Non-linear model predictive control of a small-scale fourth generation district heating network with on/off heat pumps

ISEC 2022

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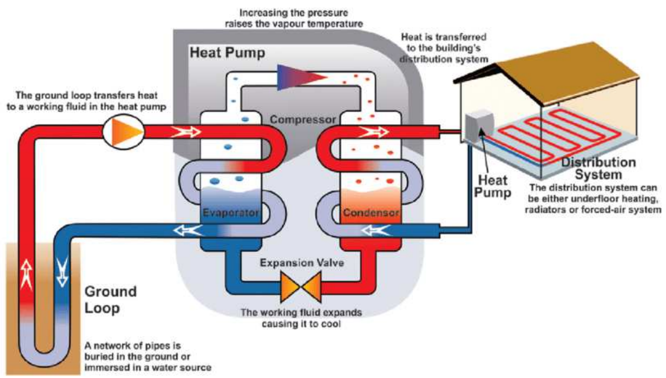
Introduction

European Green Deal → climate neutral in 2050

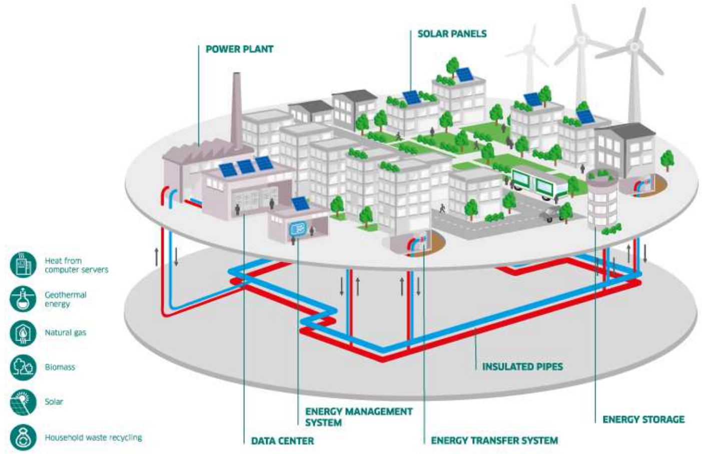
Decarbonisation of the residential heating sector

Rural areas



https://www.researchgate.net/figure/Geothermal-heat-pump-schematic-in-heating-mode_fig2_316919670

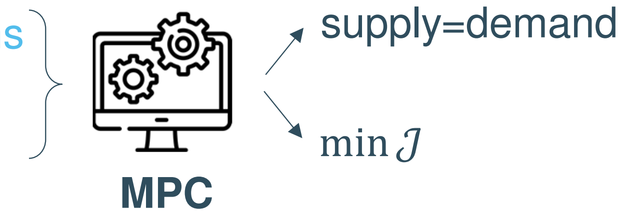
Urban areas

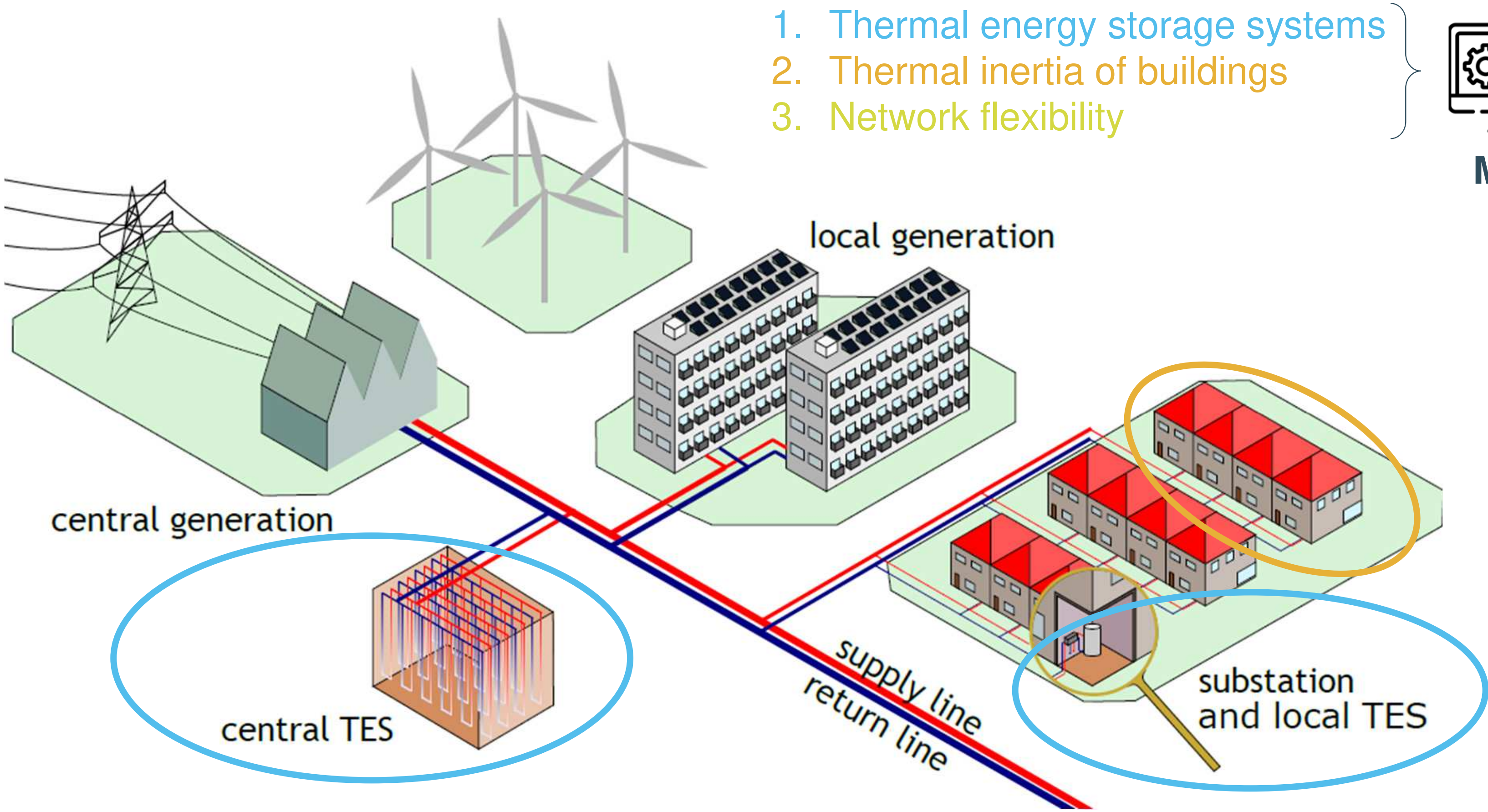


https://www.engie.com/en/businesses/district-heating-cooling-systems

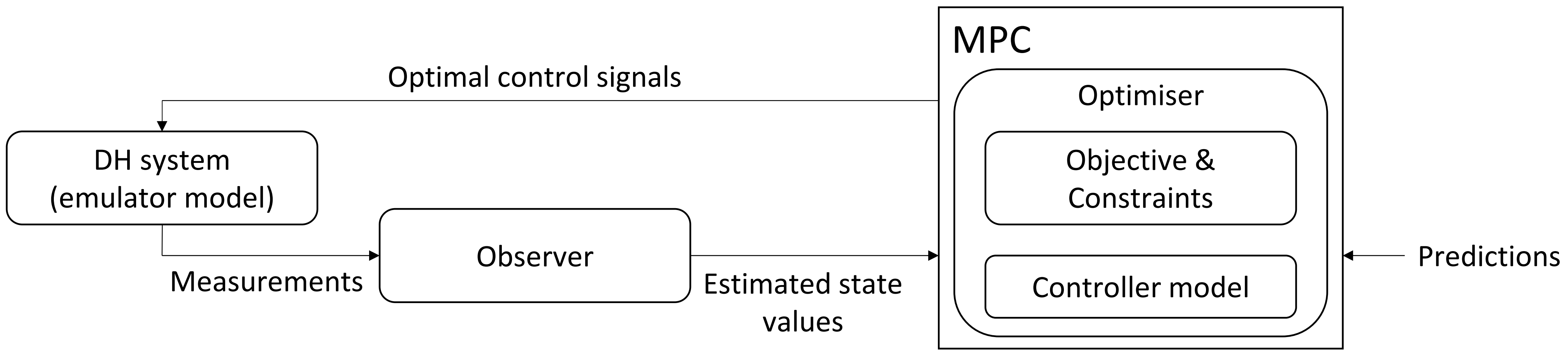
Fourth generation district heating

1. Thermal energy storage systems
2. Thermal inertia of buildings
3. Network flexibility





Model predictive control



MPC of 4GDH systems

4GDH systems

- Flexibility
- Non-linearities (pressure-mass flow relation, COP HP, …)
- Integers (on/off HP, on/off circulation pump, …)

Literature

- MPC optimal control problems: either LP, MILP, or NLP
- Limited complexity and flexibility

