FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE

Predictive control for capacity controlled heat pumps in smart grid

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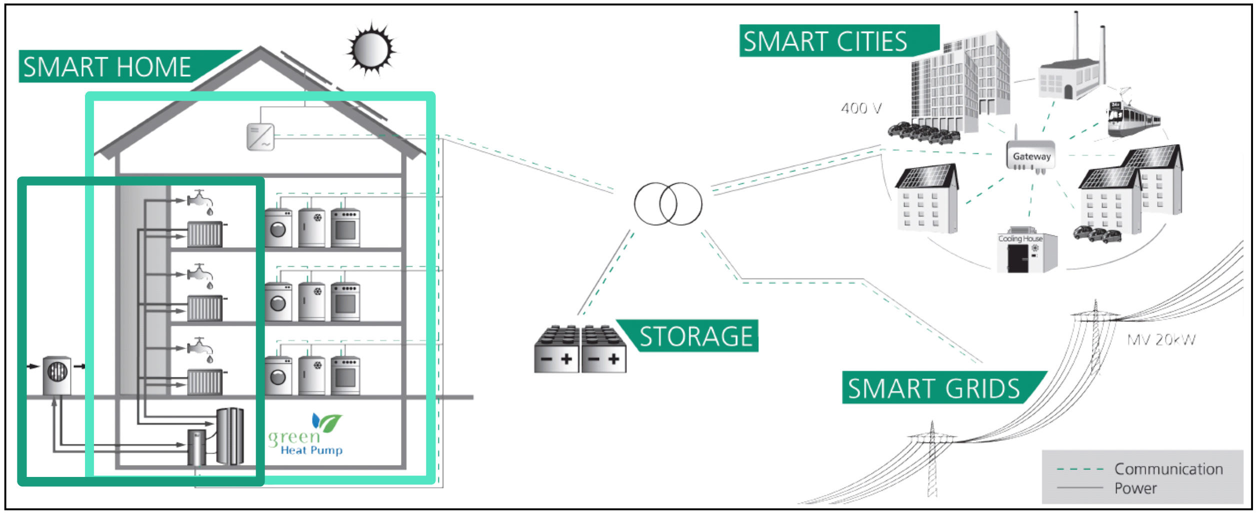
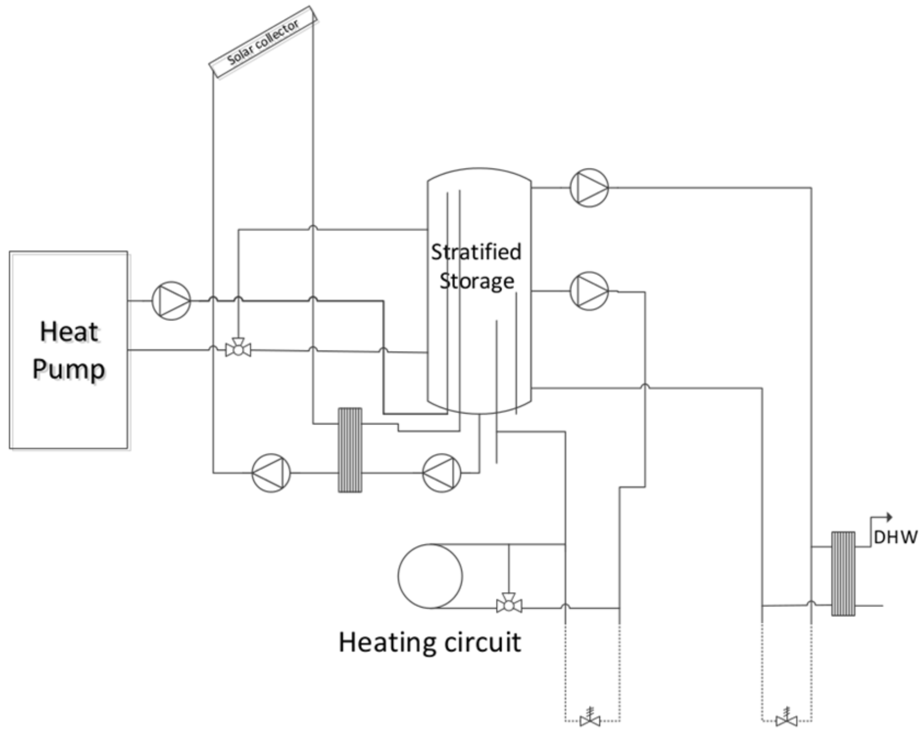
System Description
Motivation



- Residential heating system in smart grid scenario
  - Demand side management, load shifting
- Implementation – Python, ColSim (www.colsim.de), CVXOPT
- Main research questions:
  - Best optimal control problem formulation?
  - Modeling technique - approximating non-linearities

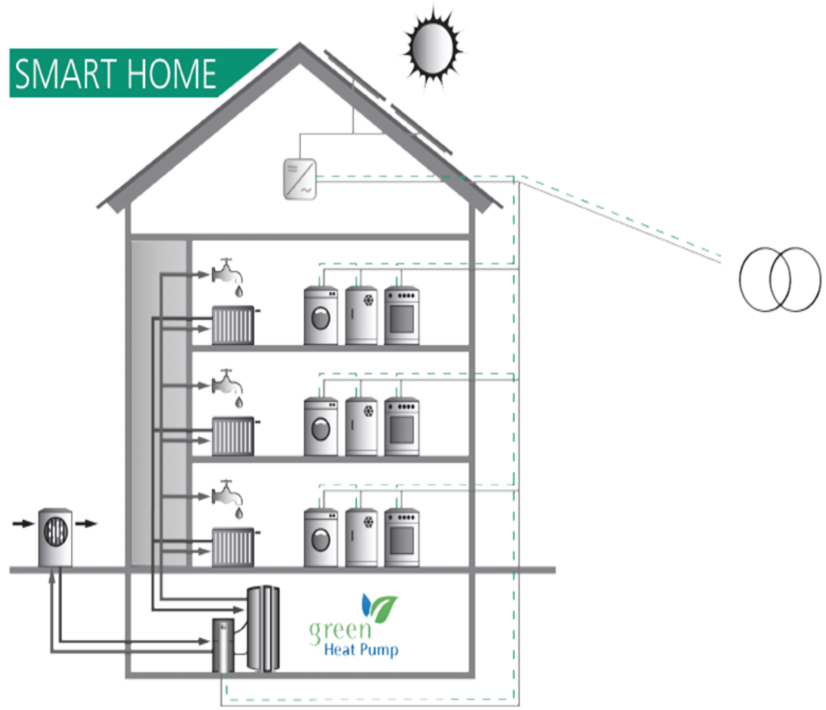
System Description

- System Components:
  - Thermal Storage (TES)
    - DHW, Space heating
  - Air-to-water Heat pump
    - Variable speed
    - 2 operating modes (T_{sup})
  - Building
  - Auxiliary heater
  - Solar devices
    - Thermal collector
    - PV panels



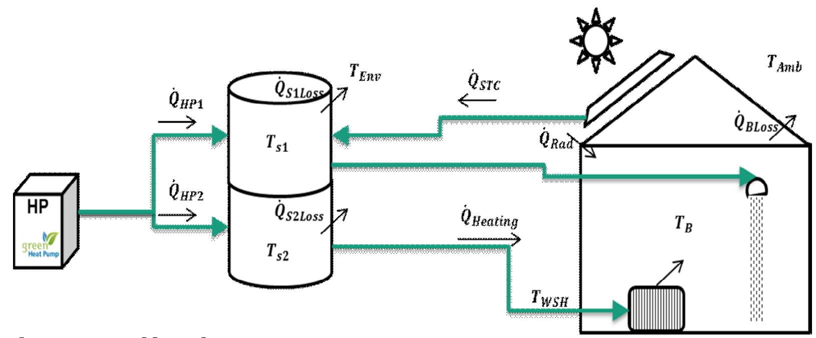
Optimization Goals

- Money spent for heating
  - In scenario: dynamic tariffs, weather and loads
- Control objectives:
  - Optimal operating points for HP, storage
  - Operating mode DHW/Htg
  - Optimal use of solar power
    - Feed-in, self consumption
  - Constraint handling
- Supervisory control strategy
- Controller: MPC



