ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

SIEMENS

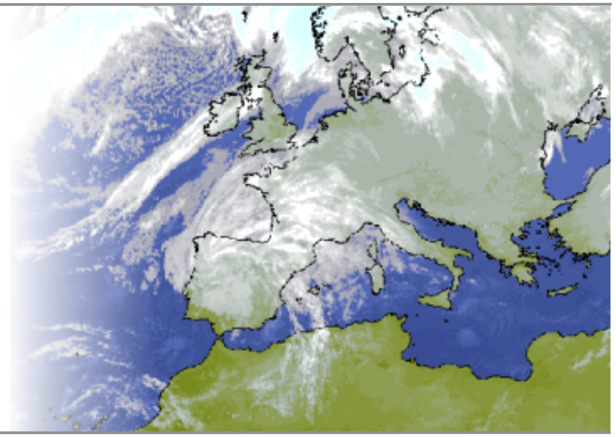
swisselectric research

gruner

CCEM-CH

EMPA
Materials Science & Technology

ACTELION



Predictive Building Control
Insights from the Research Perspective

Fachveranstaltung «Gesamtheitliche vorausschauende Gebäudeautomation»
Allschwil, 20. September 2012

Roy Smith
ETH Zürich,
Physikstrasse 3
8092 Zürich
rsmith@control.ee.ethz.ch

Overview:

The Automatic Control Laboratory / Institut für Automatik (IfA) is located within the Department of Information Technology and Electrical Engineering (D-ITET) at the ETH in Zürich.

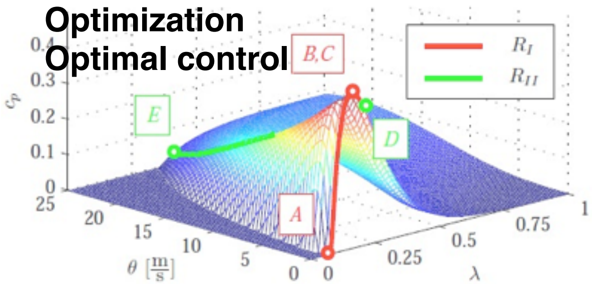
We have 4 professors: John Lygeros (Head of the Laboratory)
Heinz Köppl
Manfred Morari
Roy Smith

We also have:
- 3 senior researchers;
- 7 post-doctoral researchers;
- 34 Ph.D. students.

Institut für Automatik

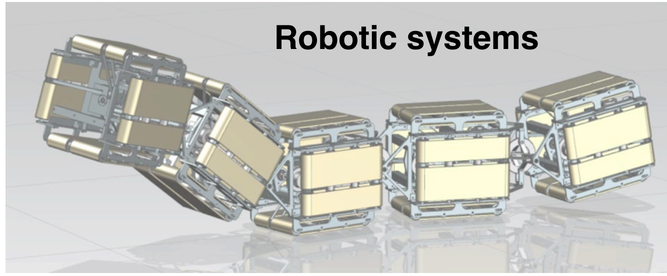
Research Activities:

Optimization
Optimal control

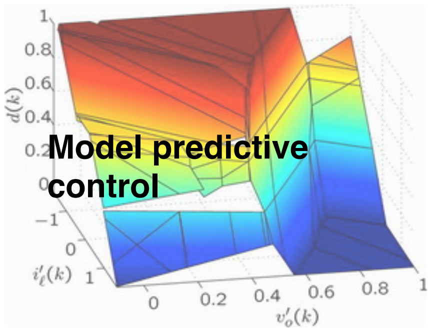


Process control

Robotic systems



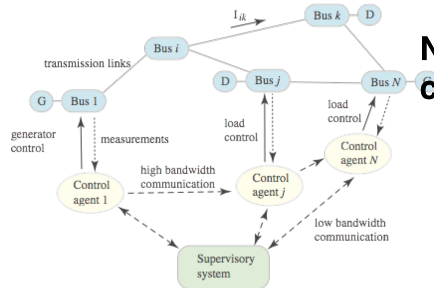
Model predictive control



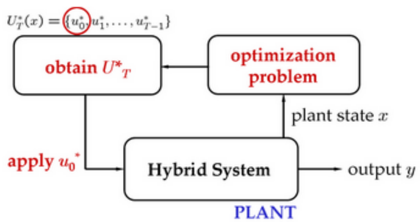
Control theory

$$\frac{dx(t)}{dt} = A\,x(t) + B\,u(t)$$
$$y(t) = C\,x(t) + D\,u(t)$$
$$u(t) = K\,y(t)$$

Networked and cooperative systems

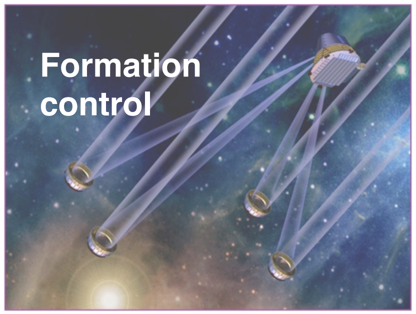


Hybrid systems



Building control

Formation control



Kite control & aerodynamics

swisselectric research · ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich · SIEMENS Building Technologies · gruner · ACTELION

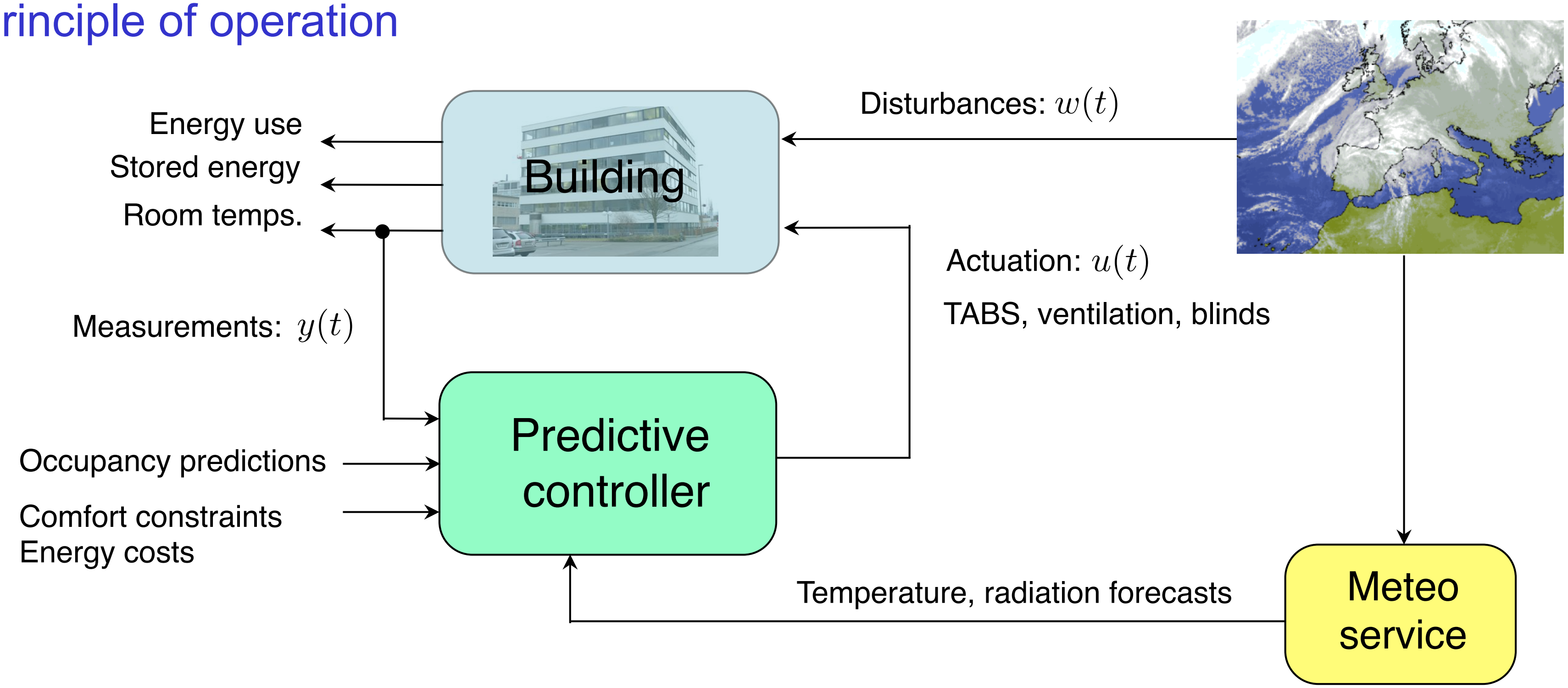
Overview

OptiControl II: Model predictive control

- An outline of Model Predictive Control (MPC)
- Control relevant description of the Actelion demonstrator building
- Building modeling for MPC
- Commissioning the MPC system
- MPC operational experience
- EnergyPlus simulation comparisons with Rule-Based Control (RBC)
- Discussion

Model predictive control (MPC)

