

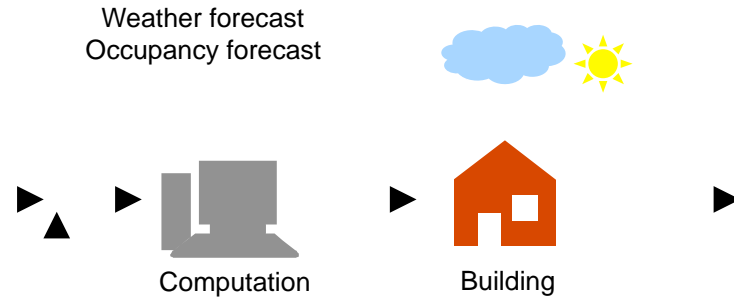
# - Energy efficient building climate control -



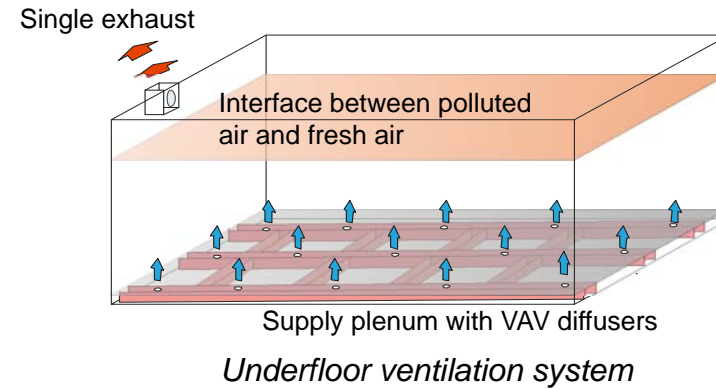
MANFRED MORARI  
KIMBERLY CHUNG  
COLIN N. JONES  
FRAUKE OLDEWURTEL  
ALESSANDRA PARISIO  
PHILIPP ROSTALSKI  
FABIAN ULLMANN



