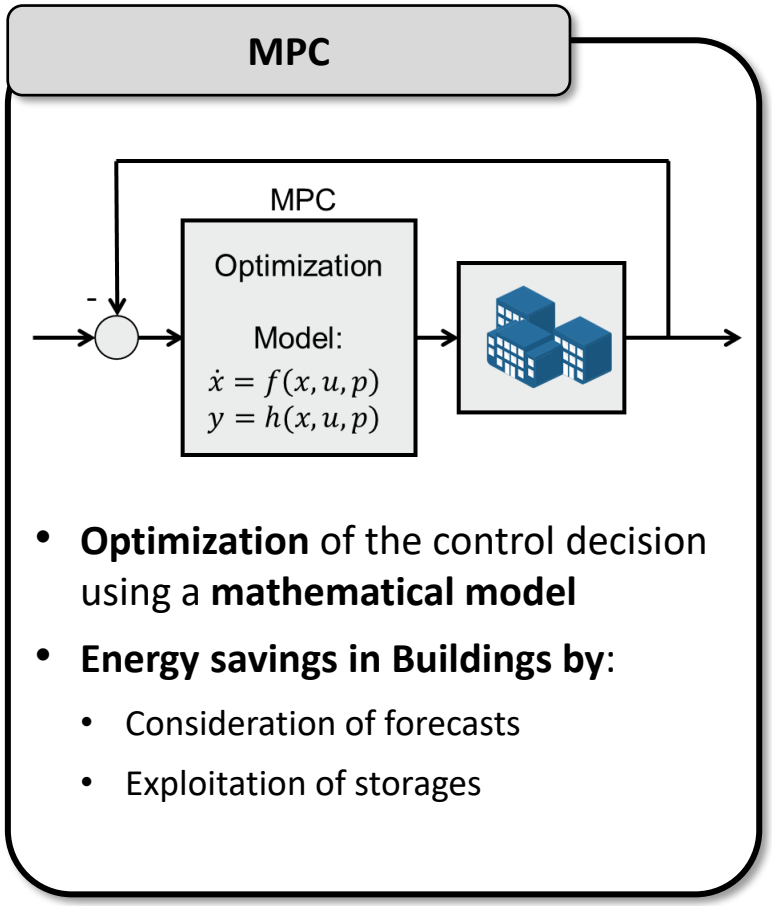
- **State of the art: heating curve**
  - Control of supply temperature T_{sup}
  - Only consideration of disturbance variable: ambient temperature (T_{amb})

- **MPC:**
  - Theoretical studies show high potential: 13 % - 18 % cost reduction [1]

