Use of MPC for Building Control

D. Gyalistras

Short Course on Model Predictive Control

4. March 2010
ETH Zurich

Research Team

D. Gyalistras, A. Fischlin [1]
M. Morari, F. Oldewurtel, C.N. Jones, A. Parisio [2]
T. Frank, S. Carl, V. Dorer, B. Lehmann, K. Wirth [3]
P. Steiner, F. Schubiger, V. Stauch [4]
J. Tödtli, C. Gähler, M. Gwerder [5]
A. Seerig, C. Sagerschnig [6]

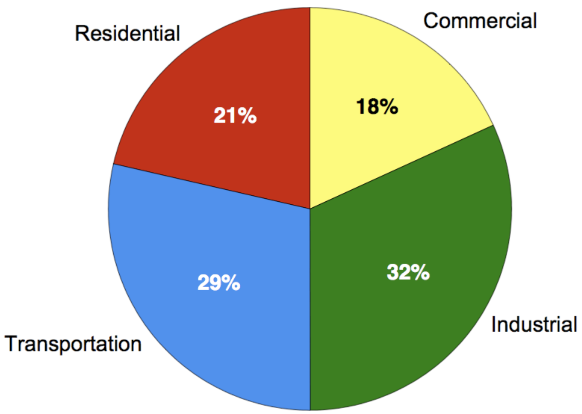
[1] Terrestrial Systems Ecology Group, ETH Zurich
[2] Automatic Control Laboratory, ETH Zurich
[3] Building Technologies Laboratory, Empa Dübendorf
[4] Federal Office of Meteorology and Climatology (MeteoSwiss), Zurich
[5] Building Technologies Division, Siemens Switzerland Ltd, Zug
[6] Building Climate Control, Building Physics & Simulations, Gruner AG, Basel

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

Overview

- Why Buildings?
- Control Tasks & Challenges
- Building Modeling
- Assessment Strategy
- Simulation Results
- Transfer to Practice
- Conclusions

Why Buildings?

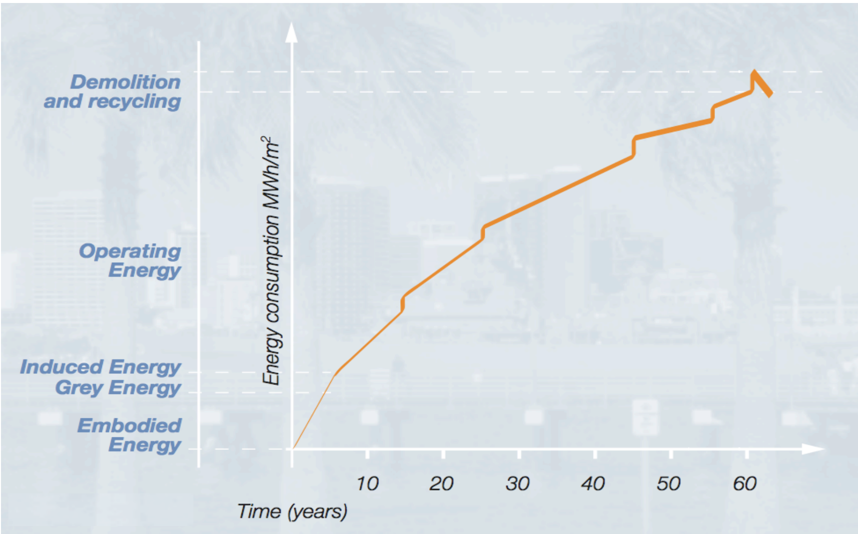


Example: end-use sector shares of total US consumption.

DOE/EIA (2008): Annual Energy Review 2007. Report No. DOE/EIA-0384(2007)

Buildings account for ~40% of global final energy use

Most of the energy is consumed during the use of the buildings



Energy consumed in the life of a building, estimated at 60 years.

Jones, D. Ll. (1998): Architecture and the Environment – Bioclimatic Building Design. Laurence King Publishing, London, 256pp.

Why Buildings? (2/4)

Buildings account for ~33% of global total CO_2 emissions (including emissions from electricity use)

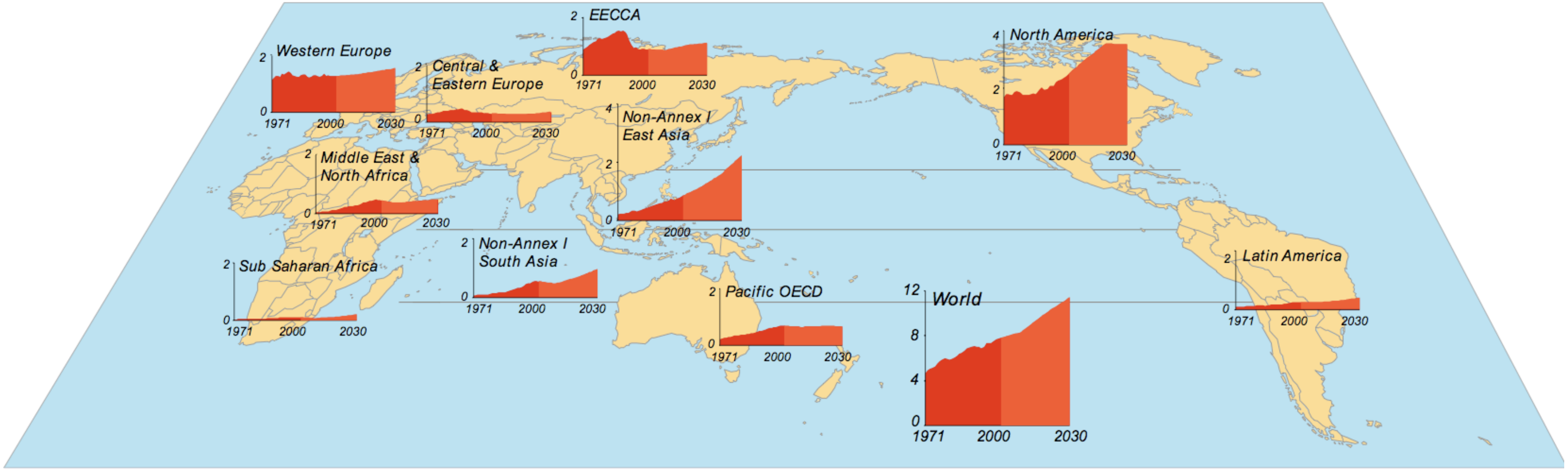


Figure TS.17: *CO_2 emissions ($GtCO_2$) from buildings including emissions from the use of electricity, 1971–2030 [Figure 6.2].*

Barker, T. et al. (2007): Technical Summary. In: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, L. A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Why Buildings? (3/4)

Building sector has large potential for cost-effective reduction of CO_2 emissions

