Building control

Lecture 6: Model Predictive Control for Buildings

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Model Predictive Control (MPC)

Idea

Exploit our ability to predict the future behaviour of the weather and the building in deciding upon the control input to apply.

Approach

1. Use the model to calculate the "best" input plan for the next M hours;

   such that:

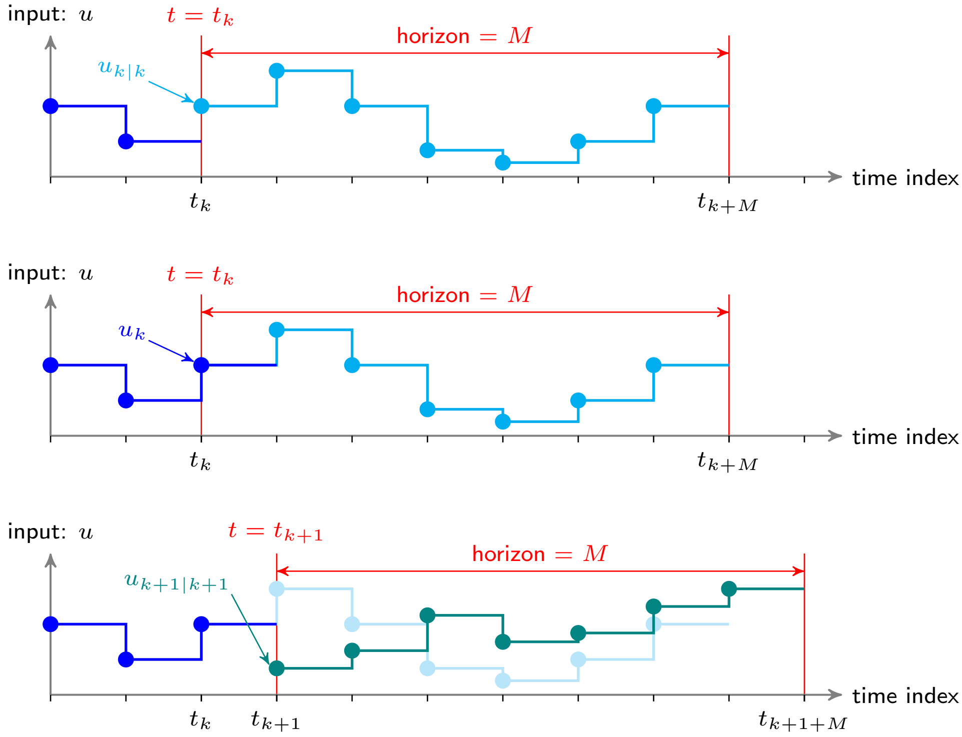
   - The input (heating/cooling) satisfies its constraints (power limits);
   - The state (room temperature) satisfies its constraints (comfort).

2. Apply the first control input of the plan.

3. At the next time step:

   - Measure our building states (room temperature);
   - and go back to step 1.

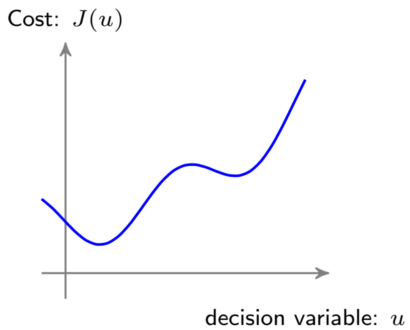
Moving horizon



Optimisation

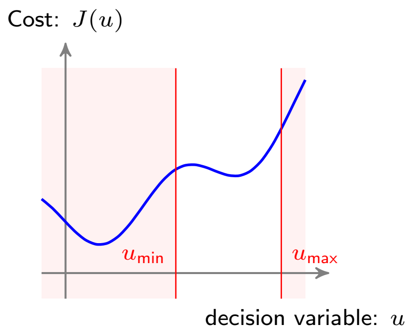
Minimising a cost function

$$\underset{u}{\text{minimise}}\, J(u)$$



Constrained minimisation

$$\begin{aligned} &\underset{u}{\text{minimise}} && J(u) \\ &\text{subject to} && u_{\min} \le u \le u_{\max} \end{aligned}$$



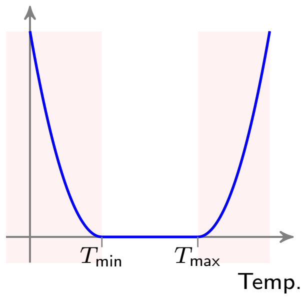
Mathematical formulation

Cost function

$J(u) = c^T u$ — Energy cost, CO_2 cost, etc.

or

$J(u) = c^T u + J_{\text{temp}}(x)$ — Temperature violation penalty



Constraints

$$u_{\text{min}} \leq u_k \leq u_{\text{max}} \qquad k = 0, \dots, M$$

$$x_{k+1} = A\,x_k + B\,u_k + B_d\,T_{\text{amb},k} \qquad k = 0, \dots, M-1.$$

Equality constraint formulation: $F \begin{bmatrix} x \\ u \end{bmatrix} + g = 0$

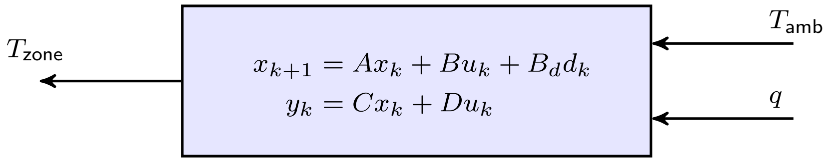
Dynamic constraint

$$x_{k+1} = Ax_k + Bu_k + B_d d_k \quad \Longrightarrow \quad \begin{cases} x_1 = Ax_0 + Bu_0 + B_d d_0 \\ x_2 = Ax_1 + Bu_1 + B_d d_1 \\ \qquad \vdots \\ x_M = Ax_{M-1} + Bu_{M-1} + B_d d_{M-1} \end{cases}$$

$$\begin{bmatrix} -I & 0 & & 0 & B & & & 0 \\ A & -I & & & & B & & \\ & \ddots & \ddots & & & & \ddots & \\ 0 & & A & -I & 0 & & & B \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_M \\ u_0 \\ \vdots \\ u_{M-1} \end{bmatrix} + \begin{bmatrix} A & B_d & & & 0 \\ & & B_d & & \\ & & & \ddots & \\ 0 & & & & B_d \end{bmatrix} \begin{bmatrix} x_0 \\ d_0 \\ \vdots \\ d_{M-1} \end{bmatrix} = 0$$