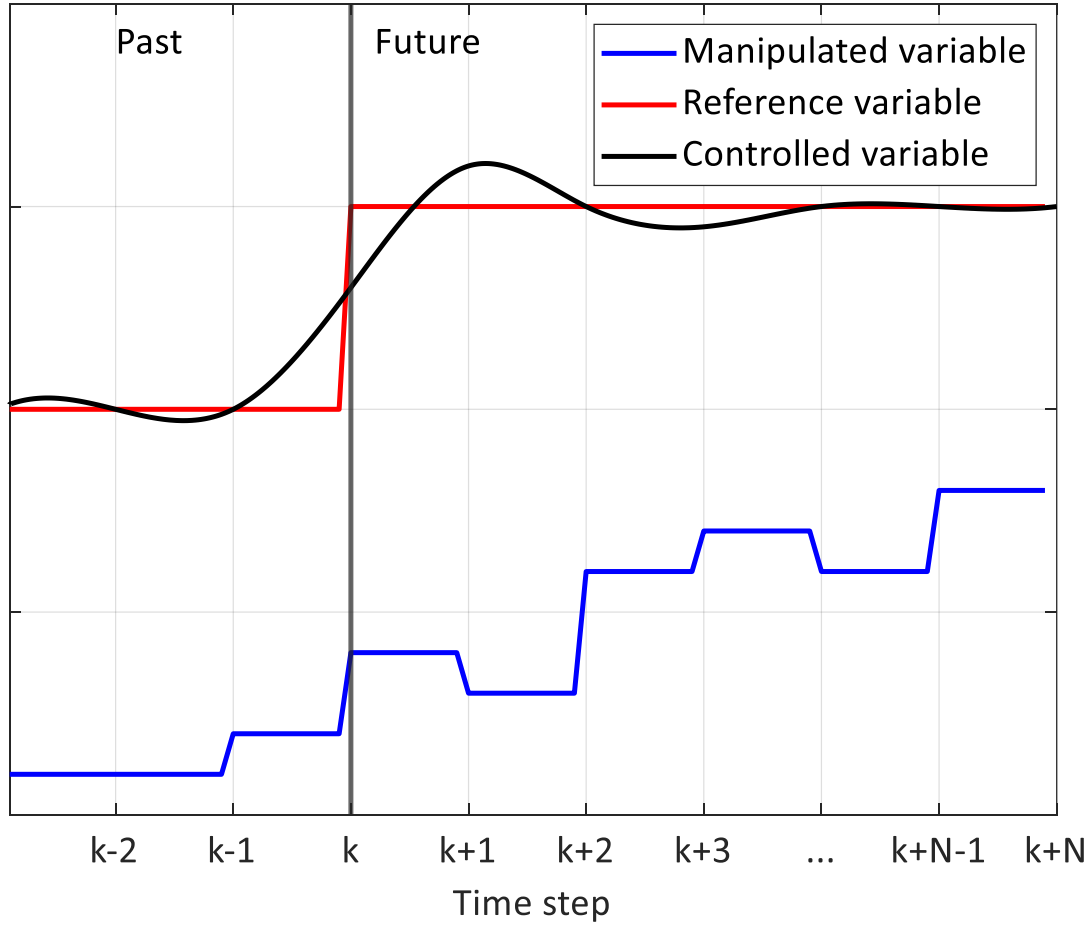


[1] J. Drgoňa et al., 2020

General MPC procedure

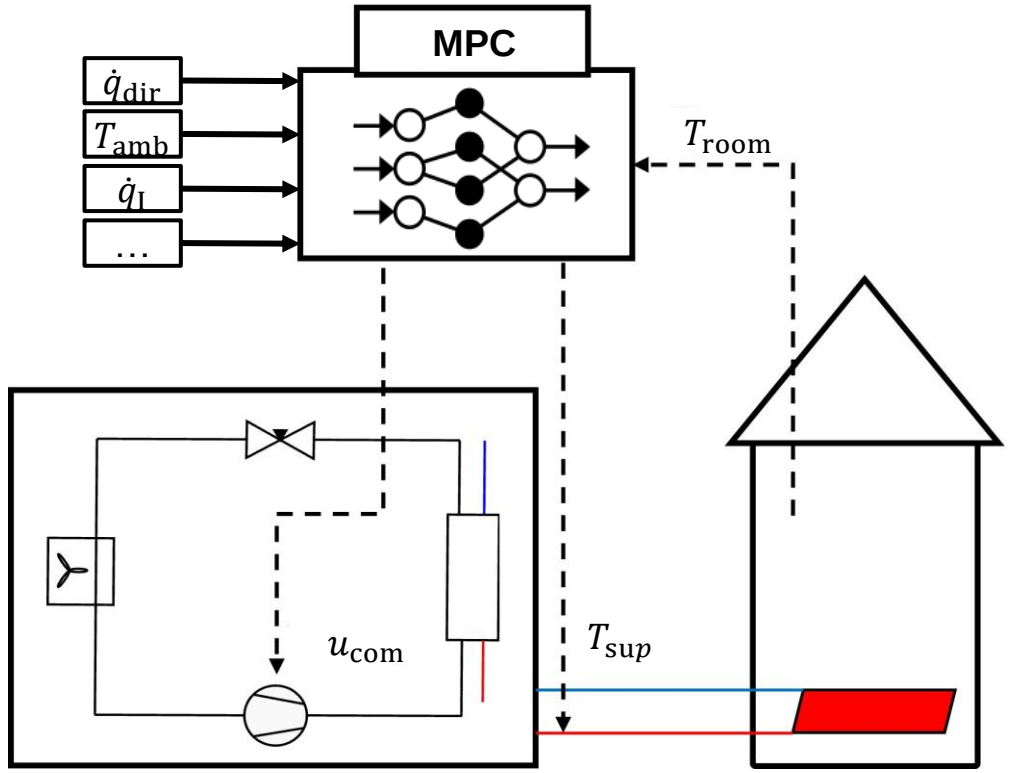


- **Optimization** of the control decision using a **mathematical model**
- **Energy savings in Buildings by**:
  - Consideration of forecasts
  - Exploitation of storages



State of the Art vs. MPC

- **State of the art: heating curve**
  - Control of supply temperature T_{sup}
  - Only consideration of disturbance variable ambient temperature (T_{amb})
- **MPC:**
  - High theoretical potential: 13 % - 18 % cost reduction [1]
  - Incorporates more disturbance variables (Weather, internal gains,...)
  - Exploitation of storages
- **Not widespread** in practice:
  - High modeling effort
  - Difficult heat pump integration – missing interfaces
  - Missing experimental case studies