Principle of operation



$$\text{Predicted Cost} = \underset{u(t)}{\text{minimize}} \quad \text{Expected} \left(\sum_{t}^{t+N} \text{energy cost(t)} \right)$$ ← Minimize the predicted energy cost

$$\begin{aligned} \text{subject to} \quad & u(t) \in \mathcal{U} \\ & x(t) \in \mathcal{X} \\ & x(t+1) = f(x(t), u(t), w(t)) \end{aligned}$$

- $u(t) \in \mathcal{U}$ ← Actuation within limits
- $x(t) \in \mathcal{X}$ ← Predicted temperatures within limits
- $x(t+1) = f(x(t), u(t), w(t))$ ← Predicted dynamics of the building

swisselectric research · ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich · SIEMENS Building Technologies · gruner · ACTELION

Model predictive control (MPC)

Main advantages of MPC

Actuation constraints can be satisfied:

- TABS heating and cooling limits
- Blind operation limits.
- Air handling flow and temperature limits

State variable constraints can be satisfied:

- Room temperatures kept within limits

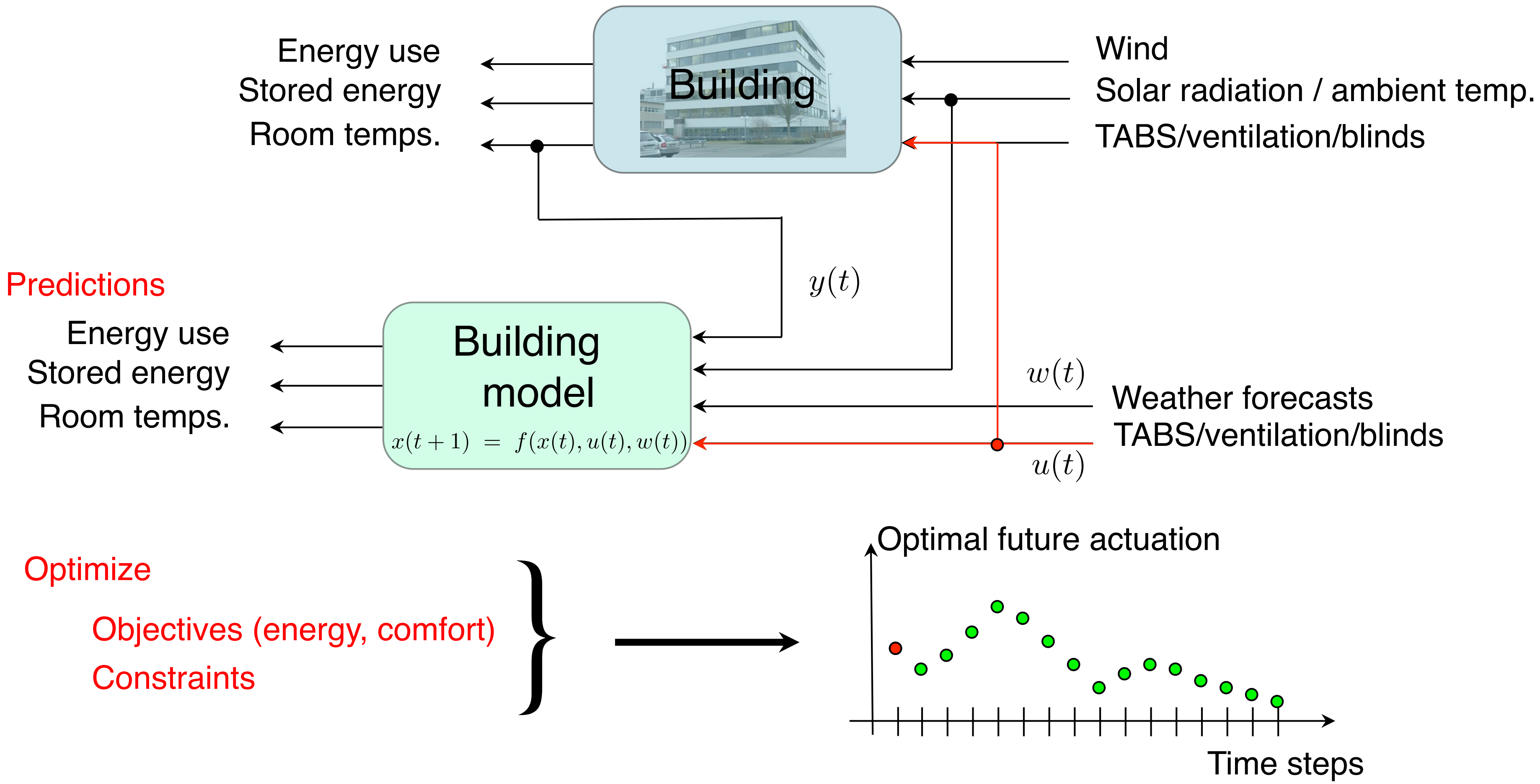
Predictions of the disturbances (weather, occupancy) can be used for an optimal strategy.

Constraints can change with time and predicted weather.

Constraints and limits can be changed in a straight-forward way.

Model predictive control (MPC)

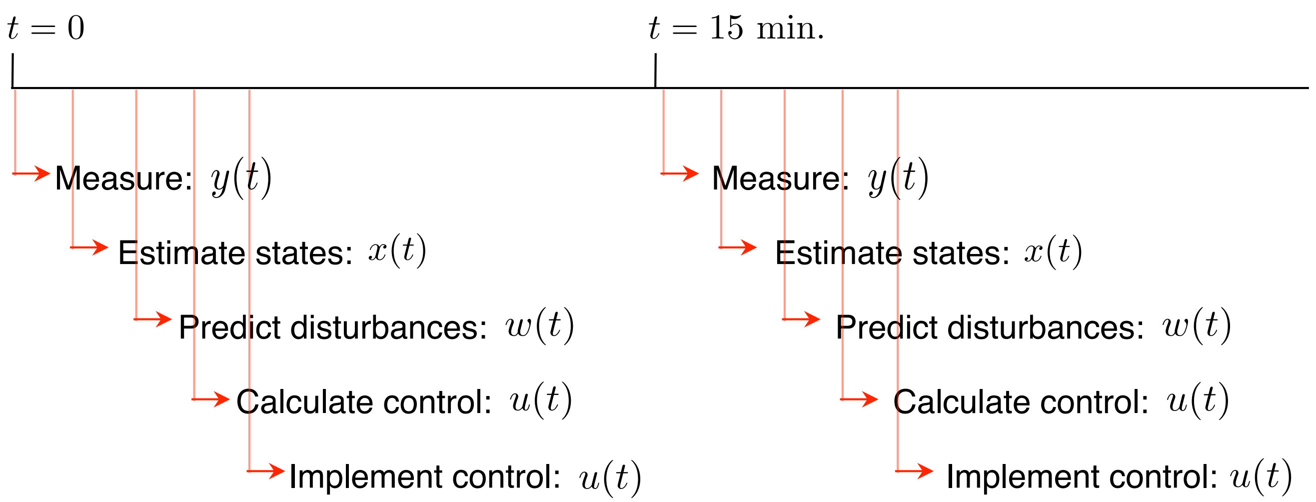
Principle of operation



At each time step: measure, calculate future optimal actuation setpoints, apply first actuation setpoints

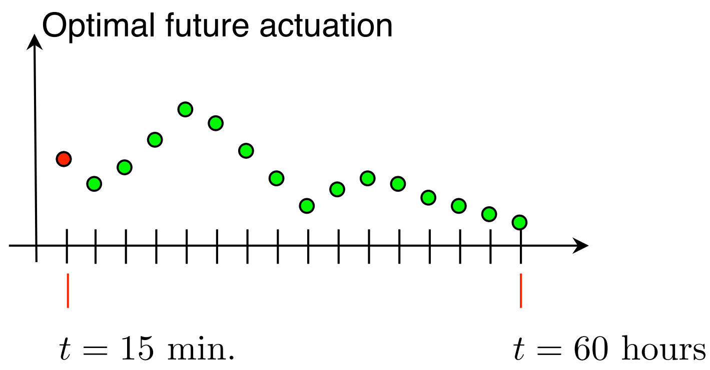
Model predictive control (MPC)

MPC controller operation



Weather forecast: 72 hours, updated every 12 hours

Prediction horizon: 60 hours (240 time steps ahead)



Actelion demonstrator building

Instrumentation for MPC

- Room temperatures (2nd floor),
- Outside air temperature,
- Solar radiation, façade illuminance.