MPC example

Plant: single zone temperature dynamics

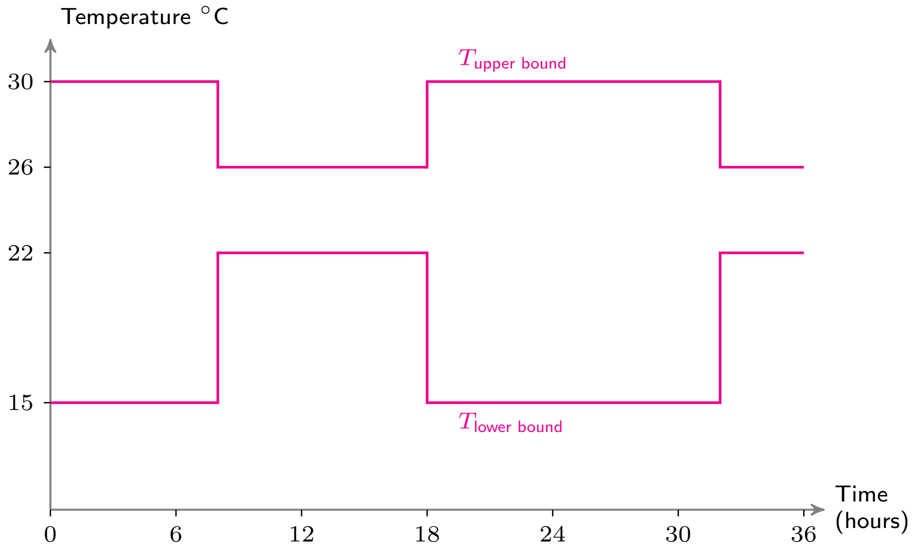


actuation input:	$u_k = q$	heat flux
disturbance:	$d_k = T_{\text{amb}}$	ambient temperature
output/measurement:	$y_k = T_{\text{zone}}$	zone temperature