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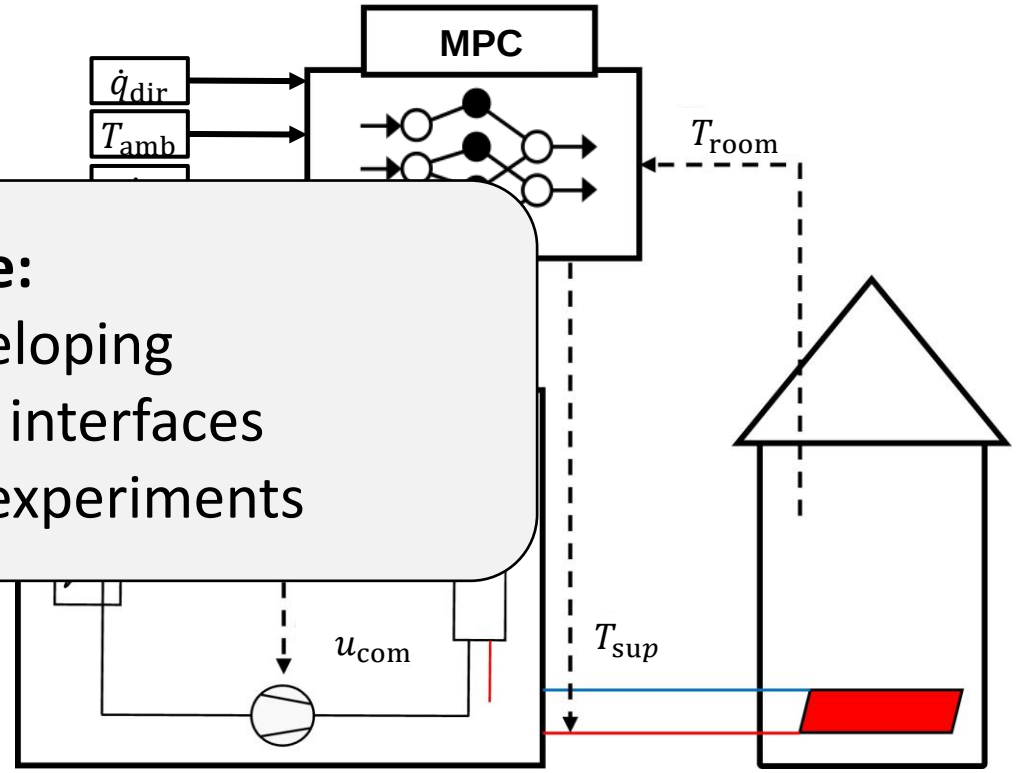
Transfer MPC into practice:

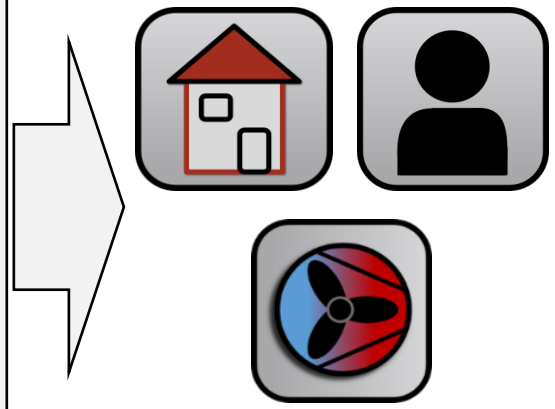
- Data-driven model developing
- Considering heat pump interfaces
- Hardware-in-the-Loop experiments



MPC Configuration
Data-driven model developing

Input

- **Weather**:
  - Temperature
  - Solar irradiation
- **Building**:
  - Current room temperature
- **Time**:
  - Time of the day
  - Day of the week
- **Heat Pump**
  - Compressor speed or supply temperature



Output

ΔT_{Room}
Room temperature change

MPC Configuration
Data-driven model developing

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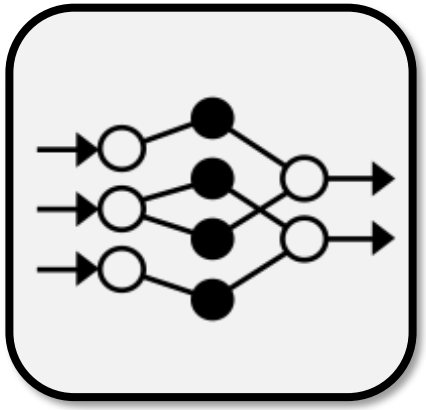

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Transfer MPC into practice:

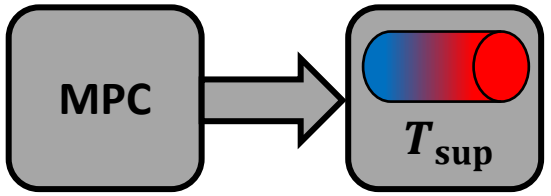
- Data-driven model developing ✅
- **Considering heat pump interfaces**
- Hardware-in-the-Loop experiments

MPC Configuration
Cost functions for supply temperature control

- Two different MPC configurations :

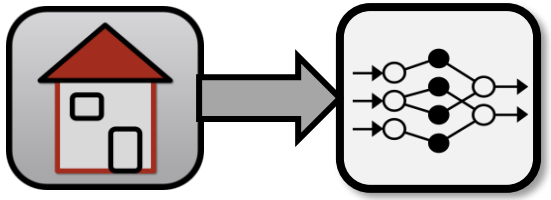
1. Manipulate **supply temperature**

Manipulated variable:



- **Artificial neural network** for building

Process model:



- **Cost function**: $J = \sum_{k=0}^{N-1} w_1 \cdot \epsilon_k^2 + w_2 \cdot T_{\mathrm{sup},k} + w_3 \cdot \Delta T_{\mathrm{sup},k}$