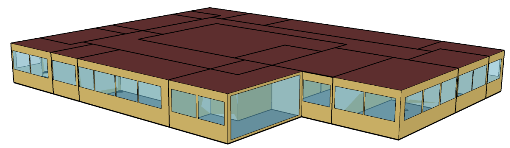
Actuation for MPC

- TABS system: (slow actuation)
    - Heating mode
    - Cooling mode uses tower (effective only at night)
- Air handling/ventilation system: (fast actuation but low power due to low air-flow)
- Blinds (limited operation while building is occupied; limited number of positions)

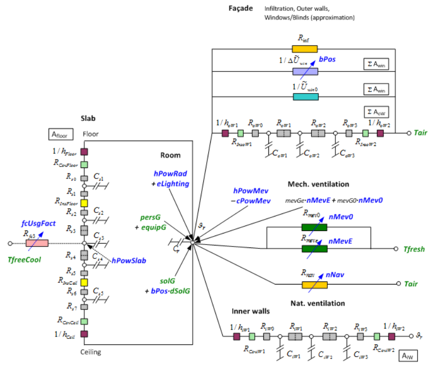
Building modeling for MPC

Models:

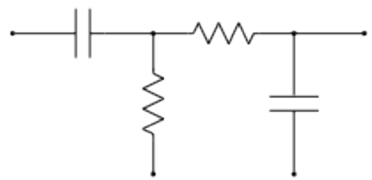
EnergyPlus: Physics based; construction/material specifications;
(Gruner)
2^{nd} floor (725 sq.m.) divided into 24 zones;
Simulation studies (via BCVTB) possible;
Unsuitable for MPC implementation.



Large-scale RC model**:** Semi-automated derivation from EP;
(ETH)
2^{nd} floor thermal model has 294 states;
Too large for MPC implementation;
Convenient test environment for MPC.



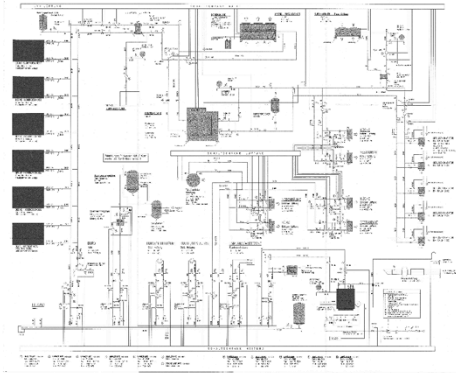
Reduced-order RC model**:** Hankel-norm reduction of thermal model;
(ETH)
Thermal model: 15 states (with 0.1% error);
Actuation adds 10 more states;
Time constants: 20, 8 and 5 hours. Majority < 30 minutes.



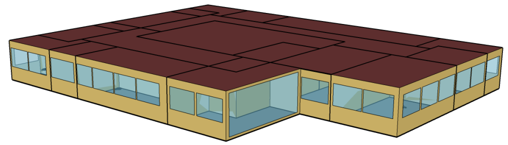
Building modeling for MPC

Modular components

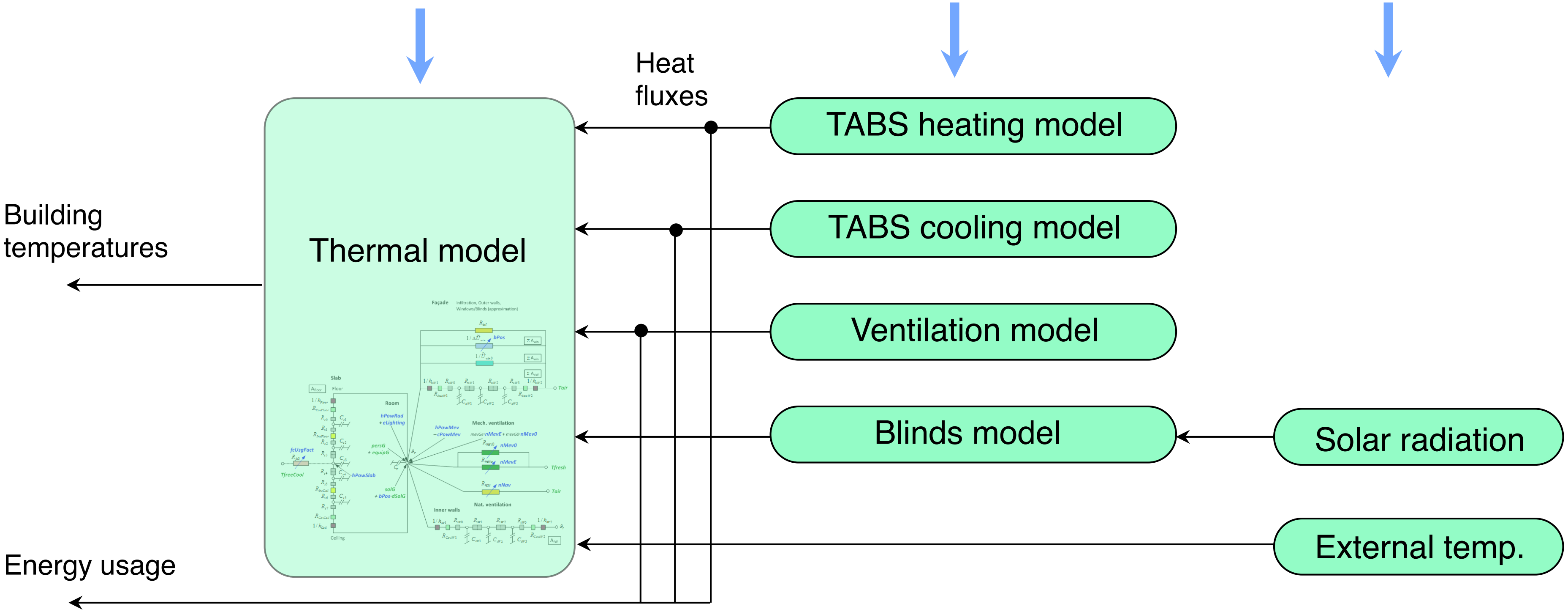
Construction material data sheets



Actuation components

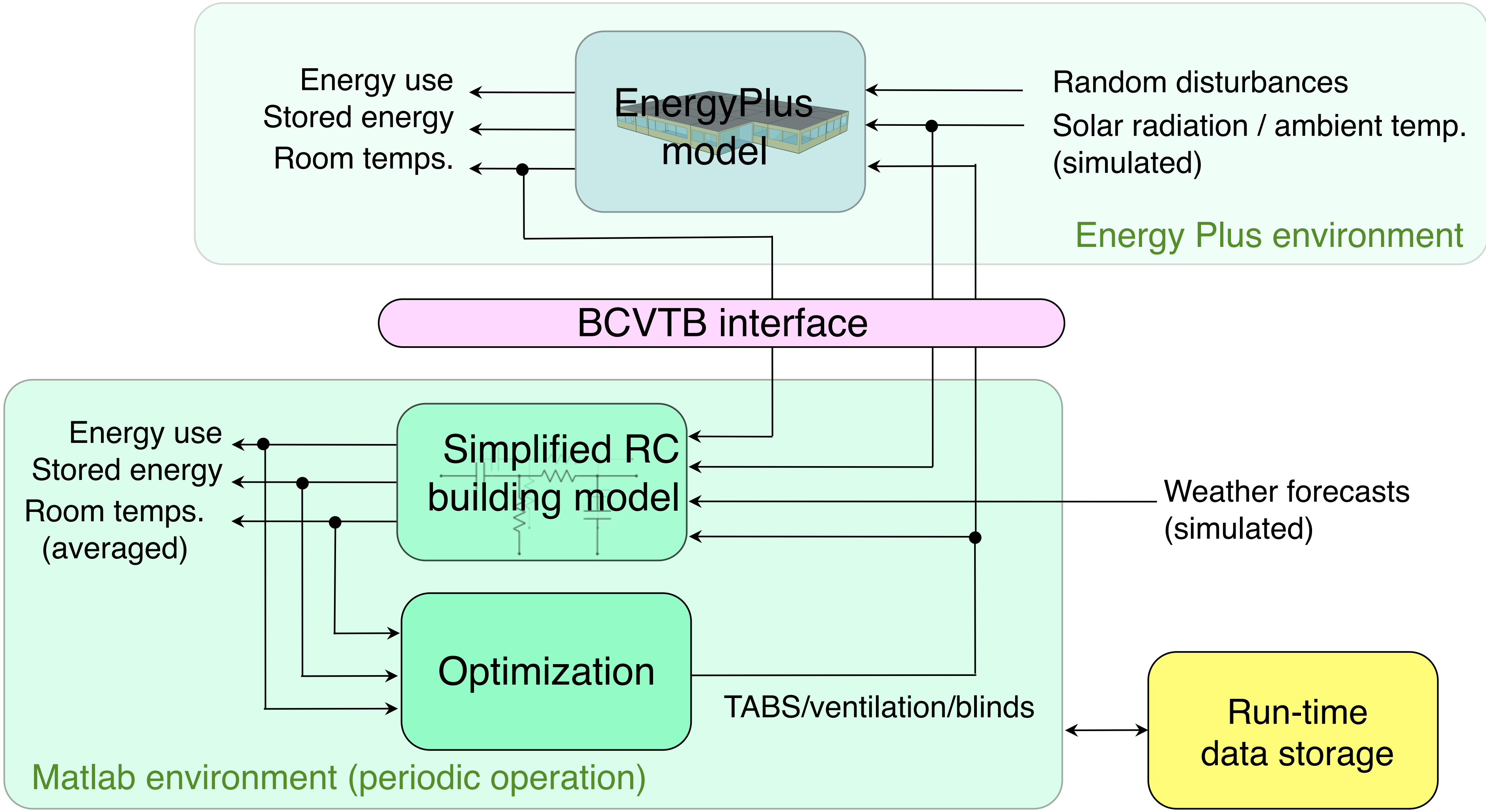


Building geometry,
location and orientation



Commissioning the MPC system

MPC controller commissioning (initial verification)



Commissioning the MPC system

MPC controller commissioning (building tests)

MPC controller run in shadow mode to confirm operation.