Key performance indicators
Heating electricity consumption
Money Spent on heating
Seasonal performance factor
No. of on-off switching of HP
Storage Losses
Solar power consumption

MPC Problem Formulation
Models

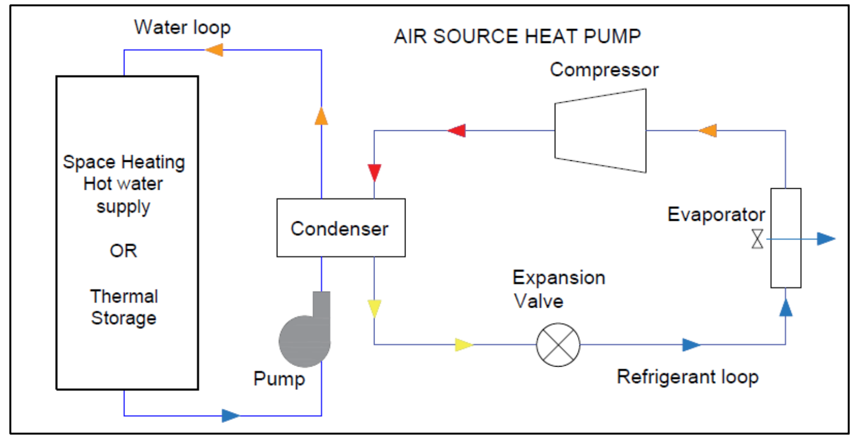


- Deterministic case study – perfect model, predictions
  - Theoretical benchmark / Performance bound
- Model: LTI state-space $\dot{x} = Ax + Bu + Ez$
- Lumped thermal energy balance equations
- States(x): T_{s1}, T_{s2} and T_B Inputs(u): $\dot{Q}_{HP_i}, \dot{Q}_{heating}, \dot{Q}_{BH_i}$ and $\dot{Q}_{STC}$
- Predicted disturbances (z): Heat losses – storage, building

$$\begin{bmatrix} \dot{T}_{s1} \\ T_{s2} \\ T_B \end{bmatrix} = \begin{bmatrix} \frac{-ks \cdot As_1}{C_{s1}} & 0 & 0 \\ 0 & \frac{-ks \cdot As_2}{C_{s2}} & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T_{s1} \\ T_{s2} \\ T_B \end{bmatrix} + \begin{bmatrix} \frac{1}{C_{s1}} & 0 & \frac{1}{C_{s1}} & 0 & \frac{1}{C_{s1}} & 0 & \frac{1}{C_{s1}} & 0 \\ 0 & \frac{1}{C_{s2}} & 0 & \frac{1}{C_{s2}} & 0 & -\frac{1}{C_{s2}} & 0 & \frac{1}{C_{s2}} \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{C_B} & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{Q}_{HP_1} \\ \dot{Q}_{HP_2} \\ \dot{Q}_{PV_1} \\ \dot{Q}_{PV_2} \\ \dot{Q}_{STC} \\ \dot{Q}_{htg} \\ \dot{Q}_{BH_1} \\ \dot{Q}_{BH_2} \end{bmatrix} + \begin{bmatrix} -\frac{1}{C_{s1}} & \frac{k_s \cdot As_1}{C_{s1}} & 0 & 0 \\ 0 & \frac{k_s \cdot As_2}{C_{s2}} & -\frac{1}{C_{s2}} & 0 \\ 0 & 0 & 0 & \frac{1}{C_B} \end{bmatrix} \begin{bmatrix} \dot{Q}_{DHW_1} \\ T_{env} \\ \dot{Q}_{DHW_2} \\ \dot{Q}_{B_{loss}} \end{bmatrix}$$

MPC Problem Formulation
Heat pump

- Variable speed
- HP model (COP):
  - Manufacturer data
  - Equation-fit model
  - Simplified non-linear model
  - Dead zone - not modeled



Compressor frequency
Load, source side Temp.

Inputs/measurements

Heat pump model

Heat Supplied ($\dot{Q}_{HP}$)

Power consumed (P_{el}), **COP** = $\frac{\dot{Q}_{HP}}{P_{el}}$

Outputs

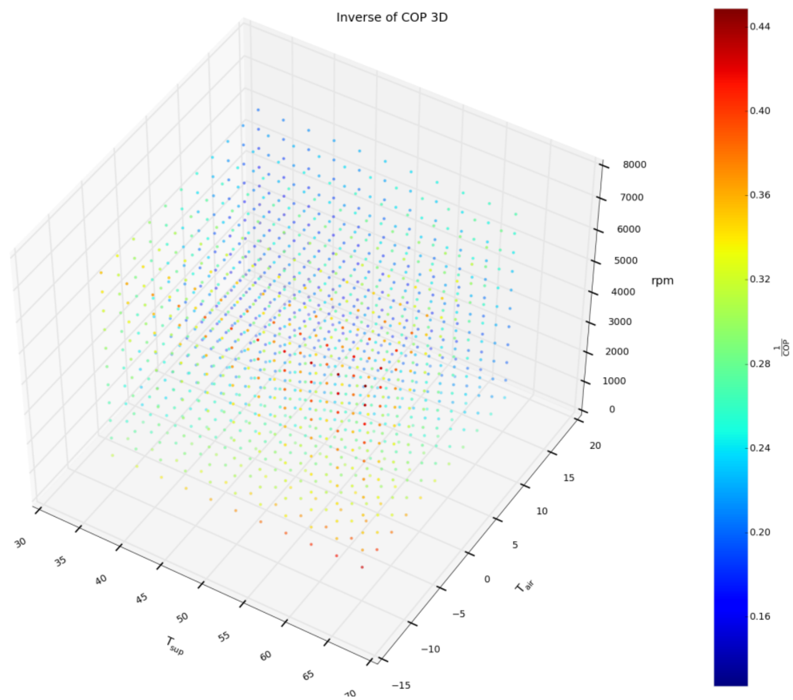
COP = Coefficient of Performance

MPC Problem Formulation
Characteristics

- HP characteristics:
  - Dead zone
  - Non-linear model:

$$P_{el_{HP}} = \frac{\dot{Q}_{HP}}{COP_i}$$

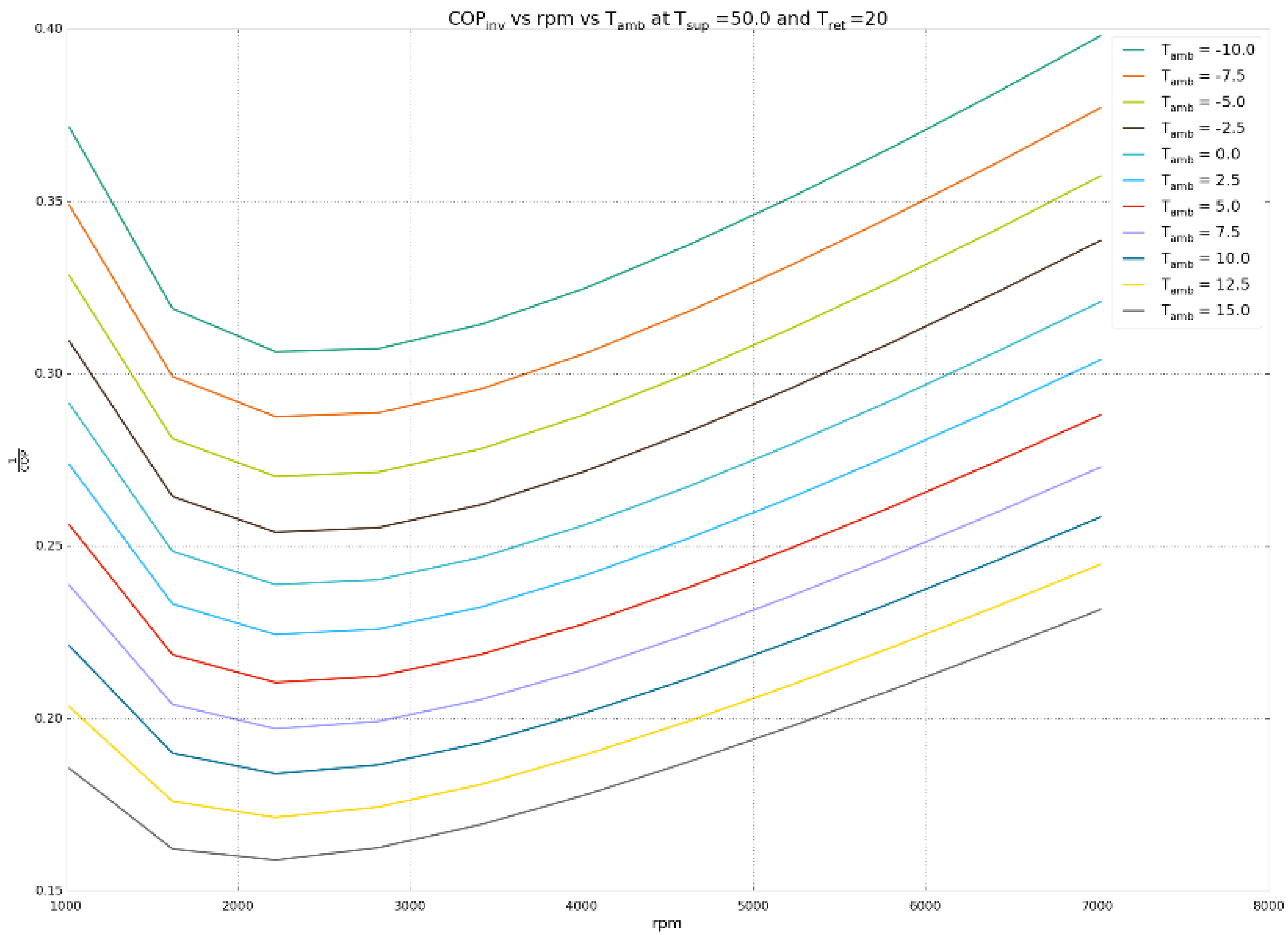
  - COP_i = f(x, u, Tamb)



- HP model to calculate:
  - Electricity consumed → Bill

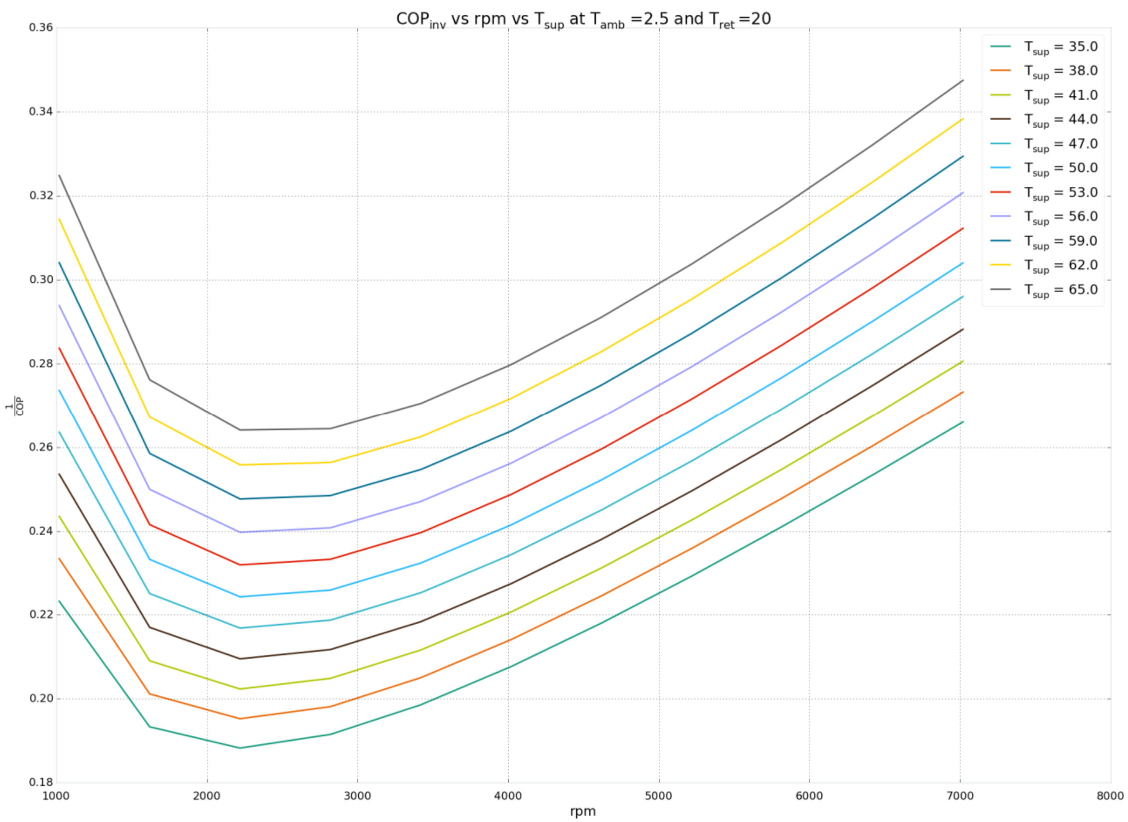
- Inverse of COP

COP inverse



- Nonlinear relation with rpm; almost linear with T_{amb} & T_{sup}

COP inverse



- Nonlinear relation with rpm; almost linear with T_{amb} & T_{sup}

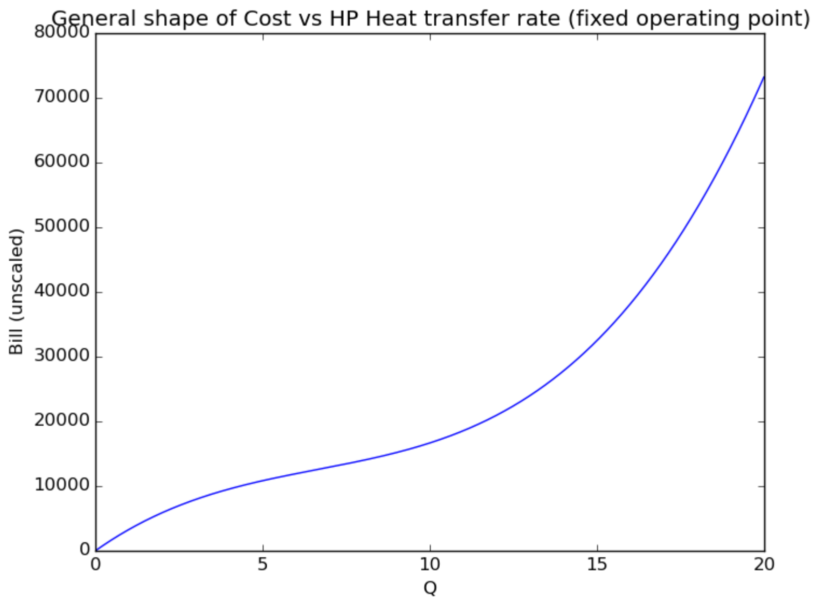
MPC Problem Formulation

- Nonlinear non-smooth objective function:

$$\min_{u} J(x_0, u) = \sum_{k=0}^{N-1} eCost * Pel$$

s.t.: $x_{k+1} = A_d x_k + B_d u_k + E_d z_k$

- Constraints: Input, state bounds
- Global optimization problem, MINLP
- Convex approximations:
  - Linearized COP about expected operating point
  - Modification: zone causing non-convexity (shape in plot)
- Formulations tried: LP, QP
- Tuning