- Terms of cost function: Comfort | Manipulated value | Value change

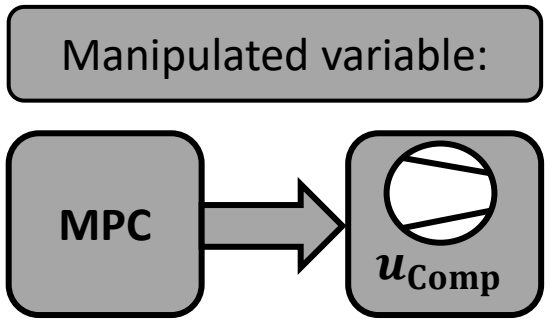
$\Delta T_{\mathrm{fl},k} = T_{\mathrm{sup},k-1} - T_{\mathrm{sup},k}$
k: time step

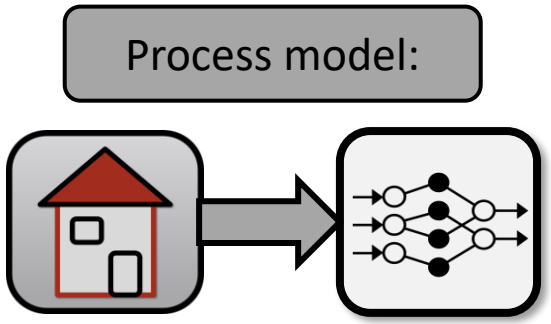
MPC Configuration
Cost functions for compressor speed control

- Two different MPC configurations:

2. Manipulate **compressor speed**

- **Artificial neural network** for building





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- Terms of cost function: Comfort | Manipulated value | Value change | Compressor start

MPC Configuration
Cost functions for compressor speed control

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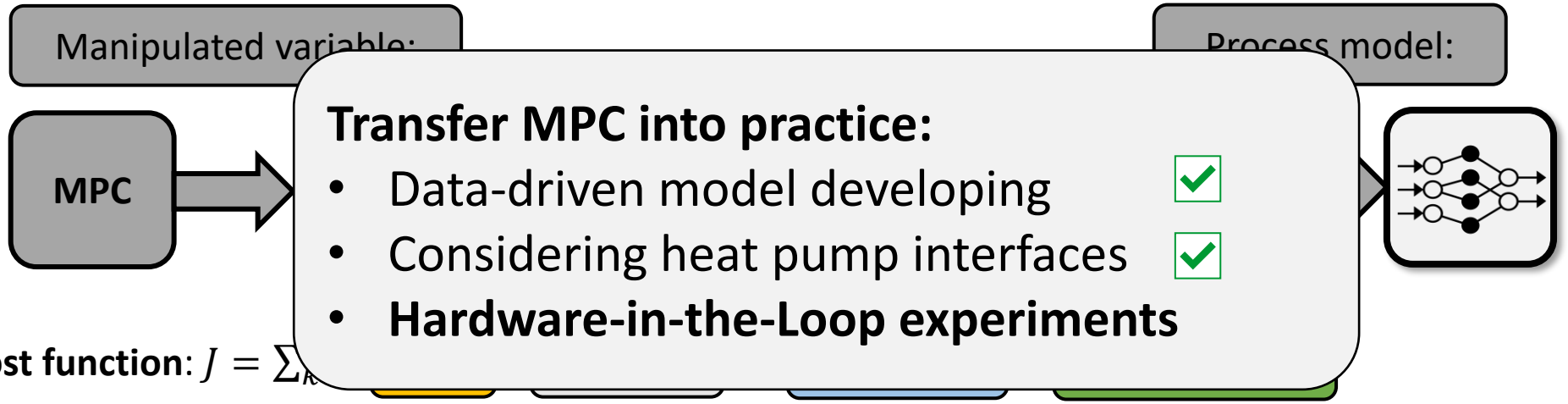