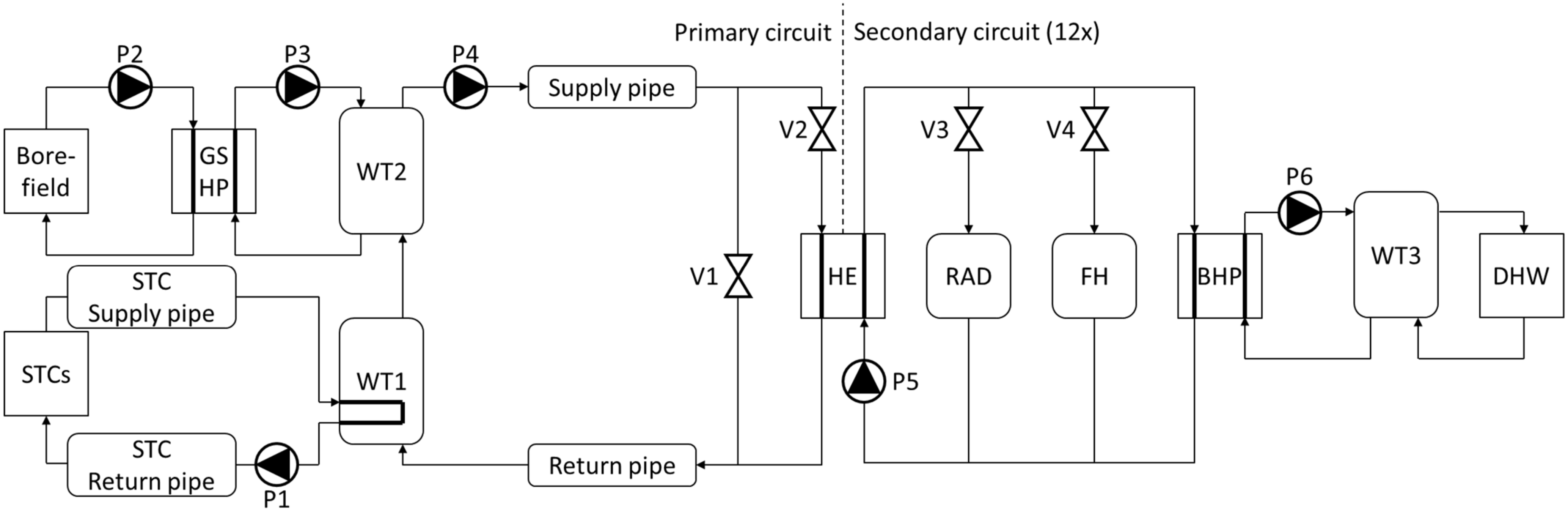
My presentation

- NLP-based MPC to control a small-scale 4GDH network with on/off heat pumps
- MPC can exploit flexibility of both TES systems and thermal building inertia

Almshouses *De Schipjes*

- Social housing neighbourhood (12 buildings)
- Retrofitted buildings
- 4GDH network

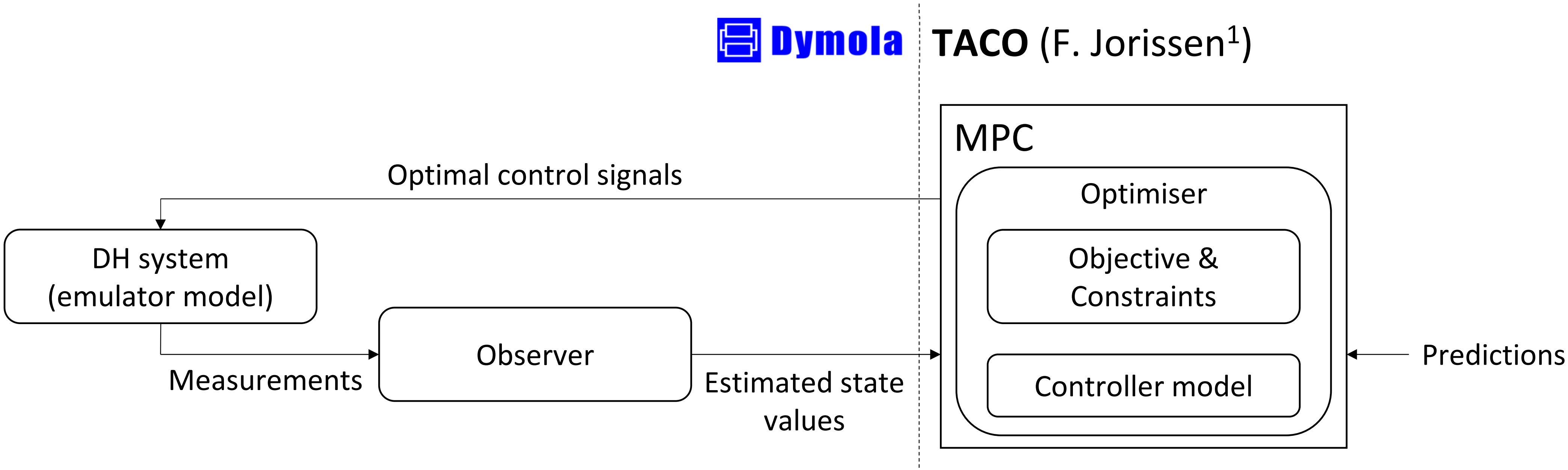
De Schipjes – DH network



Model-in-the-loop approach

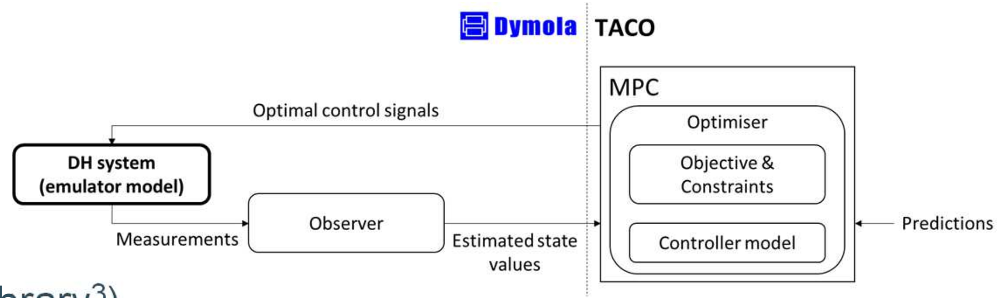
MPC settings

- $\Delta t_{prediction} = 2$ days
- $\Delta t_{control} = 15$ minutes
- Perfect predictions

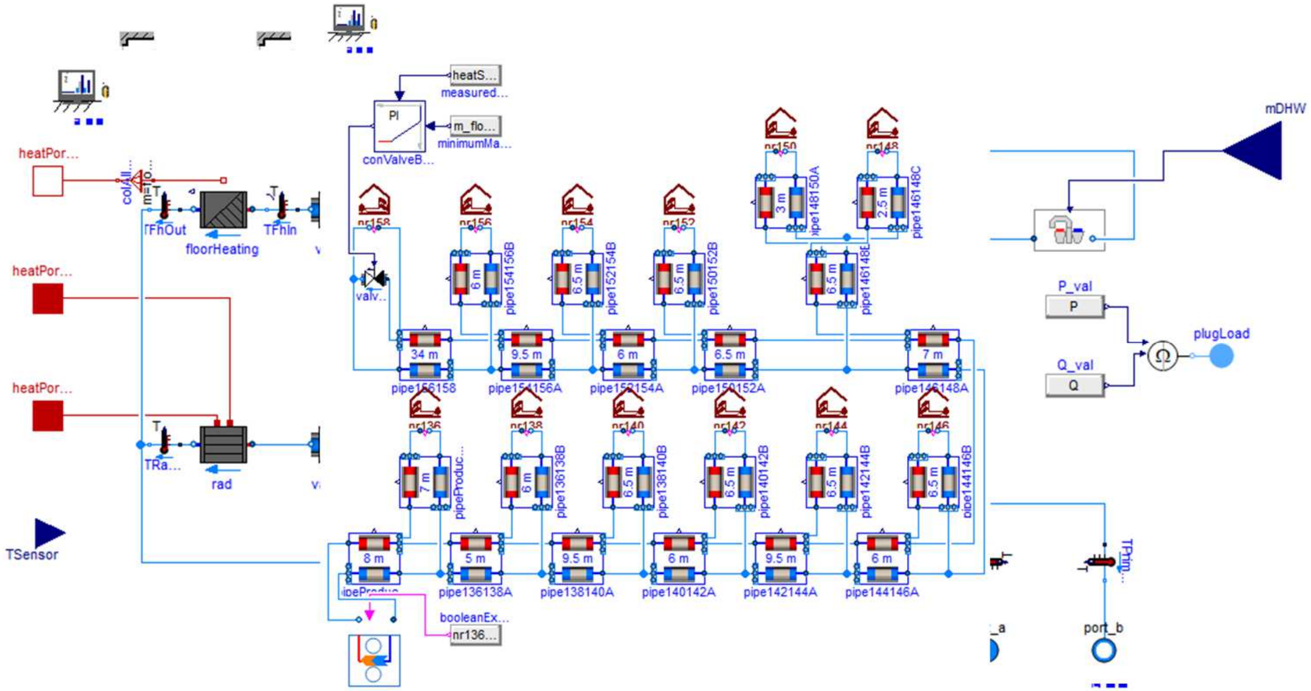


[1] F. Jorissen, W. Boydens, and L. Helsen, "TACO, an automated toolchain for model predictive control of building systems: implementation and verification," *J. Build. Perform. Simul.*, vol. 12, no. 2, pp. 180–192, 2019.