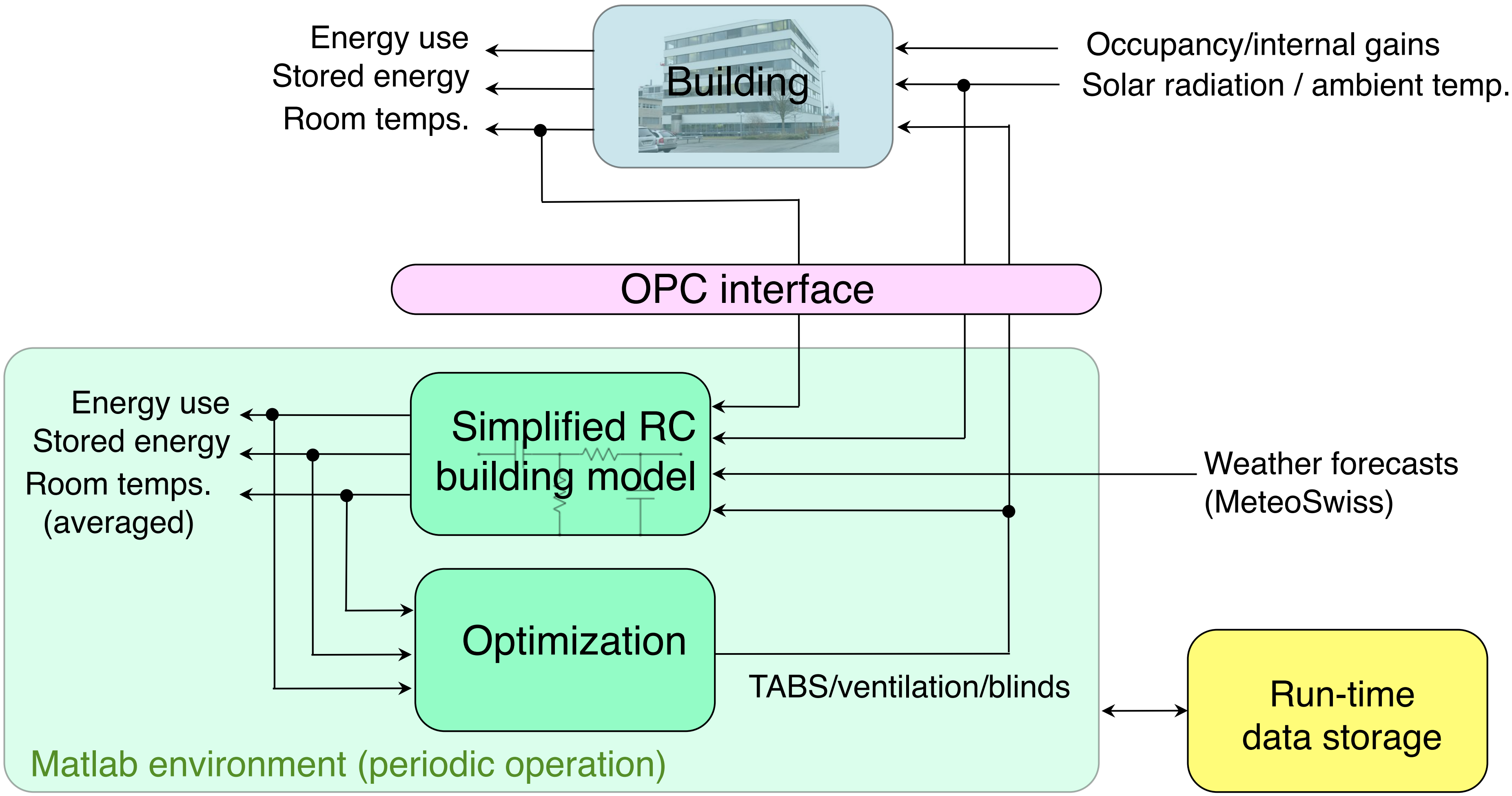
Sensor failure and bad data tests conducted.

Matlab failure test conducted.

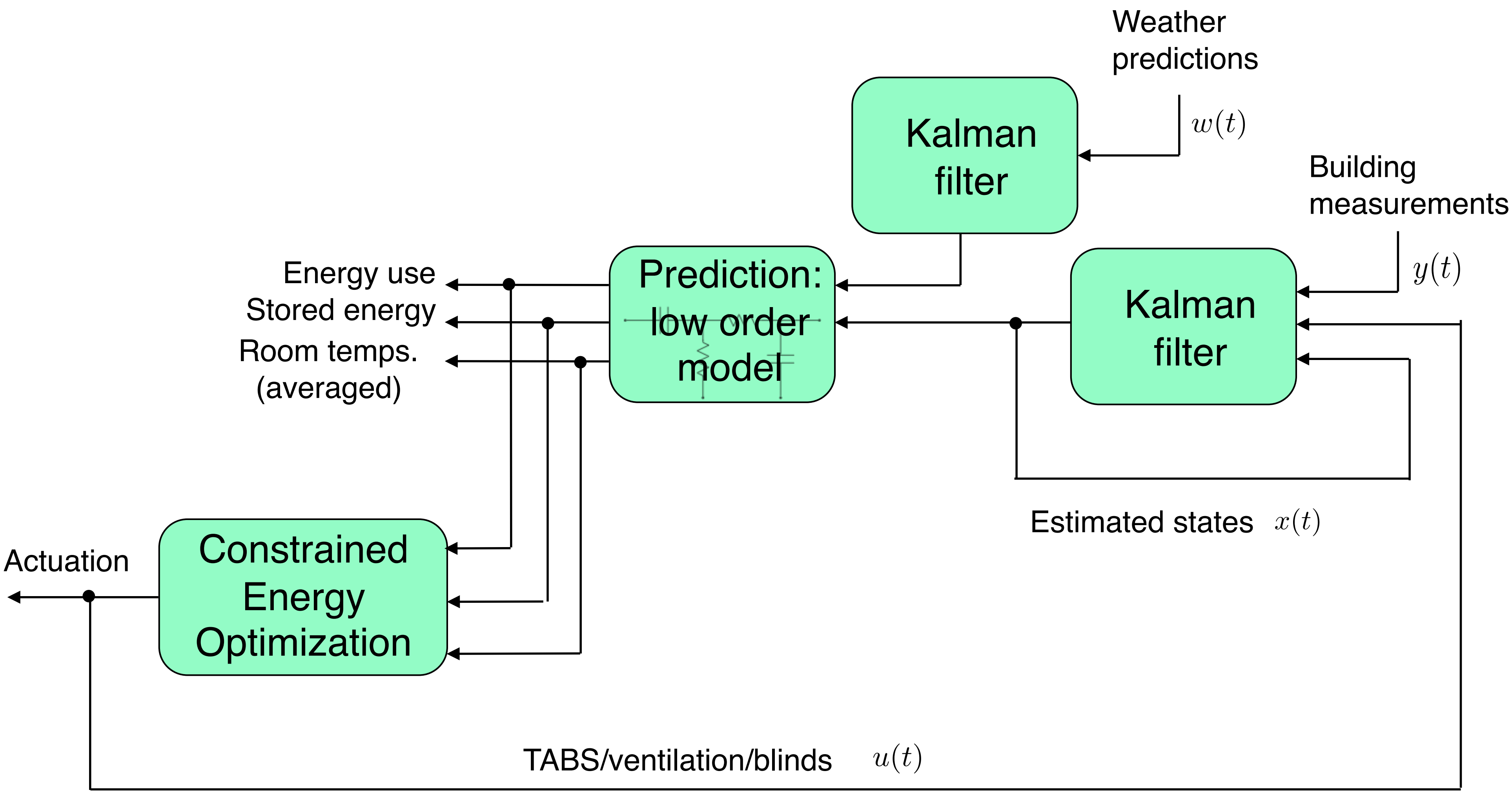
MPC controller implementation:

- TABs heating implemented: 21 April 2012.
- TABs cooling & blind control implemented: 10 May 2012
- AHU temperature control implemented: 10 June 2012.