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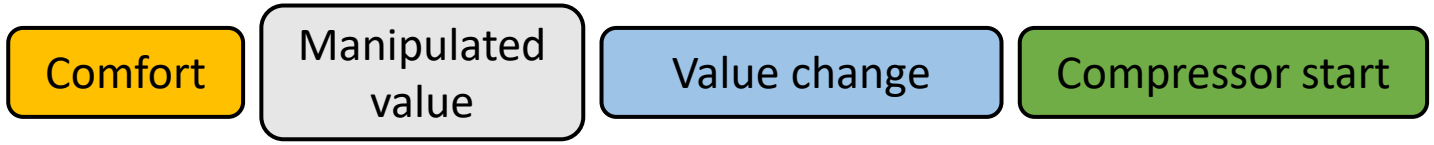
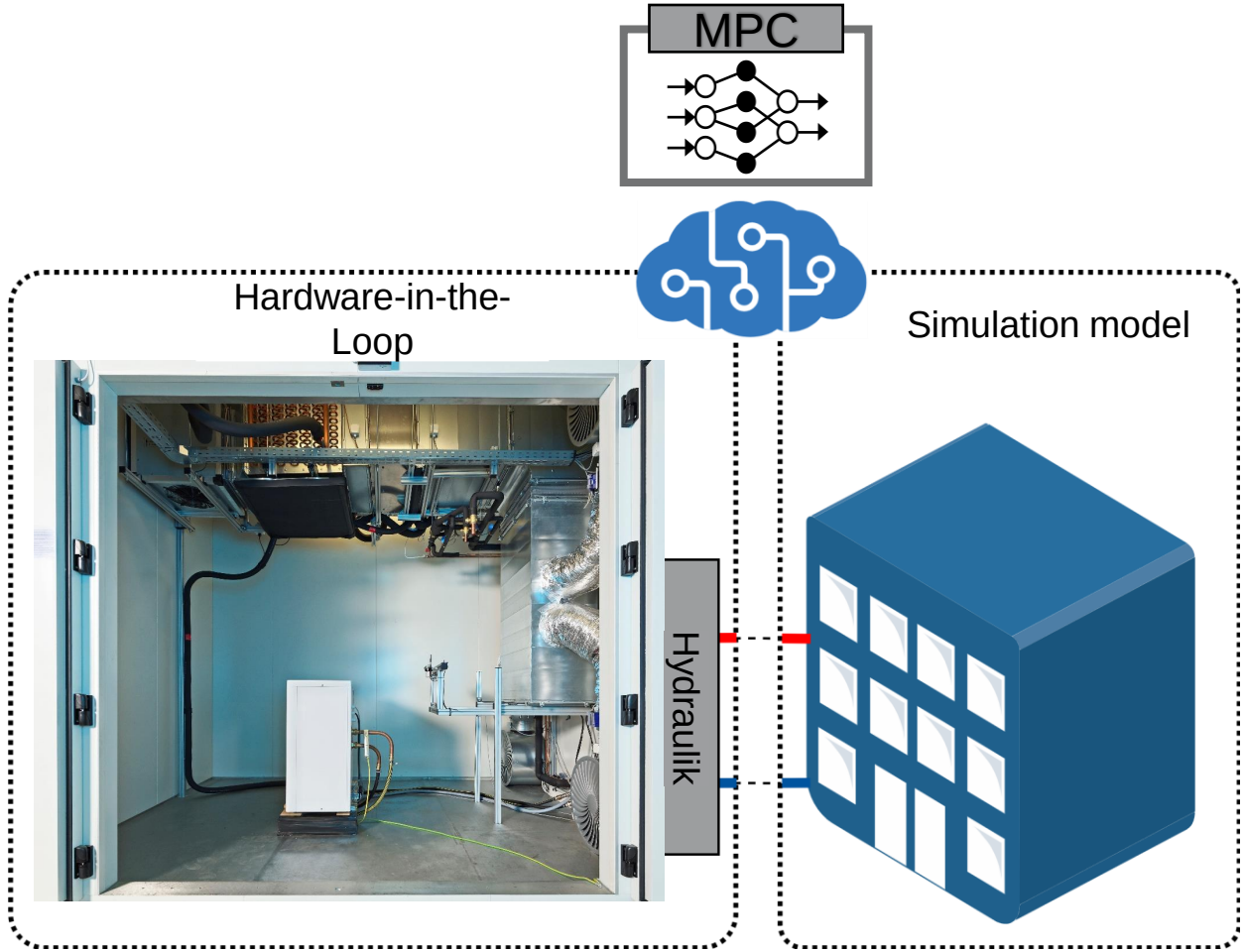
- Terms of cost function:



Hardware-in-the-Loop for heat pumps

- HiL approach connects real heat pump with virtual building model
  - Climatic chamber emulates ambient
  - Hydraulic test bench emulates building
- Heat pump test bench
  - Self-developed heat pump [2]
  - All actuators fully controllable
- Using dynamic Modelica models
  - Building envelope
  - Underfloor heating system
- Cloud-based integration of MPC
  - Communication over MQTT and HTTP
  - Local independent control



[20] Göbel et. al. 2022, „Development and experimental validation of model-based superheat control strategies for air-to-water heat pumps.”, 15th IIR-Gustav Lorentzen Conference