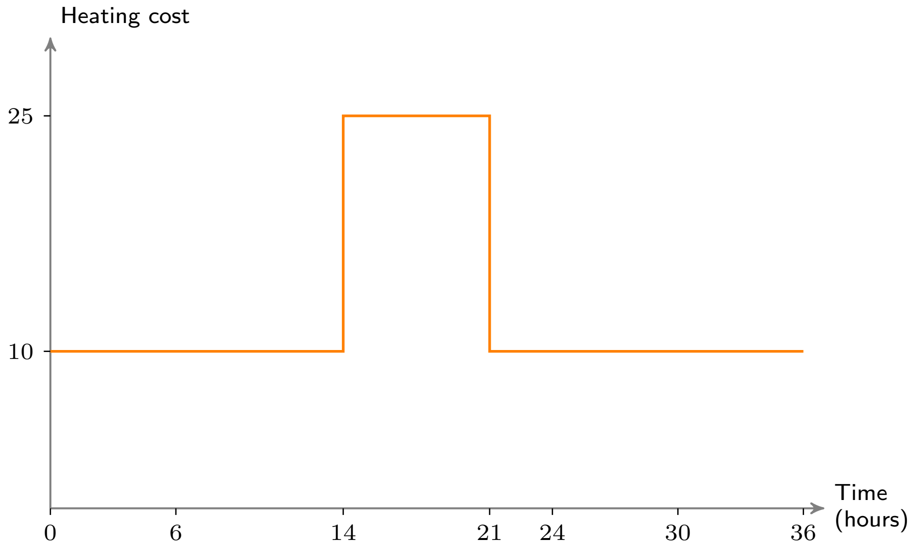
MPC optimisation formulation

Sampling period:	1 hour
Prediction horizon	$M = 12$ hours

Temperature bounds

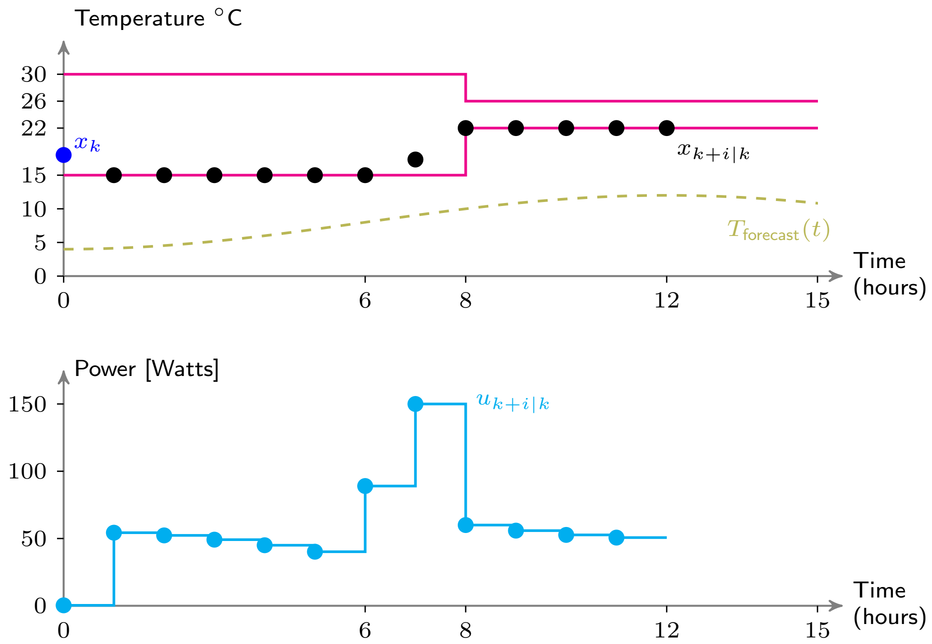


Cost function



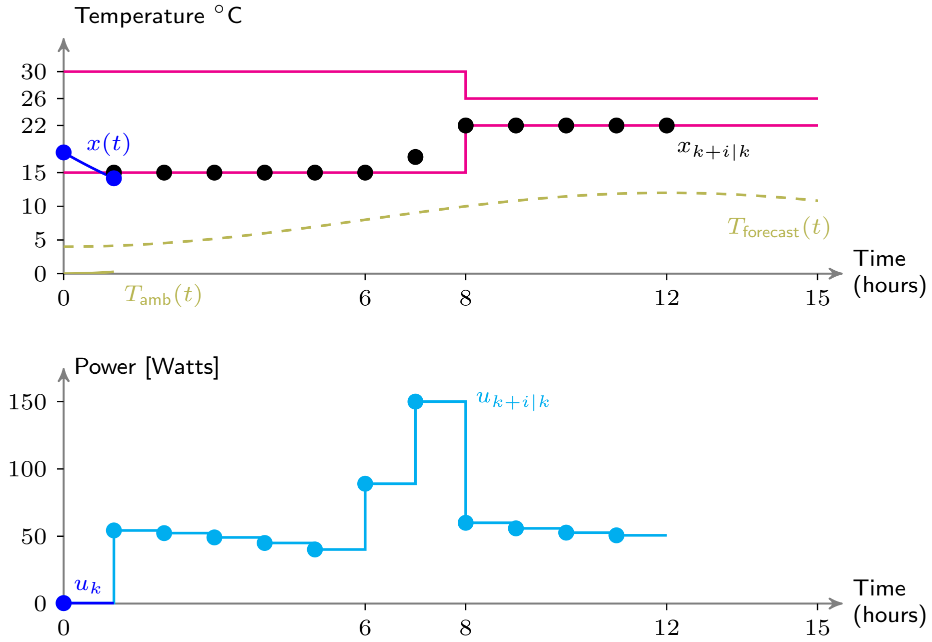
MPC optimisation result

Prediction at time $k = 0$



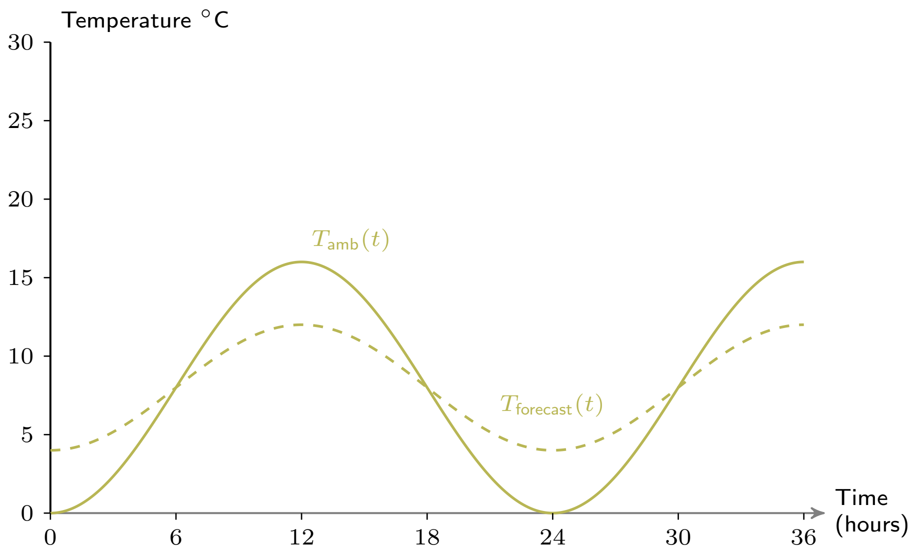
Actuation

Actuation from time $k = 0$ to time $k = 1$



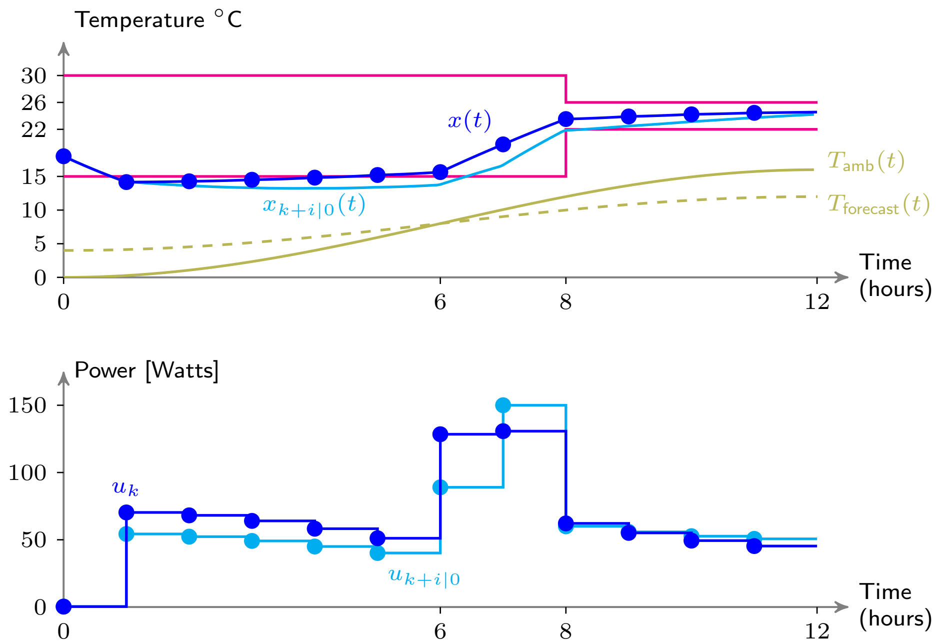
Prediction: forecasting errors

Predicted and actual ambient temperature disturbance



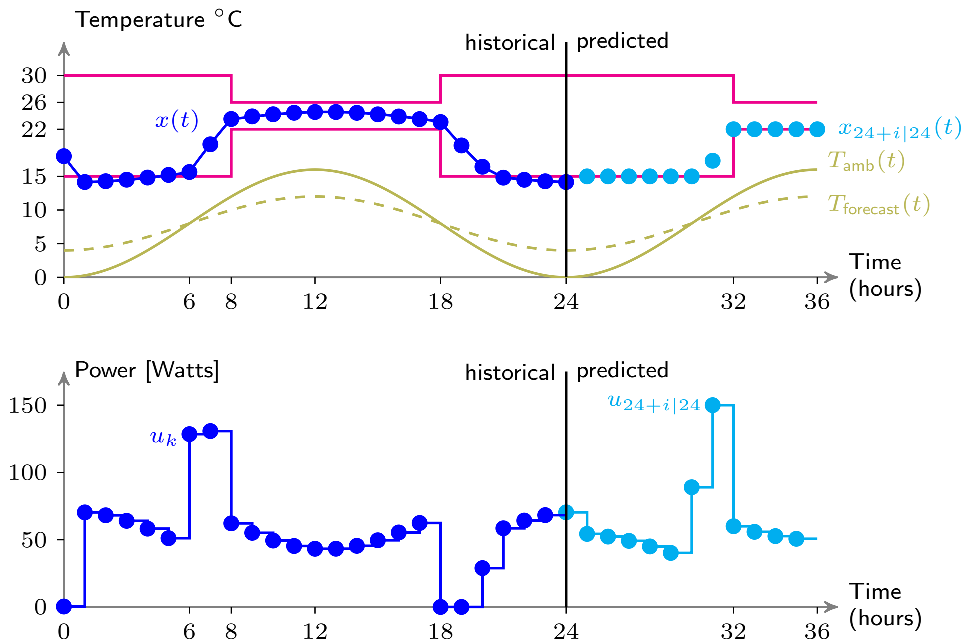
Moving horizon correction

Planned and actual trajectories



24 hour operation

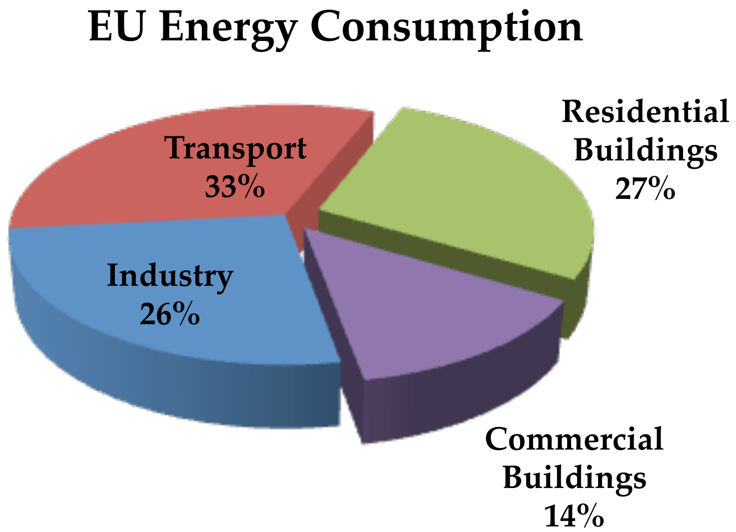
Past and predicted operation at $k = 24$



Introduction

Motivation: energy

- In Europe, 41% of energy is used within buildings;
- Also accounts for 36% of CO_2 emissions;
- Large thermal energy storage gives energy shifting options.



Introduction

Building sector

- The refurbishing rate in Switzerland is approx. 2% per annum;
- As much as 25% of the total energy is in the concrete;
- Control and commissioning occurs at building project end;
- Lack of integrated design and control;
- Currently little expertise in advanced control.

Potential MPC capabilities

- Potential use of weather forecasts;
- Potential use of occupancy forecasts;
- Dynamic electricity prices;
- Potential peak power reduction;
- Flexibility in upgrade modeling.

Introduction

Model predictive control

- Constraints determine operational modes;
- Most of the disturbances can be forecast:
  - Ambient temperature (typ. 3 days ahead);
  - Solar radiation;
  - Occupancy and energy use patterns.
- The dynamics are slow and relatively benign (time constants: 30 minutes to days);
- The sampling rate is also slow (typ. 15 minutes);
- Adequate computational power is readily available;
- Sensing is (relatively) inexpensive;

Introduction

