Practical implementation and evaluation of Model Predictive Control (MPC) for an occupied office building in Brussels

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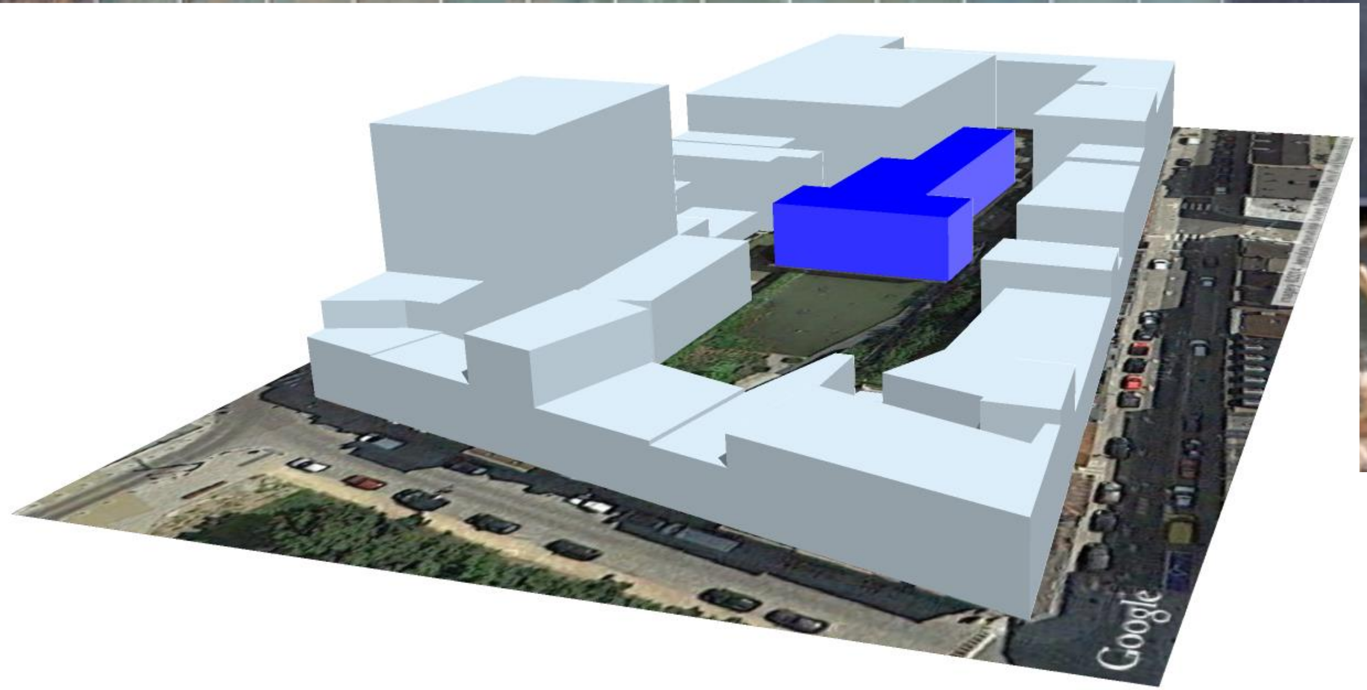
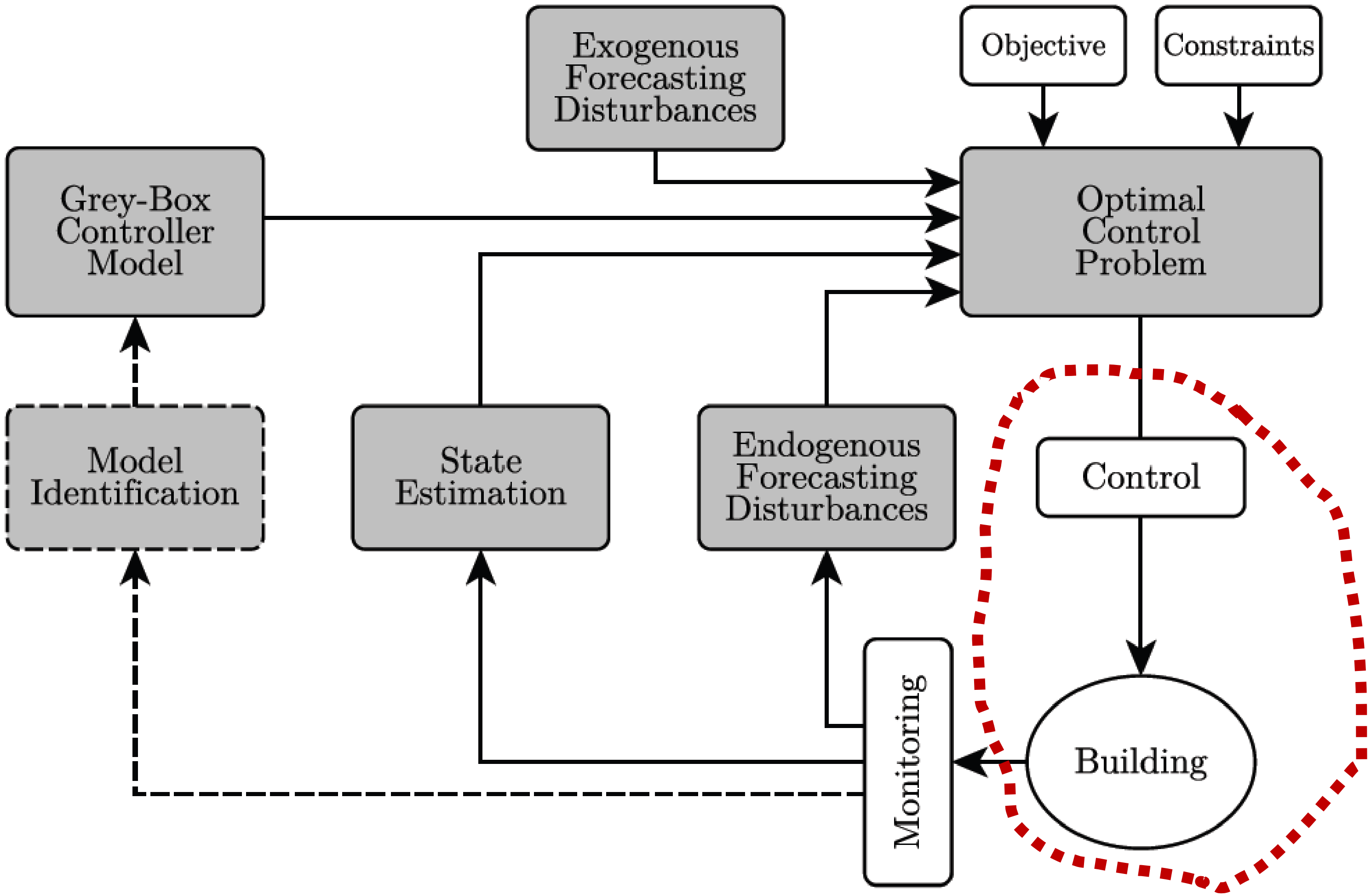
Optimal control of thermal systems in buildings using Modelica
Freiburg, 23-24 March 2015