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$\frac{1}{2}\mathbf{x}^T Q\mathbf{x} + \mathbf{c}^T\mathbf{x}.$

Performance

- Results with QP formulation (solver: CVXOPT)
  - Considering objectives
  - COP (inverse) predefined from predicted T_{amb} and linearized model
  - Partially neglecting dependency on supply temperature T_{sup} and part load
    - $\frac{1}{COP} = \frac{1}{(c_1 + c_2 T_{amb} + c_3 T_{s_{lb}})(1 + c_4 \frac{Q_{opt}}{Q_{max}})} = C_0$
  - COP inverse coefficients (C_0) squared

$$\min_{U} \sum_{i=0}^{N-1} U_i^T P_i U_i + q_i^T U_i$$
$$s.t.\ G * U \leq h, G_e * U = h_e$$

- $P_i = r_1 * \begin{bmatrix} eCost_{ui} * C_{0\,ui}^2 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & eCost * C_{0\,un}^2 \end{bmatrix}$ $q_i = r_2 * \left[eCost_{ui} * C_{0\,ui}^2 \quad \ldots \quad eCost_{ui} * C_{0\,un}^2 \right]^T$
- Lower penalty on solar variables and higher on auxiliary heater inputs
- Other formulations tried: Only linear/ only quadratic weights

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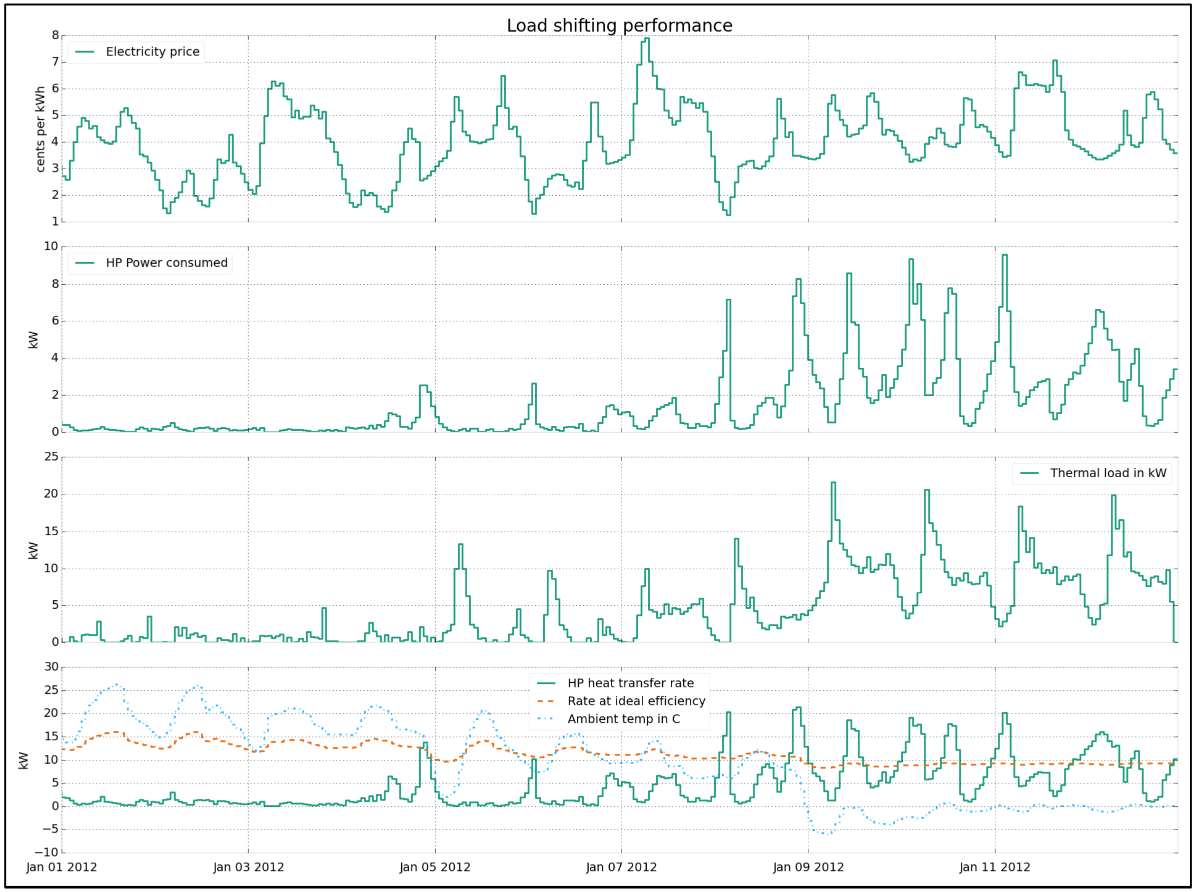
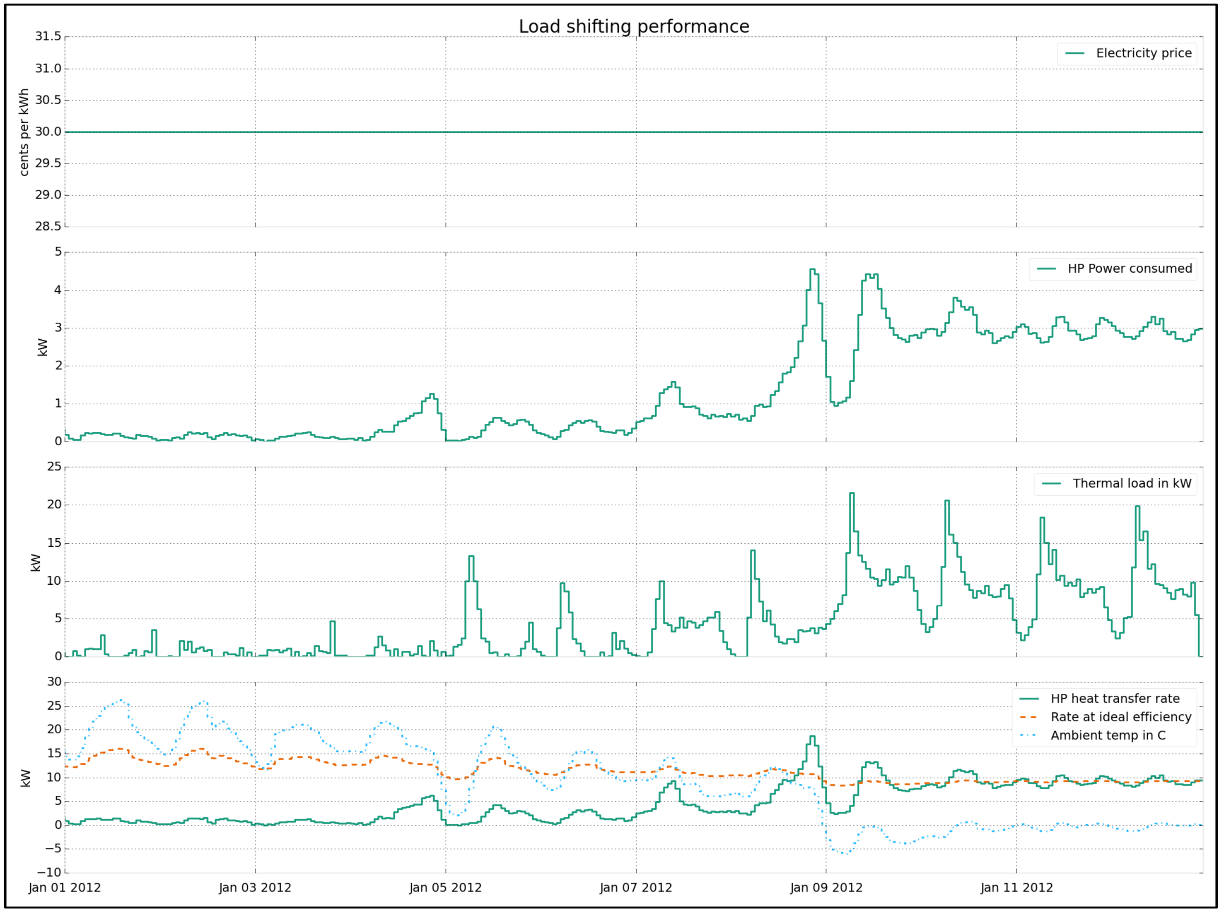
Performance
Plots