Emulator model

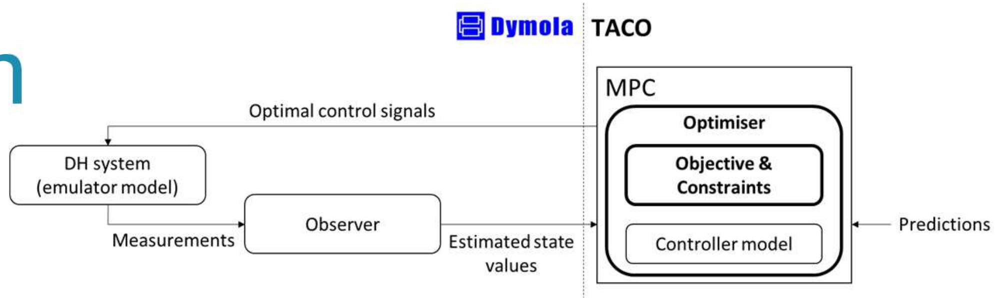


- White-box modelling approach
- Modelica modelling language (IDEAS[2] and Buildings library[3])



[2] F. Jorissen, G. Reynders, R. Baetens, D. Picard, D. Saelens, and L. Helsen, “Implementation and verification of the IDEAS building energy simulation library,” *J. Build. Perform. Simul.*, vol. 11, no. 6, pp. 669–688, 2018.
[3] M. Wetter, W. Zuo, T. S. Nouidui, and X. Pang, “Modelica Buildings library,” *J. Build. Perform. Simul.*, vol. 7, no. 4, pp. 253–270, 2014.

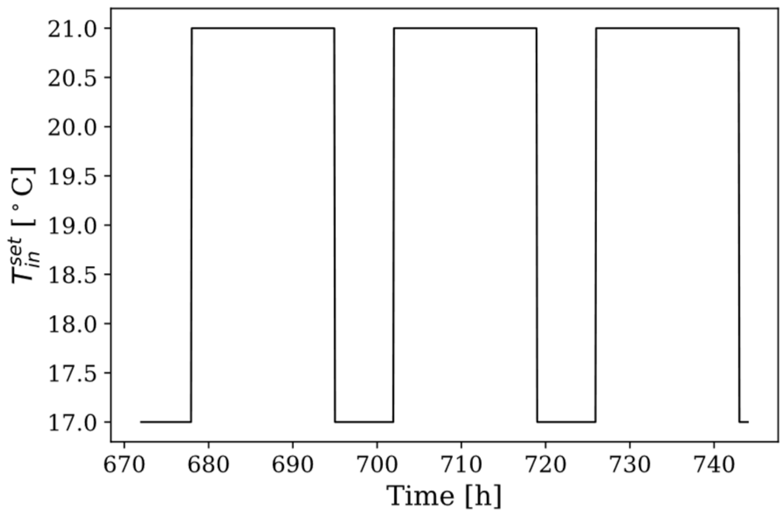
MPC's optimisation problem



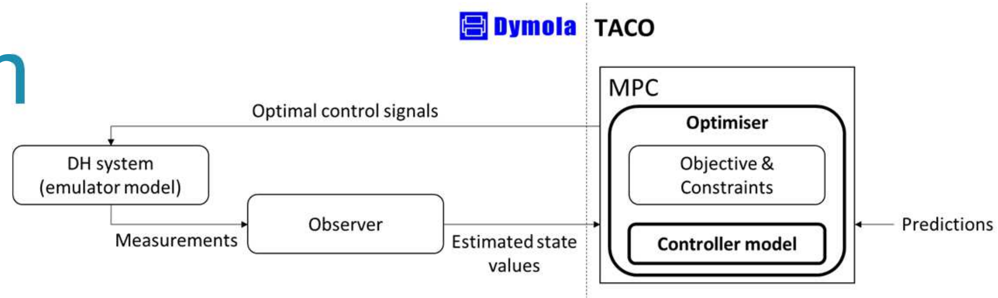
Objective and constraints

$$\min \mathcal{J}(t) = P_{GSHP}(t) + P_{P1}(t) + P_{P4}(t)$$
$$+ \sum_{i=1}^{12} \left(P_{BHP,i}(t) + P_{P5,i}(t)\right)$$
$$+ \sum_{i=1}^{12} \left(w_{SH} s_{i,SH}(t)^2 + w_{DHW} s_{i,DHW}(t)^2\right)$$

$$\text{s.t. } T_{in}^{set}(t) - s_{i,SH}(t) \leq T_{in}(t)$$
$$T_{DHW}^{set}(t) - s_{i,DHW}(t) \leq T_{DHW}(t) = 45°C$$
$$s_{i,SH}(t), s_{i,DHW}(t) \geq 0$$



MPC's optimisation problem



Objective and constraints

$$\min \mathcal{J}(t) = P_{GSHP}(t) + P_{P1}(t) + P_{P4}(t)$$
$$+ \sum_{i=1}^{12} \left(P_{BHP,i}(t) + P_{P5,i}(t)\right)$$
$$+ \sum_{i=1}^{12} \left(w_{SH} s_{i,SH}(t)^2 + w_{DHW} s_{i,DHW}(t)^2\right)$$

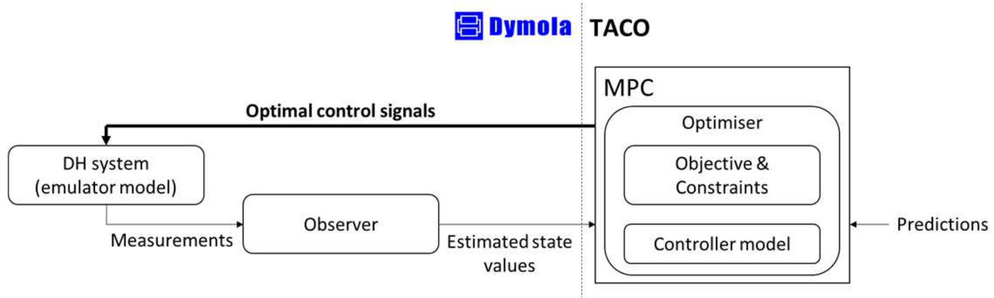
$$\text{s.t. } T_{in}^{set}(t) - s_{i,SH}(t) \leq T_{in}(t)$$
$$T_{DHW}^{set}(t) - s_{i,DHW}(t) \leq T_{DHW}(t)$$
$$s_{i,SH}(t), s_{i,DHW}(t) \geq 0$$

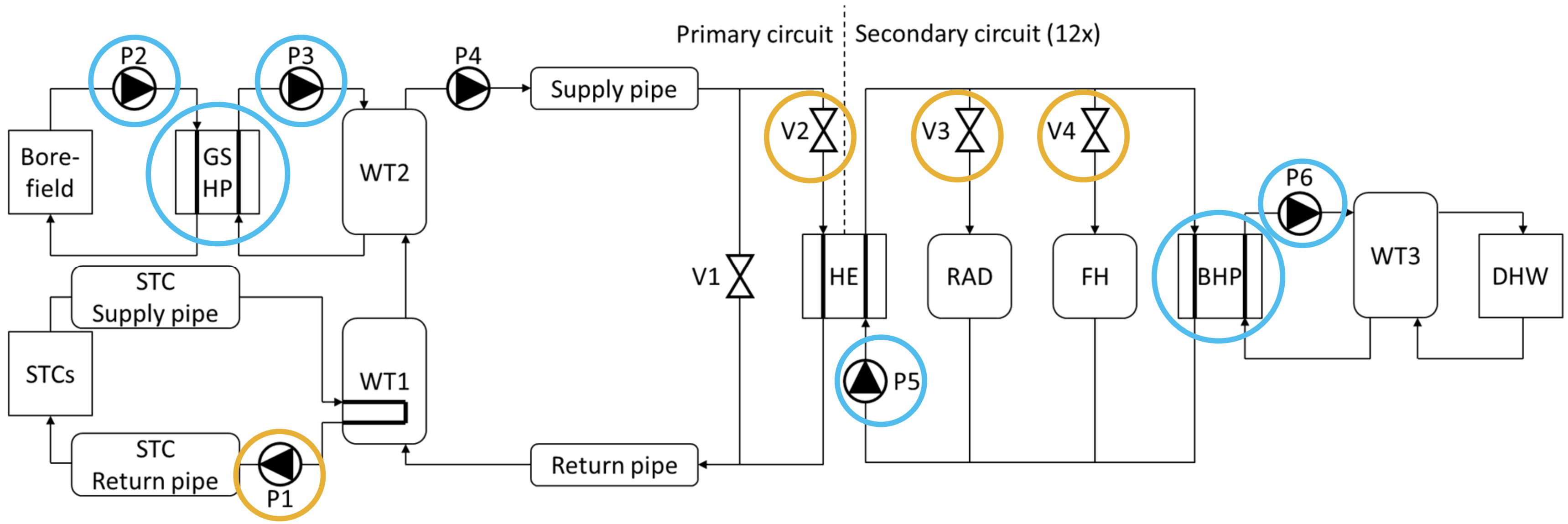
Controller model

- Derived from emulator model
- In-house developed component models (optimisation-oriented)