3E

Google

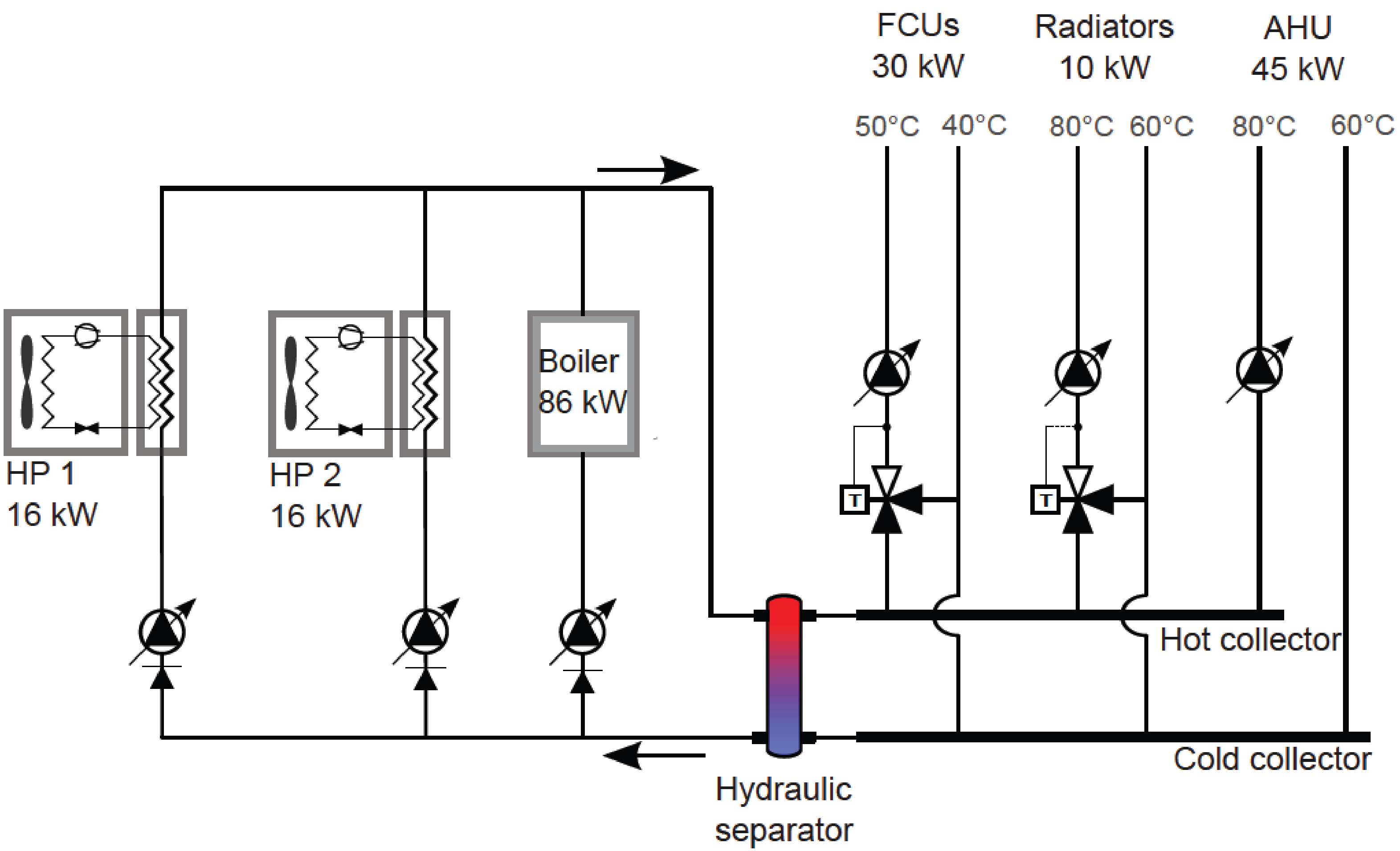
MPC framework



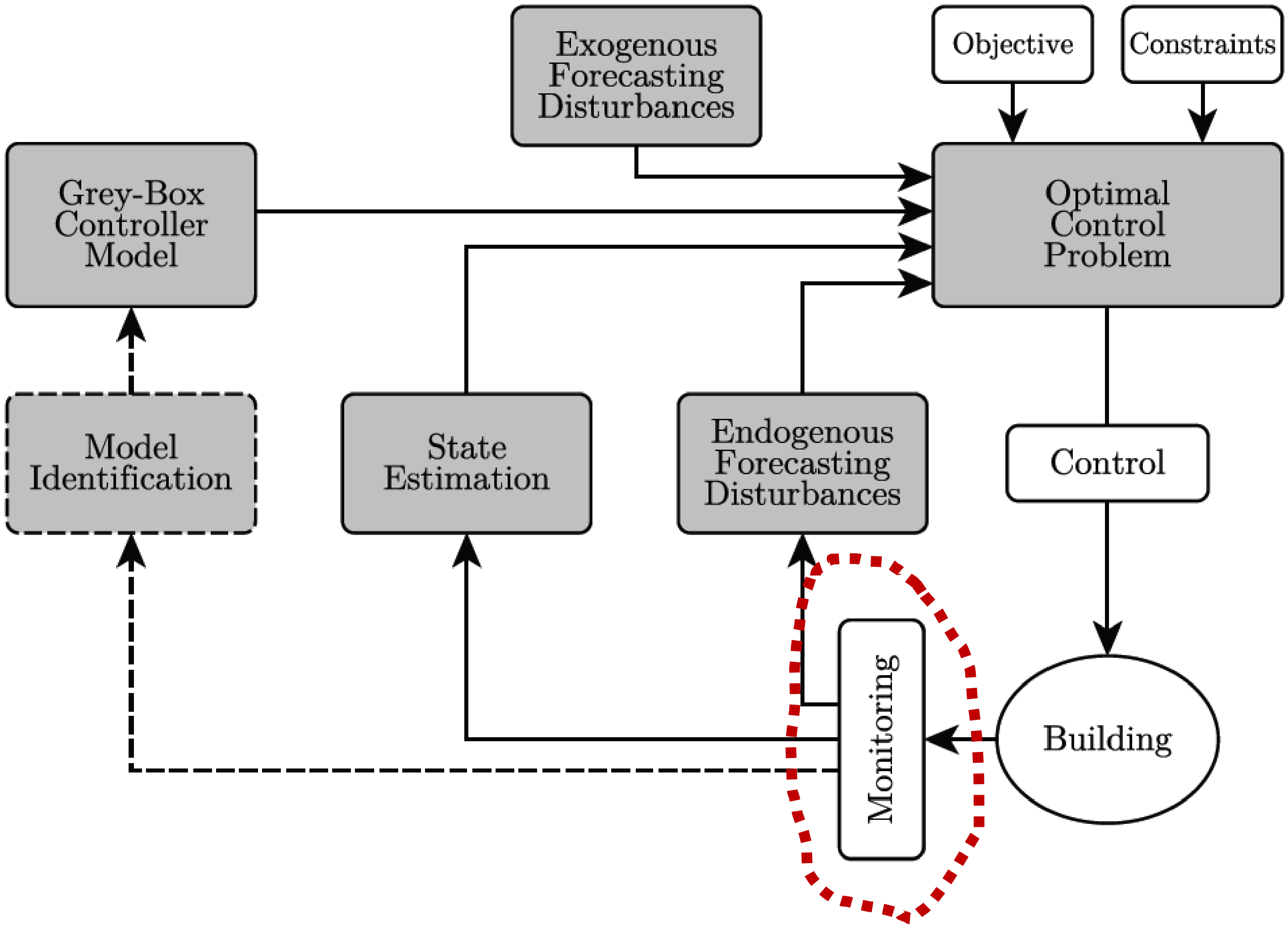
Kalkkaai building

- 2 floors of 480 m^2 each
- Only west-façade has high glazing fraction
- Landscape type offices on ground floor
- Individual / small landscapes / meeting rooms on 1^{st} floor
- Occupation: 40-70 persons, office hours
- Hybrid heating system
- Condensing gas boiler, 86 kW
- 2 identical air/water heat pumps, 16 kWth each

Hybrid heating system



MPC framework



Monitoring systems

Monitoring systems

Monitoring systems

HVAC monitoring

- Temperatures, thermal fluxes, electrical power
- Pull data from BEMS and put in Kairos TSDB (15s)