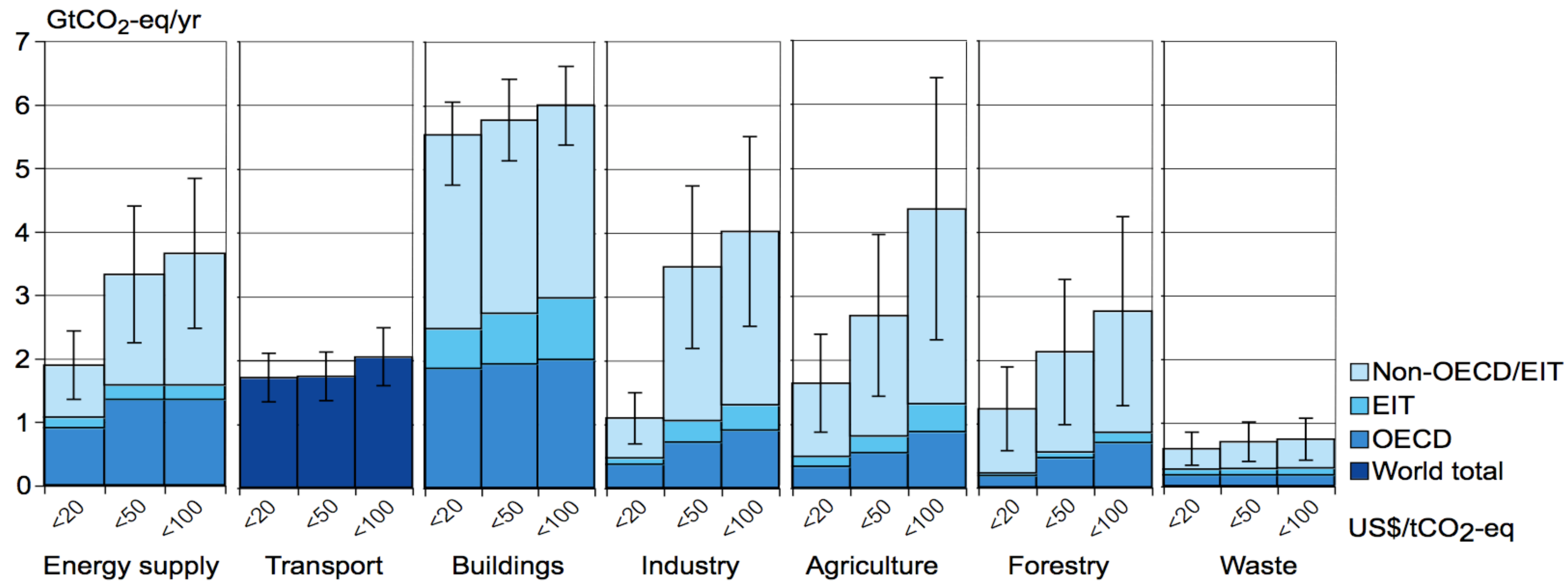
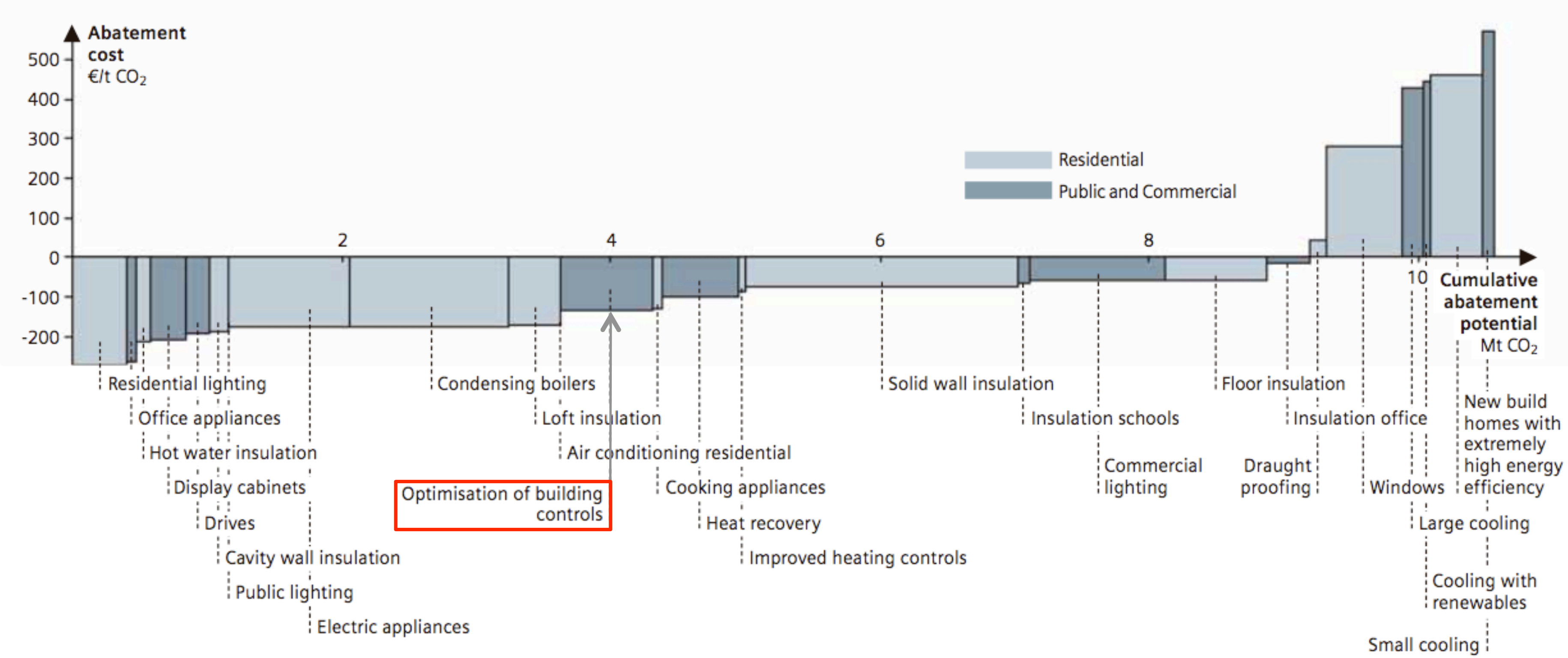


Figure TS.27: *Estimated sectoral economic potential for global mitigation for different regions as a function of carbon price in 2030 from bottom-up studies, compared to the respective baselines assumed in the sector assessments. A full explanation of the derivation of this figure is found in Section 11.3.*

Barker, T. et al. (2007).

Why Buildings? (4/4)

Most investments in buildings are expected to pay back through reduced energy bills



Greenhouse gas abatement cost curve for London buildings (2025, decision maker perspective)

Source: Watson, J. (ed.) (2008): Sustainable Urban Infrastructure, London Edition – a view to 2025. Siemens AG, Corporate Communications (CC) Munich, 71pp.

Application “Integrated Room Automation”

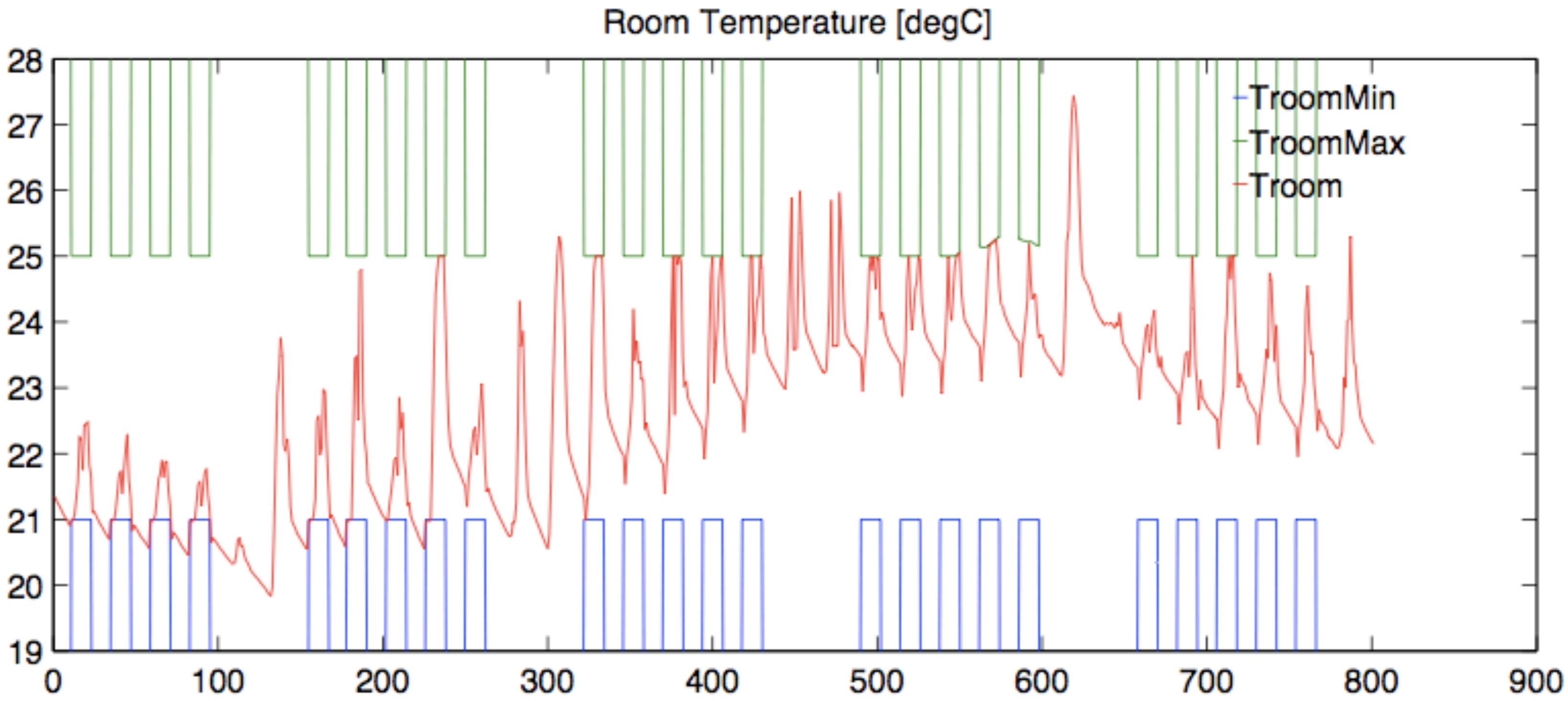
Integrated
control of the

- Heating
- Cooling
- Ventilation
- Electrical lighting
- Blinds

of a single room or
building zone

Control Task

Use minimum amount of energy (or money) to keep the room temperature, illuminance level and CO_2 concentration in prescribed comfort ranges



Control Task – Building Systems Variants

Automated Subsystems	*Building System* S1	S2	S3	S4
Blinds	x	x	x	x
Electric lighting	x	x	x	x
Mech. ventilation flow, heating, cooling	–	x	x	x
Mech. ventilation energy recovery	–	x	x	x
Natural ventilation (night-time only)	–	–	–	x
Cooled ceiling (capillary tube system)	x	x	–	–
Free cooling with wet cooling tower	x	x	–	–
Radiator heating	x	x	–	–
Floor heating	–	–	–	x

Control Task – Why MPC?

- Several HVAC System components – long-term optimal control solution often not trivial.
- Temporal variations in comfort requirements and/or energy costs introduce additional complexity.
- Predictive control opens up the possibilities
  - to exploit the building's thermal storage capacity
  - to use information on future disturbances (weather, internal gains) for better planning.