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- Adequate computational power is readily available;
- Sensing is (relatively) inexpensive;
- Actuation is typically expensive;
- Modeling can be time-consuming.

MPC for buildings

Objectives

- Minimisation of energy (NRPE) or cost.
- Potentially time-varying energy/operational costs.

Constraints

- Comfort:
  - Room temperatures within limits;
  - CO_2 level limit;
- HVAC:
  - TABS water supply temperature limits;
  - Minimum ventilation airflow;
  - Ventilation operational limits;
  - Air heating/cooling temperature limits;
  - Energy recovery system operational bounds.

MPC for buildings

Modeling

- Building thermal dynamics;
  - Room node dynamics;
  - Solar radiation;
  - Ambient air and heat exchange;
  - Energy exchange within the building;
- HVAC dynamics;
- Forecasting error dynamics.

Disturbances (partially predictable)

- Ambient temperature;
- Solar radiation;
- Occupancy and use.

Opticontrol II

Key contributors:

D. Sturzenegger, D. Gyalistras, M. Gwerder, C. Sagerschnig, M. Morari, R. Smith.

Demonstrator building

Located in Basel.
6 storeys + 2 underground.
Offices in upper 5 floors.
2nd floor instrumented.
Siemens building control system.

Actuation

TABS for heating/cooling

Water piping within floor.

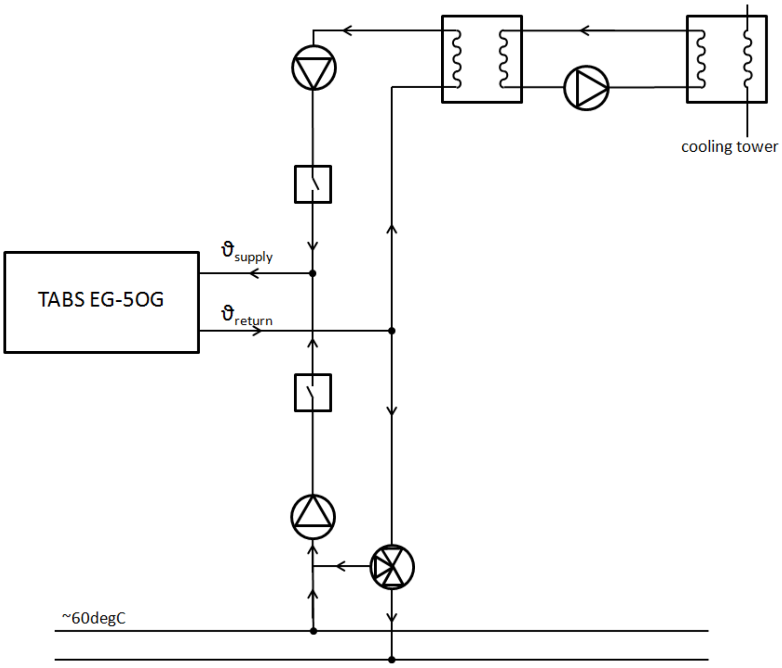
Using building thermal storage.

Heat: gas boiler.

Cooling: dry tower.

Cooling restricted to night.

Efficiency depends on ambient humidity and temperature.



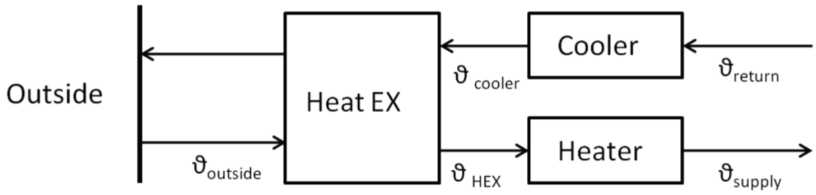
Actuation

Ventilation

Heater on incoming air.

Cooling on return air.

Energy recovery via heat exchanger.



Minimum air flow requirements.

Significant losses in ducting.

Actuation

Blinds

Control only by façade.

Limited settings: open, closed, shaded (2 levels).

Operation limited to 3 times per day for user acceptance.

Manual override possible (and undetectable).

Sensing

Additional sensors installed in 22 rooms on the 2nd floor.