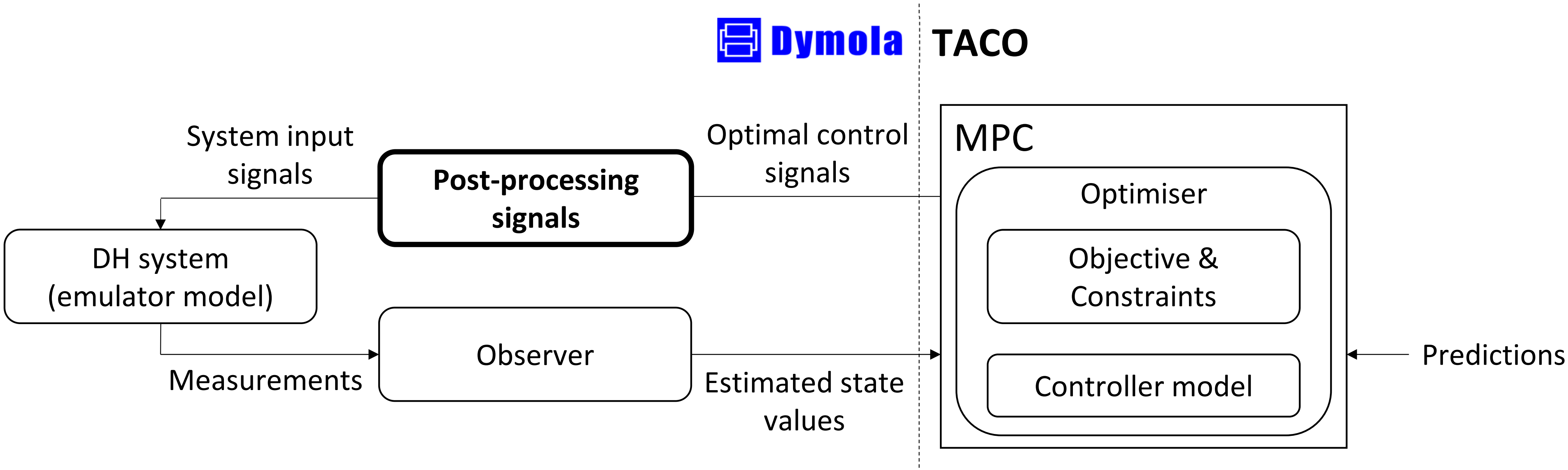
Optimal control signals

- Real-life system → continuous and integer inputs
- TACO → continuous optimisation variables

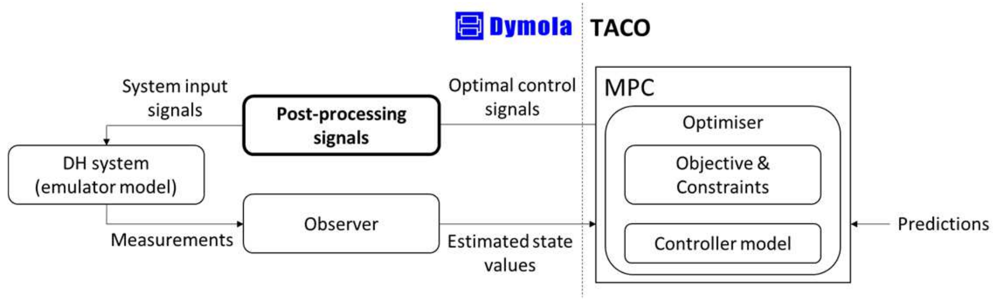




Model-in-the-loop approach



Post-processing signals

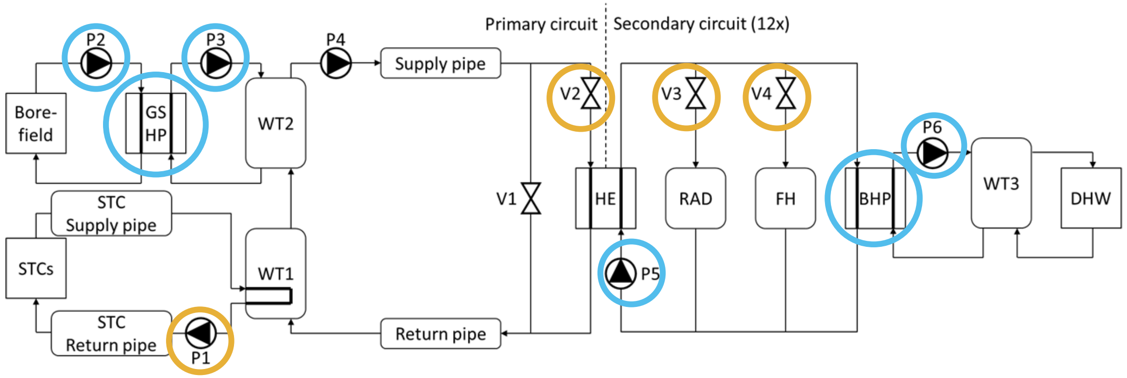


- Circulation pumps
  - P2, P3 ~ GSHP
  - P6 ~ BHP
  - P5 ~ Heat demand building
- HPs
  1. Tank method

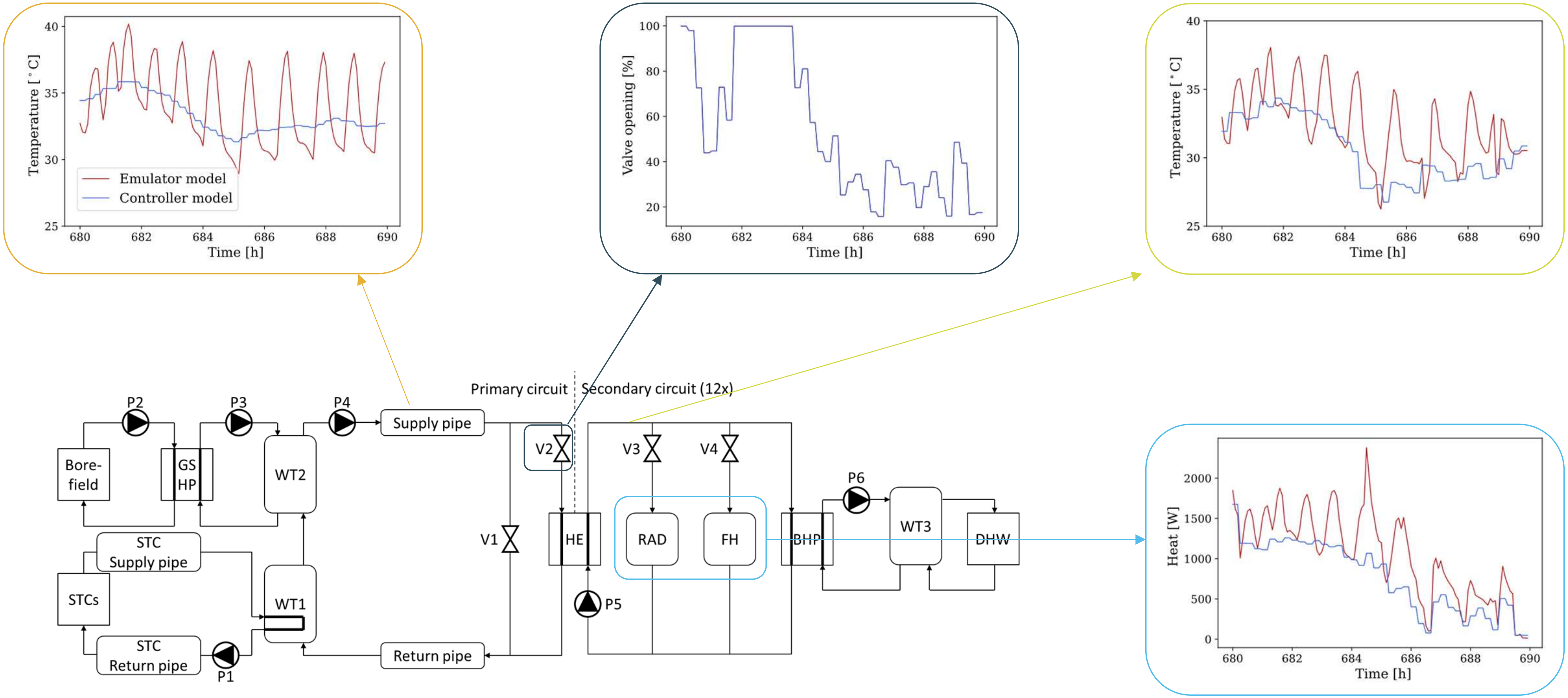
$$\begin{cases} \text{HP on if } T_{WT,top} < T_{WT}^{MPC} - \Delta T_{hys,low} \\ \text{HP off if } T_{WT,bot} > T_{WT}^{MPC} + \Delta T_{hys,up} \end{cases}$$

  2. Condenser method

$$\begin{cases} \text{HP on if } T_{con,out} + \Delta T_{nom} < T_{con,out}^{MPC} - \Delta T_{hys,low} \\ \text{HP off if } T_{con,out} > T_{con,out}^{MPC} + \Delta T_{hys,up} \end{cases}$$