Model Predictive Control implementation



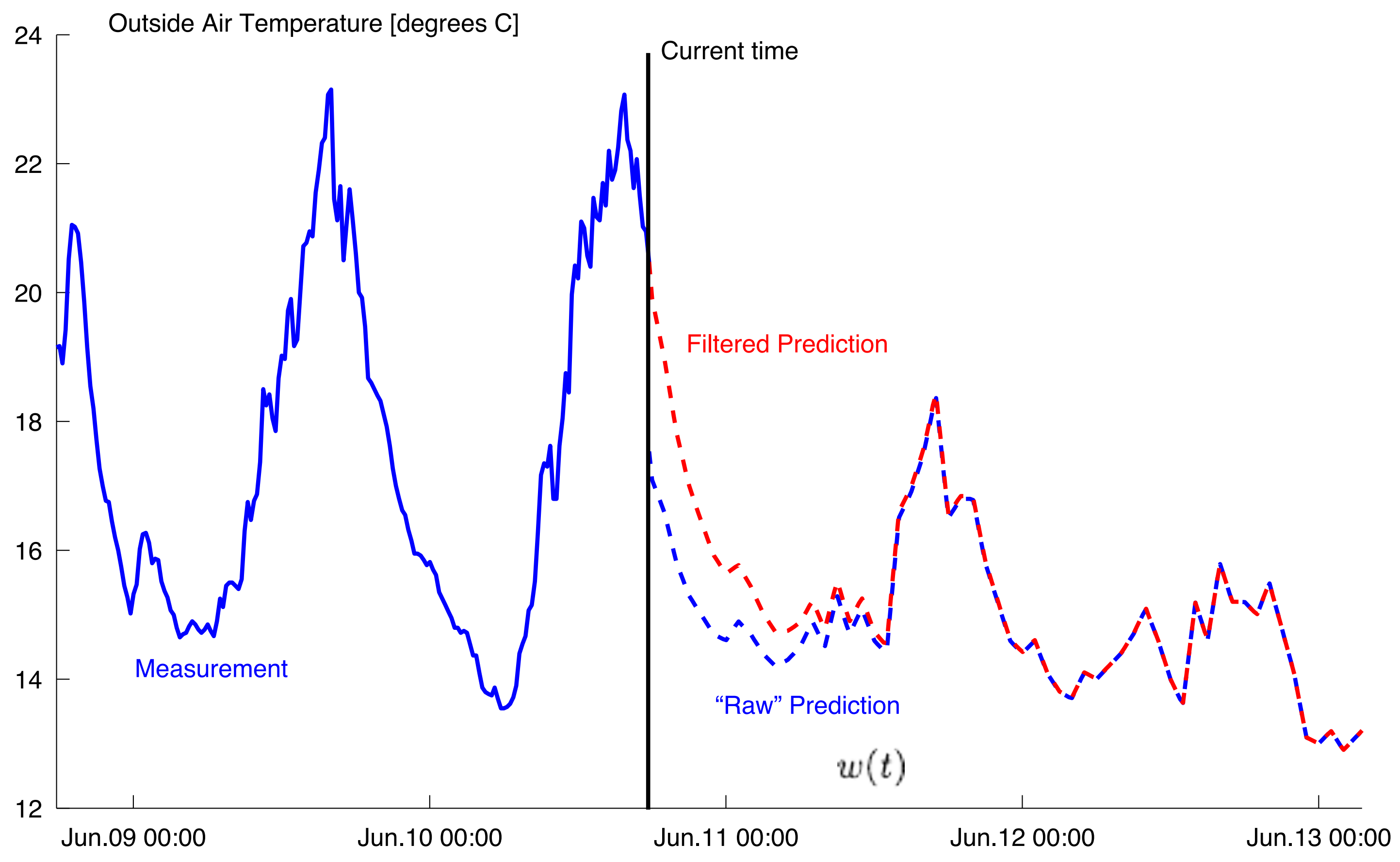
MPC implementation: Kalman filter based



Model Predictive Control operation

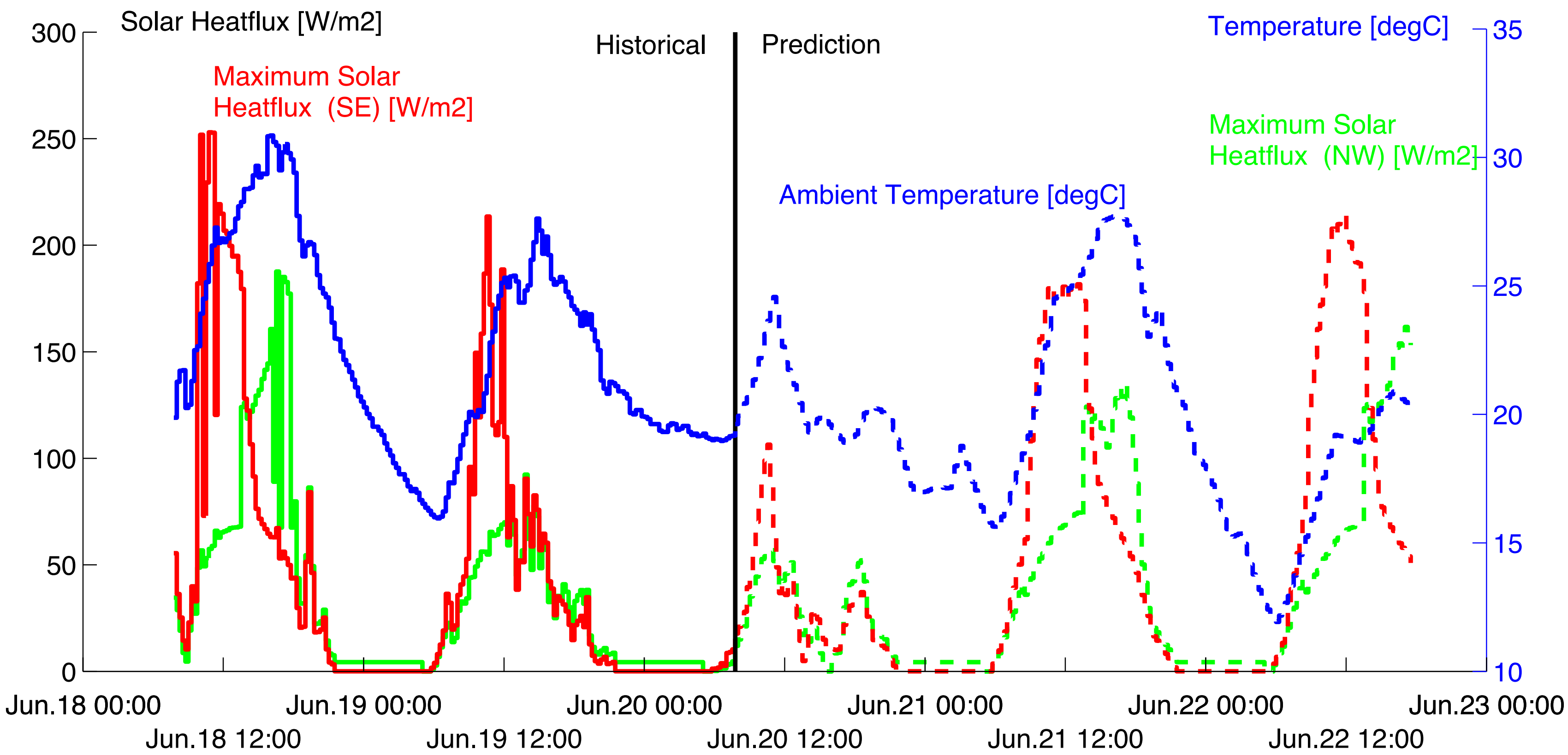
Weather prediction filtering

Filter dynamics are based on OptiControl I analyses.