Integrated Room Automation – Low-cost energy saving measures (1)

a) Reduction of thermal comfort when building is not used (room temperature set-back during nights and weekends).

b) General reduction of thermal comfort (wider room temperature range).

c) Indoor Air Quality controlled ventilation (e.g., based on use of CO_2 sensors).

d) Optimization for energetic rather than monetary cost.

e) Advanced, non-predictive control.

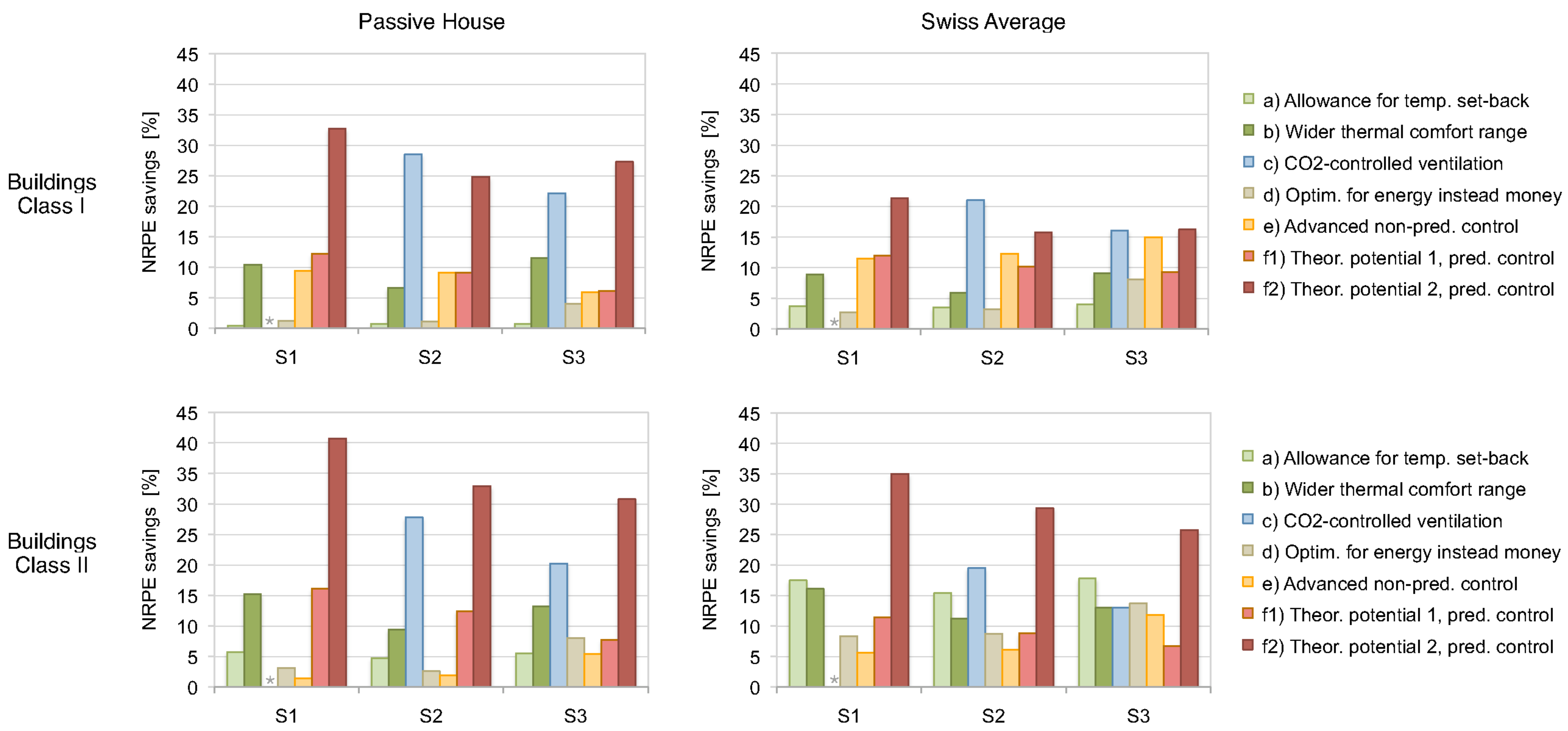
f) Predictive control.

Further measures:

– Constant lighting control.

– Automated blind control.

Integrated Room Automation – Low-cost energy saving measures (2)



Source: Gyalistras et al. (2010): Analysis of energy savings potentials for Integrated Room Automation. Paper presented at the 10th REHVA World Congress Clima 2010, Antalya, Turkey.

Building Modeling – Choice of Model?

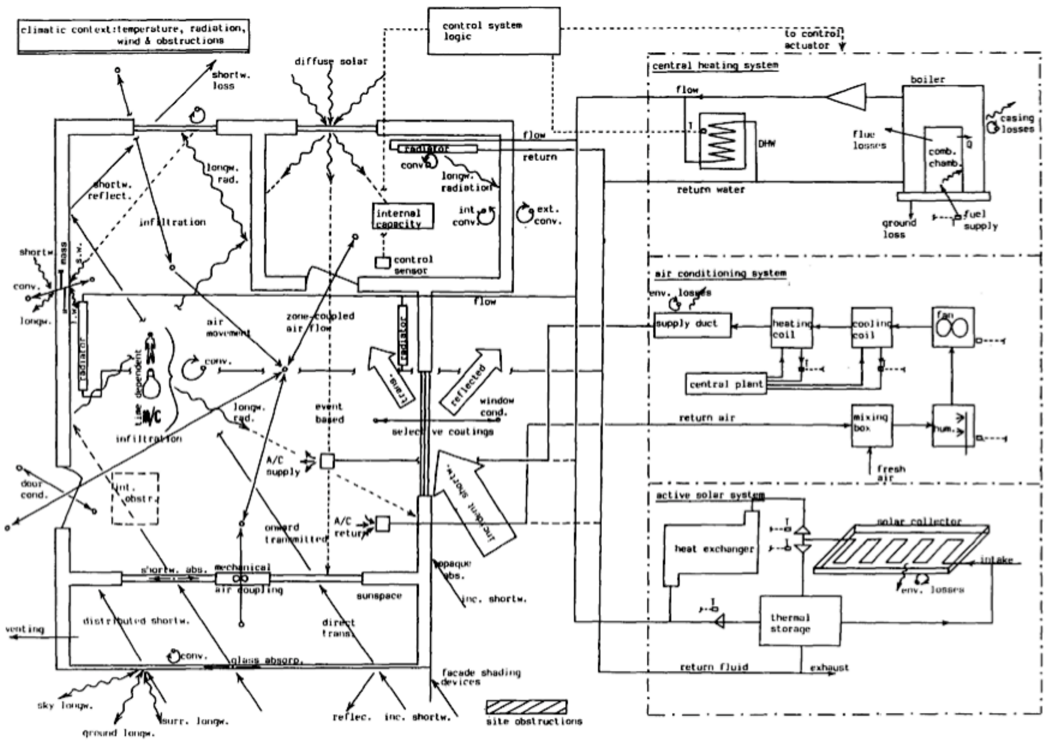
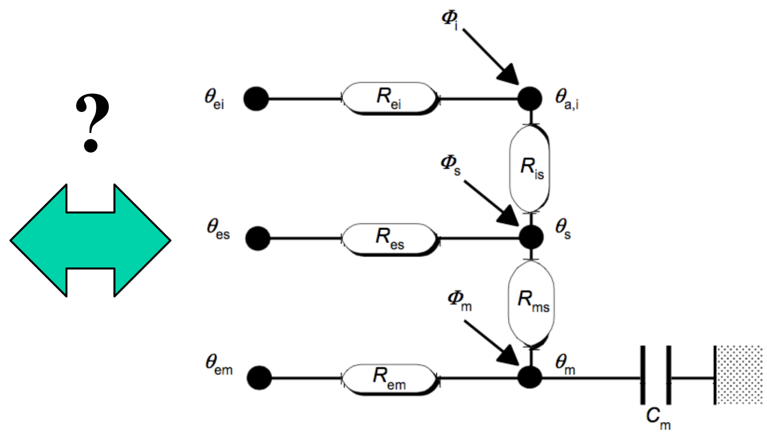


Fig. 1. Building energy flowpaths.