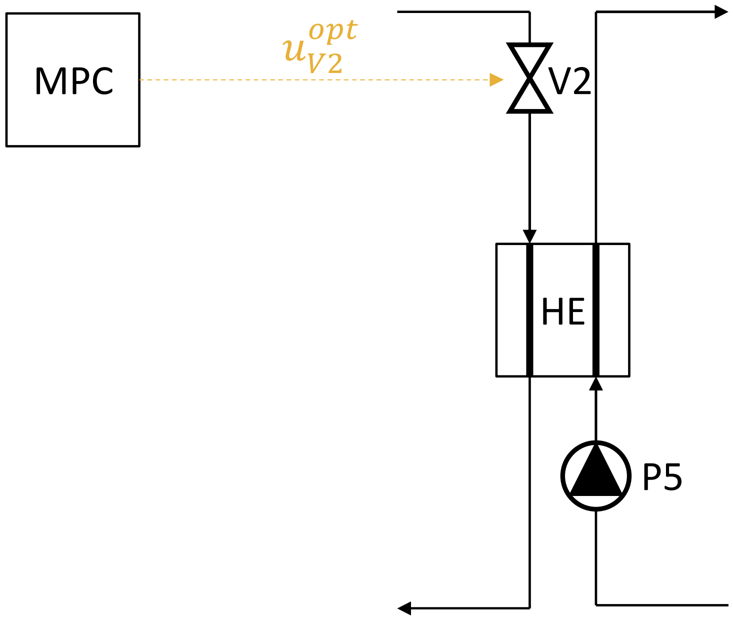


Post-processing signals – mismatch

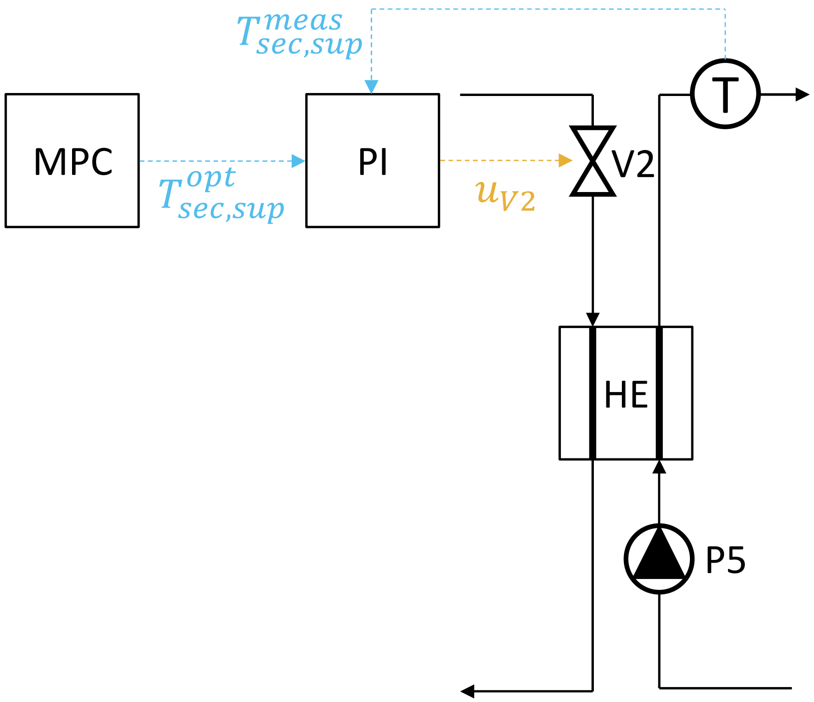


PI controller for substation valve

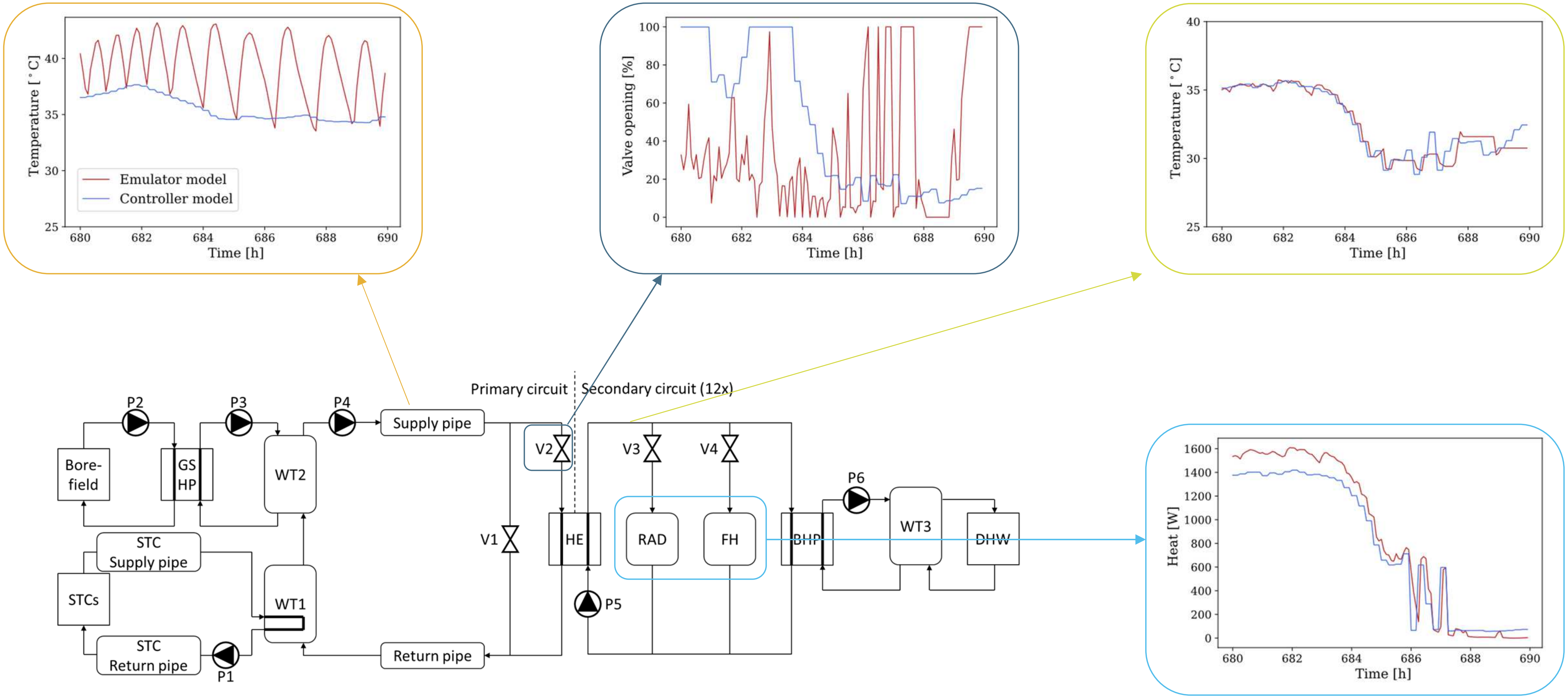
No PI controller



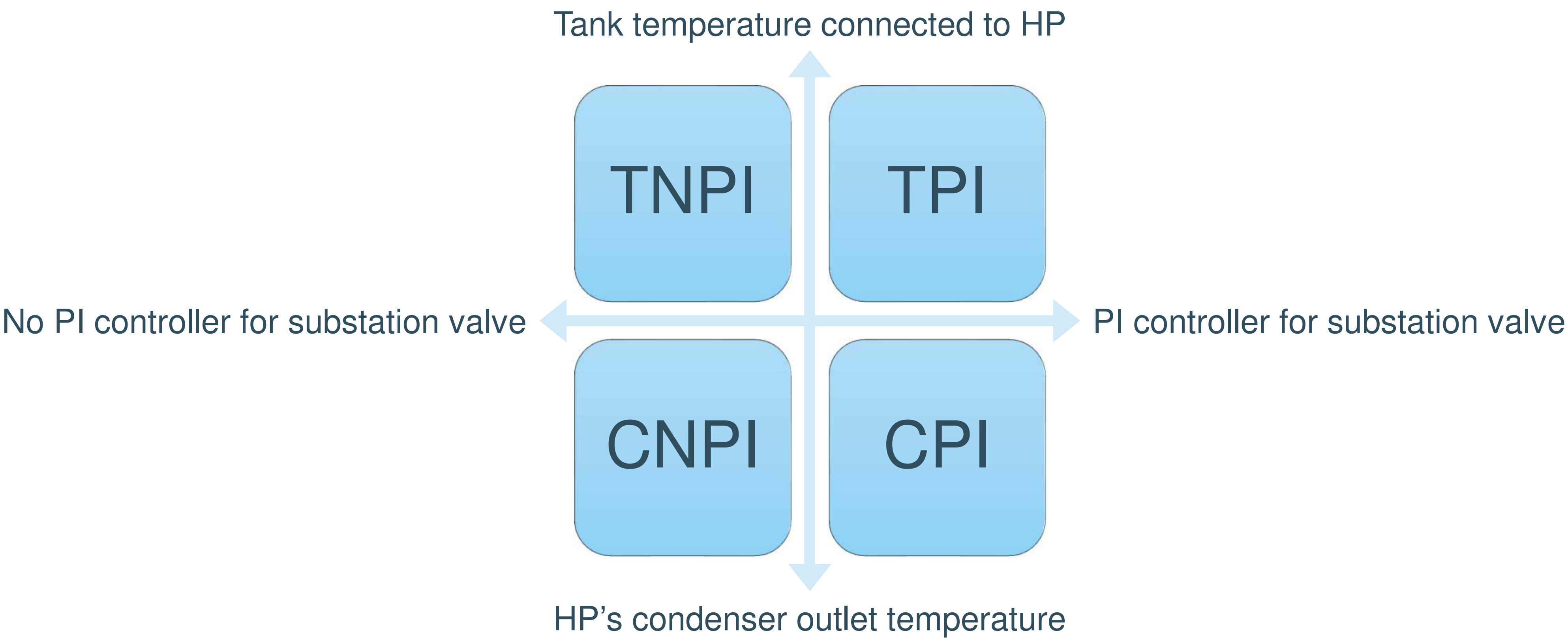
PI controller



Post-processing signals – PI controller



Post-processing methods – overview

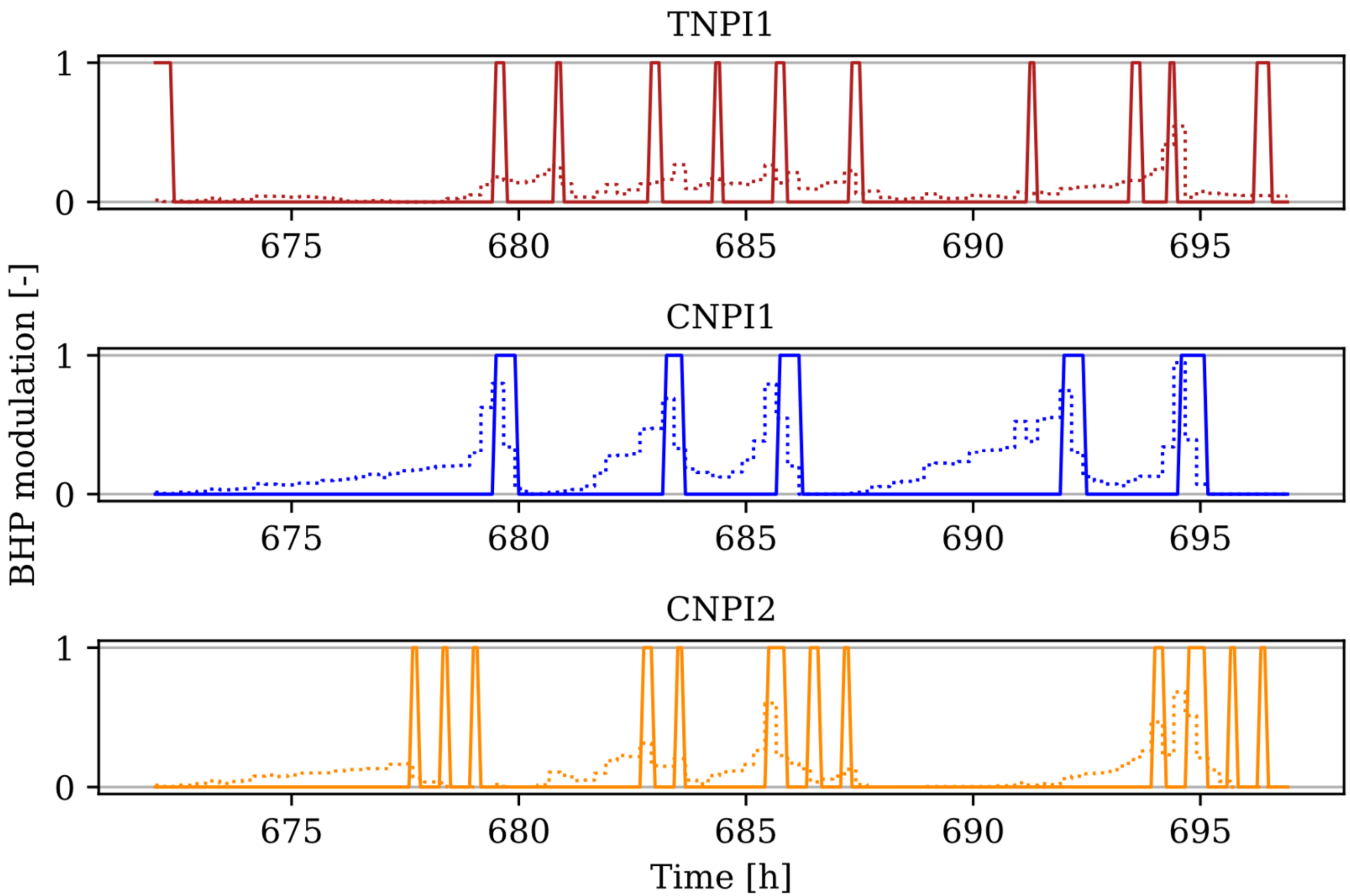


Results – tank vs. condenser approach

Simulation study of 3 days (January 28-31)

Control strategy	$\Delta T_{hys,low}$ (GSHP/BHP) [K]	$\Delta T_{hys,up}$ (GSHP/BHP) [K]	SH discomfort [Kh]	DHW discomfort [Kh]	E_{el} [kWh]	E_{HE} [kWh]	SCOP GSHP [-]	Average number of iterations
TPI1	3/0	2/3	**19**	**0**	**537**	1549	3.62	**84**
TNPI1	3/0	2/3	**1**	**0**	**530**	1658	3.90	**80**
TPI2	5/0	0/3	**23**	**0**	**506**	1547	3.85	**82**
TNPI2	5/0	0/3	**34**	**0**	**503**	1550	3.89	**83**
CPI1	0/0	8/5	**17**	**13**	**526**	1561	3.68	**426**
CNPI1	0/0	8/5	**9**	**12**	**531**	1630	3.78	**442**