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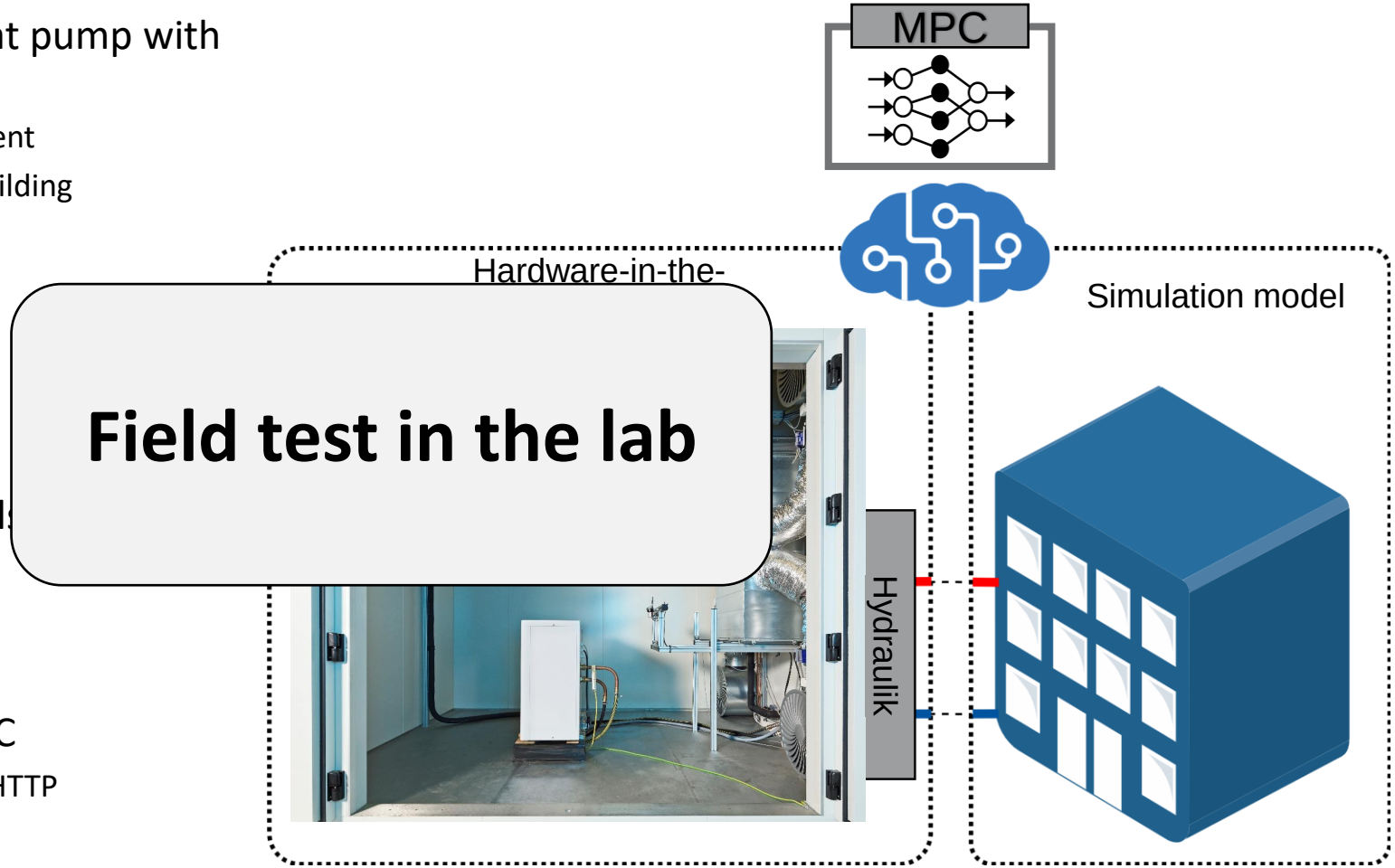

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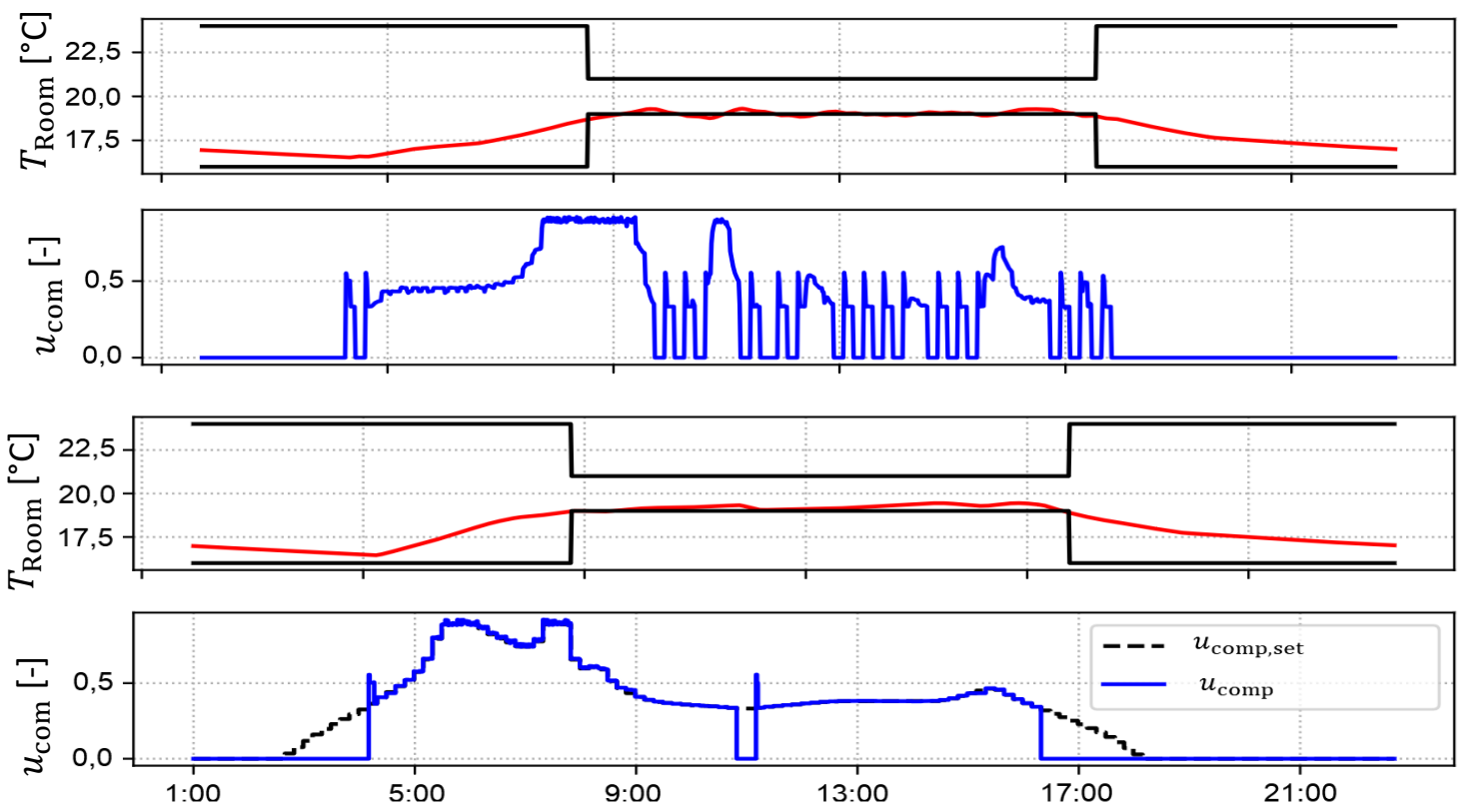
Experimental results of the winter day