Subsumed radiative and convective energy fluxes

Building Modeling – "RC Approach"

Heat transfer rate

$$\frac{dQ}{dt} = U \cdot A \cdot (\vartheta_e - \vartheta_i)$$

$$\Rightarrow \underbrace{\frac{dQ}{d\vartheta_i}}_{C_i} \cdot \frac{d\vartheta_i}{dt} = \underbrace{U \cdot A}_{K_{ie}} \cdot (\vartheta_e - \vartheta_i)$$

Thermal capacity C

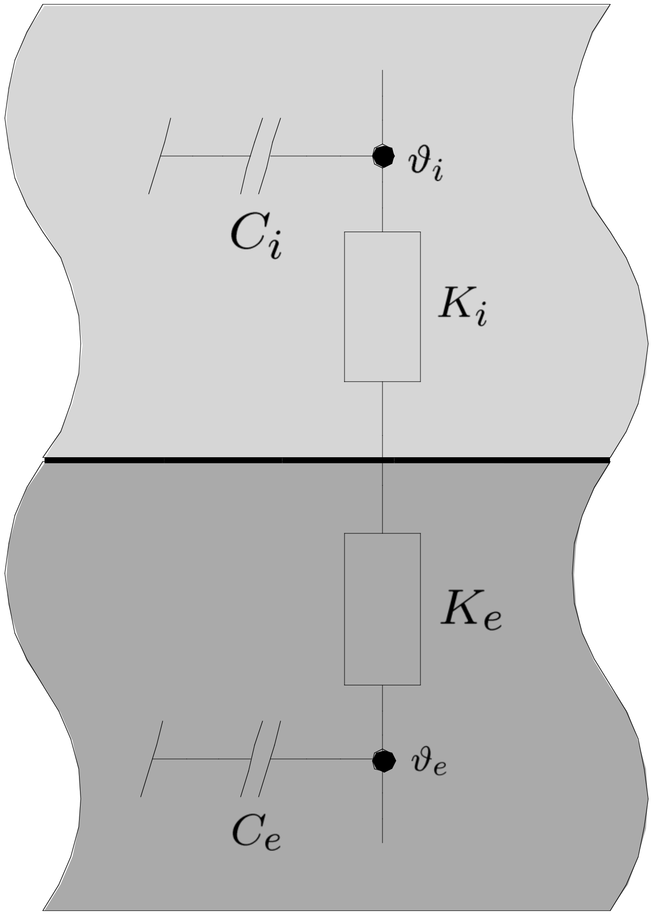
$$C_i = d \cdot A \cdot \rho \cdot c_p$$

thickness area density spec. heat capacity

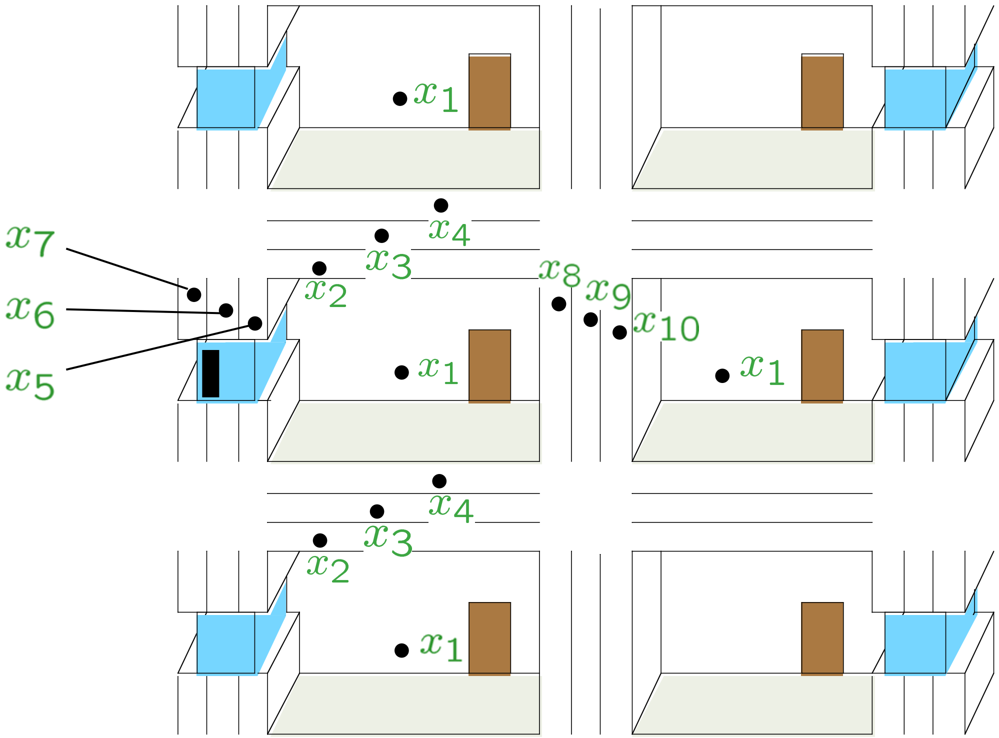
Heat transfer coefficient K

$$1/K_{ie} = 1/K_i + 1/K_e$$

$$\Rightarrow C_i \cdot \frac{d\vartheta_i}{dt} = K_{ie} \cdot (\vartheta_e - \vartheta_i)$$



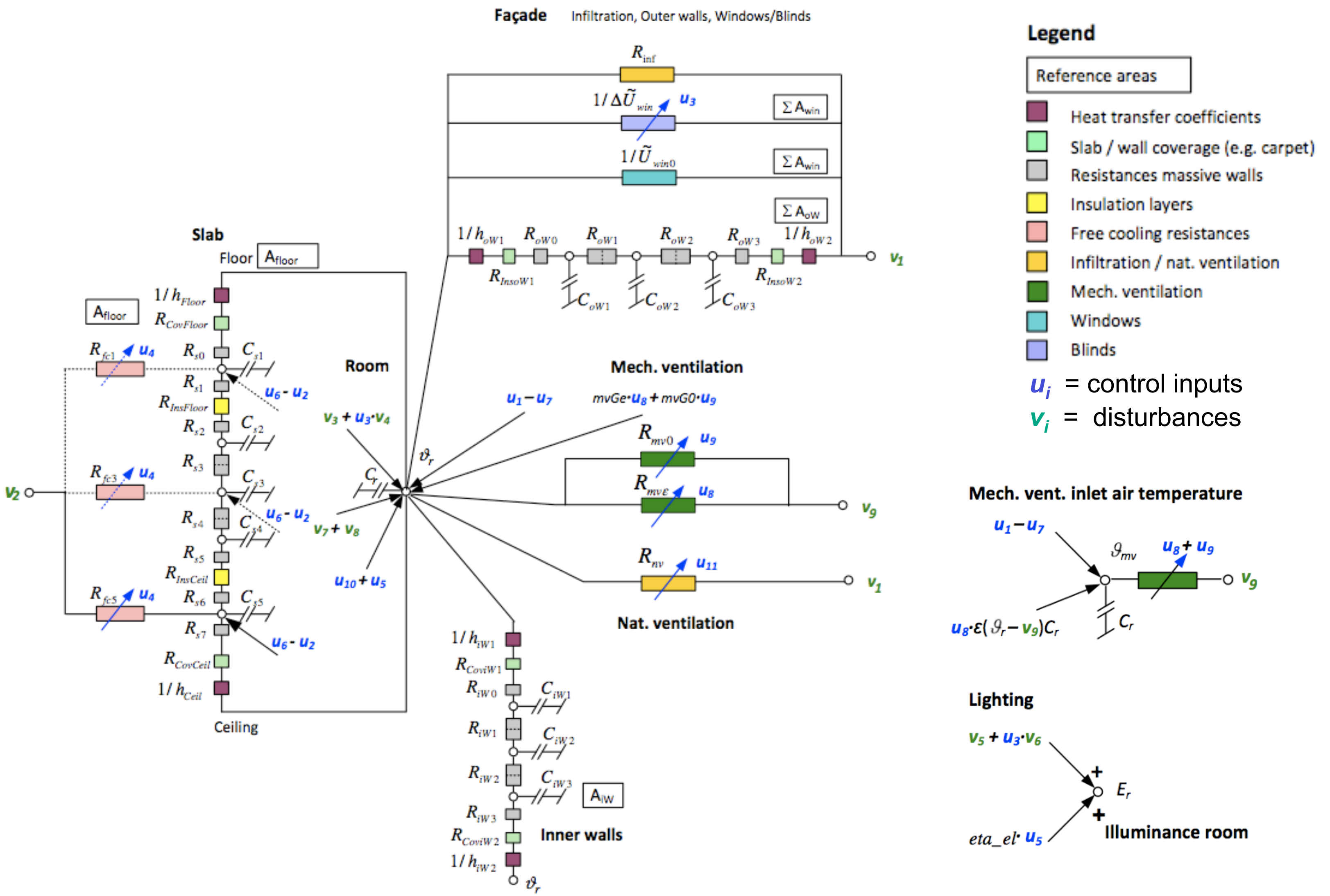
Building Modeling – System States



x_1 = room temperature [°C]
x_2 .. x_4 = temperatures of floor/ceiling [°C] *
x_5 .. x_7 = temperatures outer wall layers [°C]
x_8 .. x_{10} = temperatures inner wall layers [°C]

* Enhanced model variant:
two additional layers

Building Modeling – Model Overview



Building Modeling – System Equations

$$dx/dt = A \cdot x + B_u \cdot u + B_v \cdot v + \sum_{i=1}^{n_u} \{ (B_{vu} \cdot v + B_{xu} \cdot x) \cdot u_i \}$$

$$y = C \cdot x + D_u \cdot u + D_v \cdot v + \sum_{i=1}^{n_u} \{ D_{vu} \cdot v \cdot u_i \}$$

States

x_1 room temperature [degC]
$x_2..x_6$ slab temperatures 1...5 [degC]
$x_7..x_9$ inner wall temperatures 1...3 [degC]
$x_{10}..x_{12}$ outside wall temperatures 1...3 [degC]