# Multidisciplinary Team



*MPC controlled HVAC system*

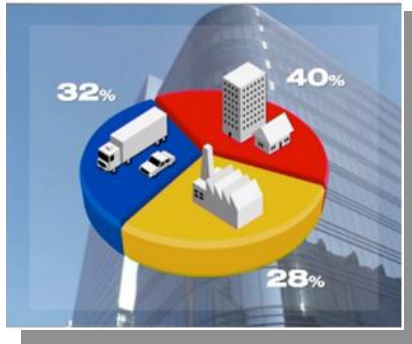


**OptiControl**

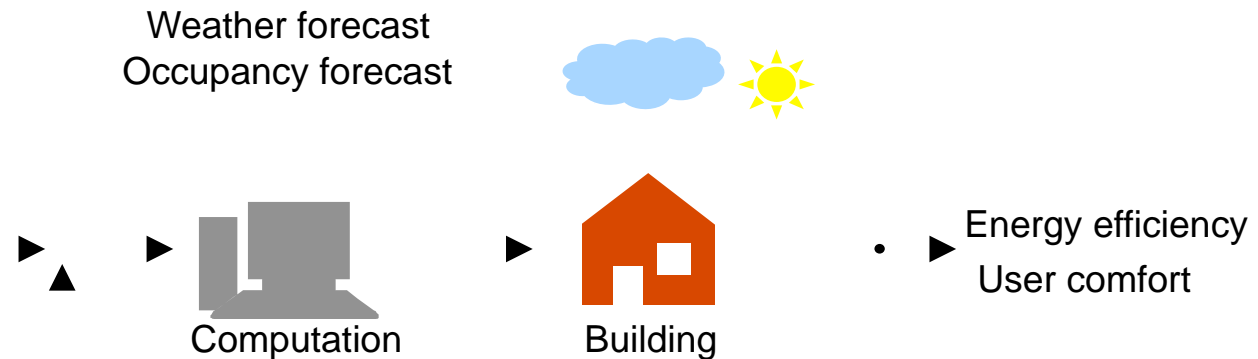
**Energy Efficient Ventilation**



# Use of weather and occupancy forecasts for optimal building climate control



Europe : 40% energy used in buildings



**Standards:** Keep room temperature in comfort range x % of time

**Goal:** Satisfy constraints with a