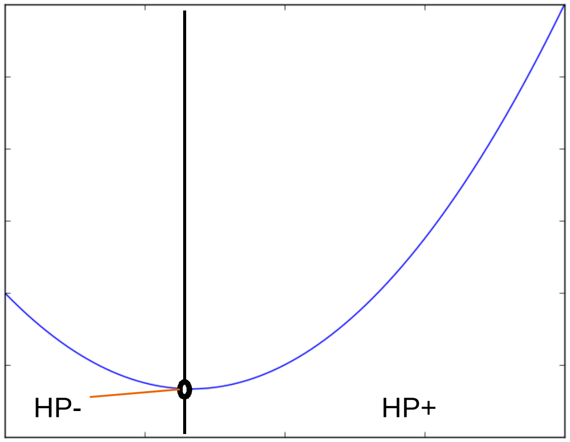


Performance
Plots



Performance

- Ideas implemented:
  - Goal oriented tuning (of P, q)
  - Modeling objective function (electricity bill)
    - HP model, COP
  - Split inputs in zones
  - Post processing step (without influencing MPC)
    - When $\dot{Q}_{HP} < \dot{Q}_{opt}$ (switch optimal rpm)
    - 10 to 17% higher savings
    - Limitation: Frequent switching
  - Soft constraints approach:



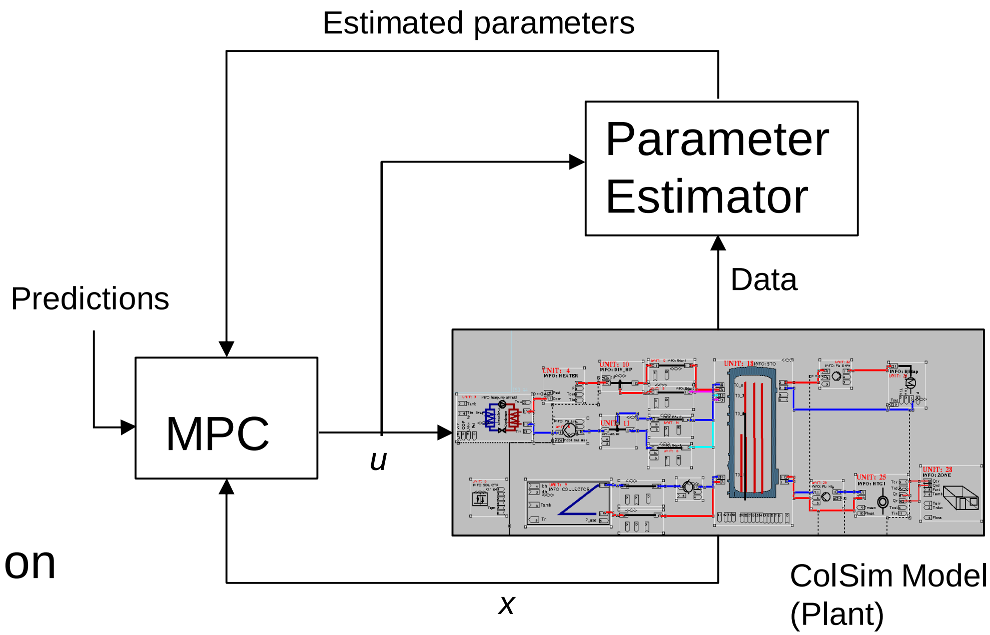
$$J_{soft} = J + \sum_{i=0}^{N-1} \epsilon^T W \epsilon + w\epsilon$$

$$x_{lb_i} - \epsilon_{lb} \leq x \leq x_{ub_i} + \epsilon_{ub}$$

$$\epsilon = [\epsilon_{lb} \quad \epsilon_{ub}]^T$$

Adaptive model

- Future problems:
  - Model mismatch
- Adaptive MPC:
  - Online parameter estimation
  - Recursive least squares
- Expected benefits:
  - Wider application of same strategy
  - Better performance of MPC (model accuracy)



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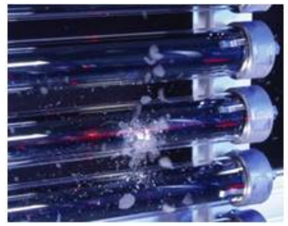
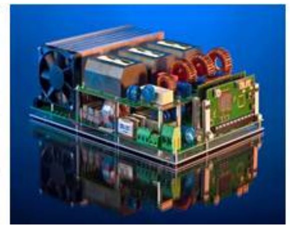
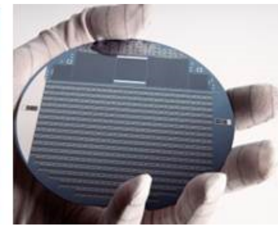
Conclusions

- Lessons learned:
  - Performance dependence on COP model
  - Solver (cvxopt) issues faced:
    - Scaling sensitivity
    - Limited warnings
- Challenges:
  - Post-processing: Frequent switching
  - Simple models for Heat pump
  - Model mismatch
- Discussion:
  - Limitation – on-off switching frequency of heat pump
  - Is nonlinear optimization a better option? Fast, reliable open-source NLP solver?

Thank you for your attention!

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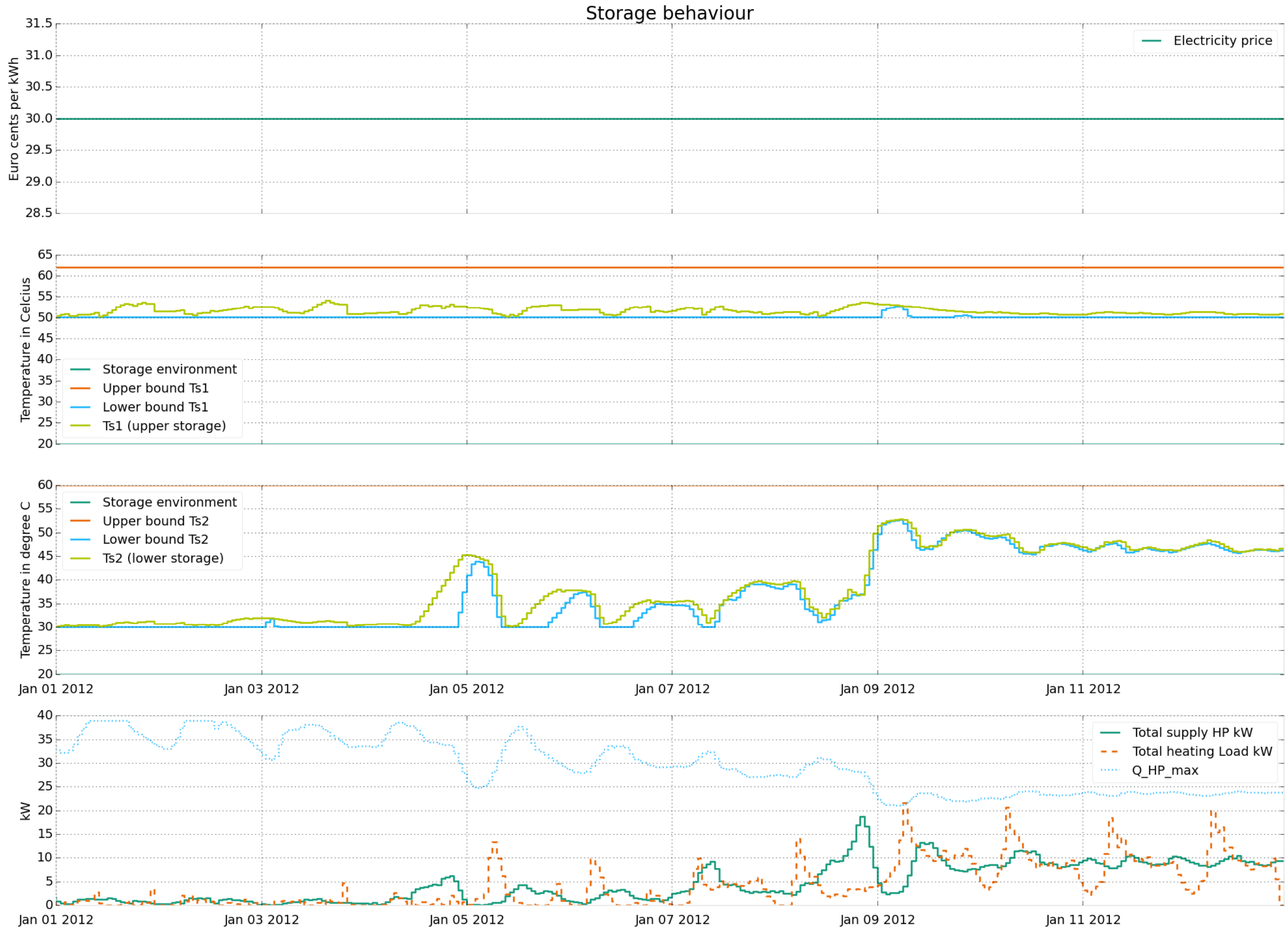
Performance