Control inputs

u_1 Heating power (mv), positive values = heating [W/m^2]
u_2 Cooling power (slab), positive values = cooling [W/m^2]
u_3 Blind position [0: closed ... 1: open] [-]
u_4 Free cooling usage factor [0: off ... 1: max] [-]
u_5 Gains electric lighting [W/m^2]
u_6 Heating power (slab), positive values = heating [W/m^2]
u_7 Cooling power (air), positive values = cooling [W/m^2]
u_8 Air change rate mech. vent. with ERC (eps>0) [1/h]
u_9 Air change rate mech. vent. without ERC [1/h]
u_{10} Heating power (radiator), positive values = heating [W/m^2]
u_{11} Air change rate nat. vent. [1/h]

Disturbances

v_1 Outside air temperature [degC]
v_2 Free cooling temperature [degC]
v_3 Solar gains with fully closed blinds [W/m^2]
v_4 Additional solar gains with open blinds [W/m^2]
v_5 Daylight illuminance with fully closed blinds [lux]
v_6 Additional daylight illuminance with open blinds [lux]
v_7 Internal gains persons [W/m^2]
v_8 Internal gains equipment [W/m^2]
v_9 Fresh air temperature mech. ventilation [degC]
v_{10} Air change rate infiltration [1/h]

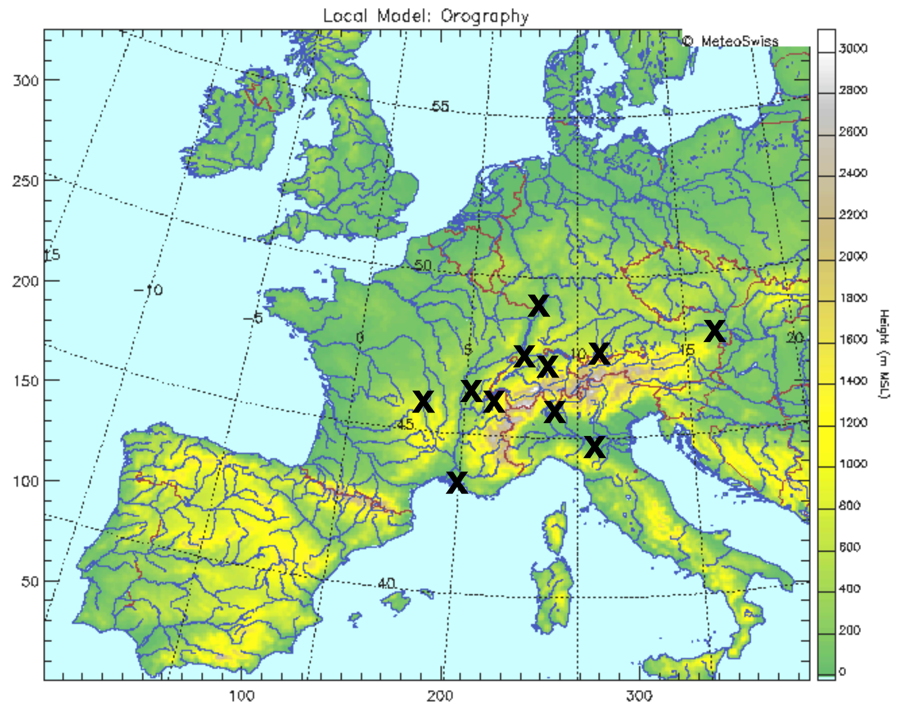
Outputs

y_1 room temperature [degC]
y_2 room illuminance [lux]
y_3 ceiling surface temperature [degC]
y_4 Sum of air change rate mech. vent u8+u9 [1/h]
y_5 Total air change rate [1/h]
y_6 Inlet temperature overheat (balance <=0 ok) [W/m2]
y_7 Inlet temperature overcool, (balance >=0 ok) [W/m2]

Controler Assessment– Challenges

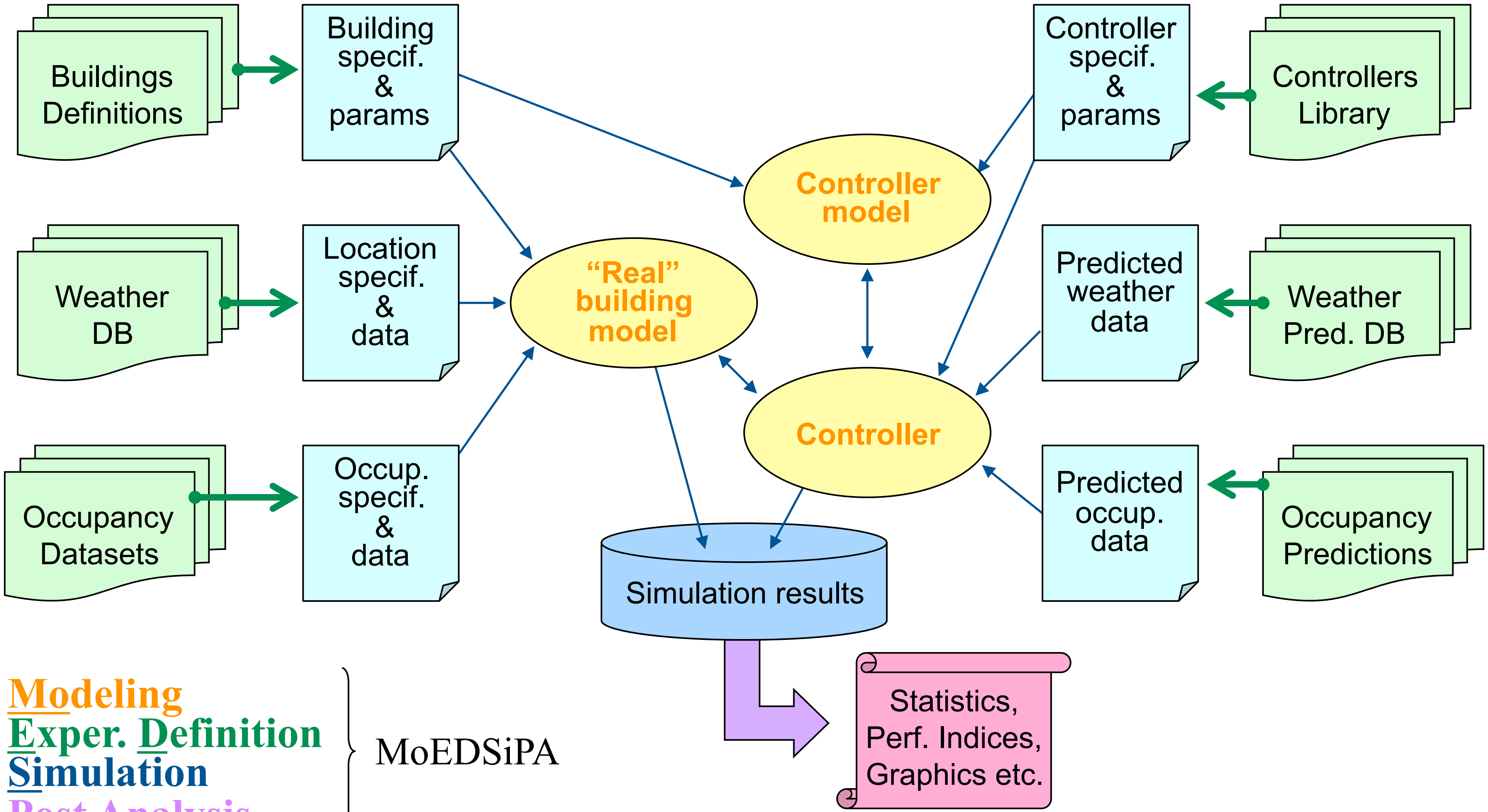
- Absolute and comparative performance of control algorithms varies strongly with building type, type of HVAC system, comfort requirements, location etc.
- Multiple assessment criteria:
  energy consumption, monetary cost,
  various comfort indices
- Relative importance of control: how does the choice of control strategy compares to variations in other important key factors?

Controler Assessment – Case Study Sites



Zürich
Basel-Binningen
Genève-Cointrin
Lugano
Modena
Marseille-Marignane
Clermont-Ferrand
Mannheim
Hohenpeissenberg
Wien Hohe Warte