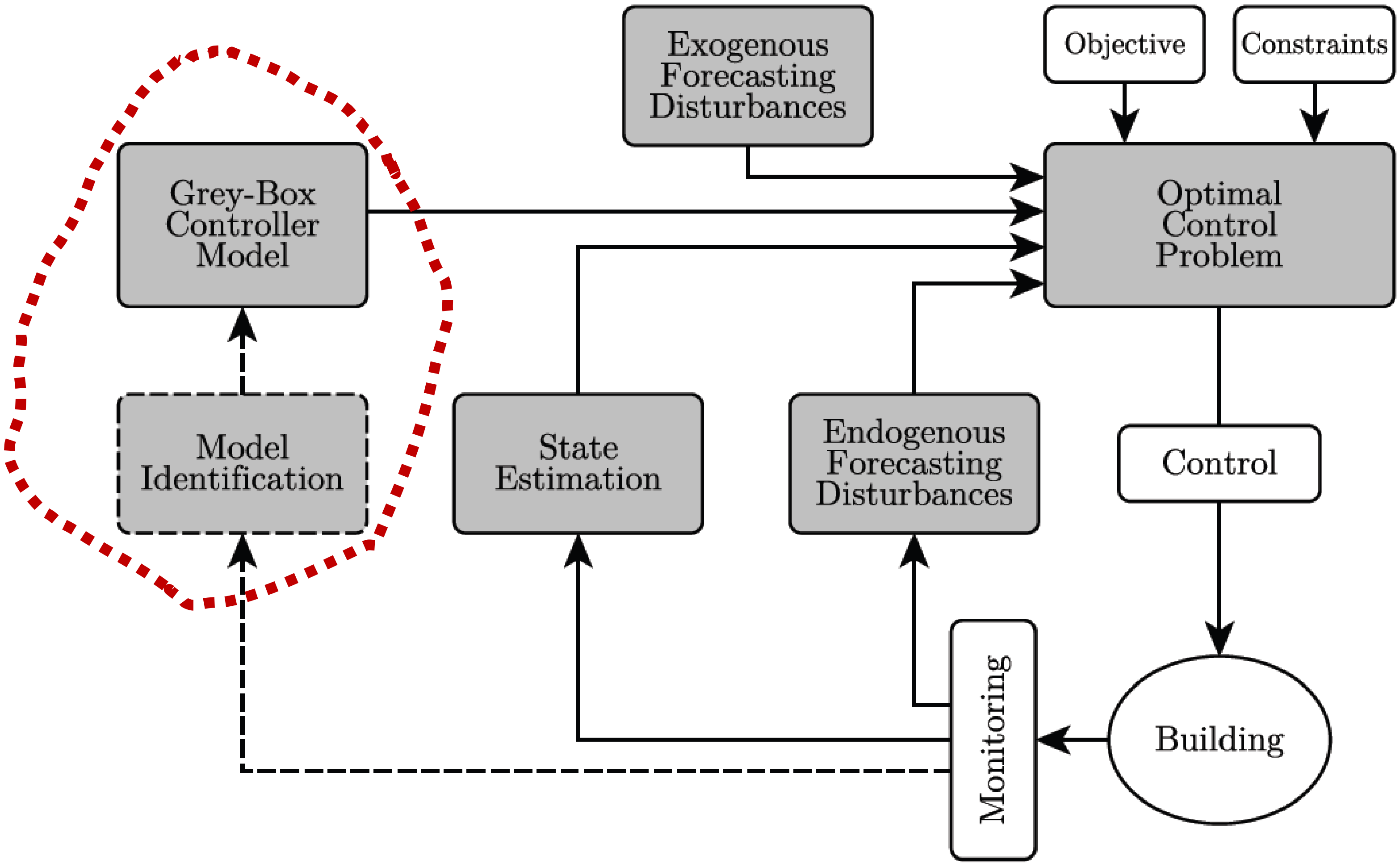
Building monitoring

- Temperature, humidity, electricity consumptions (many submeters)
- Bad resolution (15 minutes – 1 hour)
- Pull data (http requests) and put in Kairos TSDB

Weather data

- Meteo service (University Oldenburg)
- Files on FTP → processing and on Kairos TSDB

MPC framework



Selecting disturbances

Weather

- Ambient temperature: locally measured
- Solar radiation: start with global horizontal

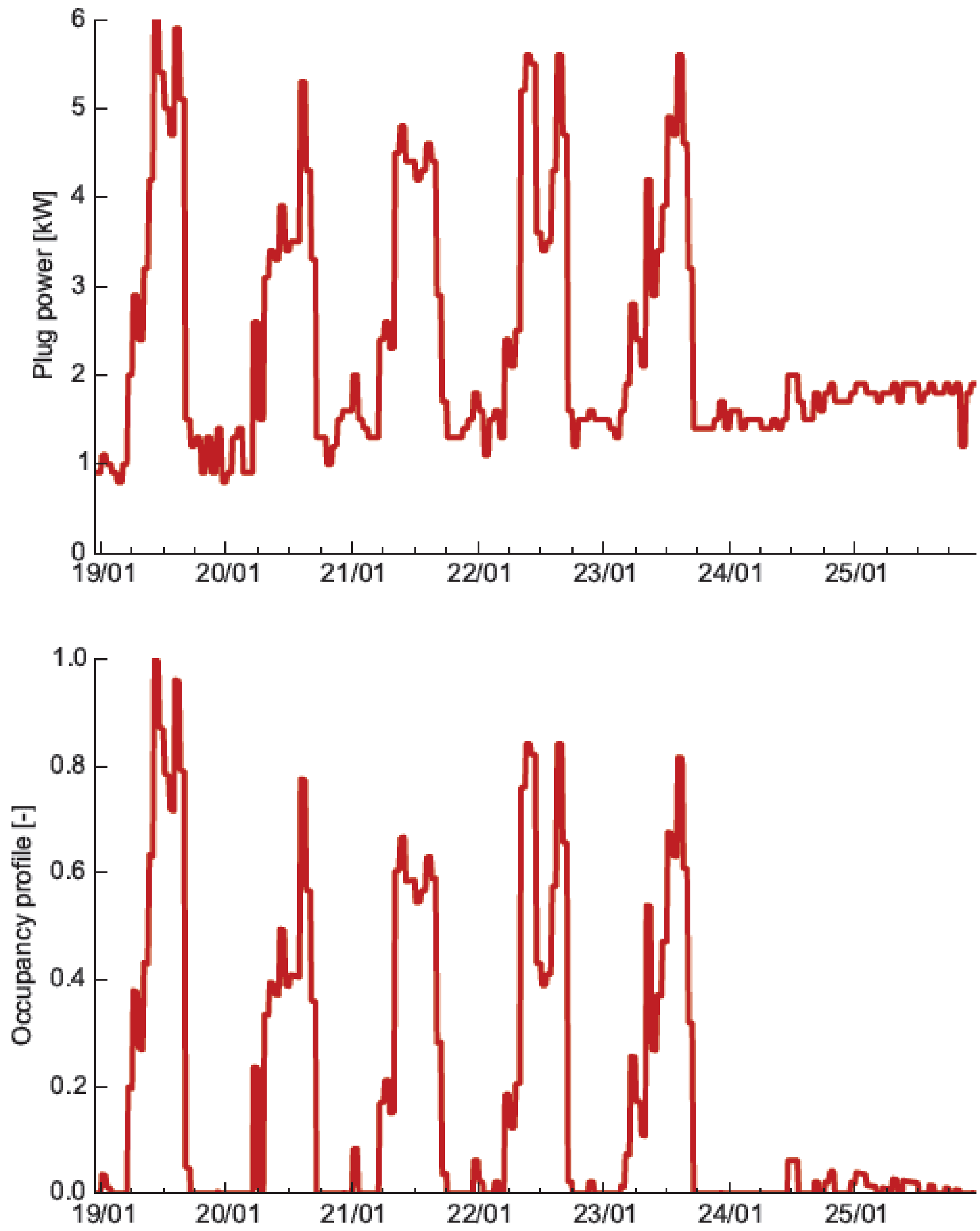
Building

- Zone temperature: arithmetic mean of 5 zones
- Heating power: total emission by 3 circuits
- Air handling unit: schedule from monitoring data
- Internal gains: electrical appliances and body heat gains

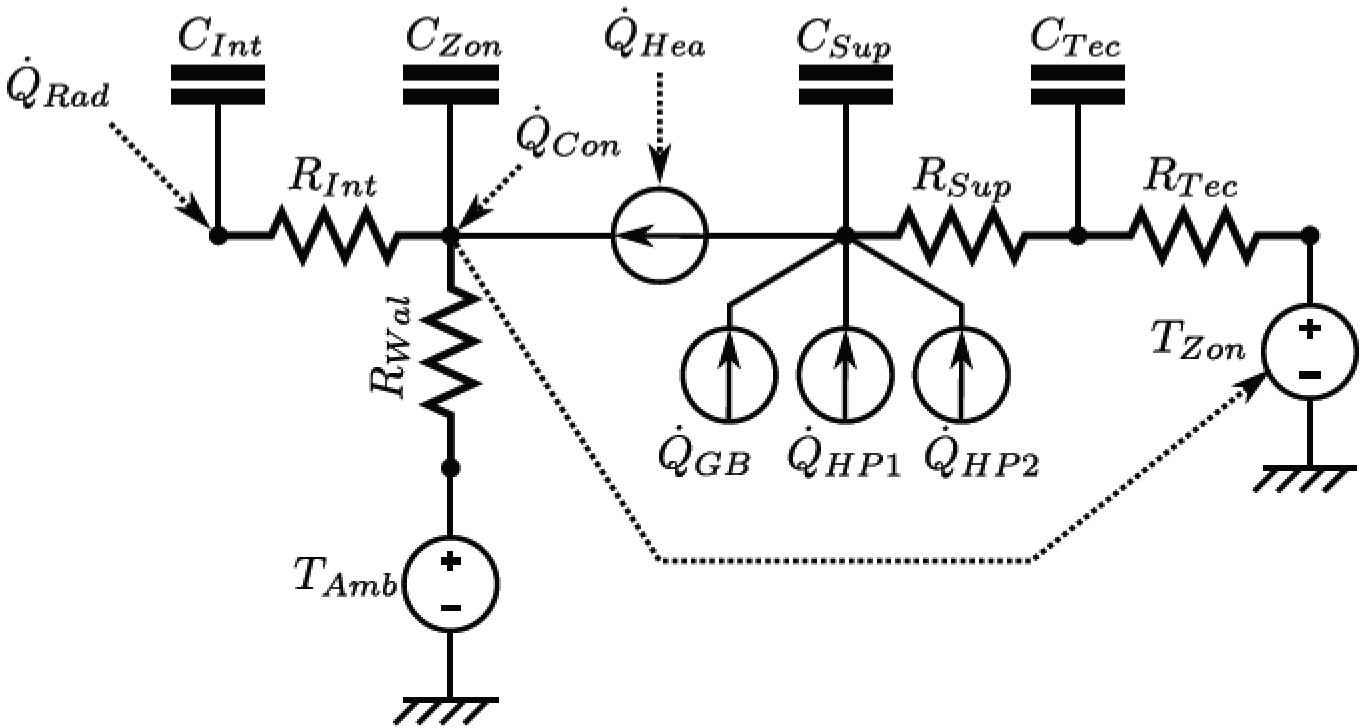
Electricity measurements:
All - HVAC

Occupancy from plug power

Occupancy profile



Control model: building



4 control variables in optimal control problem (OCP)