Window sensor

Room temperature

Illumination/presence

Sensing

Weather station on roof

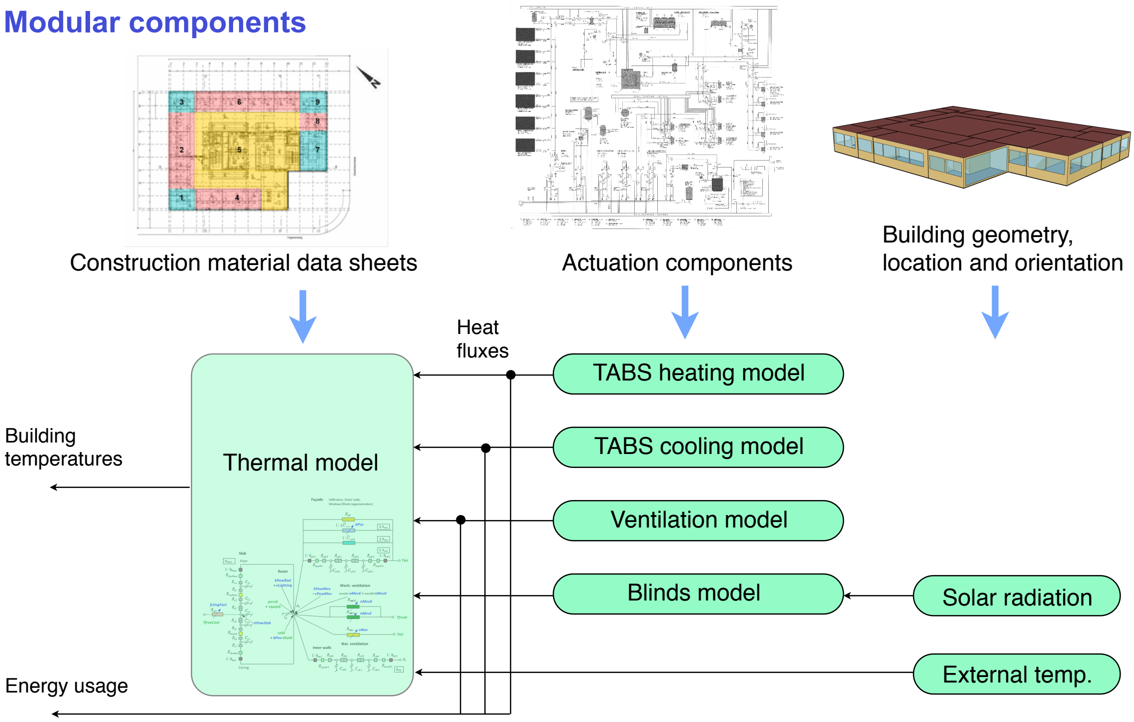
Measurements:

Ambient temperature;
Solar radiation (4 directions);

Additional radiation sensor on each façade;

Existing building control sensing
(HVAC, cooling tower, etc.).

Modeling



Modeling

RC modeling

Thermal dynamics model:

$$x_{k+1} = Ax_k + B_q q_k(x, u_k, v_k) \qquad \text{(linear thermal dynamics)}$$

External heatflux model:

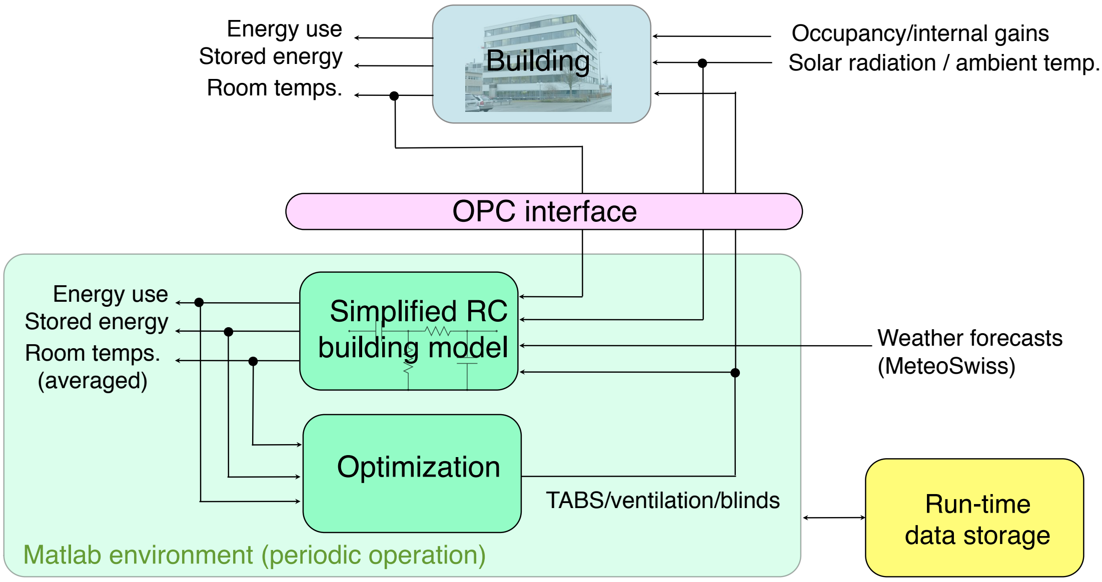
$$q_k(x_k, u_k, v_k) = A_q x_k + B_{q,u} u_k + B_{q,v} v_k + \sum_{i=1}^{n_u} (B_{q,vu} v_k + B_{q,xu} x_k) u_{i,k}$$

Bilinear actuation/heatflux dynamics.

Thermal model reduced to approximately 25 states in total.

Another 10 states are used in modeling the actuation.

MPC building operation structure



MPC algorithm

Problem framework

- Sampling period is 15 minutes.
- Prediction horizon is 54 hours.
- Three weather forecasts per day (each valid for 72 hours).