Controler Assessment – Modeling & Simulation Environment



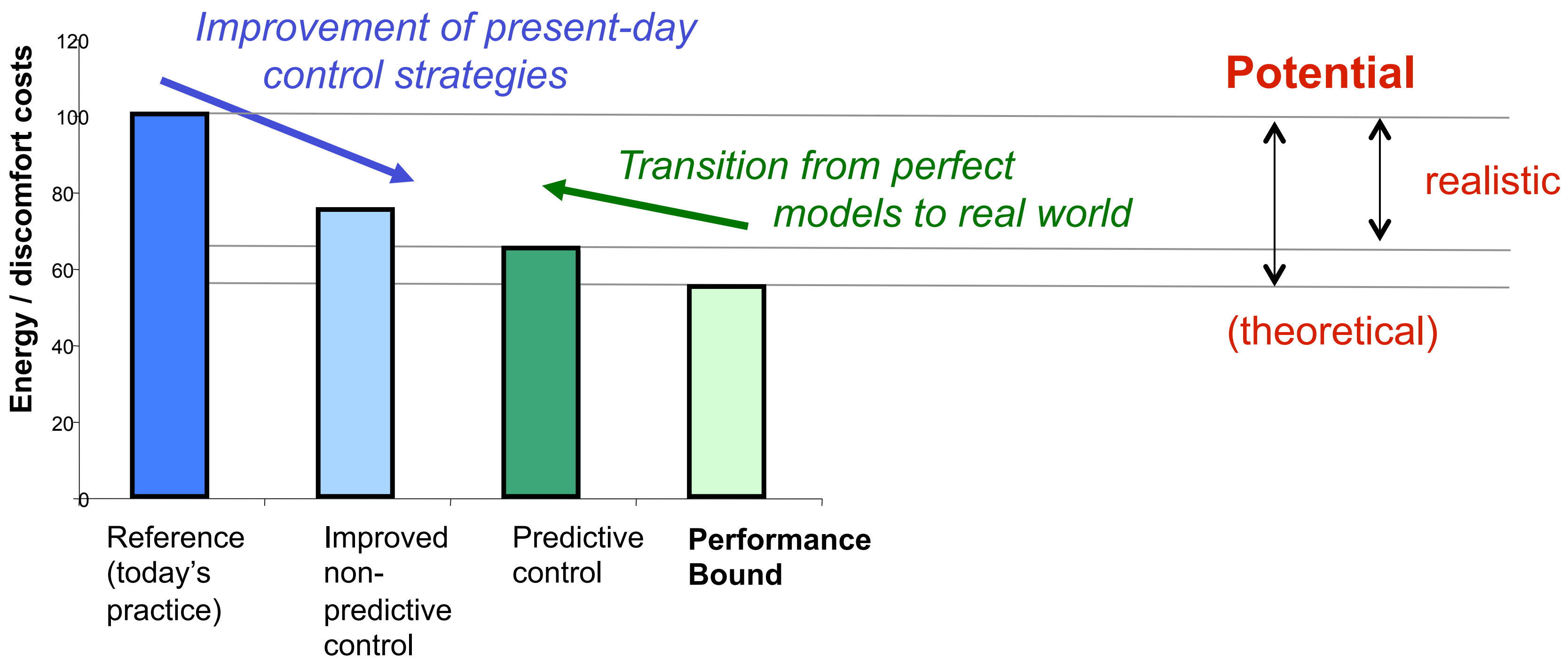
Modeling
Exper. Definition
Simulation
Post Analysis

} MoEDSiPA

Controller Assessment – Concept

Information Levels:

1. "perfect world – we know everything"
2. "real world, no weather forecasts"
3. "real world, with weather forecasts"



Controler Assessment – Definition of Simulation Experiments

16 building zone types:

Thermal insulation level	Swiss Average, Passive House
Façade orientation	SW (corner)
Construction type	Heavyweight, Lightweight
Window area fraction	30%, 80 %
Internal gains level	low, high

Building System:	S01
Sites:	9 European sites
Control Strategies:	(see next slide)
Assessment Criterium:	Annual total Non-Renewable Primary Energy (NRPE) usage

Controler Assessment – Control Strategies Considered

- **RBC_{bas}** Basic rule based control
- **RBC_{adv}** Advanced rule based control (newly developed)
- **MPC-CE** MPC-Certainty Equivalent control *)
- **PB** Performance Bound

n = Narrow thermal comfort range

w = Wide thermal comfort range

*) Using "COSMO-7" weather forecasts by MeteoSwiss, preliminary results.

Controler Assessment – "Basic Rule Based Control"

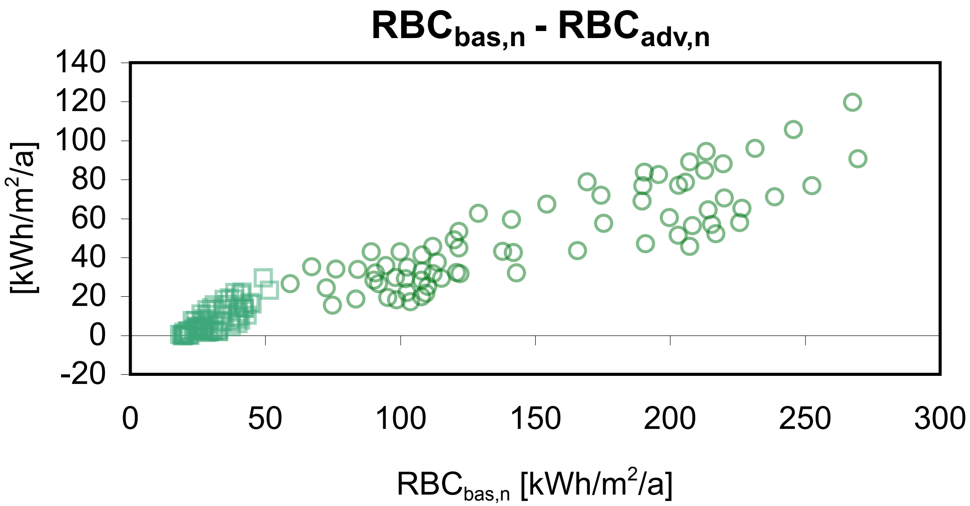
- A solar radiation sensor measures total solar gains on room orientation(s)

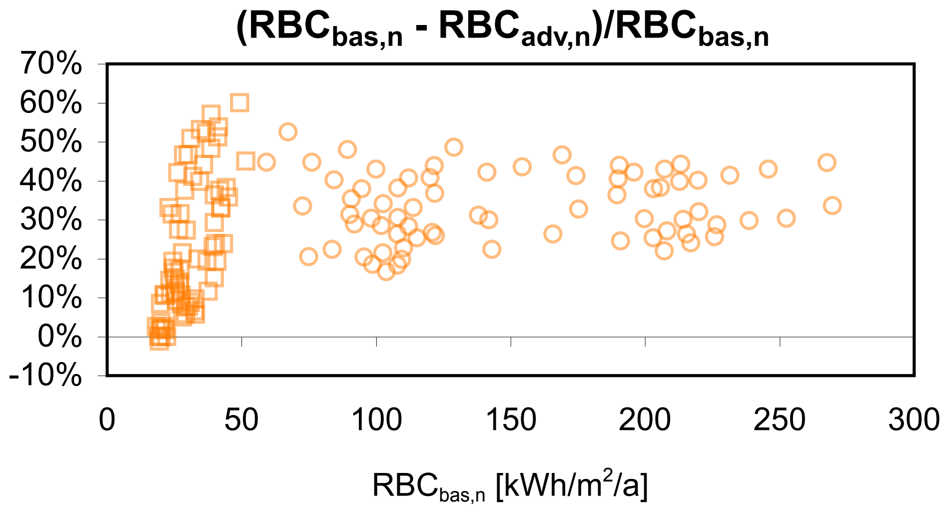
- Rule based blinds positioning:

```
if ( solar gains < threshold value )
        blinds are fully opened
else
        if (room is not occupied)
                blinds are fully closed
        else
                blinds are closed to a predefined position that attempts
                to maintain luminance setpoint (if possible)
        end
end
```

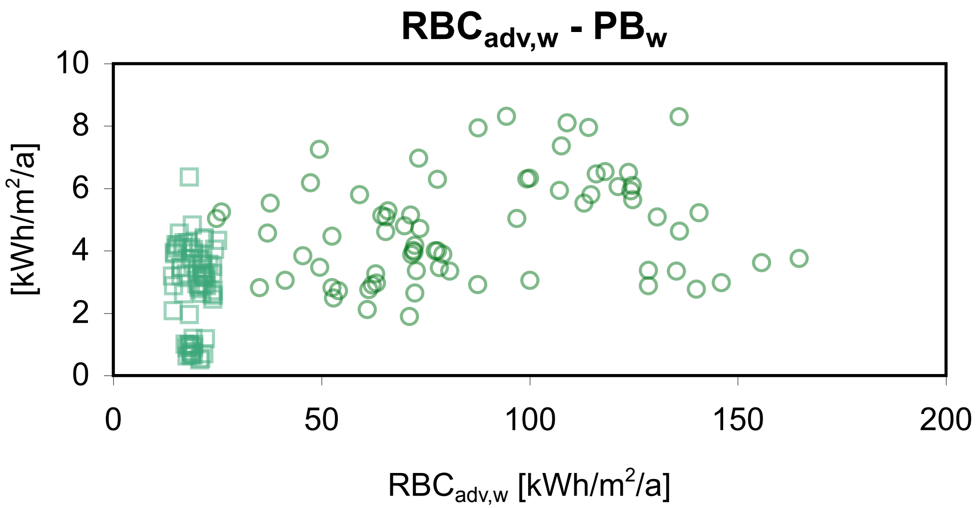
- For all remaining control actions is used instantaneous optimal control