Model Predictive Control operation

Disturbances: measured and filtered predictions $w(t)$

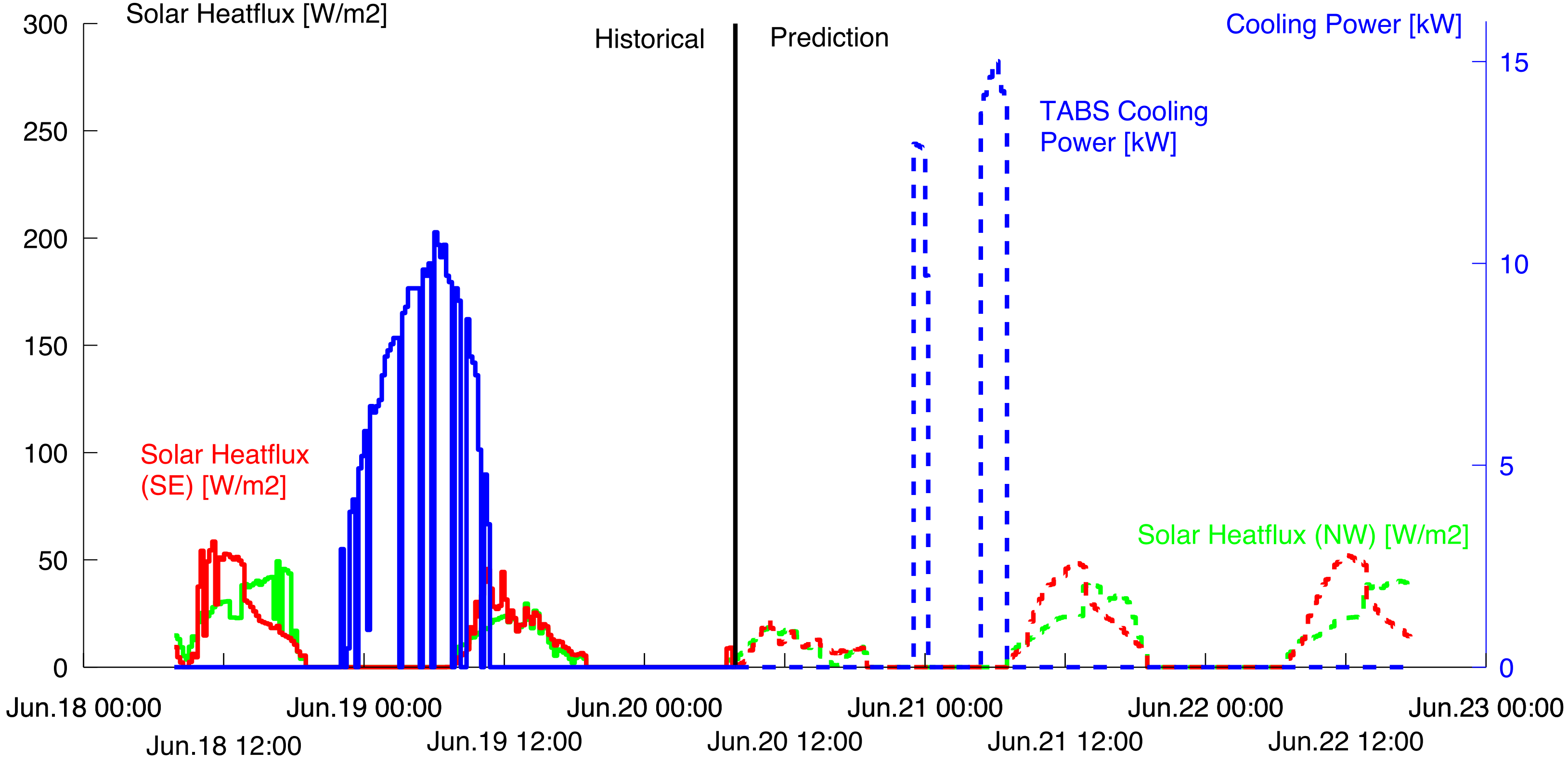


Model Predictive Control operation

Actuation: TABS cooling and blinds $u(t)$

Blind actuation uncertainty:
- based on predicted solar radiation;
- limited to only four possible positions;
- occupants may over-ride blind settings.

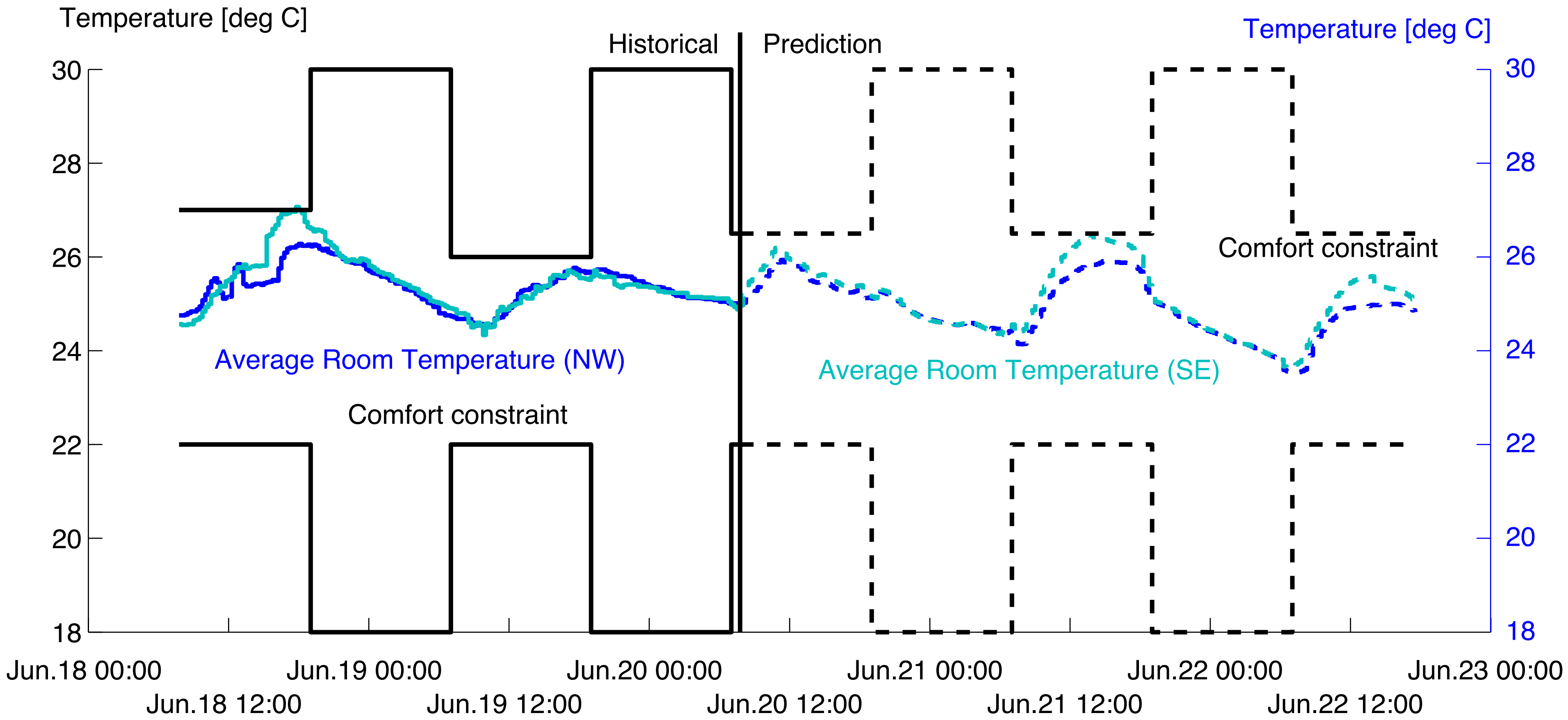
TABS cooling uncertainty:
- based on predicted overnight temperatures.



swisselectric research | ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich | SIEMENS Building Technologies | gruner | ACTELION

Model Predictive Control operation

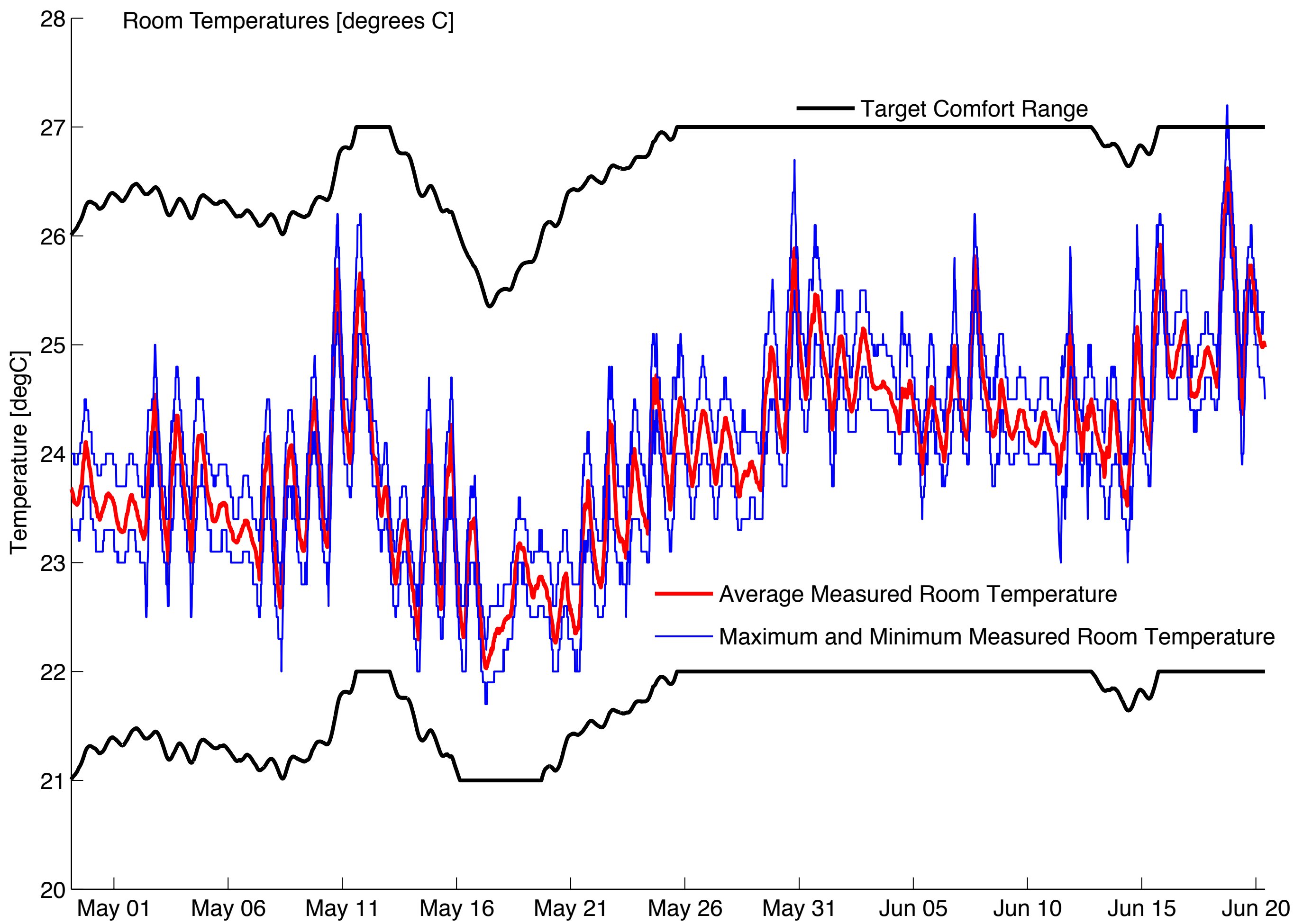
Controlled variables: room temperatures $y(t)$