CPI2	-8/-4	5/5	**1**	**0**	**601**	1669	3.52	**125**
CNPI2	-8/-4	5/5	**0**	**0**	**633**	1863	3.69	**125**
RBC	/	/	164	0	579	1501	3.31	/
Modulating	/	/	1	0	481	1651	4.71	80

Results – tank vs. condenser approach



80 iterations

442 iterations

125 iterations

Results – tank approach

Control strategy	$\Delta T_{hys,low}$ (GSHP/BHP) [K]	$\Delta T_{hys,up}$ (GSHP/BHP) [K]	SH discomfort [Kh]	DHW discomfort [Kh]	E_{el} [kWh]	E_{HE} [kWh]	SCOP GSHP [-]	Average number of iterations
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RBC	/	/	164	0	579	1501	3.31	/
Modulating	/	/	1	0	481	1651	4.71	80

Results – PI vs. NPI

Control strategy	$\Delta T_{hys,low}$ (GSHP/BHP) [K]	$\Delta T_{hys,up}$ (GSHP/BHP) [K]	SH discomfort [Kh]	DHW discomfort [Kh]	E_{el} [kWh]	E_{HE} [kWh]	SCOP GSHP [-]	Average number of iterations
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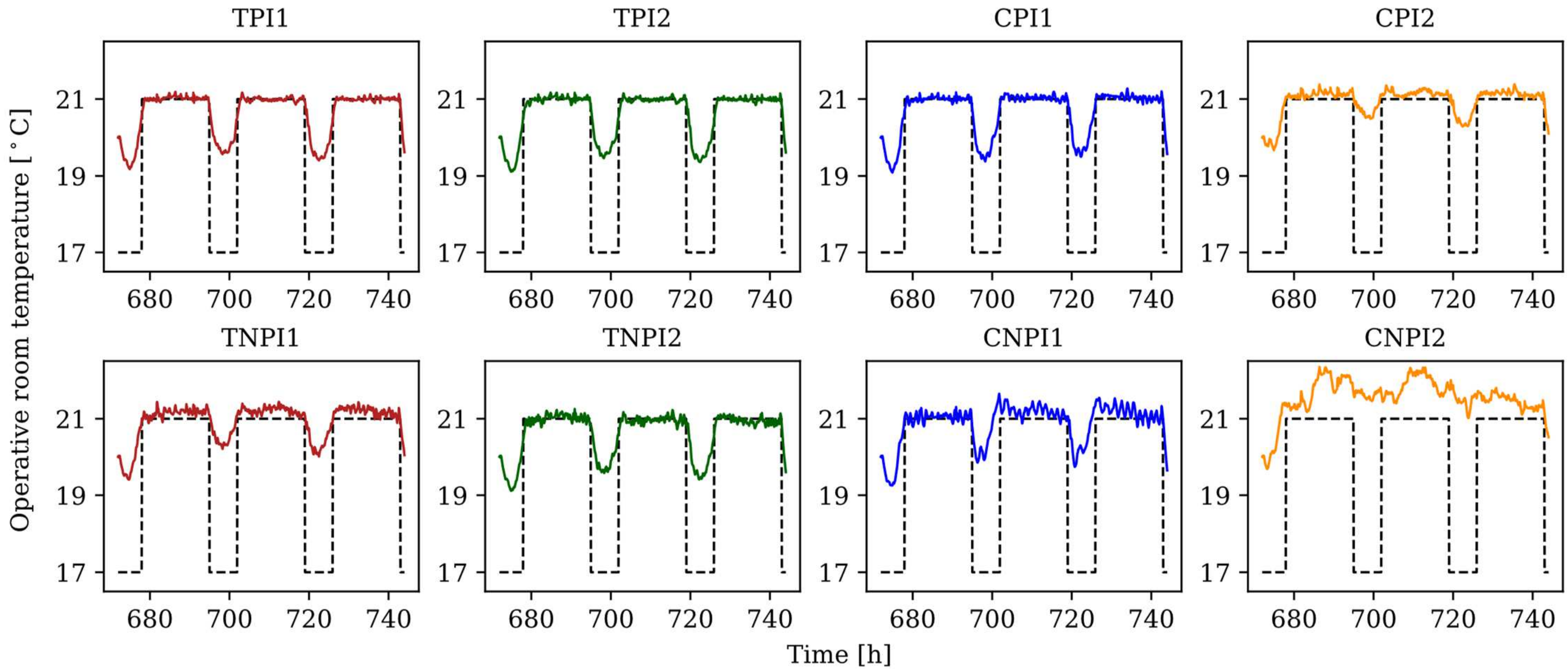
RBC	/	/	164	0	579	1501	3.31	/
Modulating	/	/	1	0	481	1651	4.71	80