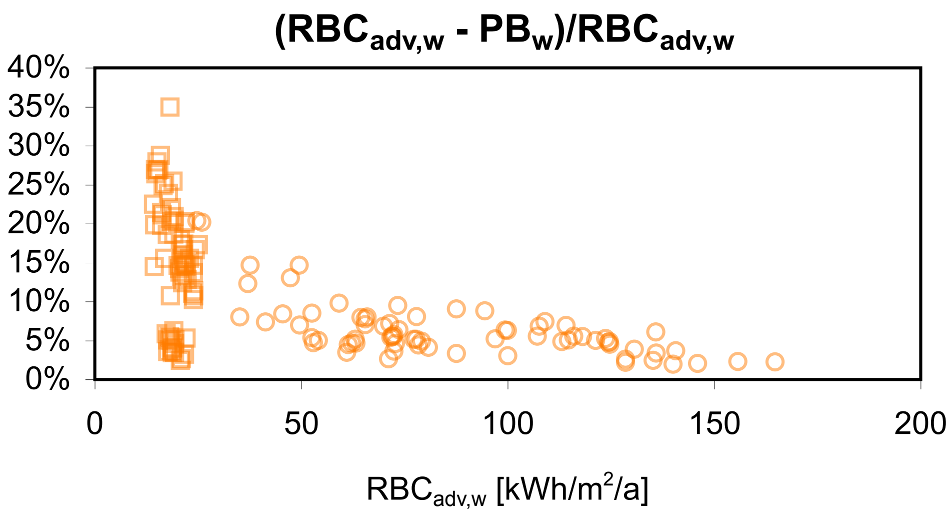
Results (1) – Improved Rule Based Control



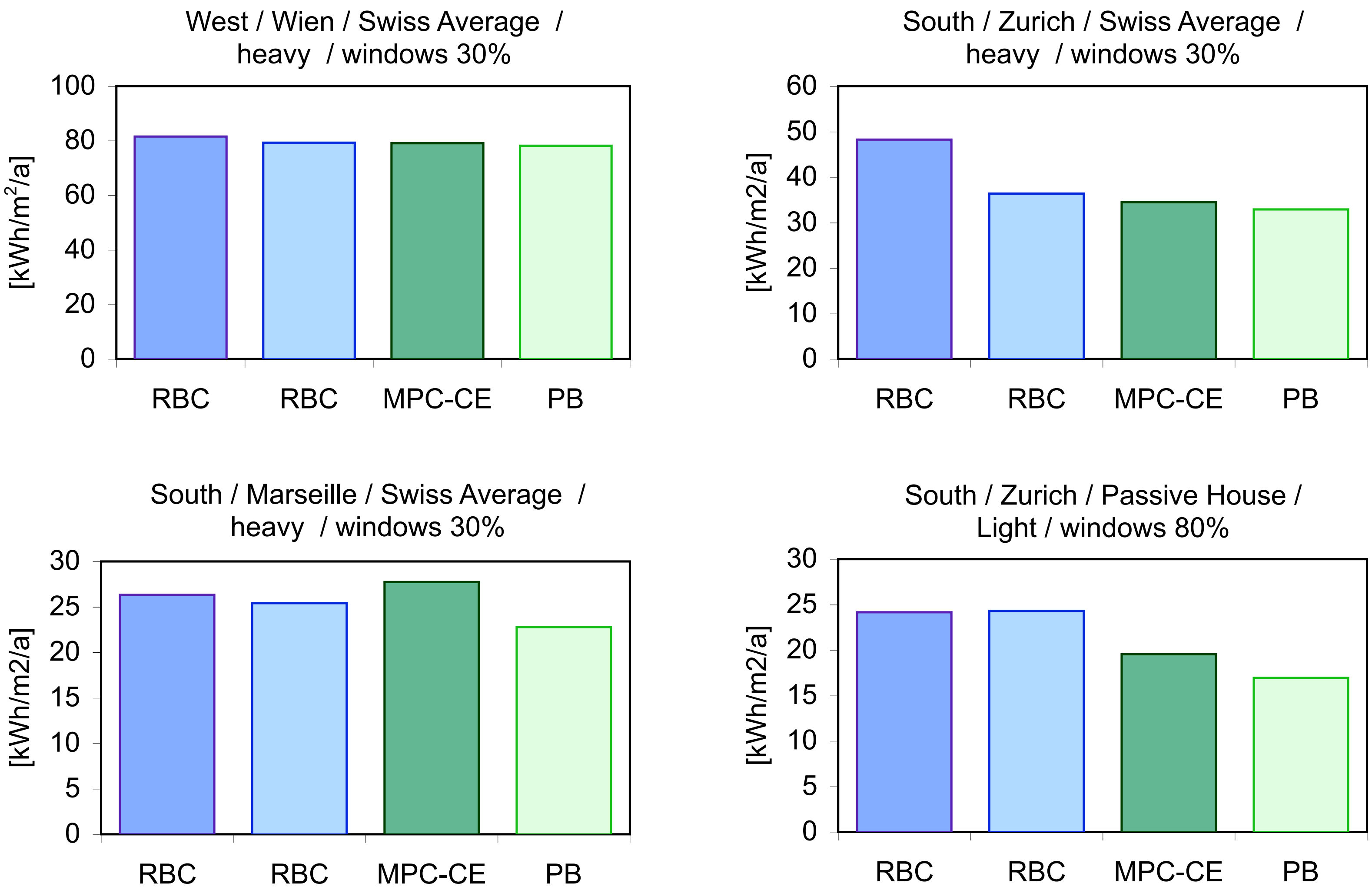


Results (2) –
Potential of Predictive Control





Results (3) – Comparison of Control Strategies



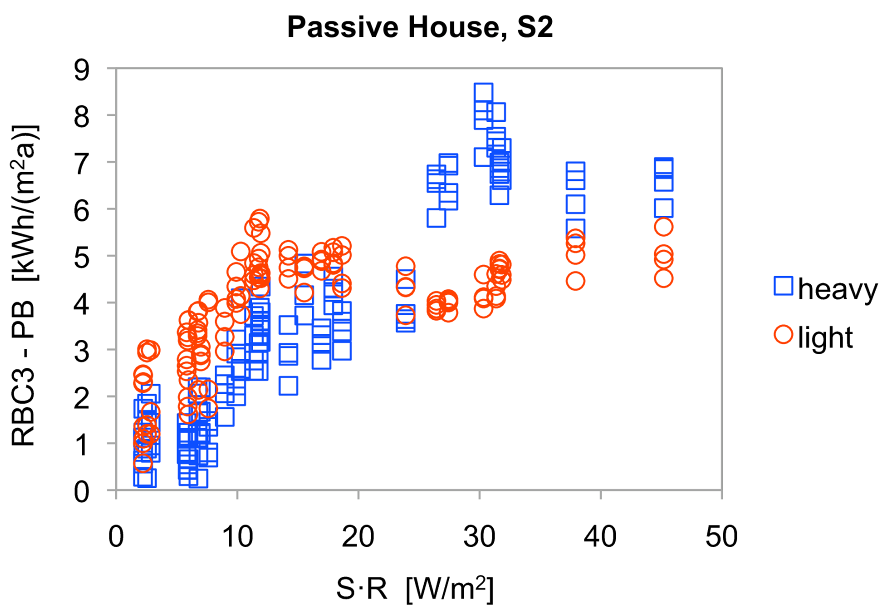
Controler Assessment – Simulation Experiments (2)

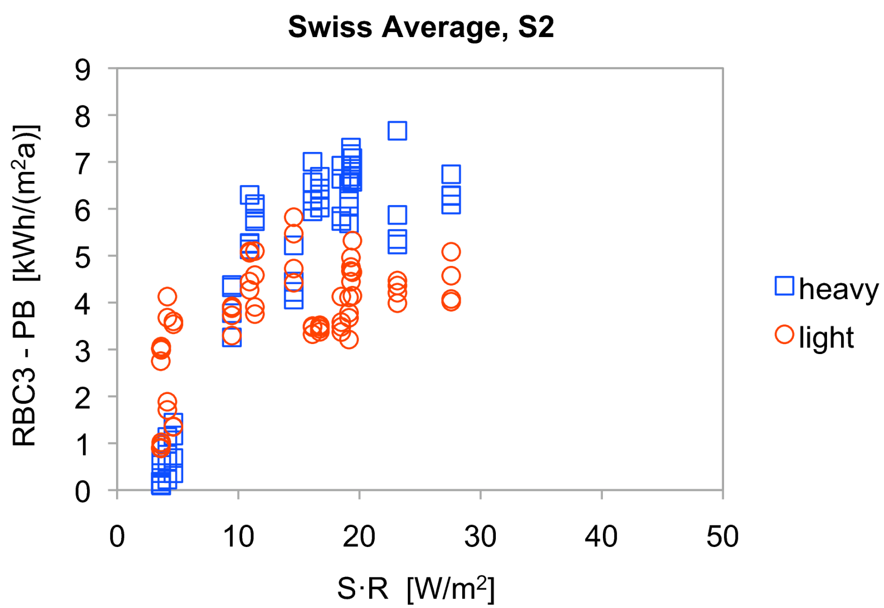
16 (Swiss Average), resp. 32 (Passive House) building zone types:

Thermal insulation level	Swiss Average, Passive House
Façade orientation	N, S and SE, SW (corner rooms)
Construction type	Heavyweight, Lightweight
Window area fraction	30%, 80 % (Passive House only)
Internal gains level	low, high

Building System:	S02
Sites:	Zurich, Lugano, Vienna, Marseille
Thermal comfort:	No set-back, wide comfort range
Ventilation strategies:	With/without CO_2-based control
Control Strategies:	RBC_{adv} (=RBC-3), Performance Bound
Assessment Criterium:	Annual total Non-Renewable Primary Energy (NRPE) usage

Results –
Savings Potential = f(Solar Heat Gains)