Control model: HVAC efficiencies

$$
\begin{aligned}
\eta &= 0.87 - 8.85e^{-7}\dot{Q}^*_{GB} + 4.82e^{-3}T^*_{Amb} \\
COP_{HP1} &= 2.61 + 5.45e^{-2}T^*_{Amb} - 1.23e^{-2}T^*_{Sup} \\
&\quad - 1.18e^{-4}\dot{P}^*_{HP1} - 1.54e^{-5}T^*_{Amb}\dot{P}^*_{HP1} \\
COP_{HP2} &= 2.58 + 3.84e^{-2}T^*_{Amb} - 2.50e^{-2}T^*_{Sup} \\
&\quad - 1.42e^{-4}\dot{P}^*_{HP2} - 1.50e^{-5}T^*_{Amb}\dot{P}^*_{HP2}
\end{aligned}
$$

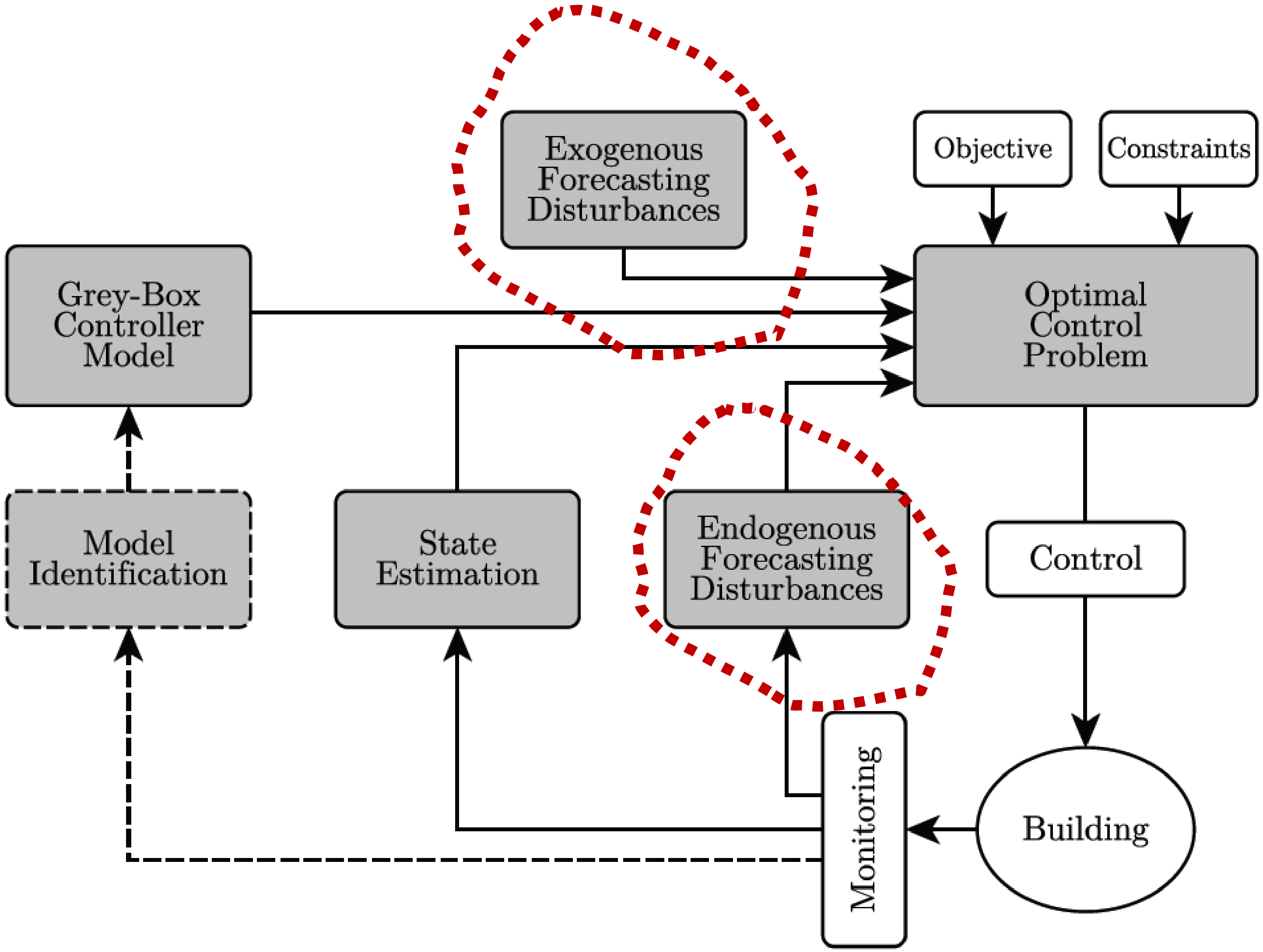
Linear regression based on 3 predictors and their combination:

- TAmb,
- TSup
- Q or P

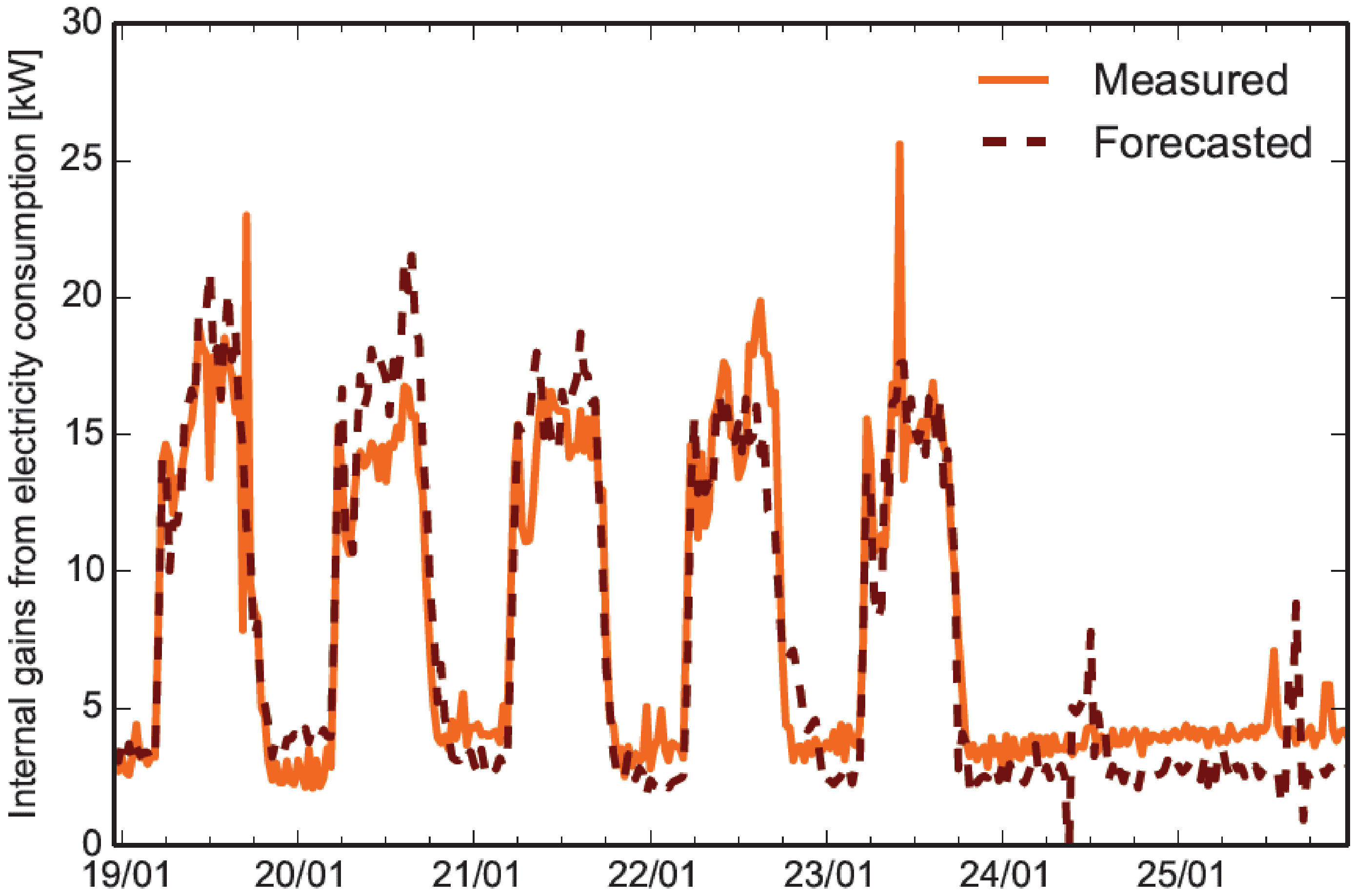
Shifting of predictors to obtain physically interpretable parameters

$$
\begin{aligned}
\dot{Q}^*_{GB} &= \dot{Q}_{GB} - 86000 \\
\dot{P}^*_{HP} &= \dot{P}_{HP} - 6500 \\
T^*_{Amb} &= T_{Amb} - (7 + 273.15) \\
T^*_{Sup} &= T_{Sup} - (35 + 273.15)
\end{aligned}
$$