minimum amount of energy

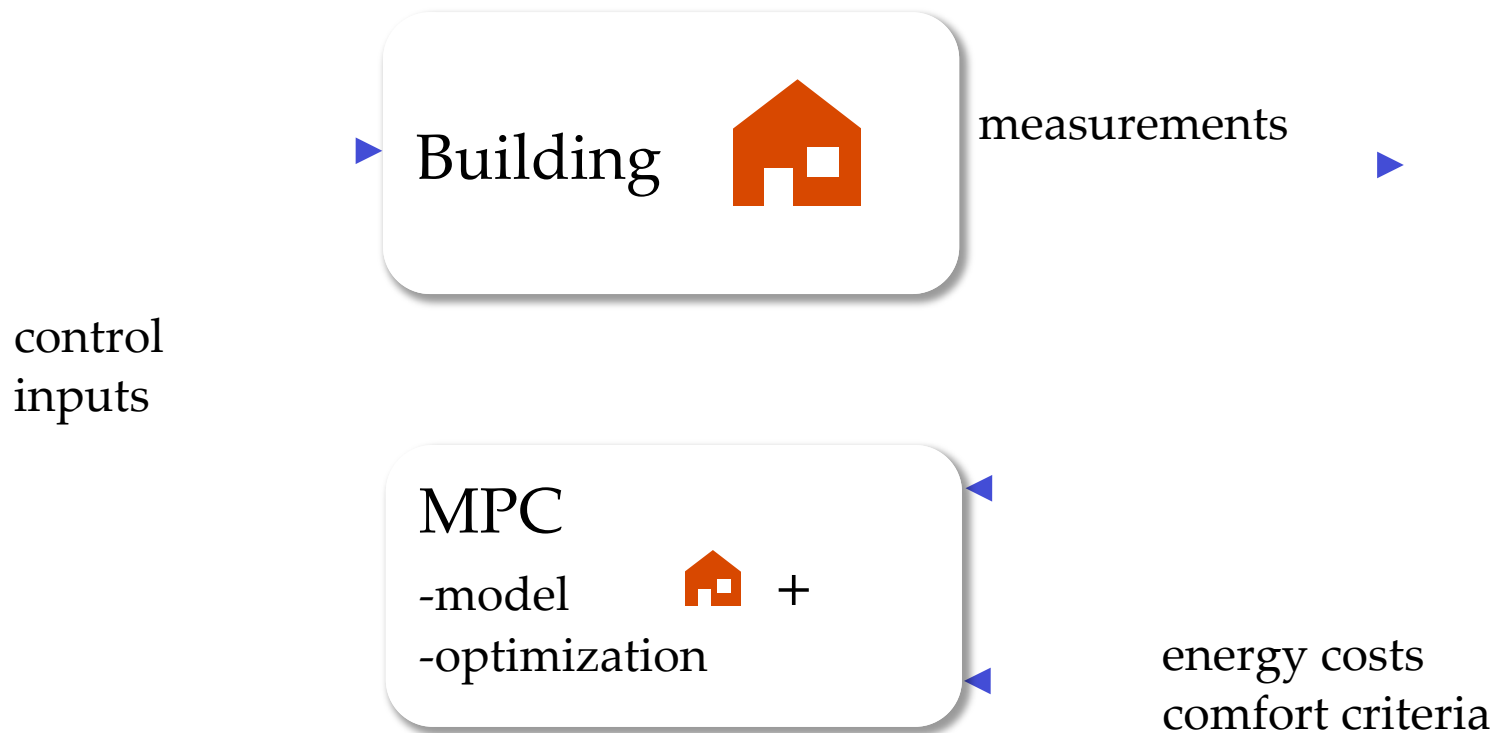
**Idea:** Low carbon energy sources intermittent, building dynamics slow  
– use weather forecast for planning

**Method:** Model Predictive Control using weather and occupancy forecasts

# ▪ Motivation

## - Model predictive control for buildings

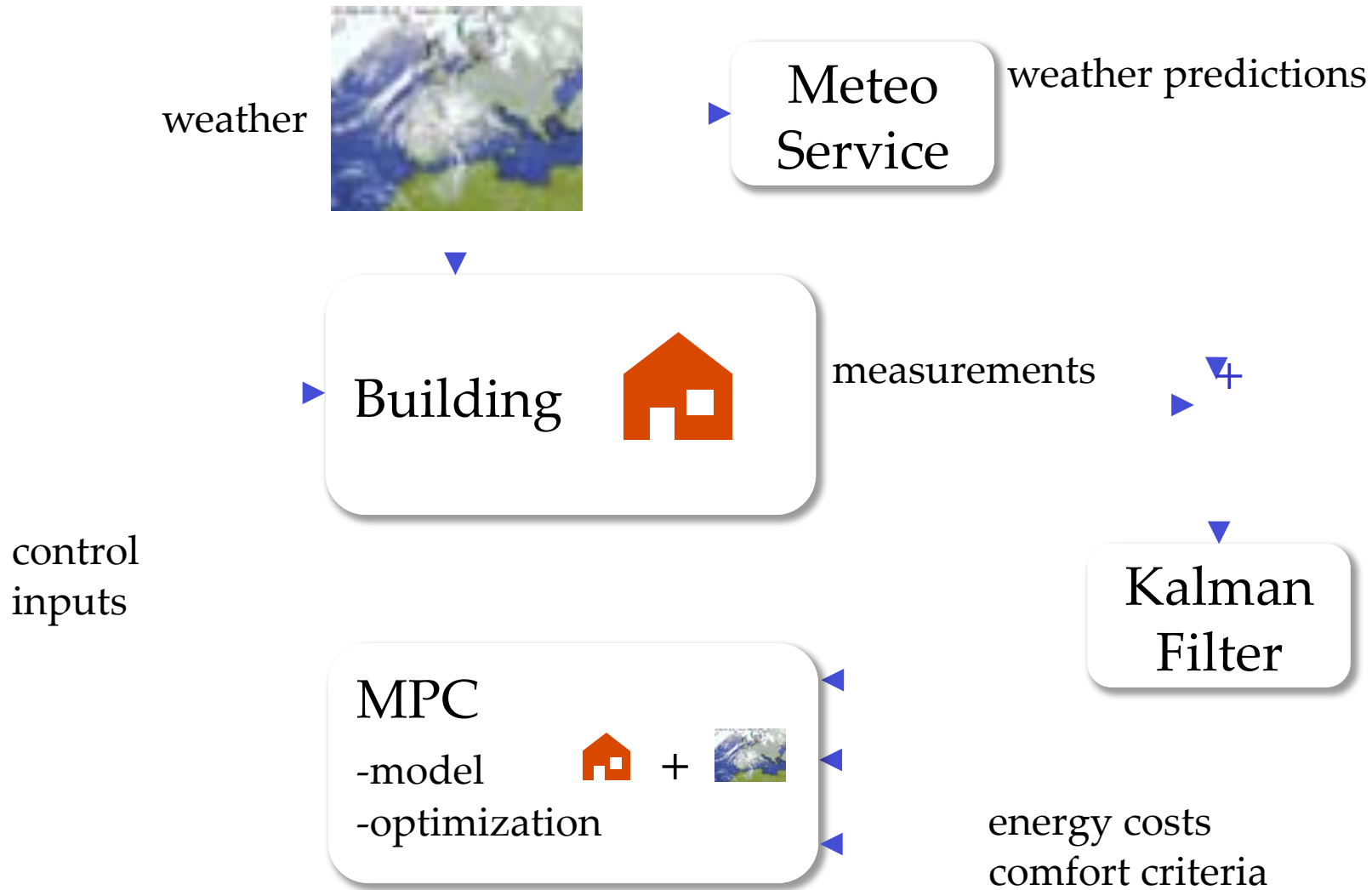
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# Motivation