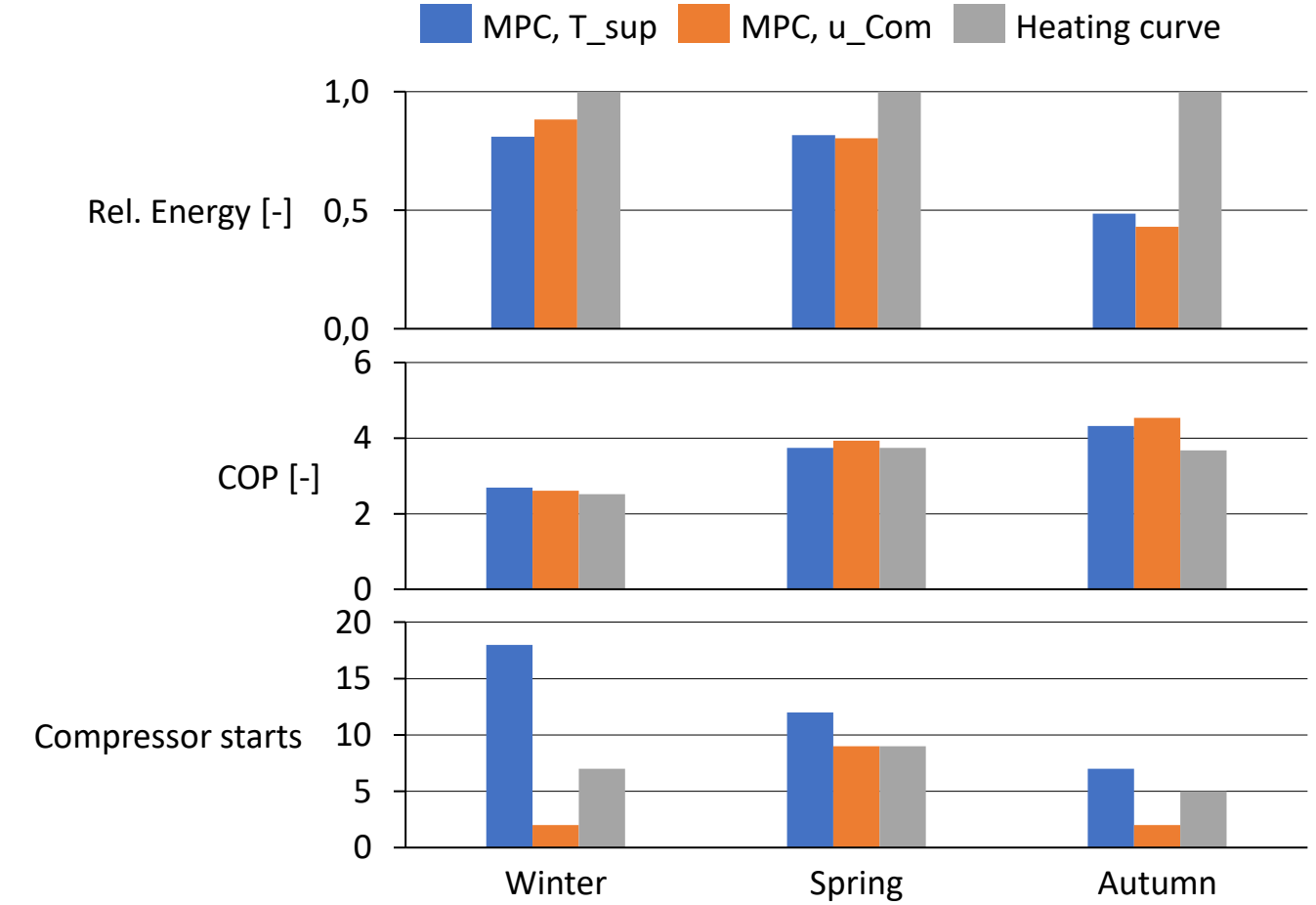
- Interface **supply temperature**
  - Well-controlled room temperature
  - Many compressor starts during low part-load operation