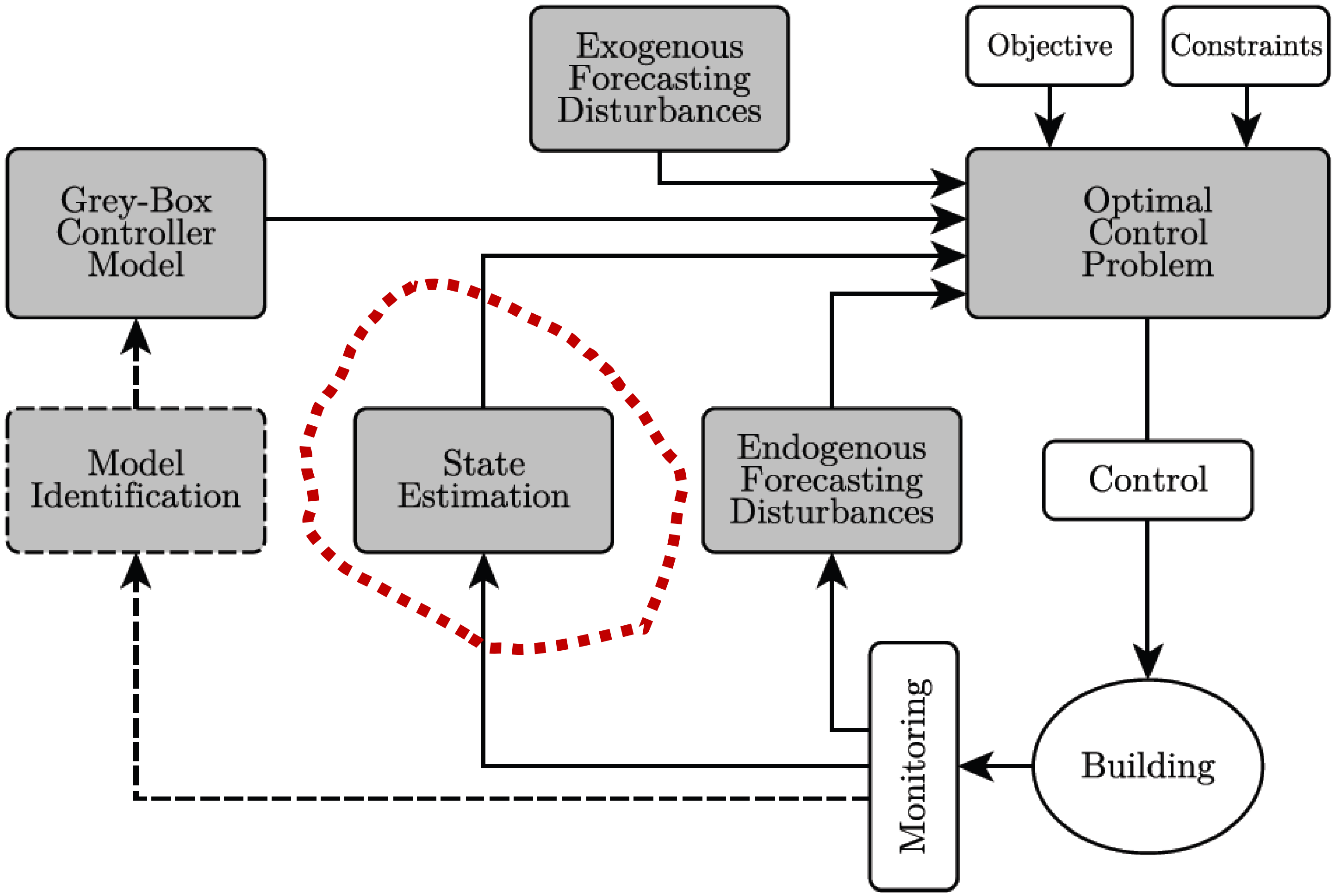
MPC framework



Internal gains from electrical appliances



MPC framework

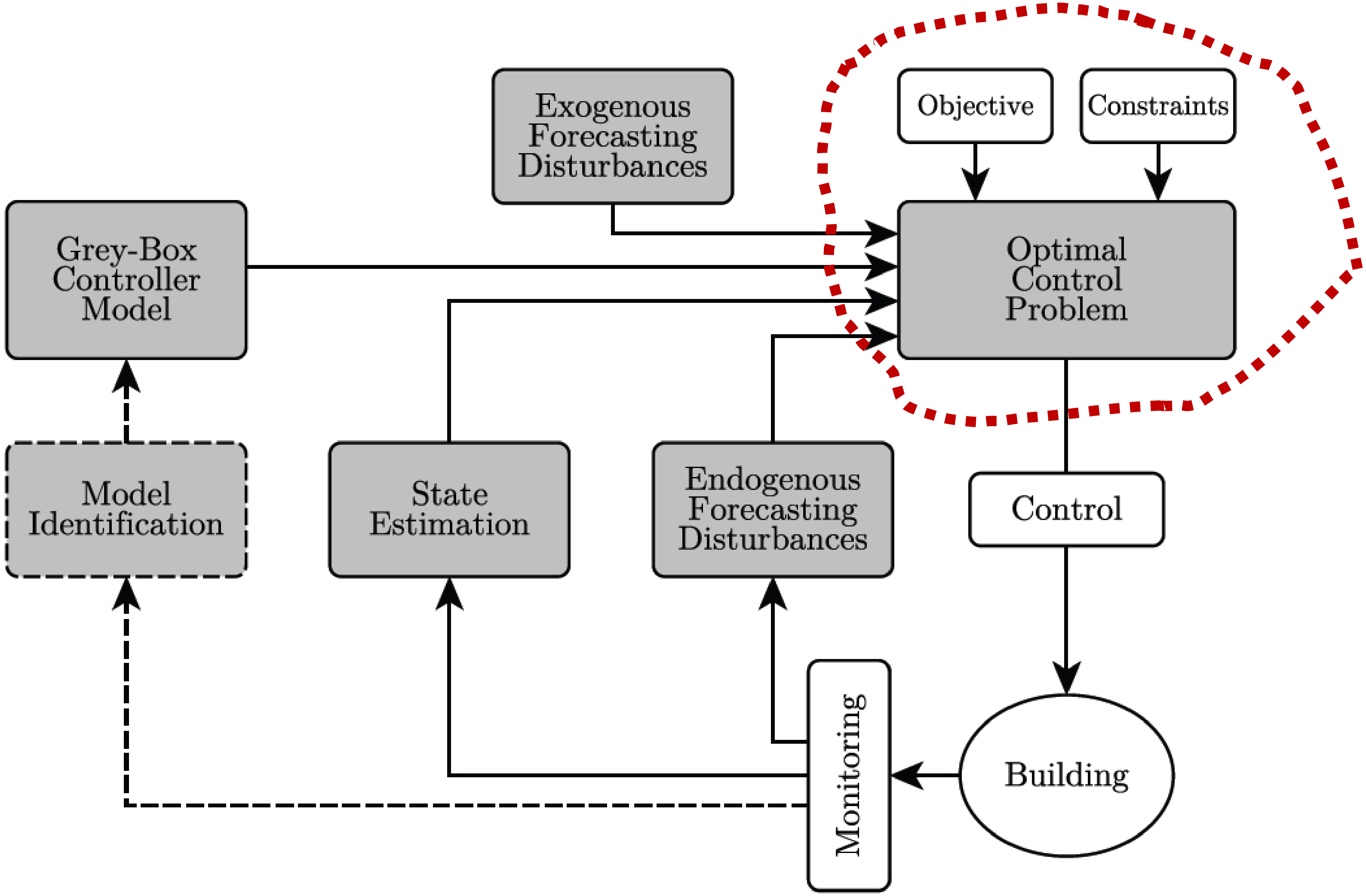


State estimation

- Very simple implementation of moving horizon estimation
- Based on grey-box toolbox
- ~ parameter estimation, free parameters are initial state 24h ago
- Corrections:

1. For measured states, take measurement
2. For TZon, if deviation from tracking setpoint TSet < 0.2 K: use TSet

MPC framework



Objective

$$J = J_c + \gamma J_d$$

$$J_c = \int_0^{t_h} (c_g \dot{P}_g + c_e \dot{P}_e)\mathrm{d}t$$

$$J_d = \int_0^{t_h} \theta_{occ}(T_{Zon} - T_{Set})^2 \mathrm{d}t$$

Constraints

- Maximal thermal power of production units
- Minimal thermal power = 0
- Fix starting values for thermal power control signals at last sent control values

Horizon and numerical options

1 day horizon
15 minute collocation elements
2 collocation points per element
IPOPT / MA27 solver

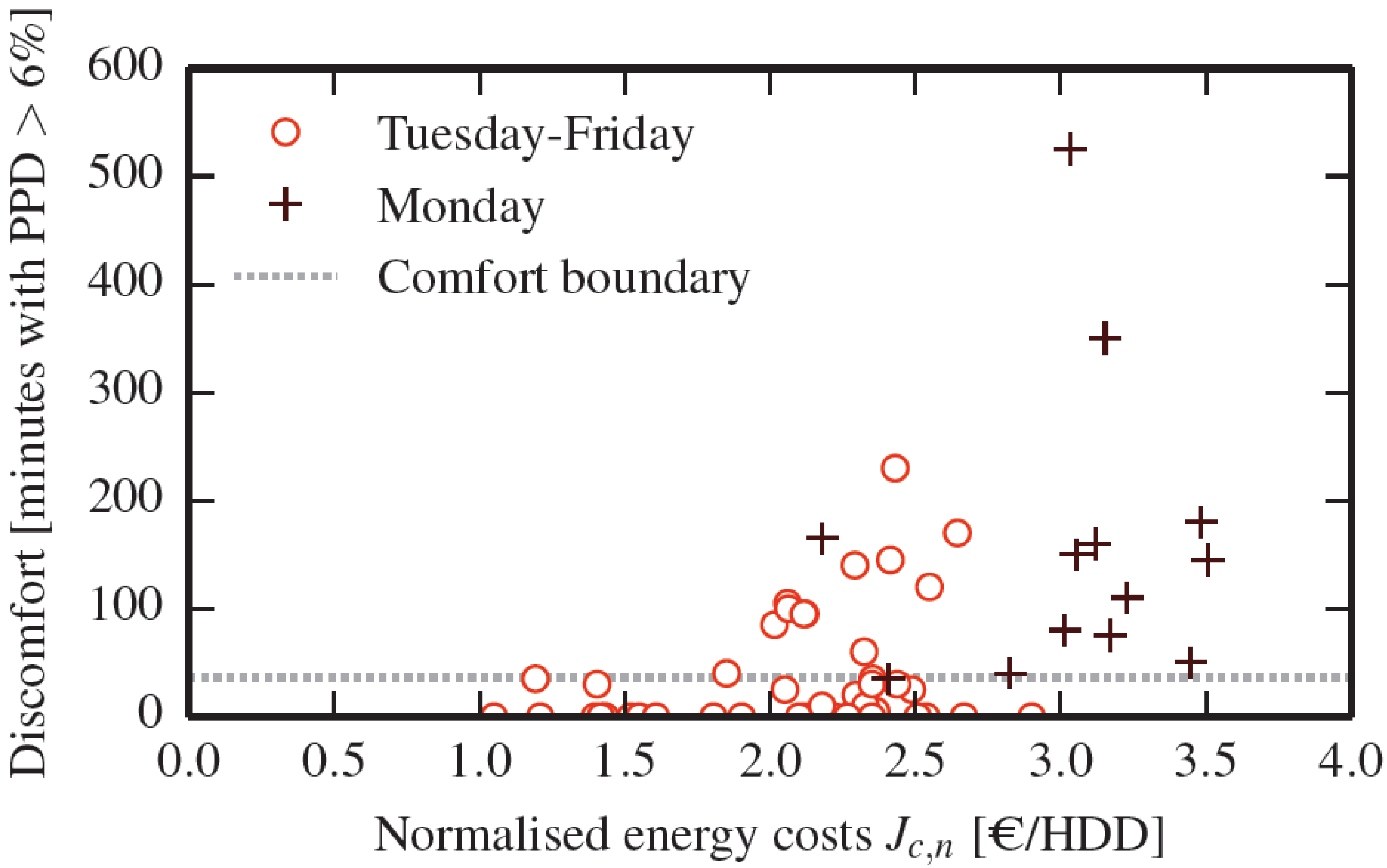
Results

Winter 2014-2015
Periods with RBC / MPC
How to analyse the performance?

Building performance indicators

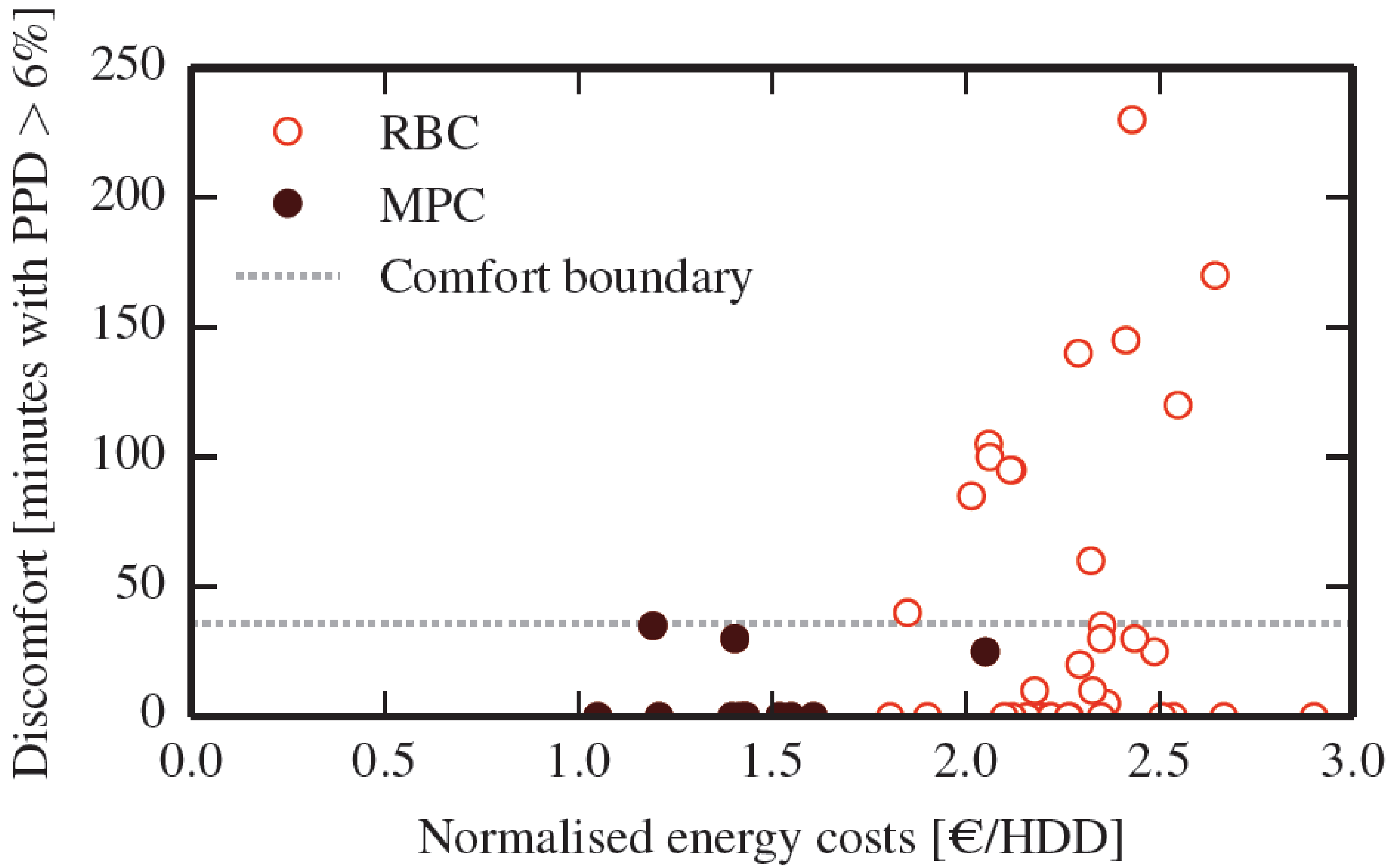
Symb.	**Unit**	**Meaning**
J_c	€	Energy cost
J_e	kWh	Primary energy consumption
J_d^*	minutes	Thermal discomfort
HDD	K d	Heating degree days (normalisation variable)