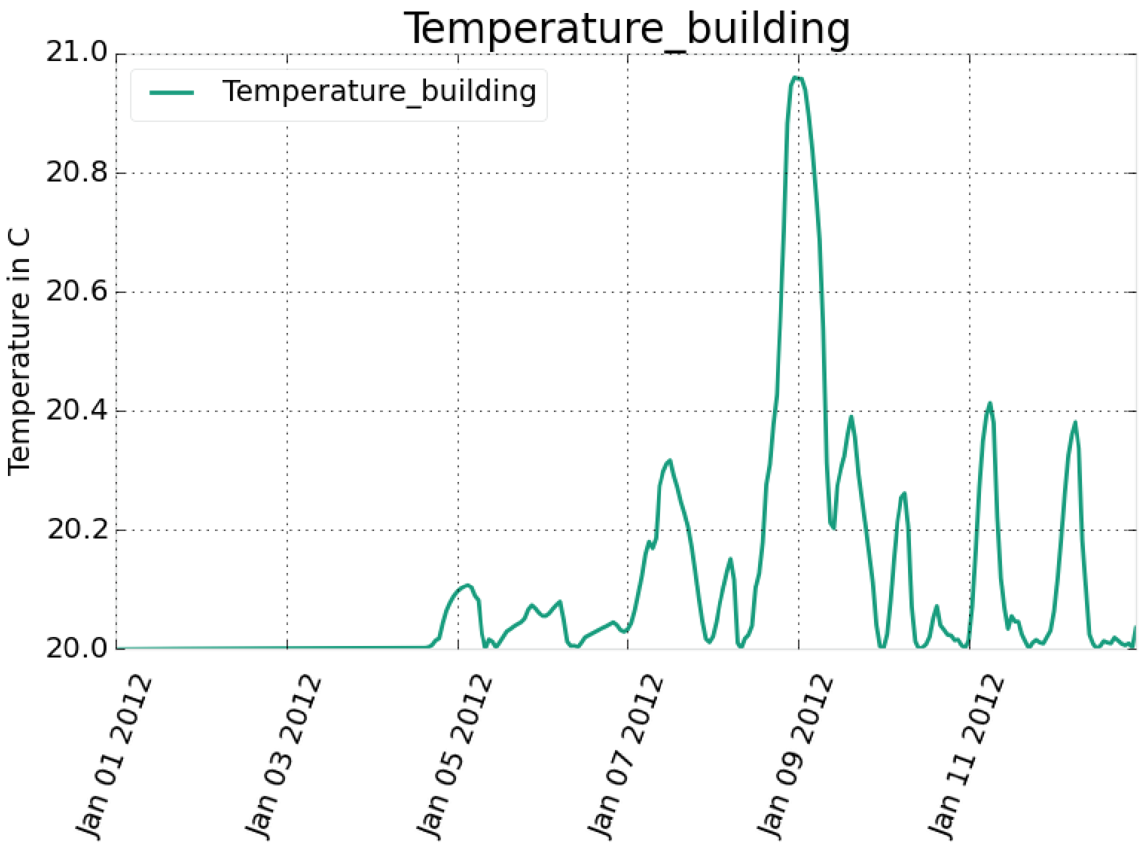
Plots – constraints



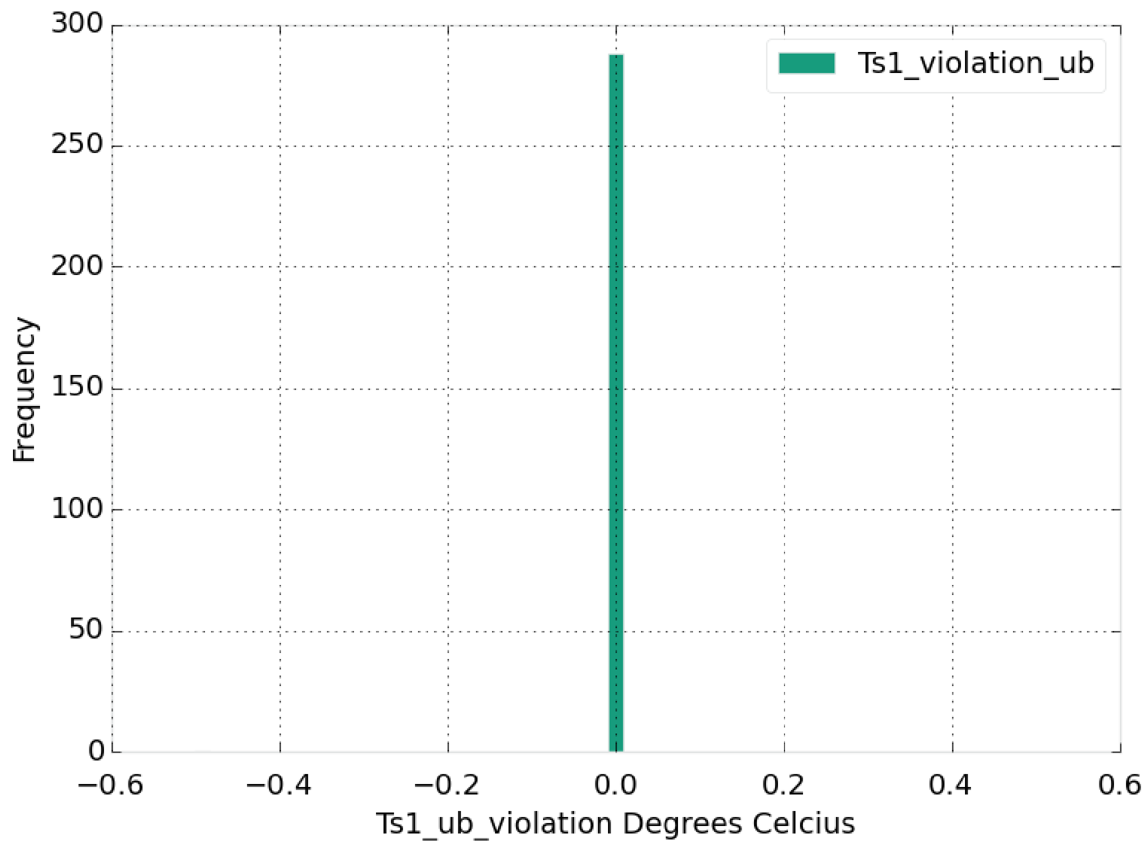
Performance

Plots

Performance
Plots - Comfort



Performance
Plots - Comfort



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