Results – operative room temperature



Results – RBC scenario

Control strategy	$\Delta T_{hys,low}$ (GSHP/BHP) [K]	$\Delta T_{hys,up}$ (GSHP/BHP) [K]	SH discomfort [Kh]	DHW discomfort [Kh]	E_{el} [kWh]	E_{HE} [kWh]	SCOP GSHP [-]	Average number of iterations
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CNPI2	-8/-4	5/5	0	0	633	1863	3.69	125
RBC	/	/	164	0	579	1501	3.31	/
Modulating	/	/	1	0	481	1651	4.71	80

Results – modulating HP scenario

Control strategy	$\Delta T_{hys,low}$ (GSHP/BHP) [K]	$\Delta T_{hys,up}$ (GSHP/BHP) [K]	SH discomfort [Kh]	DHW discomfort [Kh]	E_{el} [kWh]	E_{HE} [kWh]	SCOP GSHP [-]	Average number of iterations
TPI1	3/0	2/3	19	0	537	1549	3.62	84
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RBC	/	/	164	0	579	1501	3.31	/
Modulating	/	/	1	0	481	1651	4.71	80

Conclusion

- NLP-based MPC needs an additional post-processing step to control a DH system with integer-based input signals

- Post-processing step
  - Suboptimality
  - Ad hoc approach

➔MINLP-based MPC
  - No loss of optimality due to post-processing
  - Reduce model mismatch

Questions?

Additional slides

Simulation study

- 3 days (January 28-31)
- MPC
  - $\Delta t_{prediction} = 2$ days
  - $\Delta t_{control} = 15$ minutes
  - Perfect predictions
- Metrics
  - SH discomfort $= \int_{t_{start}}^{tend} \max\left(0, \left(T_{in}^{set} - 1\right) - T_{in}\right) dt$
  - DHW discomfort $= \int_{t_{start}}^{tend}$ [if $\dot{m}_{DHW} > 0$ then $\max(0, (T_{DHW}^{set} - 1) - T_{DHW})$ else $0]dt$
  - Electricity use E_{el}
  - SCOP GSHP
  - Substation heat E_{HE}
  - Average # iterations optimiser

Results – PI vs. NPI

Control strategy	$\Delta T_{hys,low}$ (GSHP/BHP) [K]	$\Delta T_{hys,up}$ (GSHP/BHP) [K]	SH discomfort [Kh]	DHW discomfort [Kh]	E_{el} [kWh]	E_{HE} [kWh]	SCOP GSHP [-]	Average number of iterations
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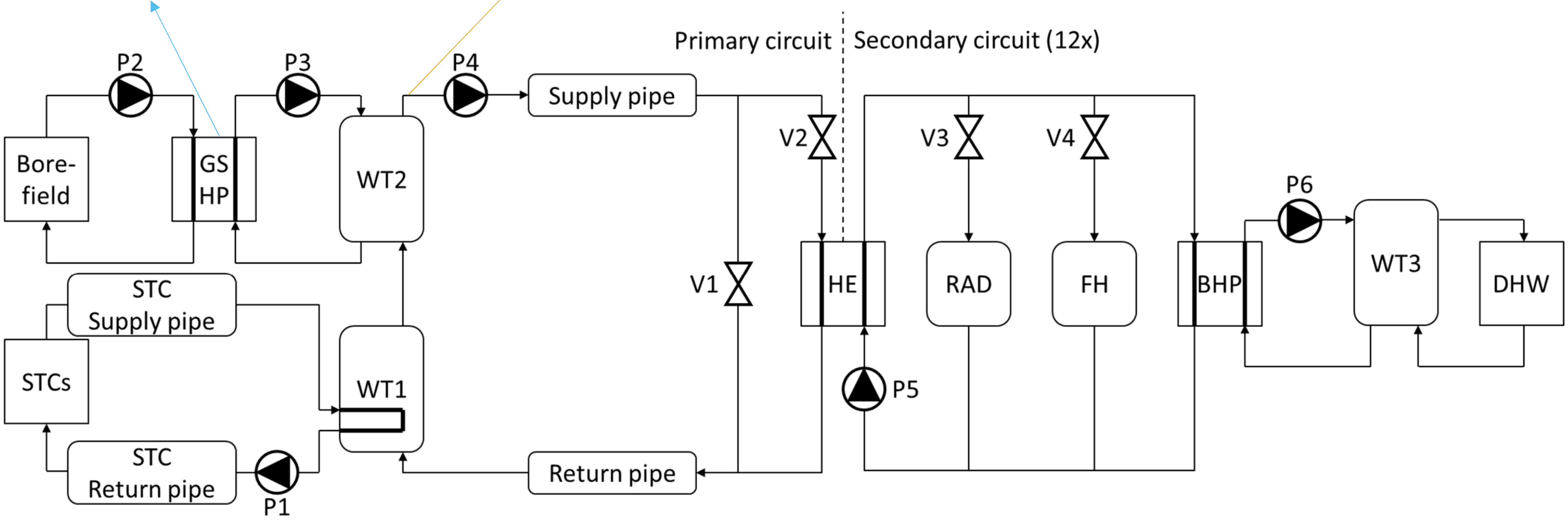
CPI2	-8/-4	5/5	1	0	601	1669	**3.52**	125
CNPI2	-8/-4	5/5	0	0	633	1863	**3.69**	125
RBC	/	/	164	0	579	1501	3.31	/
Modulating	/	/	1	0	481	1651	4.71	80