Results



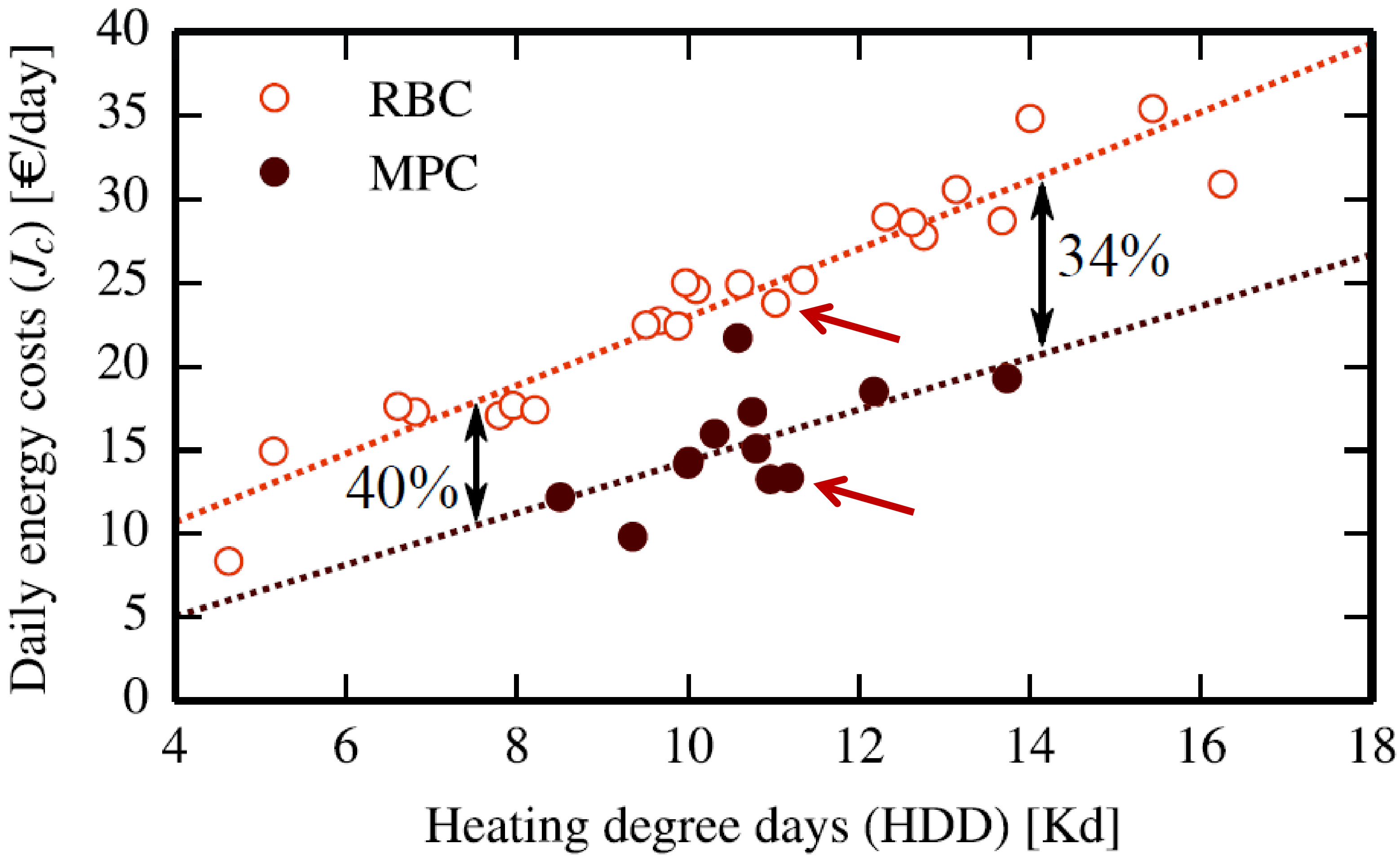
Discomfort [minutes with PPD > 6%]
600
500
400
300
200
100
0
Tuesday-Friday
Monday
Comfort boundary
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Normalised energy costs $J_{c,n}$ [€/HDD]

Results



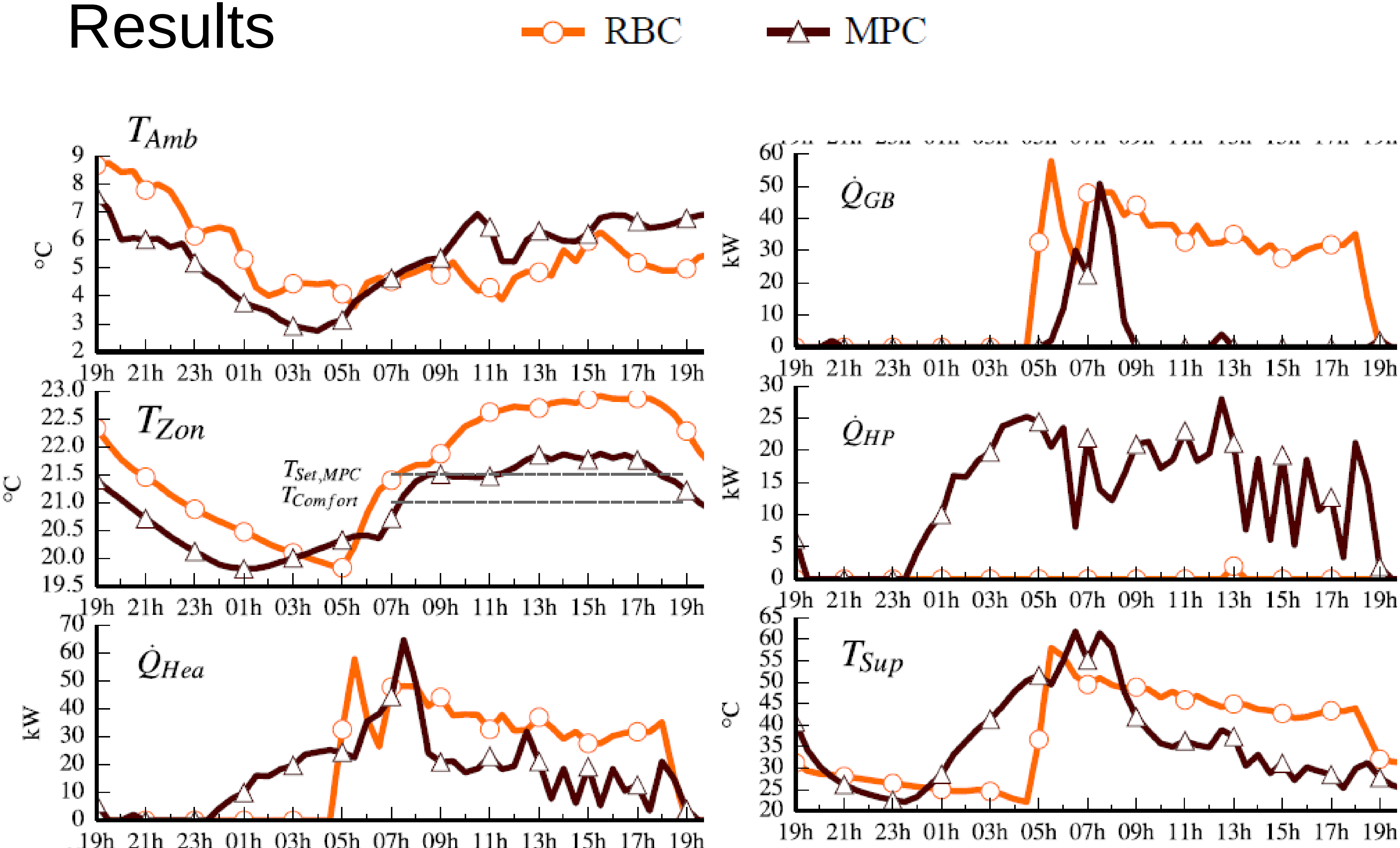
RBC
MPC
Comfort boundary
Discomfort [minutes with PPD > 6%]
250
200
150
100
50
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Normalised energy costs [€/HDD]