## - Model predictive control for buildings

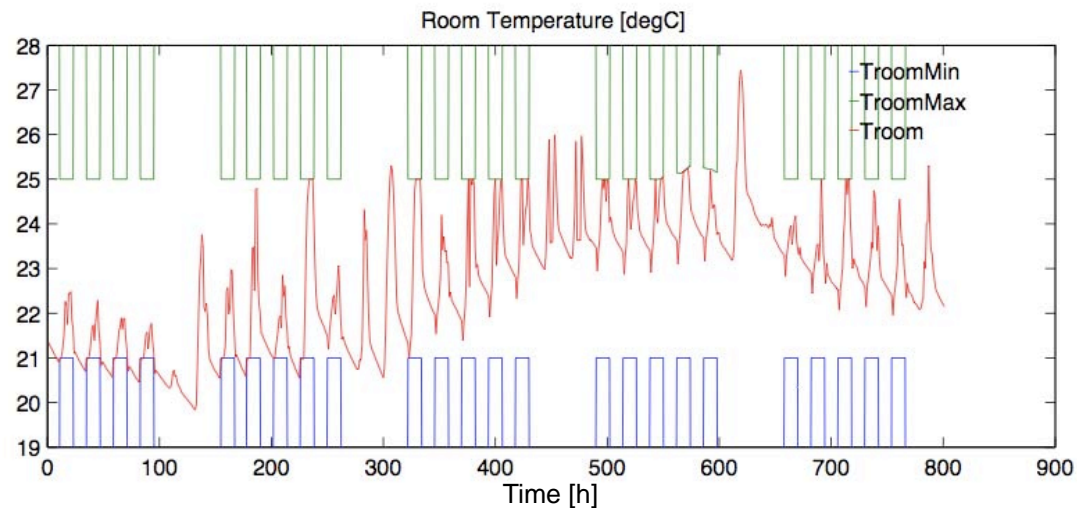
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# Application - Integrated room automation

## Integrated room automation means:

Integrated control of the heating and cooling system, the blinds and the electrical lighting of a room



## Control task:

Keep the room temperature, illuminance level and CO<sub>2</sub> concentration in prescribed ranges

# Research questions

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- How much energy can be saved by using advanced control techniques and weather predictions?
- In which buildings and in which weather conditions can savings be achieved?

**Approach:** Large-scale simulation study

# Controller assessment

## – Concept

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### Consideration of weather prediction:

1. “perfect world, perfect weather prediction”
2. “real world, no weather prediction”
3. “real world, real weather prediction”

Energy use

120

*Improvement of present-day control strategies*

100

80

60

40

20

0

Reference  
(current practice)

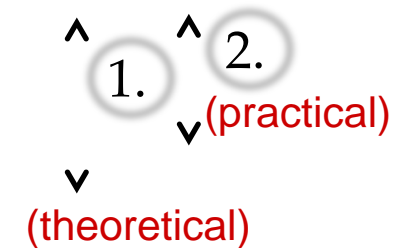
Improved non-predictive control

Model predictive control

**Performance Bound**

*Transition from perfect weather predictions to real weather predictions*

**Potential**



**Simulation studies:**

1. Potential analysis
2. In-depth analysis

# Outline

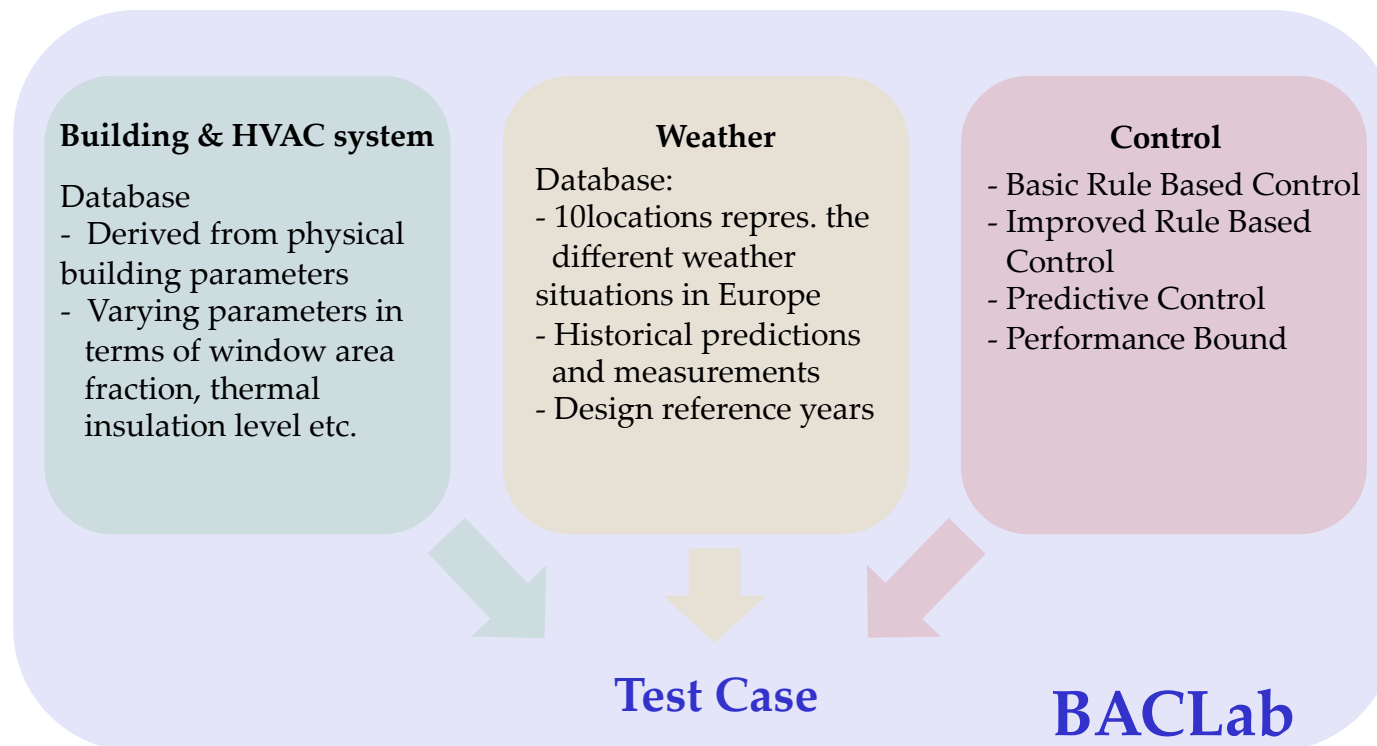
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- Modeling/ Setup simulation study
- Potential analysis
  - Comparison of current practice with Performance Bound
    - Example 1: Importance of blind control
    - Example 2: Potential of advanced control
    - Example 3: Prediction horizon length
- In-depth analysis
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    - Stochastic MPC
- Hierarchical control with hybrid MPC