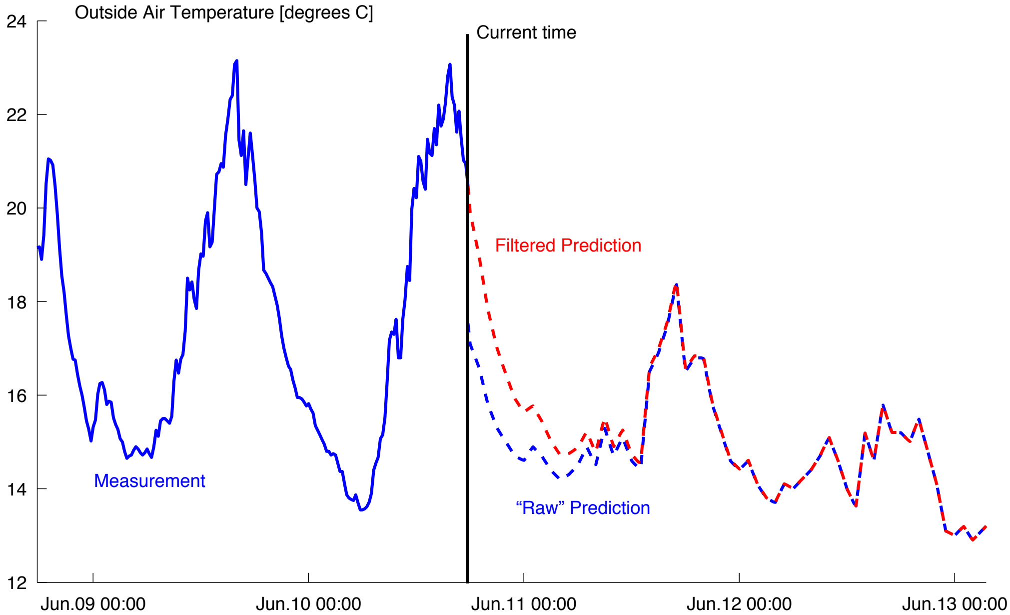
Optimisation

- Mixed integer problem (quantized blind positions)
- Two step sub-optimal solution:
  - Solve with continuous blind positions.
  - Round blind controls to allowed values.
  - Resolve over remaining control variables.

Operation

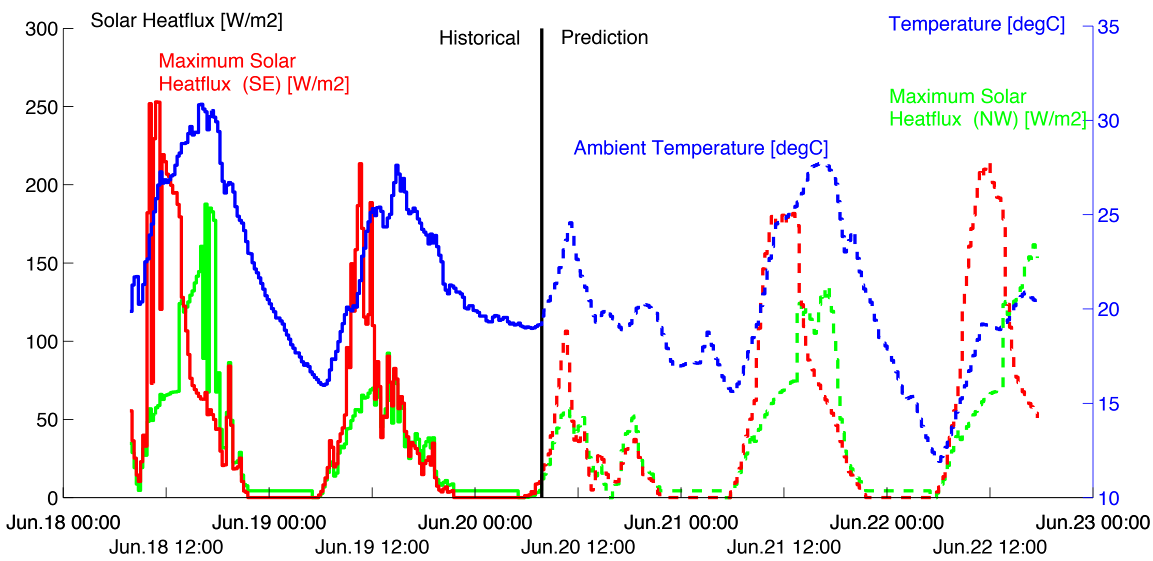
Weather prediction filtering

Filter dynamics are based on OptiControl I analyses.



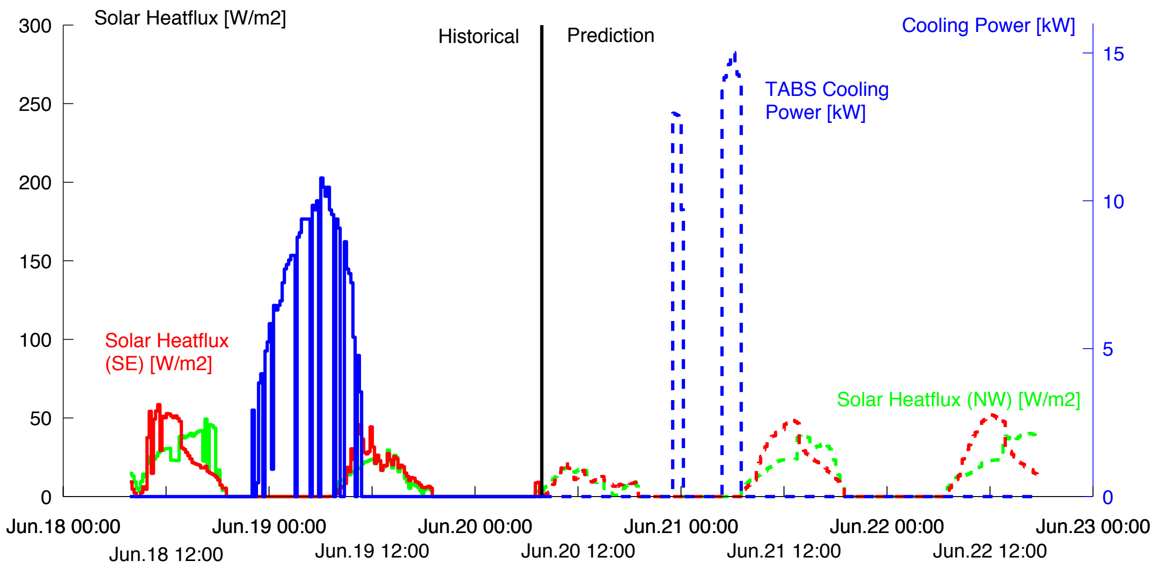
Operation

Disturbances (measured and filtered predictions)