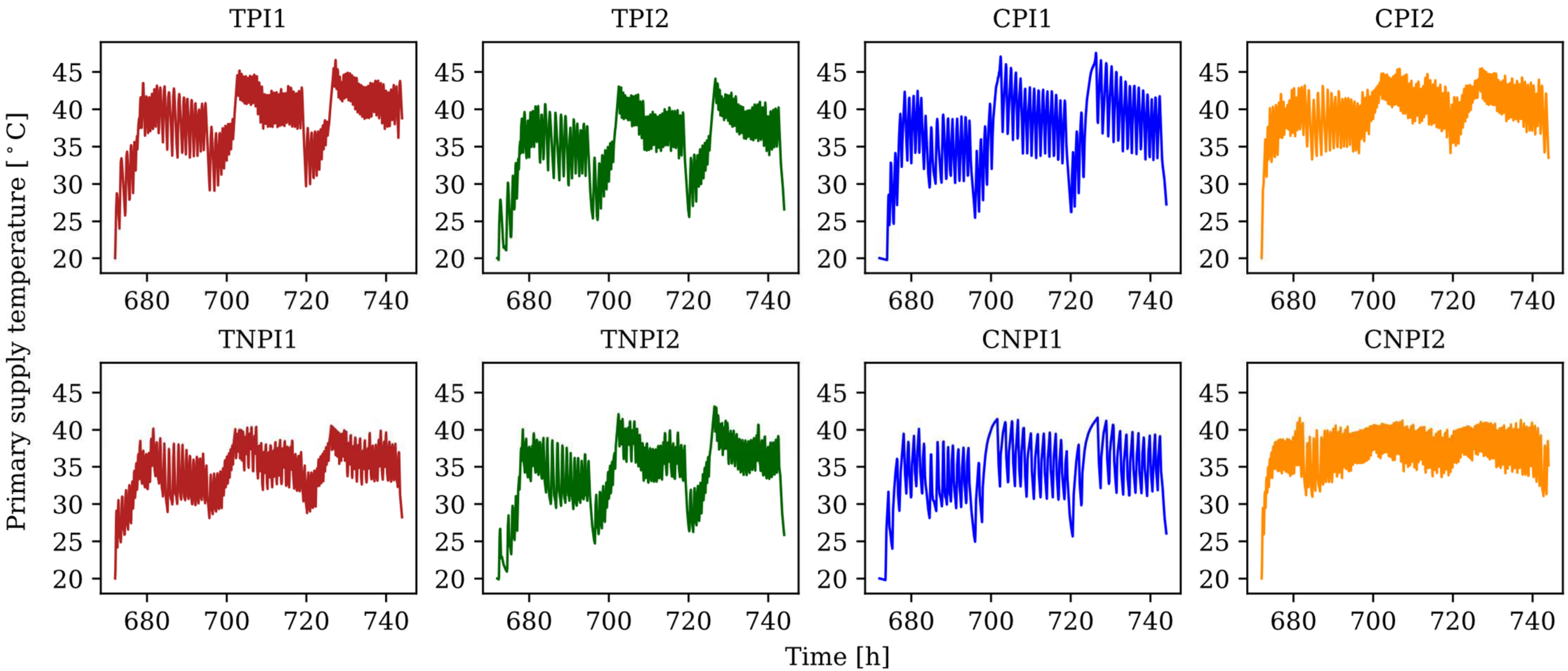
Results – PI vs. NPI – SCOP

$COP_{GSHP} \sim 1/T_{con}$

$T_{con} \sim T_{WT2} \sim T_{prim,sup}$



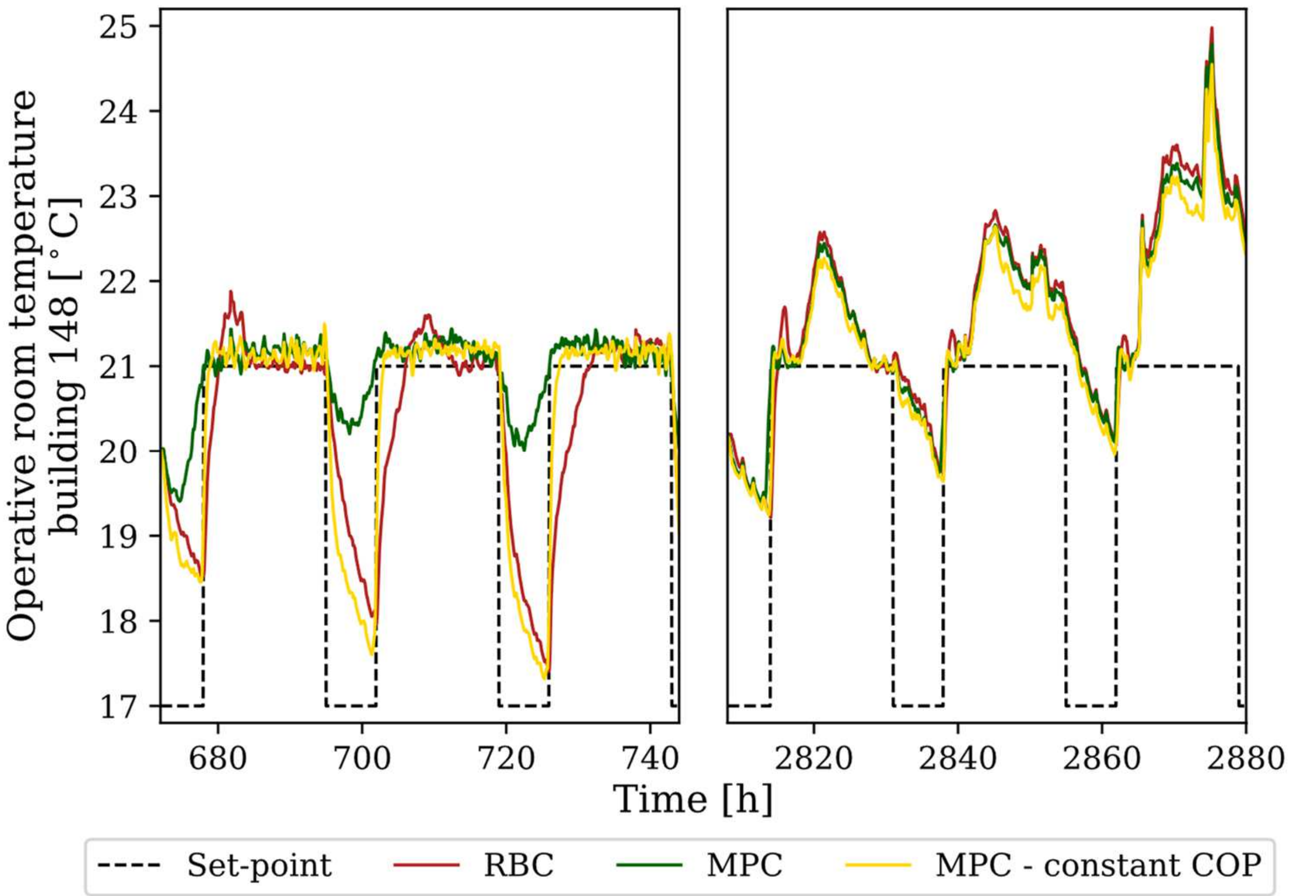
Results – primary supply temperature



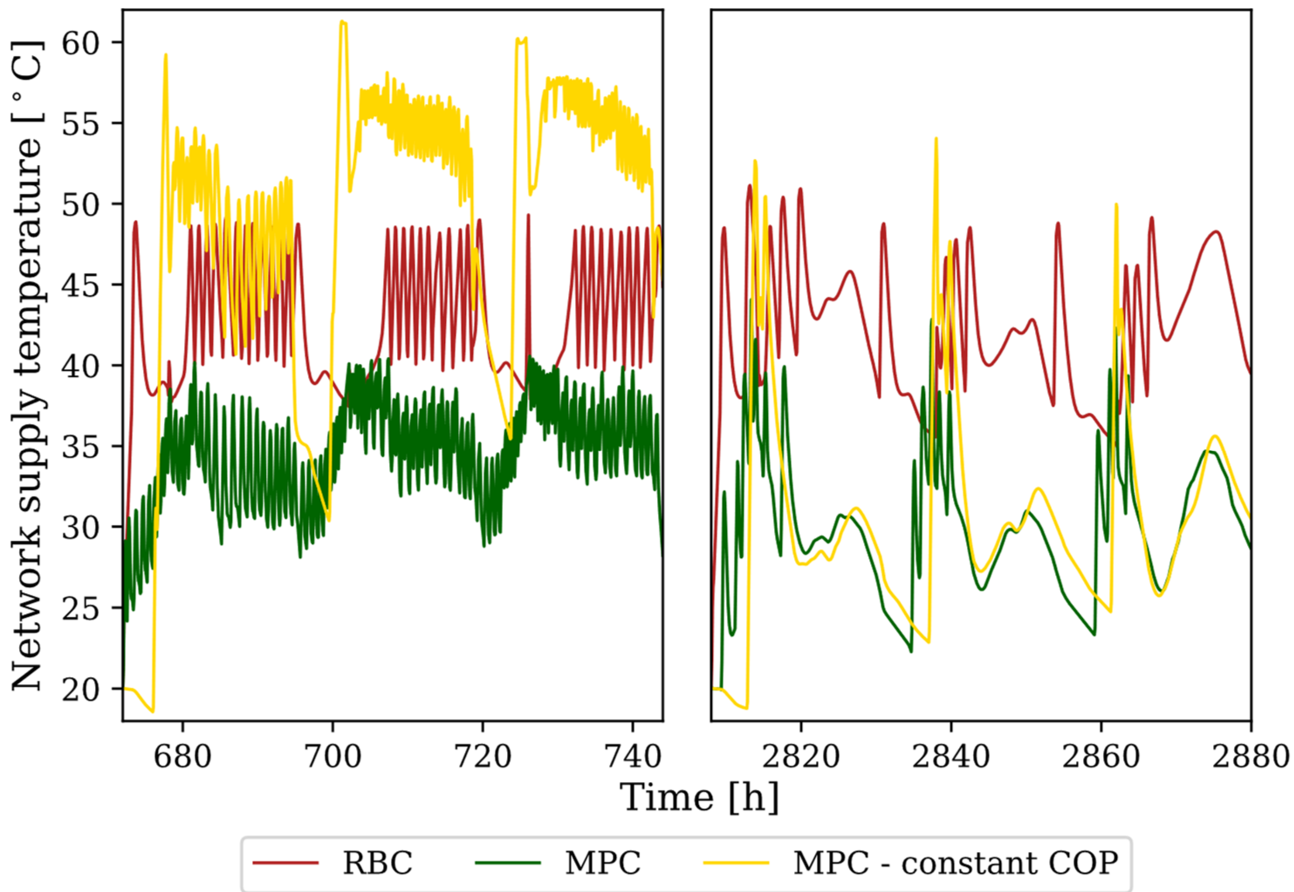
MPC vs. RBC

Control strategy	SH discomfort [Kh]	DHW discomfort [Kh]	Electricity use [kWh]			Heat demand [kWh]		SCOP [-]	
			$E_{el,tot}$	$E_{GSHP,el}$	$E_{BHP,el}$	E_{HE}	$E_{distr,loss}$	GSHP	BHP
Winter									
RBC	164	0	579	509 (88%)	36 (6%)	1500	126	3.31	3.63
MPC	1	0	530	456 (86%)	29 (5%)	1657	107	3.90	3.87
MPC – constant COP	25	0	720	636 (88%)	49 (7%)	1431	144	2.52	2.65
Spring									
RBC	21	0	165	115 (69%)	40 (24%)	343	117	3.62	3.62
MPC	2	0	119	65 (54%)	41 (34%)	319	83	4.29	3.14
MPC – constant COP	8	0	141	71 (51%)	56 (40%)	279	84	3.51	2.49

Operative room temperature



Network supply temperature



DHW supply temperature