Results



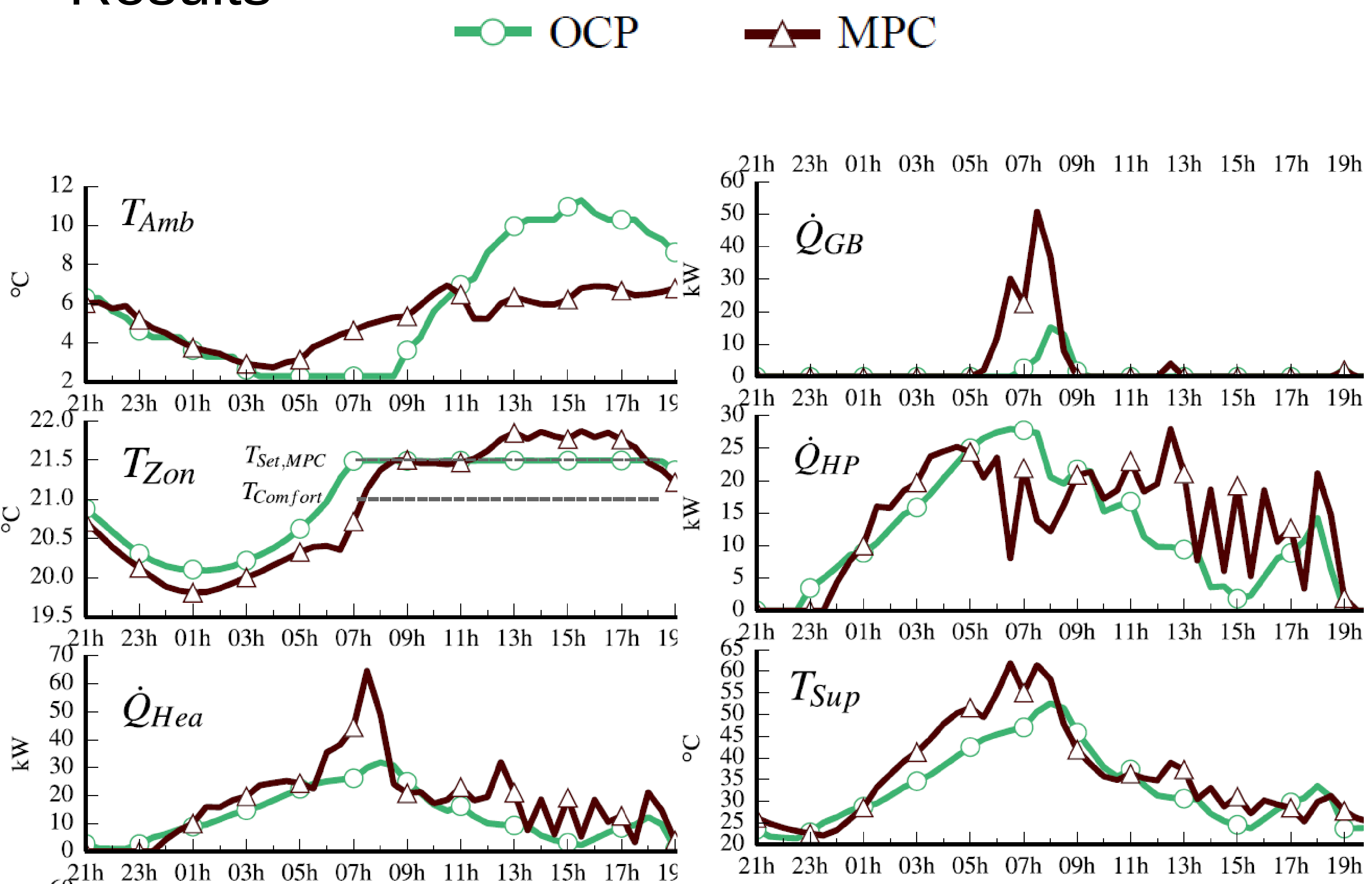
RBC
MPC
34%
40%
Daily energy costs (J_c) [€/day]
Heating degree days (HDD) [Kd]
0
5
10
15
20
25
30
35
40
4
6
8
10
12
14
16
18

Results



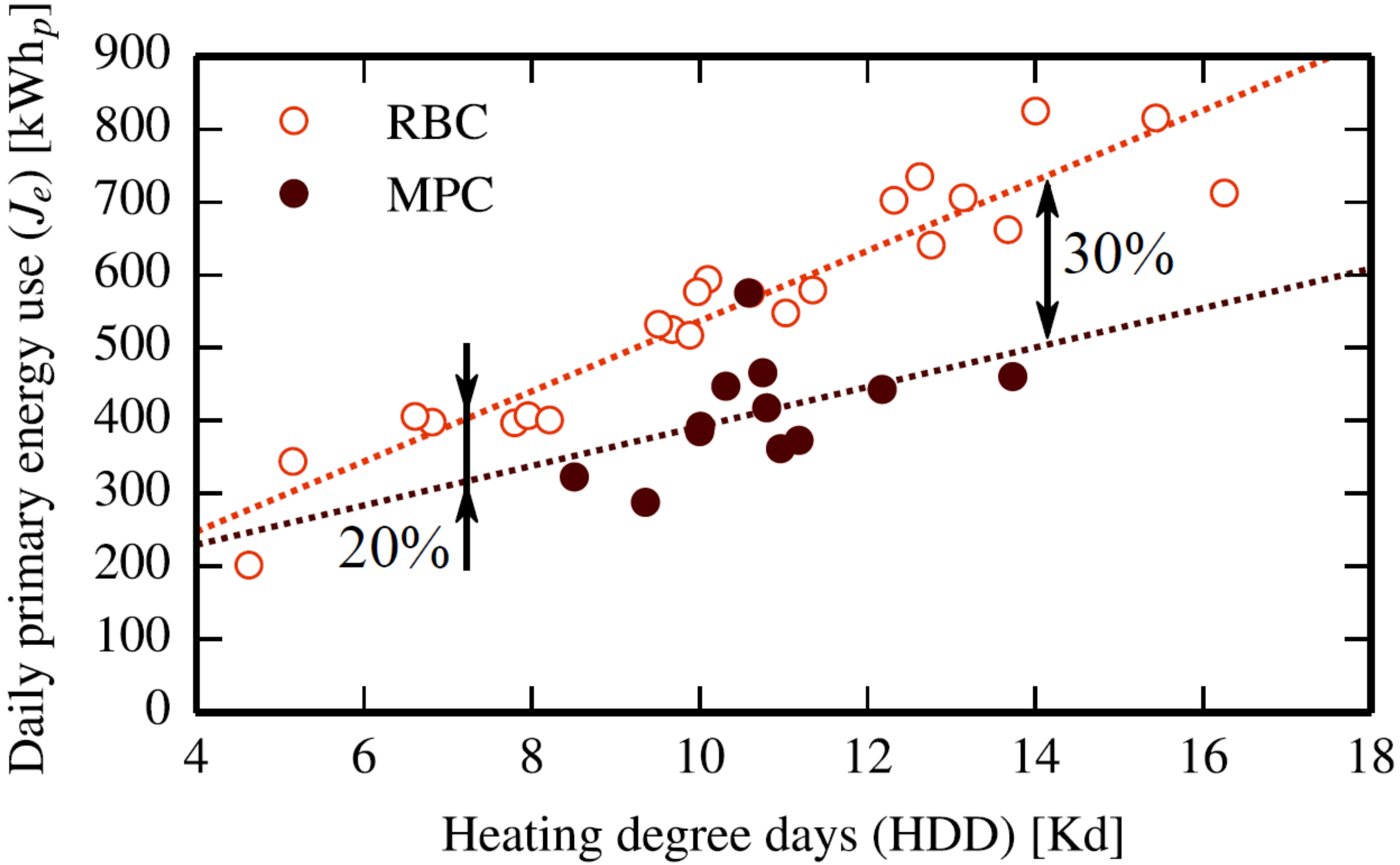
RBC
MPC
T_{Amb}
°C
T_{Zon}
$T_{Set,MPC}$
$T_{Comfort}$
°C
$\dot{Q}_{Hea}$
kW
$\dot{Q}_{GB}$
kW
$\dot{Q}_{HP}$
kW
T_{Sup}
°C
19h 21h 23h 01h 03h 05h 07h 09h 11h 13h 15h 17h 19h

Results



OCP
MPC
T_{Amb}
T_{Zon}
$T_{Set,MPC}$
$T_{Comfort}$
$\dot{Q}_{Hea}$
$\dot{Q}_{GB}$
$\dot{Q}_{HP}$
T_{Sup}
°C
kW
21h
23h
01h
03h
05h
07h
09h
11h
13h
15h
17h
19h

Energy consumption



Conclusion

- Tool chain MPC
- Implementation on real building <==> implementation on emulator
- Good results by
- Better use of heat pumps
- Adapted TSup : not possible to describe by rules
- Still many opportunities for improvements?
- Tests on emulator model for isolation of effects

Thank you for your attention!

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