# BACLab – Software tool

---

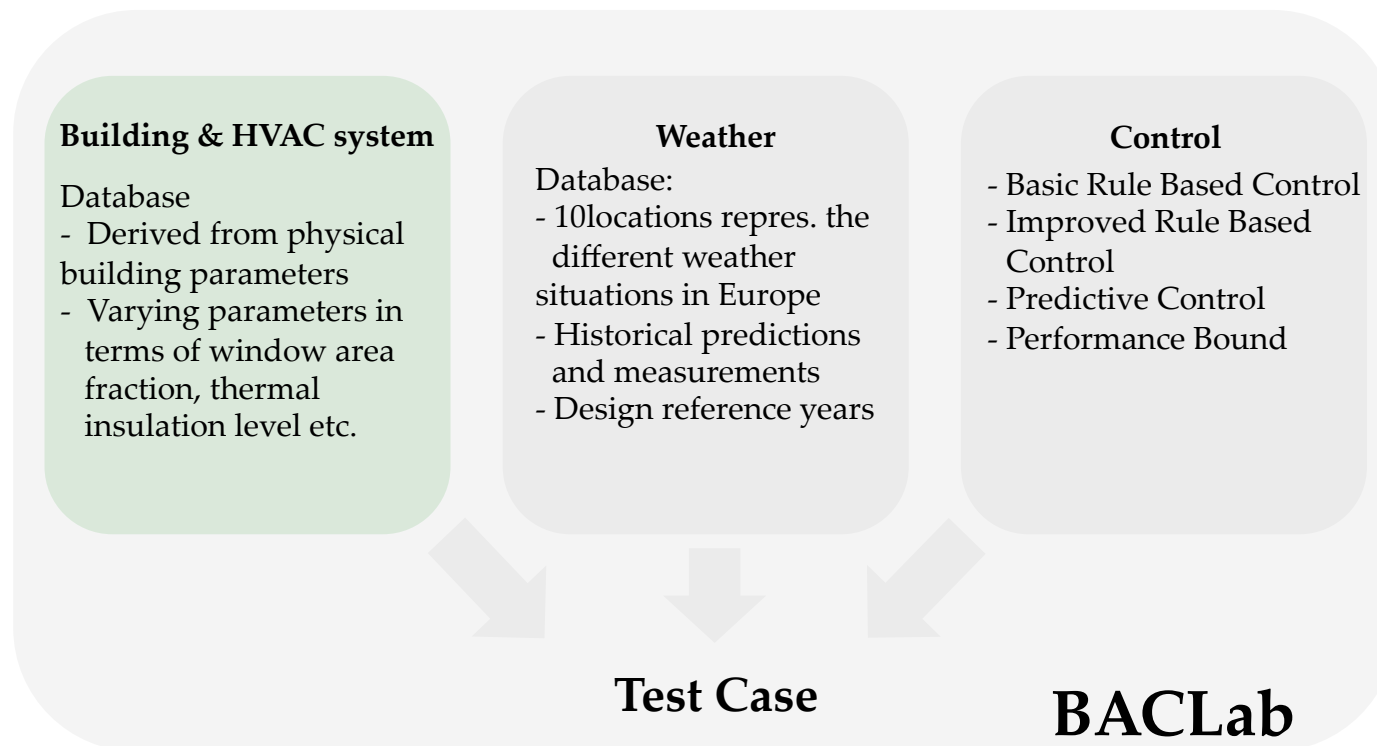
- **B**uilding **A**utomation and **C**ontrol **L**aboratory
- MATLAB-based building modeling and simulation environment
- Developed within OptiControl project



# BACLab – Software tool

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# Factorial study

## 5 building systems – 7 parameter sets

- Database of building & HVAC models typical for Europe
- Models validated with TRNSYS

### Building systems

	S1	S2	S3	S4	S5
Blinds	X	X	X	X	X
Electric lighting	X	X	X	X	X
Mech. ventilation flow, heating, cooling	–	X	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	–
TABS	–	–	–	–	X