- Interface **compressor speed**
  - Well-controlled room temperature
  - Only two compressor starts in 24 h



Experimental results of reference days

- MPC reduces energy consumption
  - Greatest impact on spring and autumn days
  - Up to 48% energy savings per day
- Efficiency of the heat pump is influenced by the MPC:
  - Higher SCOPs due to the MPC compared to the heating curve
  - Improvement, especially on warm days
- Evaluation of operating behavior by number of start operations:
  - Interface supply temperature more start operations than heating curve
  - MPC compressor speed fewest start operations



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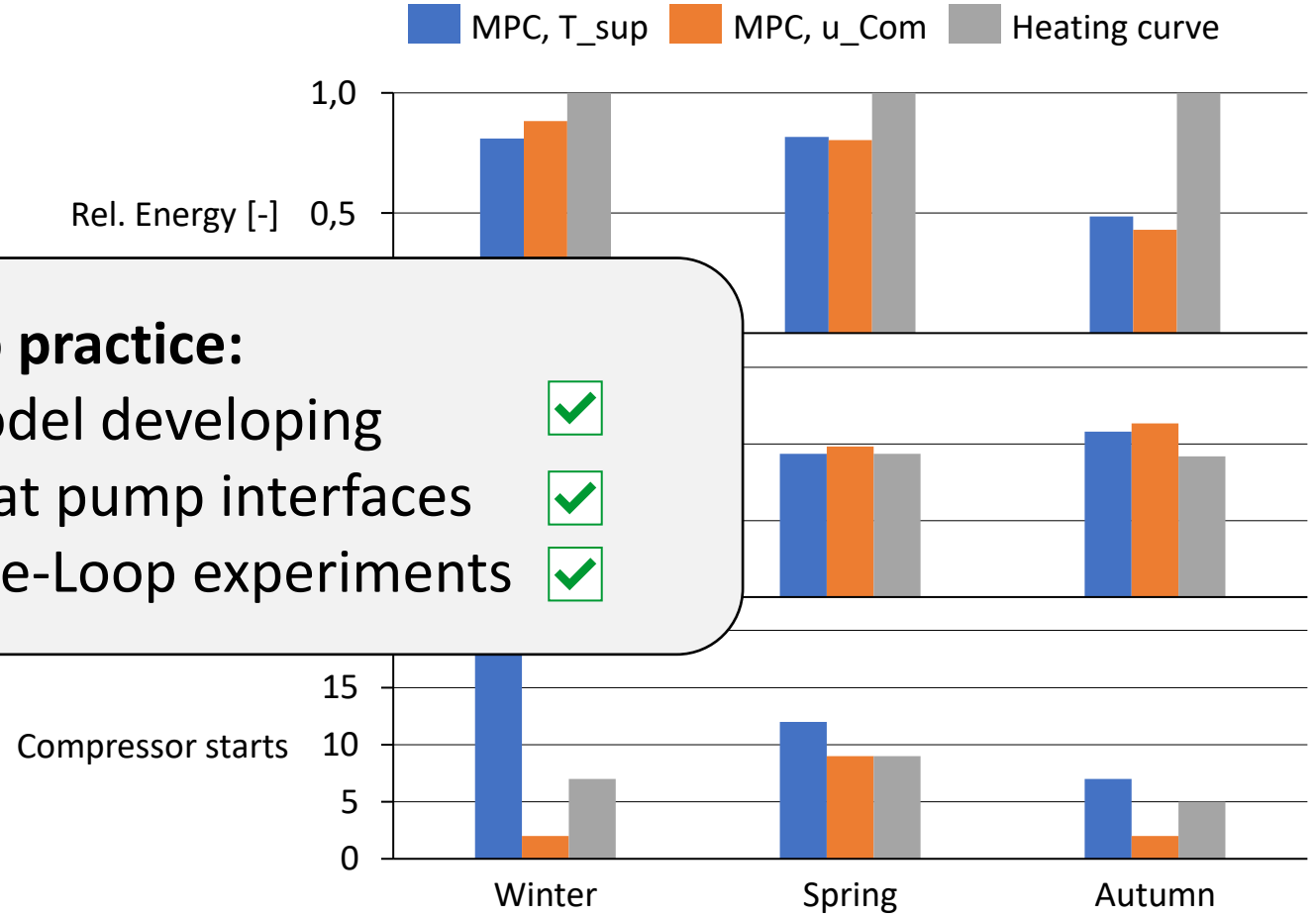

Findings of the work

Summary:

- Data-driven models reduce modeling effort
- Direct compressor speed control beneficial
- Experimental approved

Outlook

- Integration of further components, e.g., PV
- Persuade manufacturers for open interfaces
- Reproduce results in field test

Thanks for your attention!

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Projektträger Jülich
Forschungszentrum Jülich