Model Predictive Control operation

Performance: room temperatures (50 days)

TABS heating was required on 18 May.



Model Predictive Control operation

MPC controller operation: 21 April 2012 to 31 July 2012.

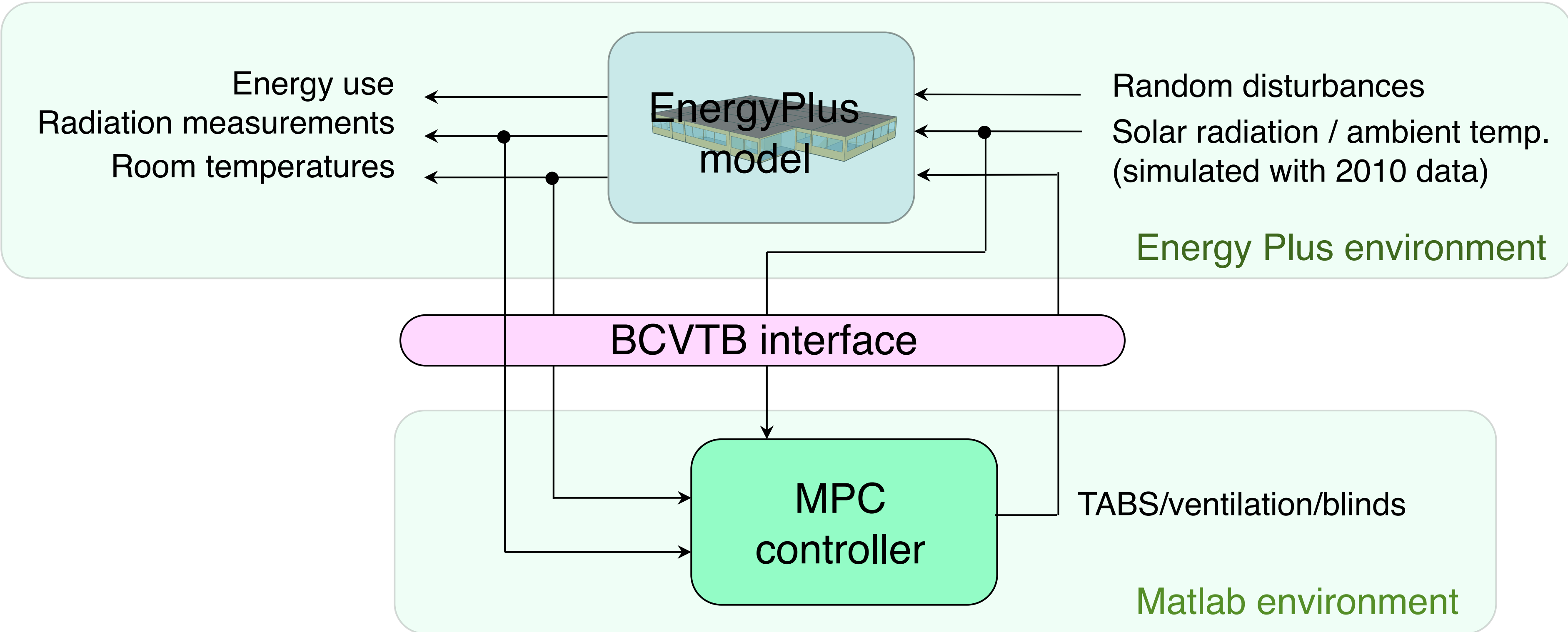
Operational modes demonstrated:

	TABS	Ventilation	TABS & Ventilation	Blinds
Cooling operations:	✓	✓	✓	✓
Heating operations:	✓ (limited)			

Heating operations to be tuned and tested in November and December 2012.