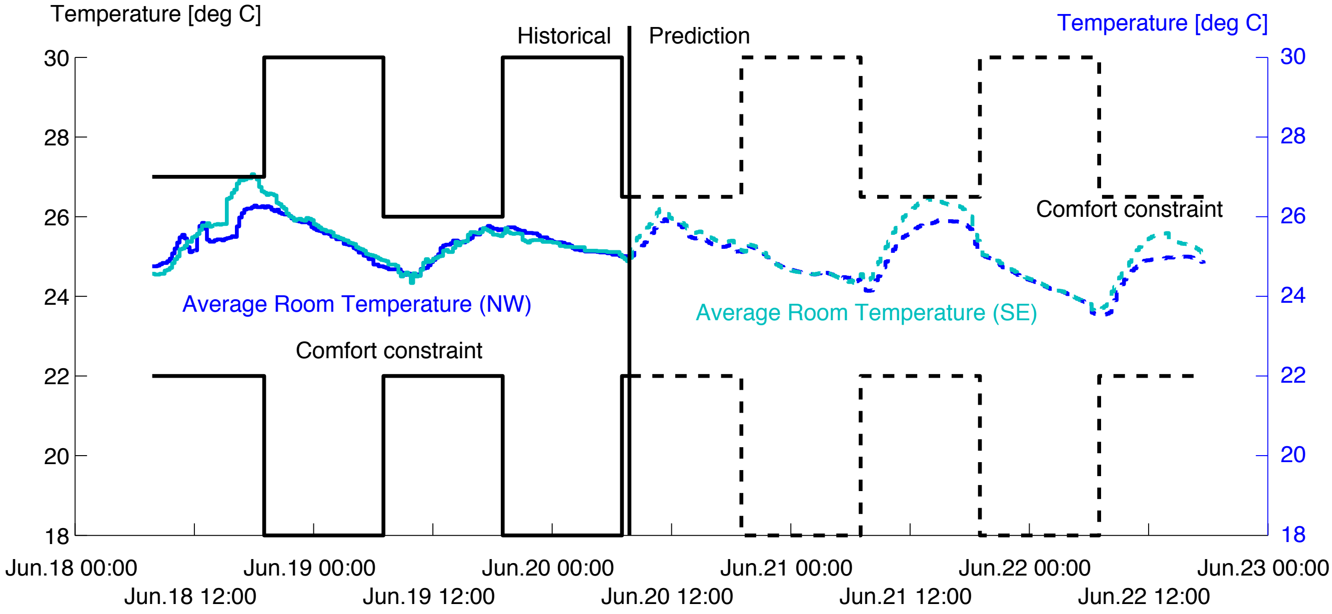
Operation

Actuation (TABS and blinds)

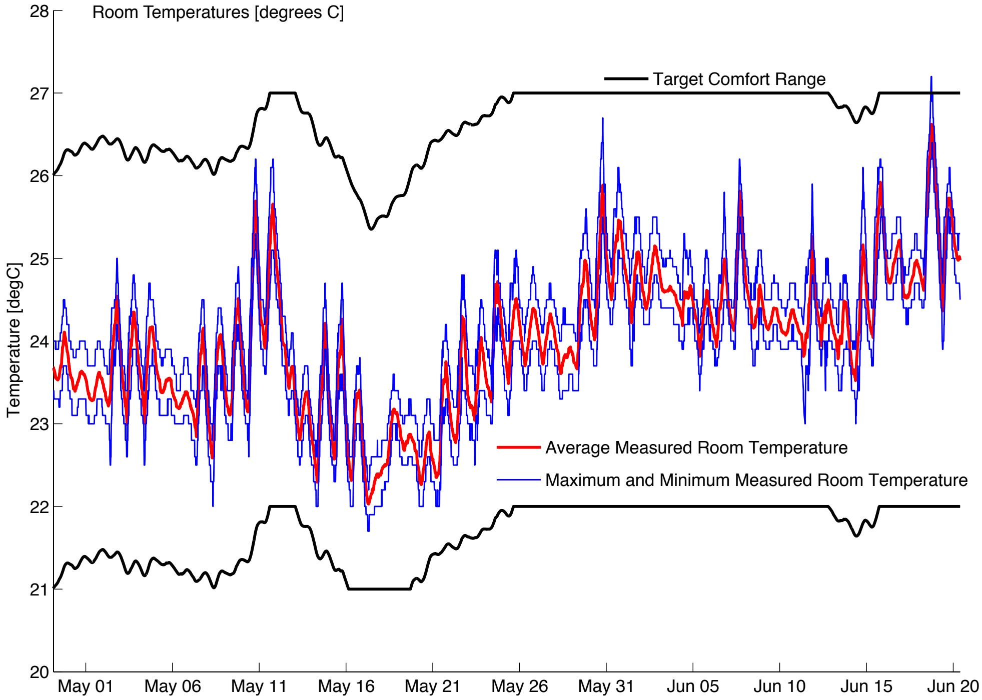


Operation

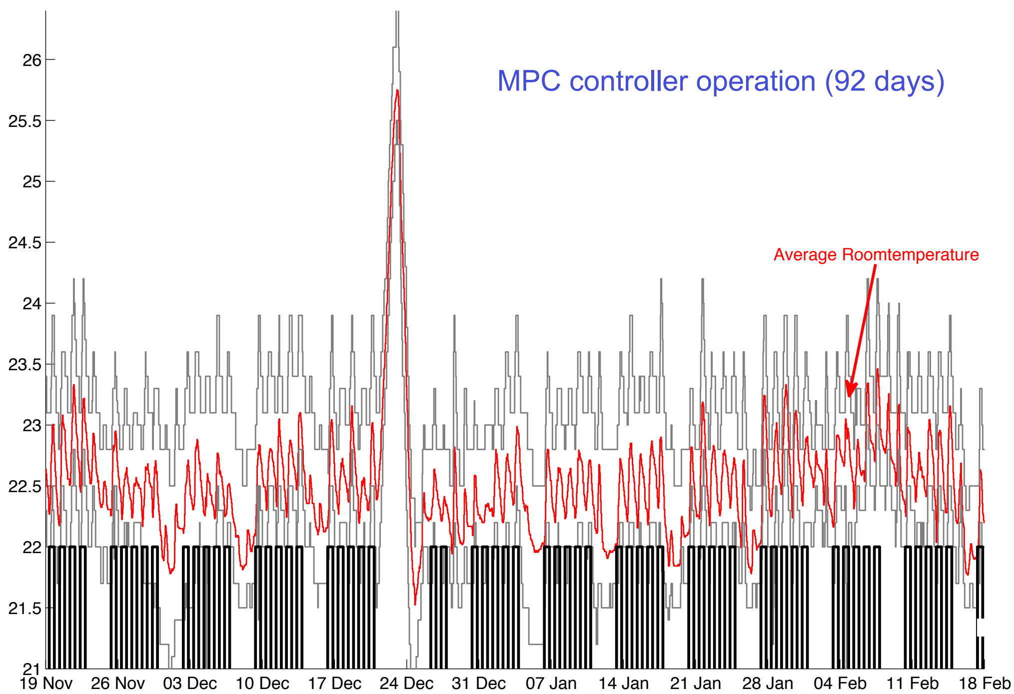
Room temperatures (2 façades)