# Factorial study

## 5 building systems – 7 parameter sets

- Database of building & HVAC models typical for Europe
- Models validated with TRNSYS

### Parameter Sets:

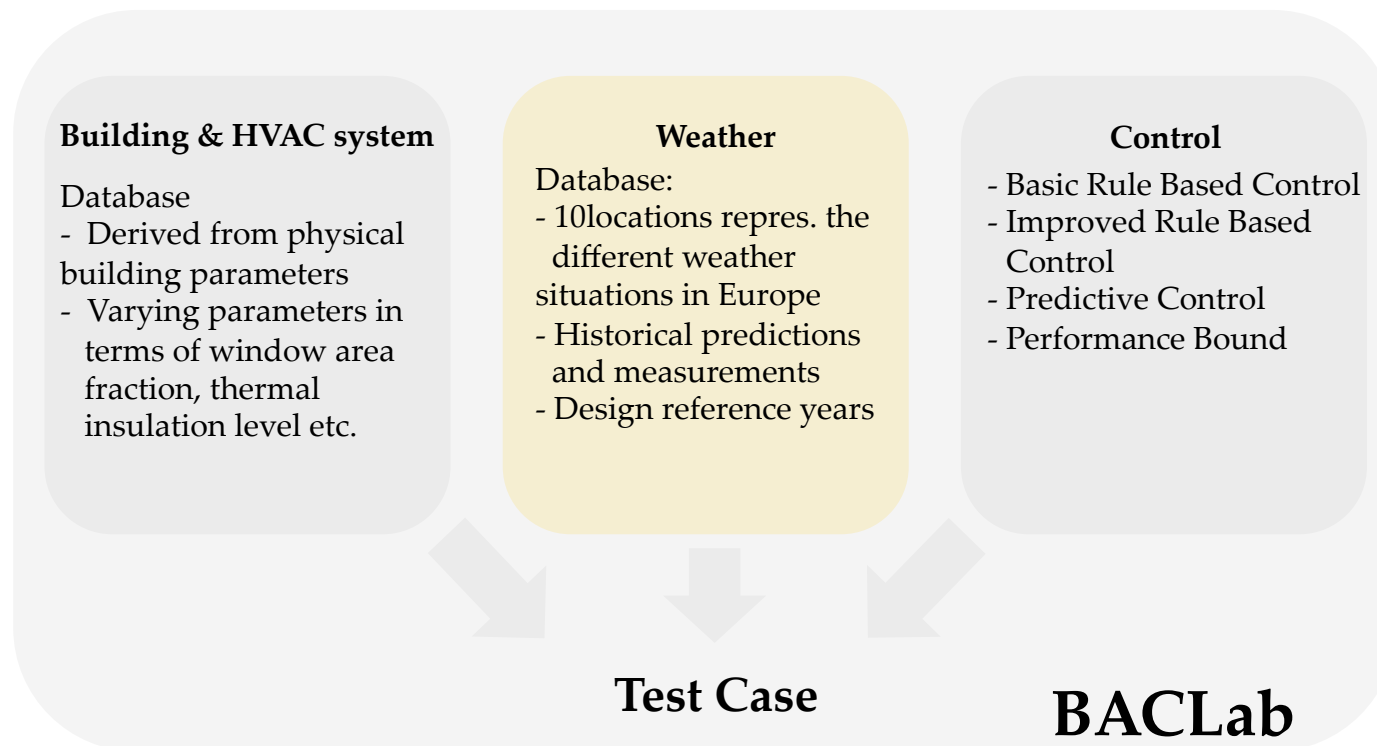
Building standard	Swiss average	Passive house	
Construction type	heavy	light	
Window area fraction	high	low	
Internal gains (occupancy/equipment)	high	low	
Thermal comfort: Setbacks	yes	no	
Thermal comfort: Comfort range	wide	narrow	
Ventilation	none	two-stage	CO <sub>2</sub> sensor

960 building cases · 10 locations · 4 orientations = 38.400 cases

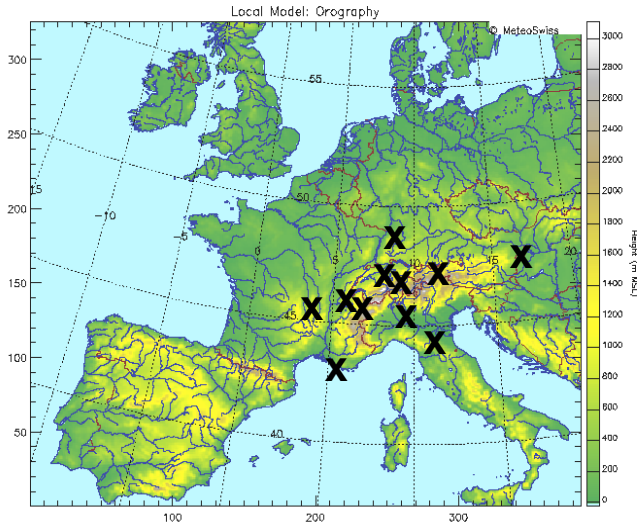
# BACLab – Software tool

---

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# Weather predictions



## Weather data:

- Historical measurements
- Design reference year: representative annual data sets (according to SIA standard)

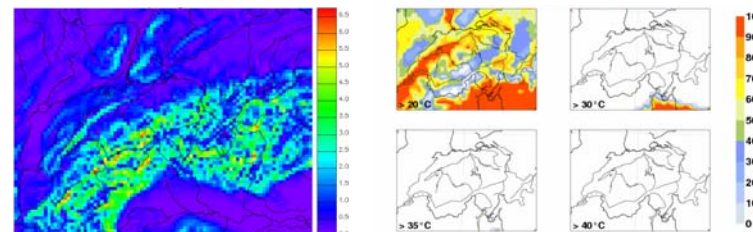
## Weather predictions:

- Output of weather model by MeteoSwiss
- Persistence: next hour is like 24 hours ago

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

## COSMO 7 weather model

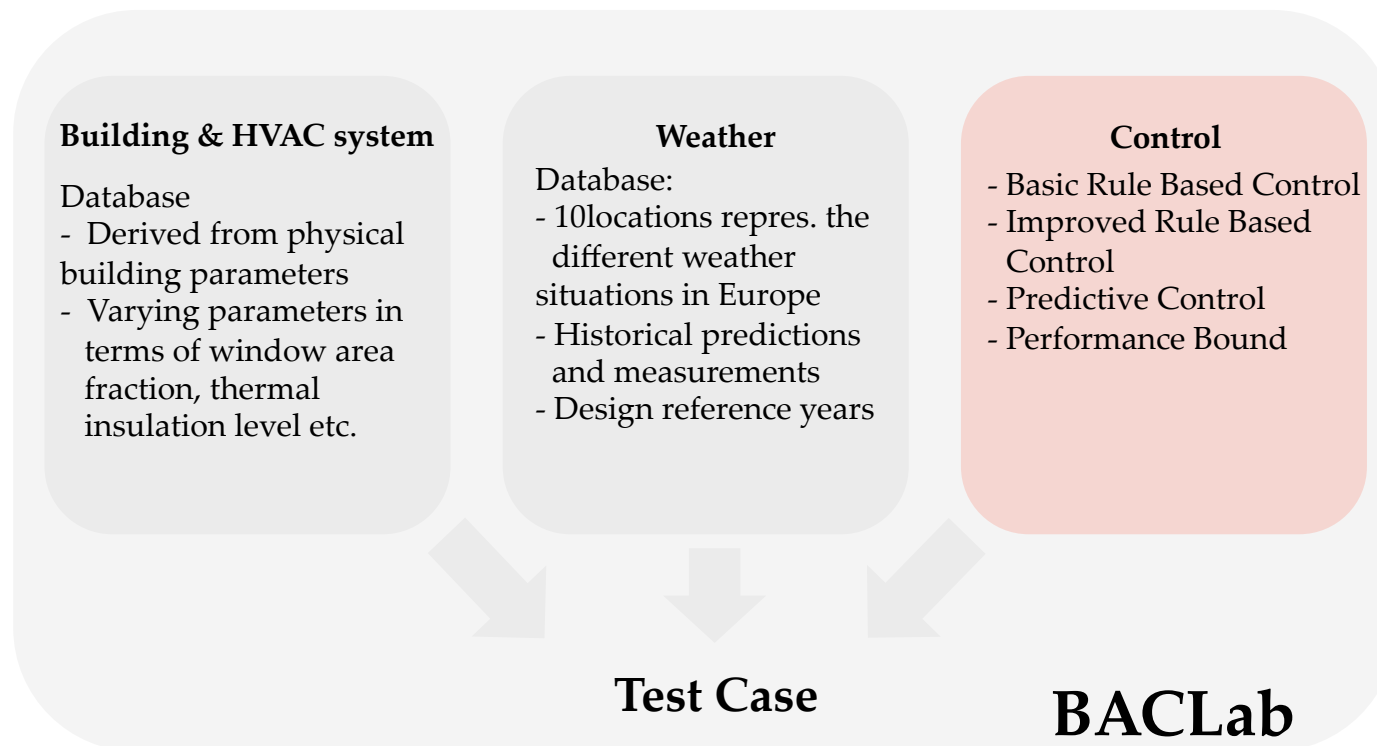
- deterministic forecast
- 2 daily 72 hour forecast
- Region of Europe
- 385 x 325 gridpoints, 7km mesh
- 45 terrain following levels



# BACLab – Software tool

---

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- MATLAB-based building modeling and simulation environment
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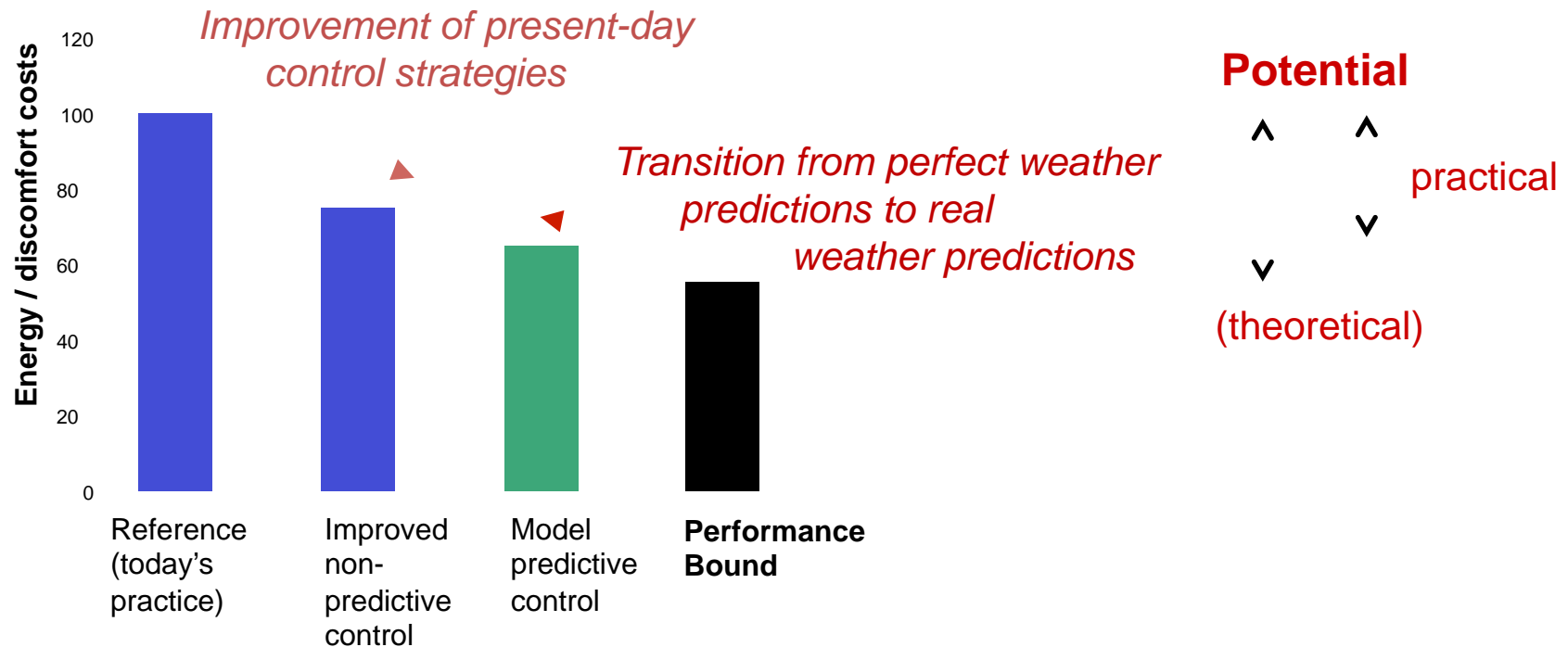
# Controller approaches