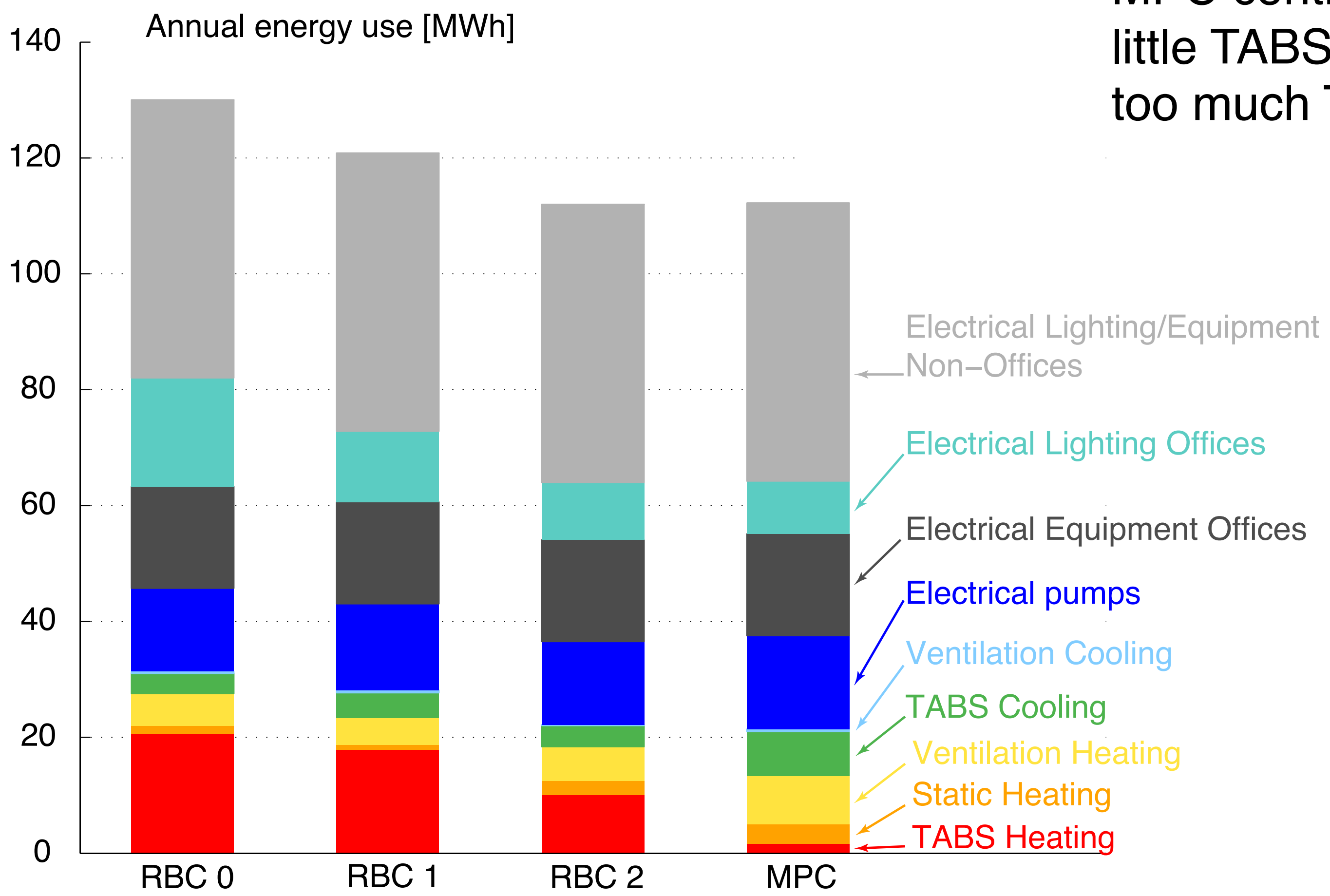
MPC simulation studies

MPC simulation comparisons using EnergyPlus



MPC simulation studies

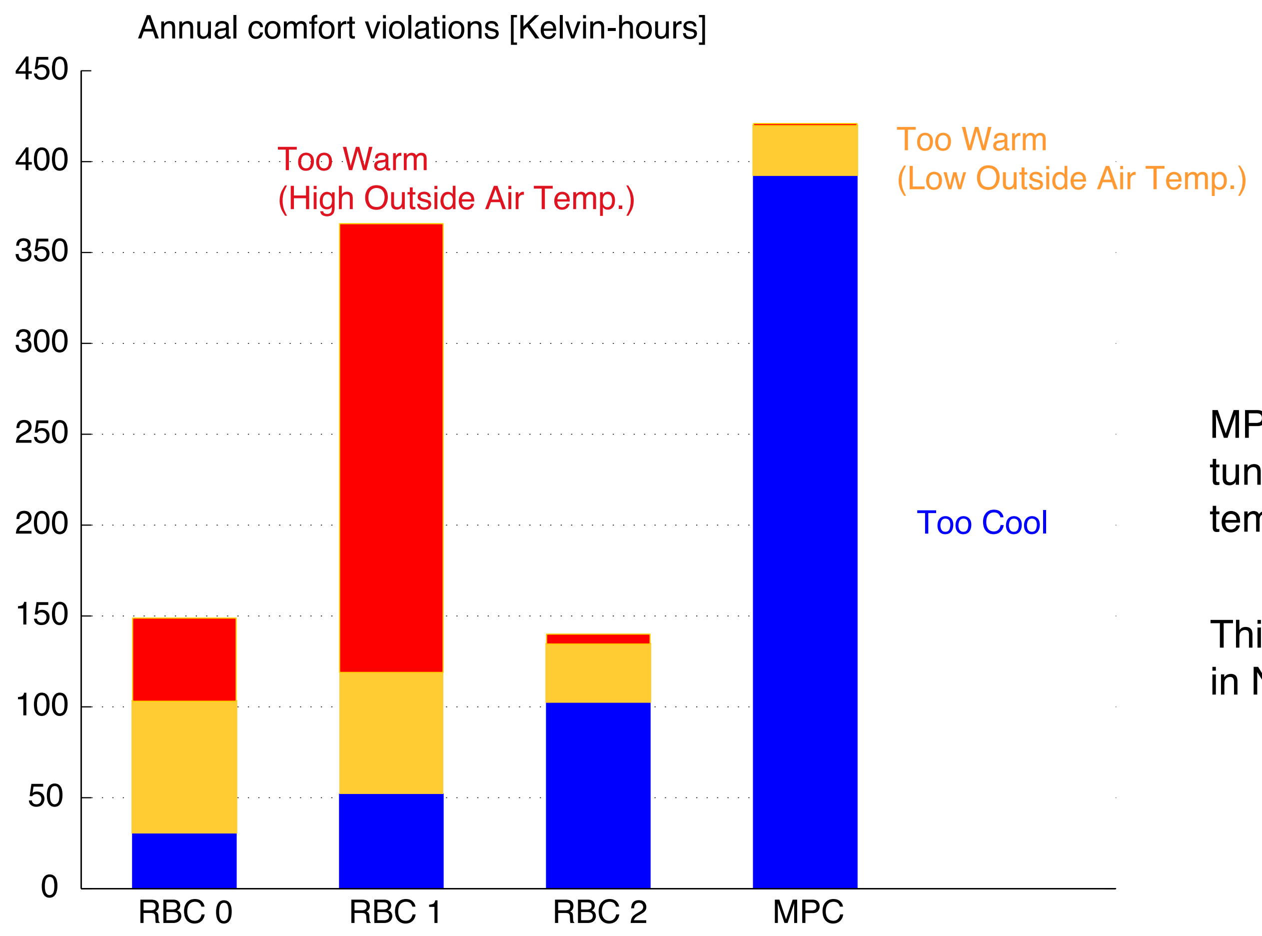
MPC simulation comparisons using EnergyPlus (work in progress)



MPC controller uses too little TABS heating and too much TABS cooling.

MPC simulation studies

MPC simulation comparisons using EnergyPlus (work in progress)



MPC controller requires tuning to increase temperatures.

This will be done on the building in November & December 2012.

Discussion

MPC controller has been successfully demonstrated on the building during Spring/Summer period.

Tuning of the objectives and constraints is simple and straightforward.

Initial models can be obtained from EnergyPlus models or building construction data sheets.

Models were refined by simulation-based regression analysis using EnergyPlus.

Model development and refinement is the most time-consuming aspect of the control design.

Future work will look at automatic or simplified model refinement based on building operation data.

Acknowledgments

OptiControl I:

IfA (ETH): F. Oldewurtel, C. Jones, A. Parisio, F. Ullmann, T. Baltensberger, A. Domahidi, M. Morari
TSE (ETH): D. Gyalistras, A. Fischlin
EMPA: T. Frank, B. Lehmann, K. Wirth, V. Dorer, S. Carl
MeteoSwiss: P. Steiner, F. Schubiger, V. Stauch
Siemens: J. Tödtli, M. Gwerder, B. Illi, C. Gähler
Gruner: A. Seerig, C. Sagerschnig

OptiControl II:

IfA (ETH): D. Gyalistras, D. Sturzenegger, M. Morari, R. Smith
Siemens: D. Habermacher, M. Gwerder, B. Illi, M.Winter, M. Hubacher, S. Bötschi
Gruner: C. Sagerschnig, A. Seerig
Actelion Pharmaceuticals: A. Gaiser, G. Maltese

Funding support:

swisselectric research
Siemens
Gruner
ETH
Actelion Pharmaceuticals.

Further information...

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

Institut für Automatik: http://control.ee.ethz.ch/

References:

F. Oldewurtel, A. Parisio, C.N. Jones, D. Gyalistras, M. Gwerder, V. Stauch, B. Lehmann, M. Morari, Use of Model Predictive Control and Weather Predictions for Energy Efficient Building Climate Control. Energy and Buildings, vol. 45, p. 15-27, Elsevier, 2012.

F. Oldewurtel, C.N. Jones, A. Parisio, M. Morari, Stochastic Model Predictive Control for Energy Efficient Building Climate Control, Submitted for IEEE Transaction on Control Systems Technology, 2012.

J. Siroky, F. Oldewurtel, J. Cigler, S. Privara, Experimental Analysis of Model Predictive Control for an Energy Efficient Building Heating System, Applied Energy, vol. 88, pp. 3079-3087, 2011.

F. Oldewurtel, A. Ulbig, G. Andersson, M. Morari, Building Control and Storage Management with Dynamic Tariffs for Shaping Demand Response in Electricity Grids, Proc. of IEEE PES Conference on Innovative Smart Grid Technologies Europe, Manchester, UK, 2011.

F. Oldewurtel, A. Ulbig, A. Parisio, G. Andersson, M. Morari, Reducing Peak Electricity Demand in Building Climate Control using Real-Time Pricing and Model Predictive Control, Proc. of 49th IEEE Conference on Decision and Control, CDC, Atlanta, USA, 2010.

R. Gondhalekar, F. Oldewurtel, C. N. Jones, Least-Restrictive Robust MPC of Periodic Affine Systems with Application to Building Climate Control, Proc. of 49th IEEE Conference on Decision and Control, CDC, Atlanta, USA, 2010.

F. Oldewurtel, A. Parisio, C.N. Jones, M. Morari, D. Gyalistras, M. Gwerder, V. Stauch, B. Lehmann, K. Wirth, Energy Efficient Building Climate Control using Stochastic Model Predictive Control and Weather Predictions, Proc. of American Control Conference, Baltimore, USA, 2010.

F. Oldewurtel, D. Gyalistras, M. Gwerder, C.N. Jones, A. Parisio, V. Stauch, B. Lehmann, M. Morari, Increasing Energy Efficiency in Building Climate Control using Weather Forecasts and Model Predictive Control, Proc. of Clima - RHEVA World Congress, Antalya, Turkey, 2010.

M. Gwerder, D. Gyalistras, F. Oldewurtel, B. Lehmann, K. Wirth, V. Stauch, J. Tödtli, Potential Assessment of Rule-Based Control for Integrated Room Automation, Proc. of Clima - RHEVA World Congress, Antalya, Turkey, 2010.

F. Oldewurtel, C.N. Jones, M. Morari, A Tractable Approximation of Chance Constrained Stochastic MPC based on Affine Disturbance Feedback, Proc. of 47th IEEE Conference on Decision and Control, CDC, Cancun, Mexico, 2008.