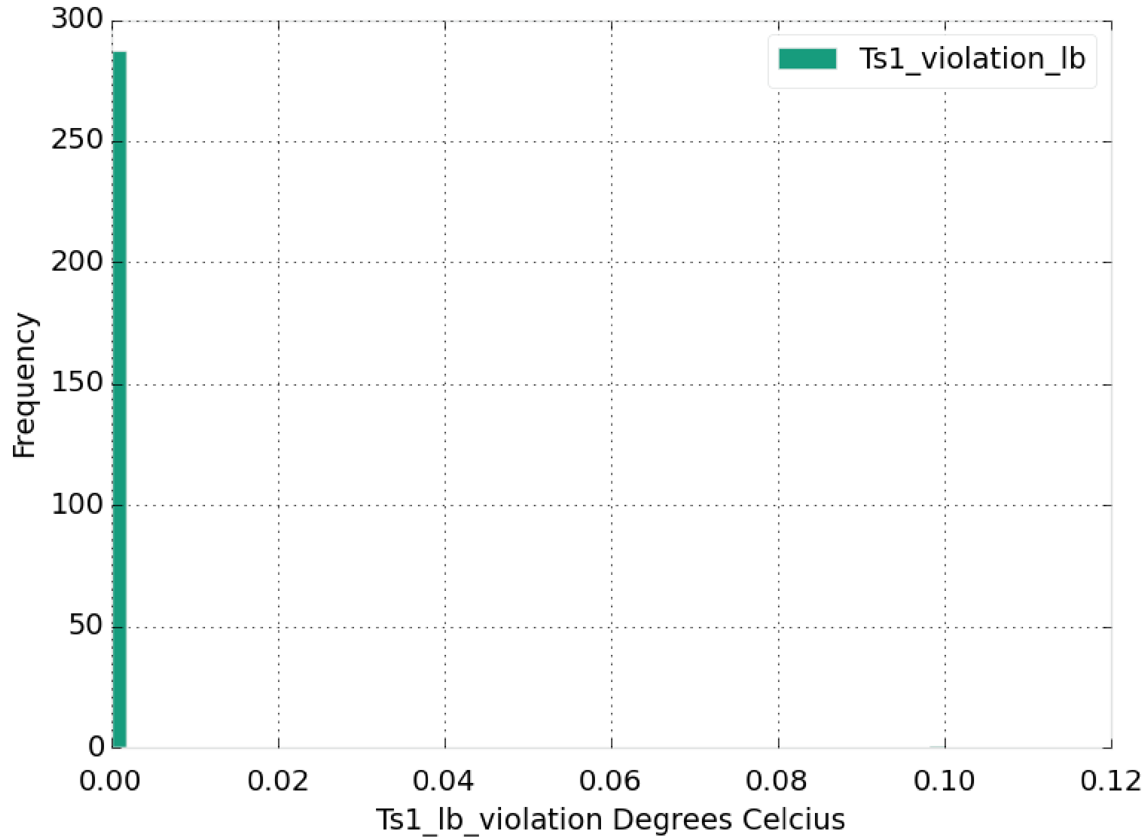
Plots - Comfort



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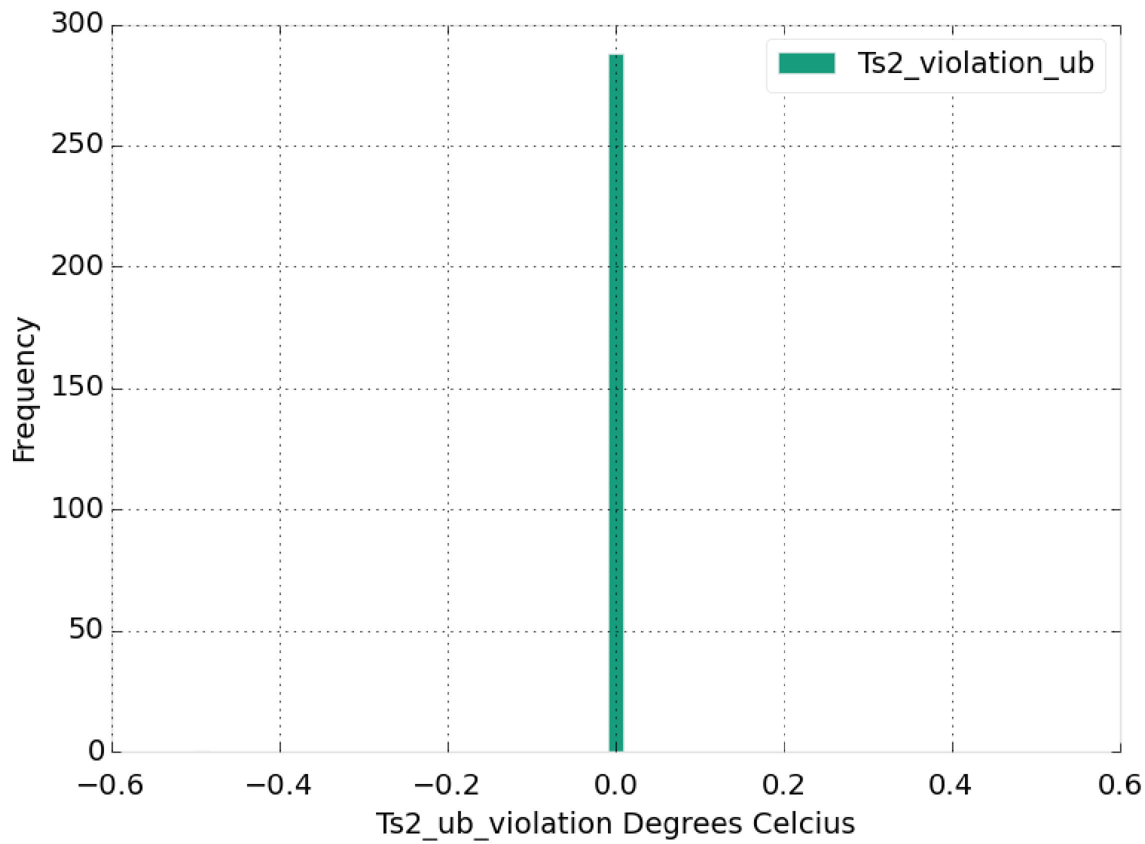
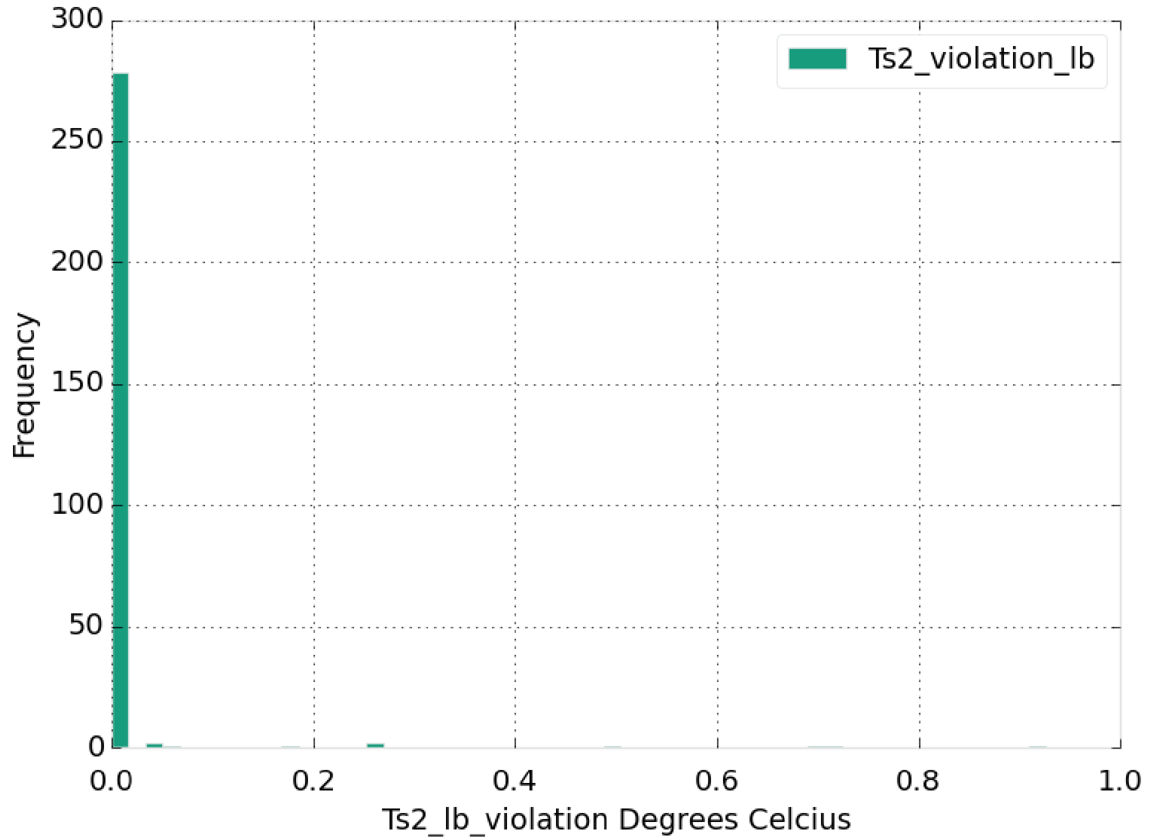
Plots - Comfort