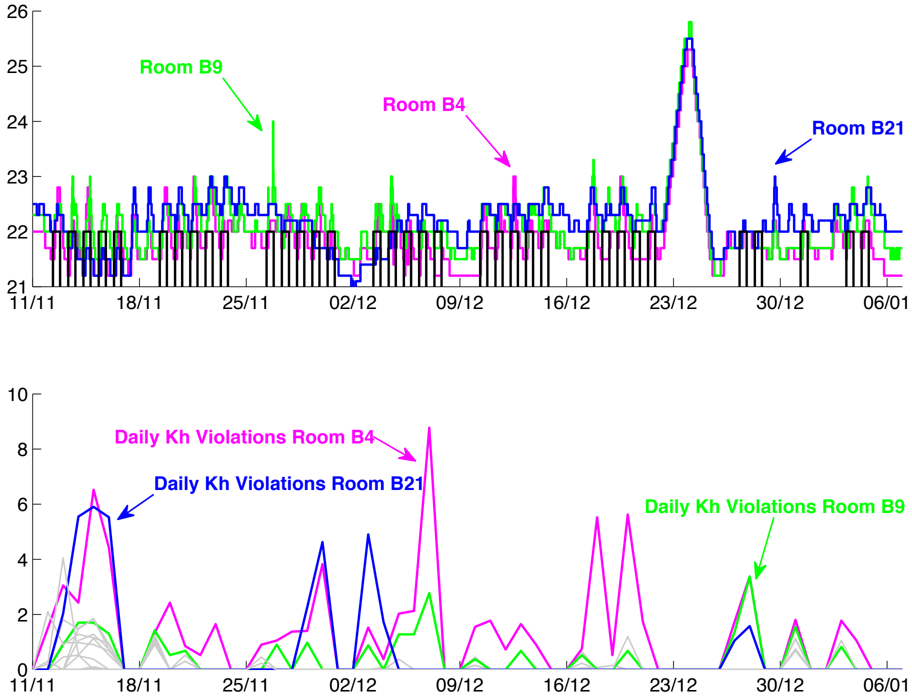
Room temperatures (summer operation)



Room temperatures (winter operation)

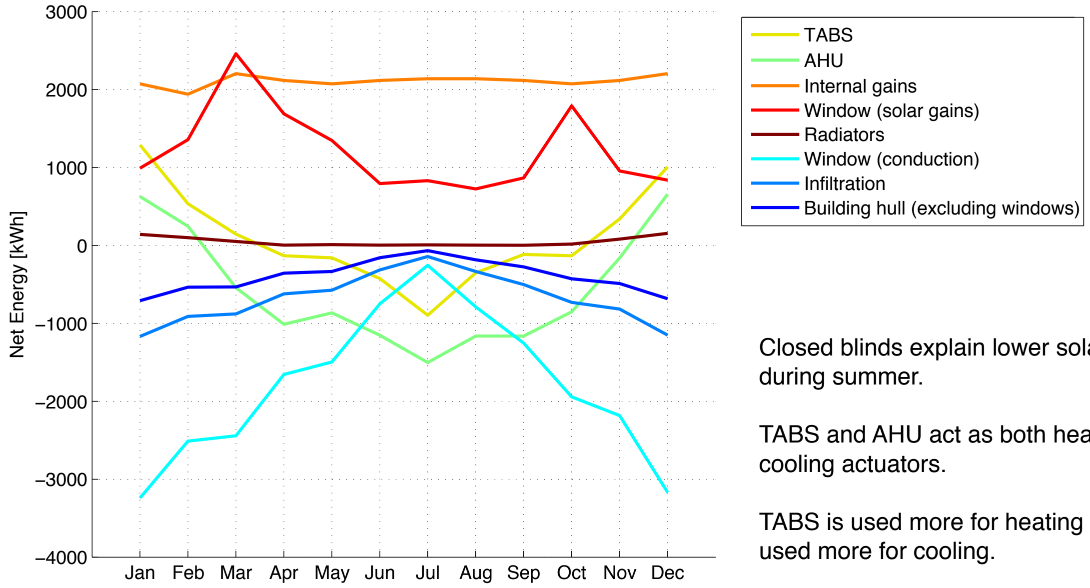


Comfort violations



Energy balance (simulated operation)

Energy balance within the controlled building



The data is averaged by month

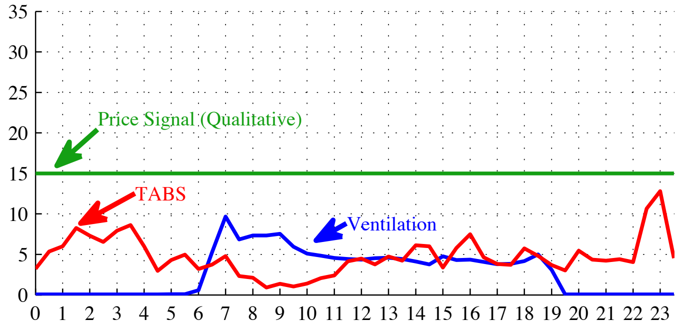
Closed blinds explain lower solar gains during summer.

TABS and AHU act as both heating and cooling actuators.

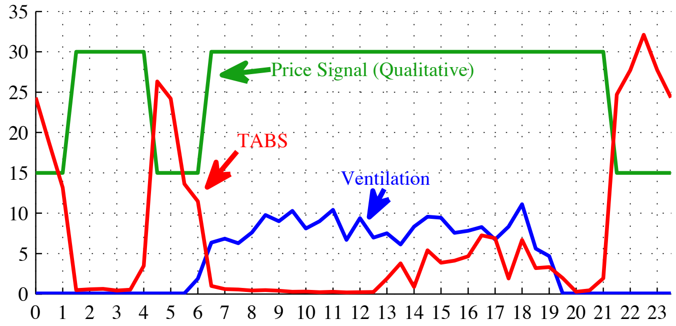
TABS is used more for heating and AHU is used more for cooling.

Demand reduction experiments

MPC can use constraints and/or price signals to shift electrical load or gas consumption



Measured average hourly power consumption.
(18 Nov 2012 - 01 Feb 2013)



Measured average hourly power consumption.
05 Feb 2013 - 14 Feb 2013)

Conclusions

- MPC is effective at managing energy and thermal comfort in the building.
- MPC gives approximately 15% reduction in heating/cooling energy.
- Thermal comfort is significantly improved over original building RBC.
- Tuning is relatively straightforward.
- Good user acceptance (6 months of operation).
- Modeling is a significant effort.
- Potential for load shifting within the grid.
- Flexibility is one of the most significant benefits.

References

There are many...

See http://www.opticontrol.ethz.ch.