Results – Comparison of Controller Behaviors

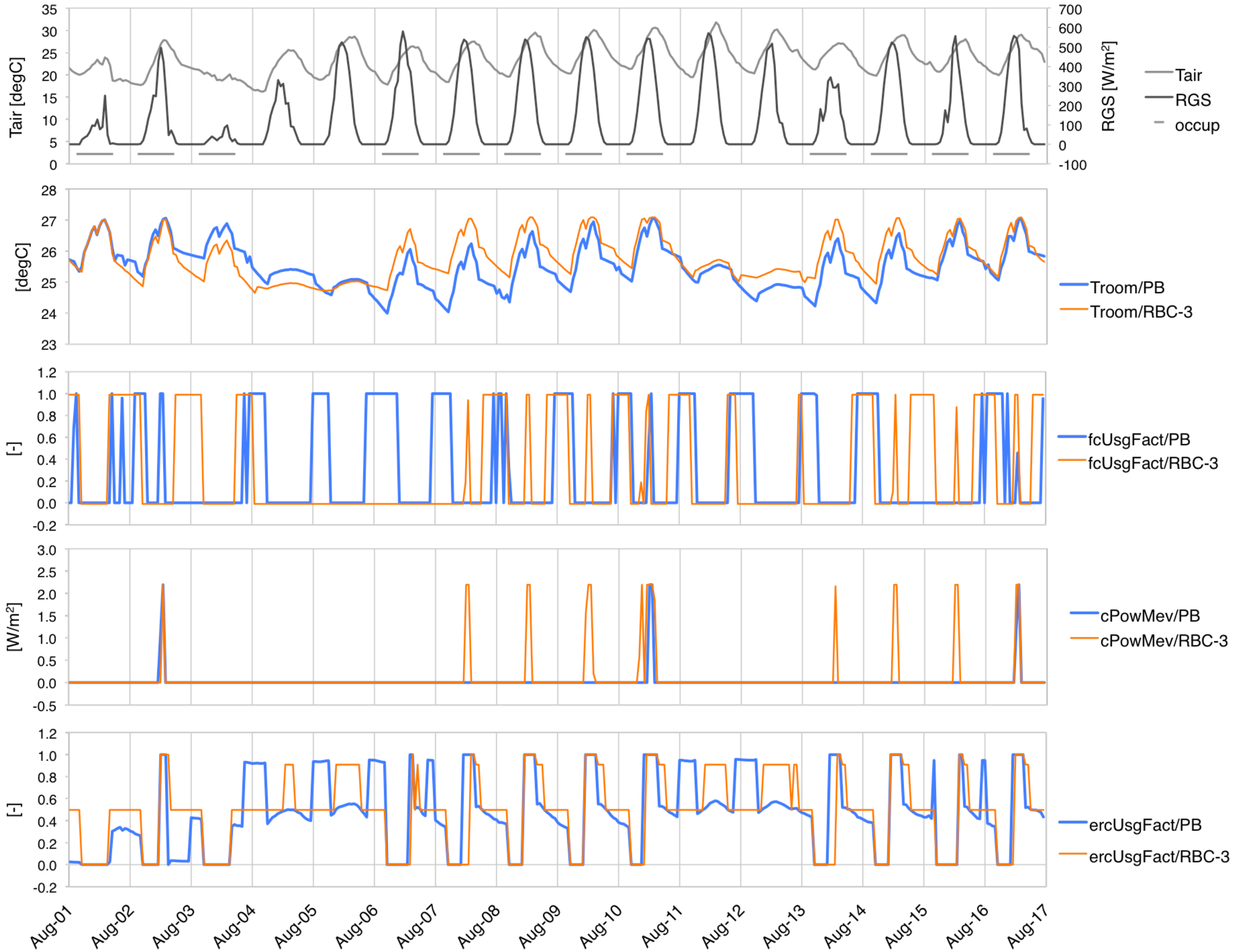
Weather

Room Temperature

Free Cooling Usage Factor

Cooling by Mech. Ventil.

Energy Recovery Usage Factor

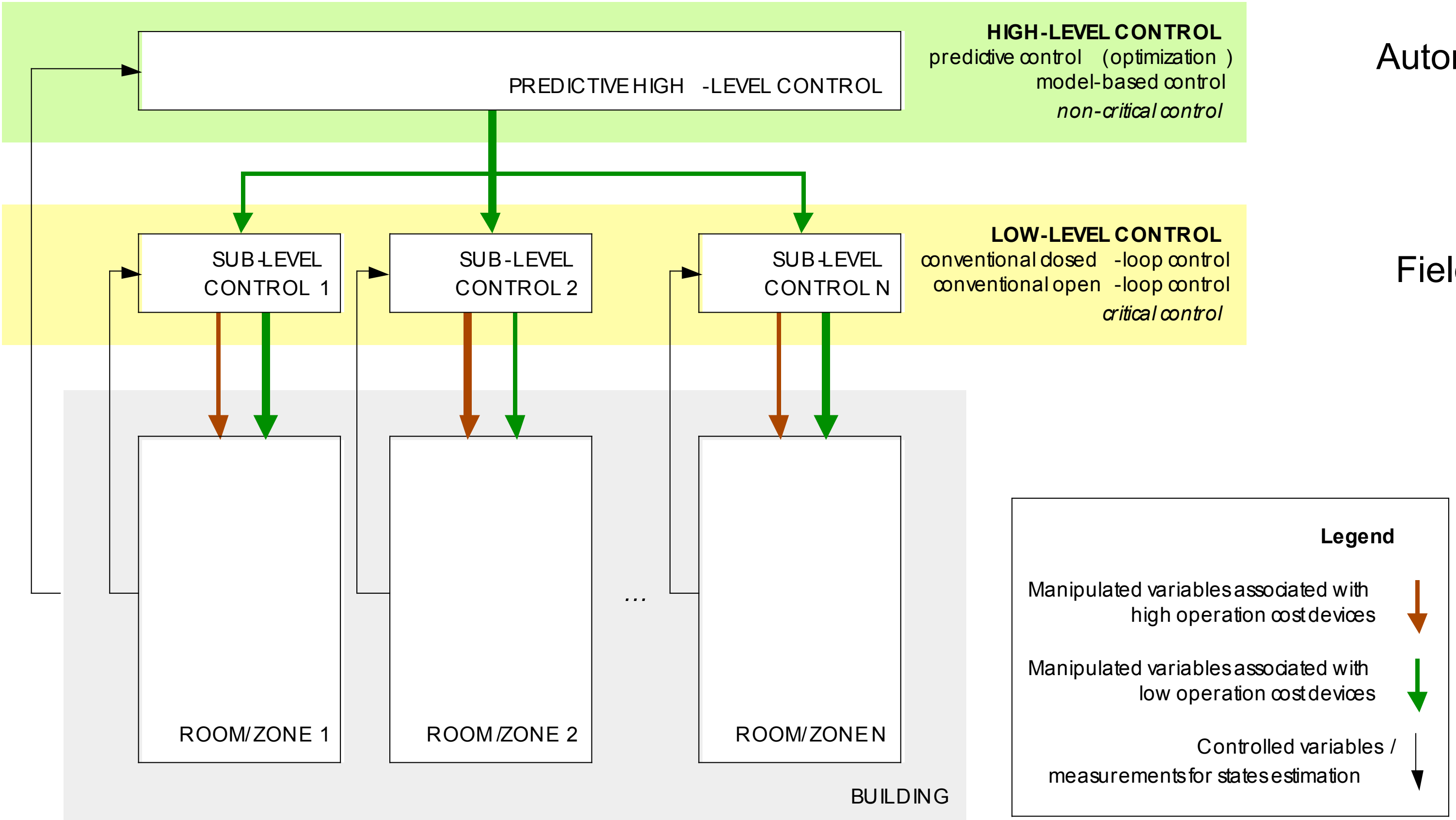


Transfer to Practice – Challenges for MPC approach (1)

- Exploitation of theoretical potentials:
  - Imperfect disturbances predictions → "Stochastic MPC"
  - Estimation of system state
  - Robustness (e.g. to modeling errors)
- Prove added value (benefit/cost analysis)
- Commissioning & tuning aspects
- Plausibility / User acceptance

Transfer to Practice – Challenges for MPC approach (2)

- Embedding of MPC in existing
  Building Automation and Control systems



Automation level

Field level

Transfer to Practice – General Challenges

- Conservative Industry
- Fragmented Field
- Lowest First Cost
- Lack of Incentives
- Poor Education
- Lack of information
  - Performance Projections
  - Results from New Buildings
- Linear Designs

Glicksman, L.R. (2009). Transforming the Building Stock: Opportunities and Barriers. Presentation at the Annual Meeting of The Alliance for Global Sustainability: Urban Futures: the Challenge of Sustainability, 26-29 January 2009, ETH Zurich, Switzerland.

Conclusions

- Demonstration of significant savings potentials.
- Potentials are highly case and system dependent.
- Benefit of weather predictions varies also strongly from case to case.
- Appropriate tools and data sets are important for investigations on a case-by-case basis.
- MPC results are physically plausible.
- Examination of sophisticated control strategies can be useful for identifying improved simpler strategies.
- Transfer to practice is challenging.