Performance
Plots - Comfort



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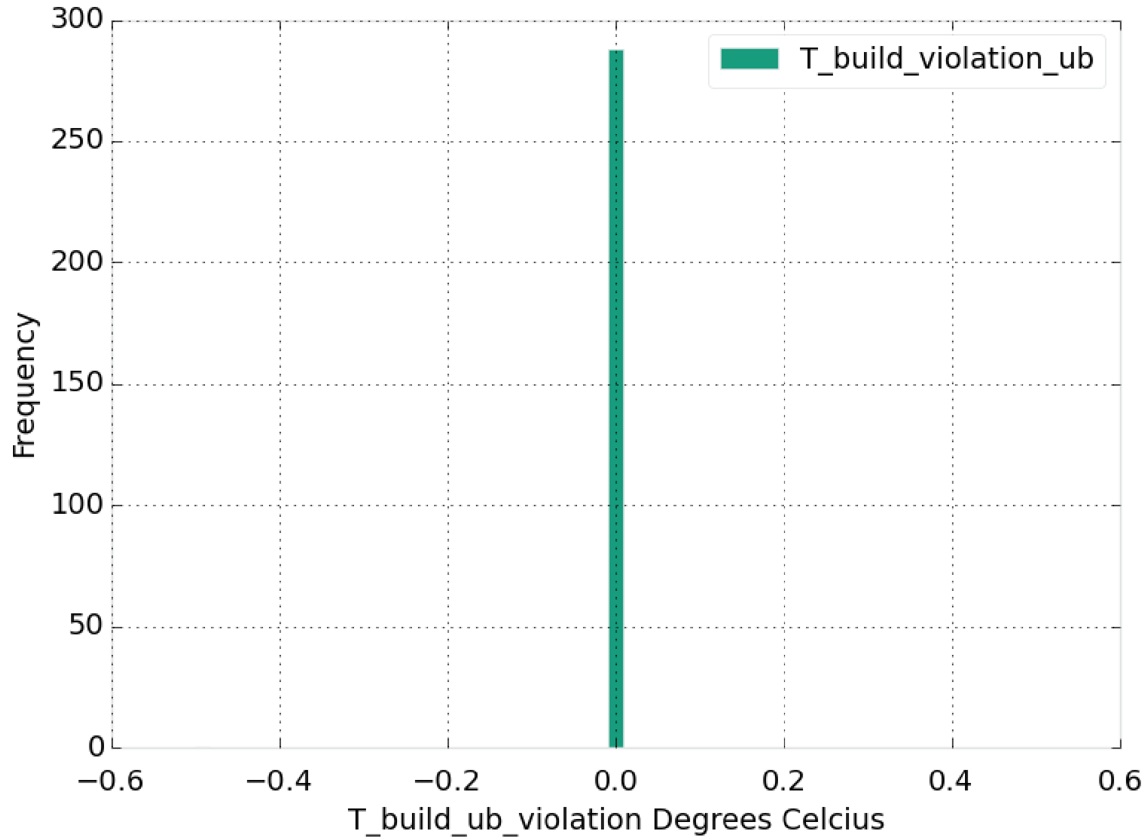

Performance
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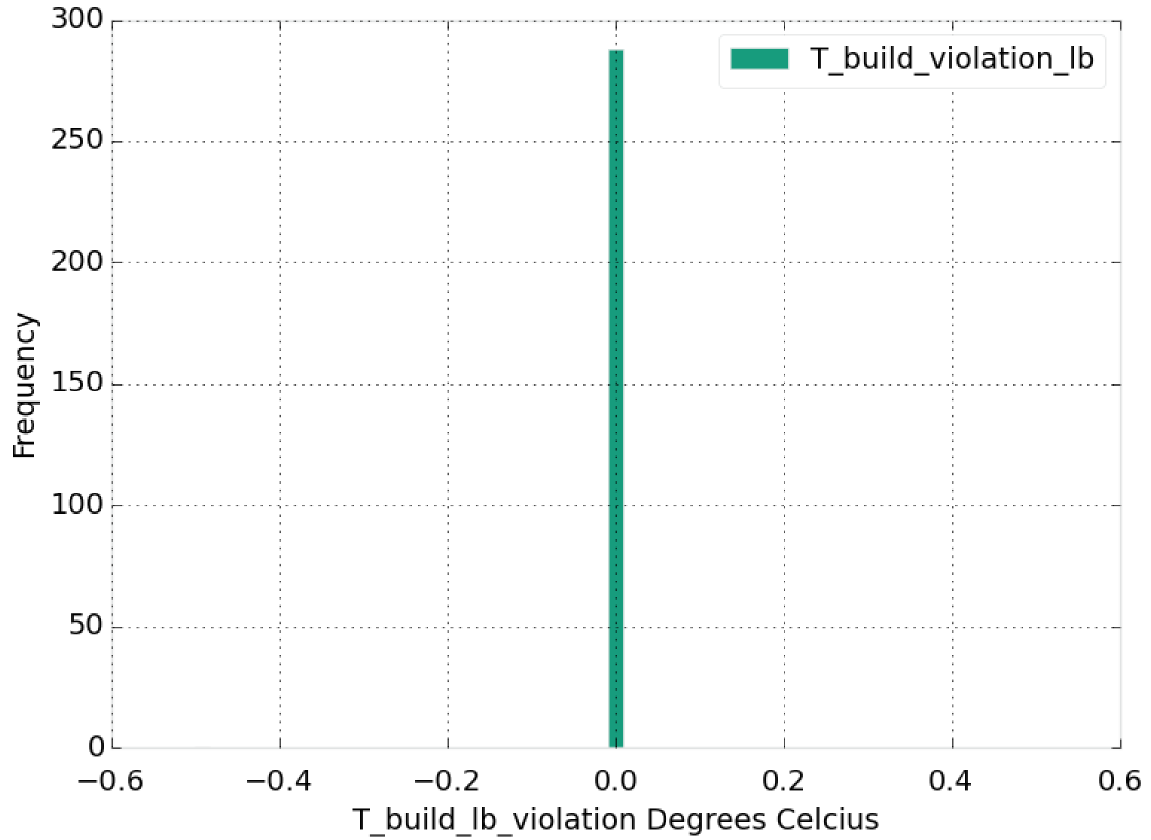

2012 data

- Target system: German multi-family houses
- Data: 12 representative test days (year 2012, location: Potsdam)
- eCost: EEX price (European Energy eXchange)