realistic < > theoretical

Based on rules

Based on MPC

Performance Bound



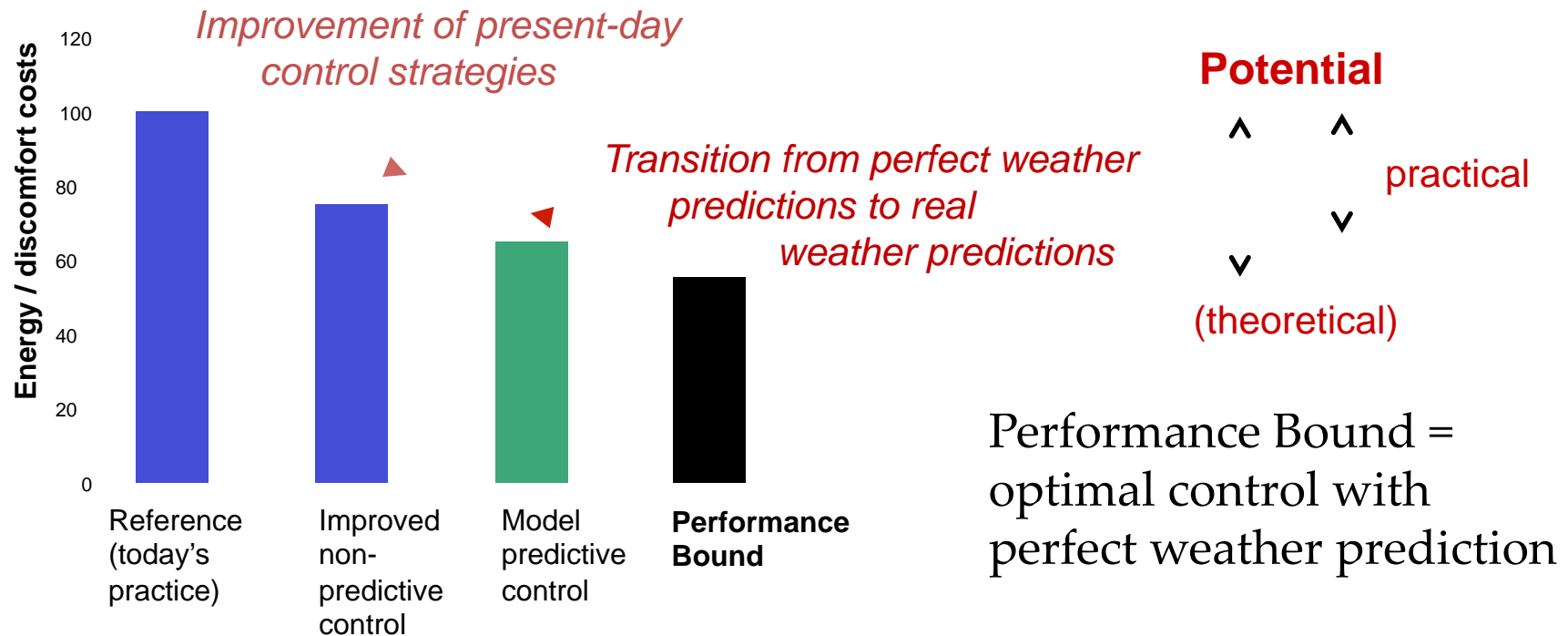
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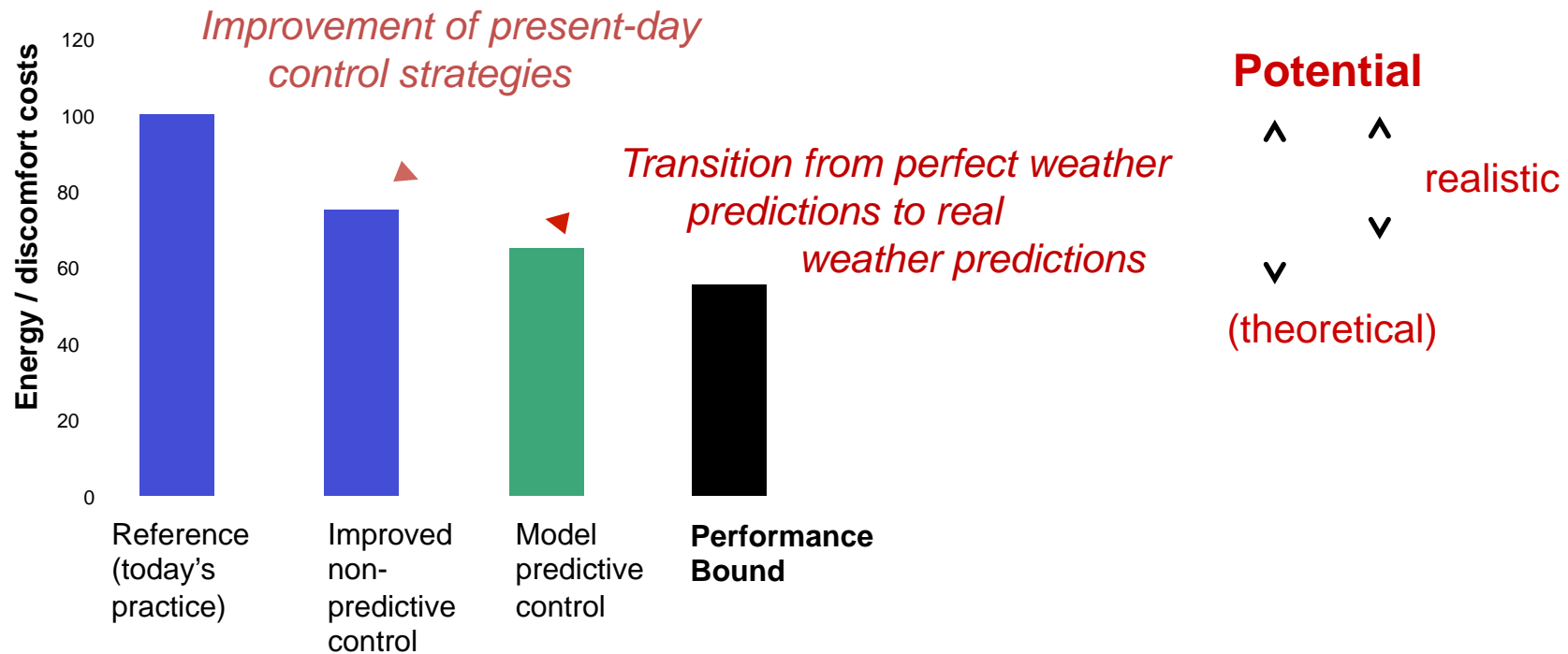
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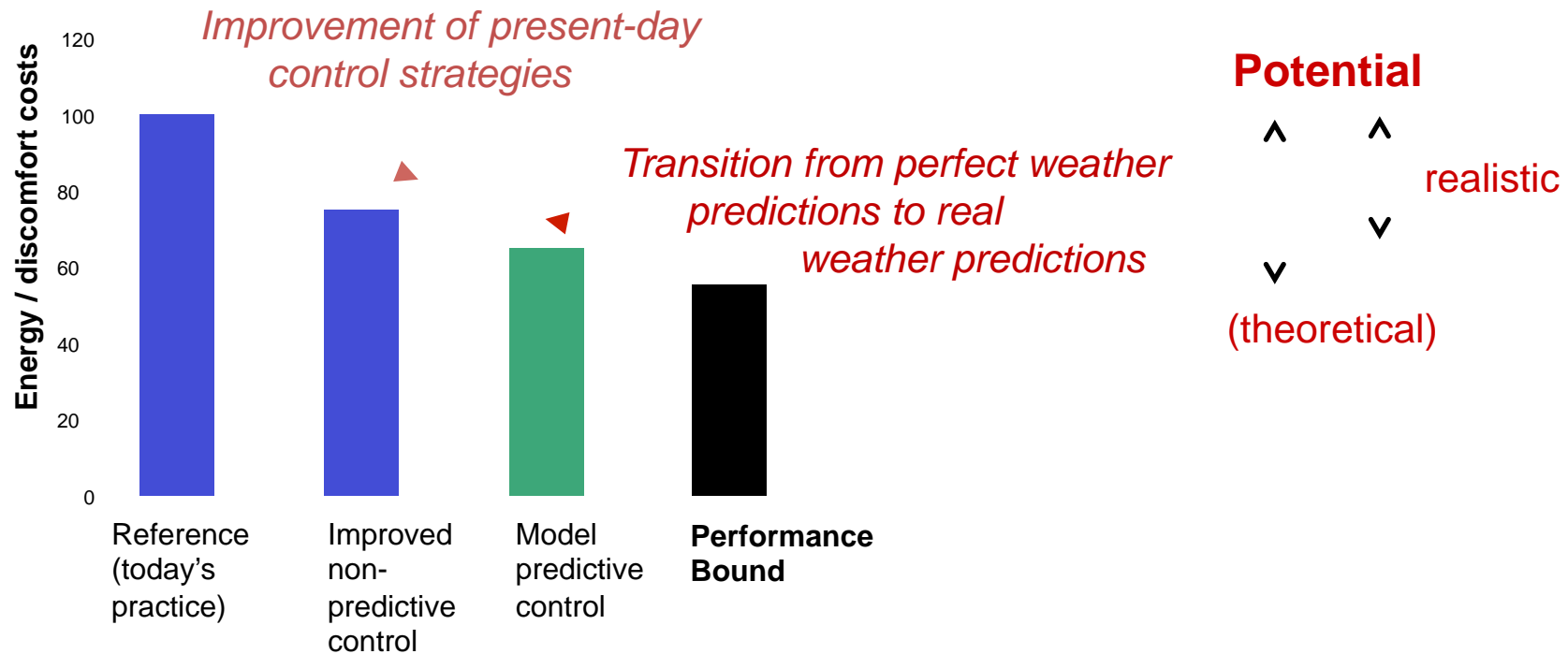
Based on MPC

Performance Bound



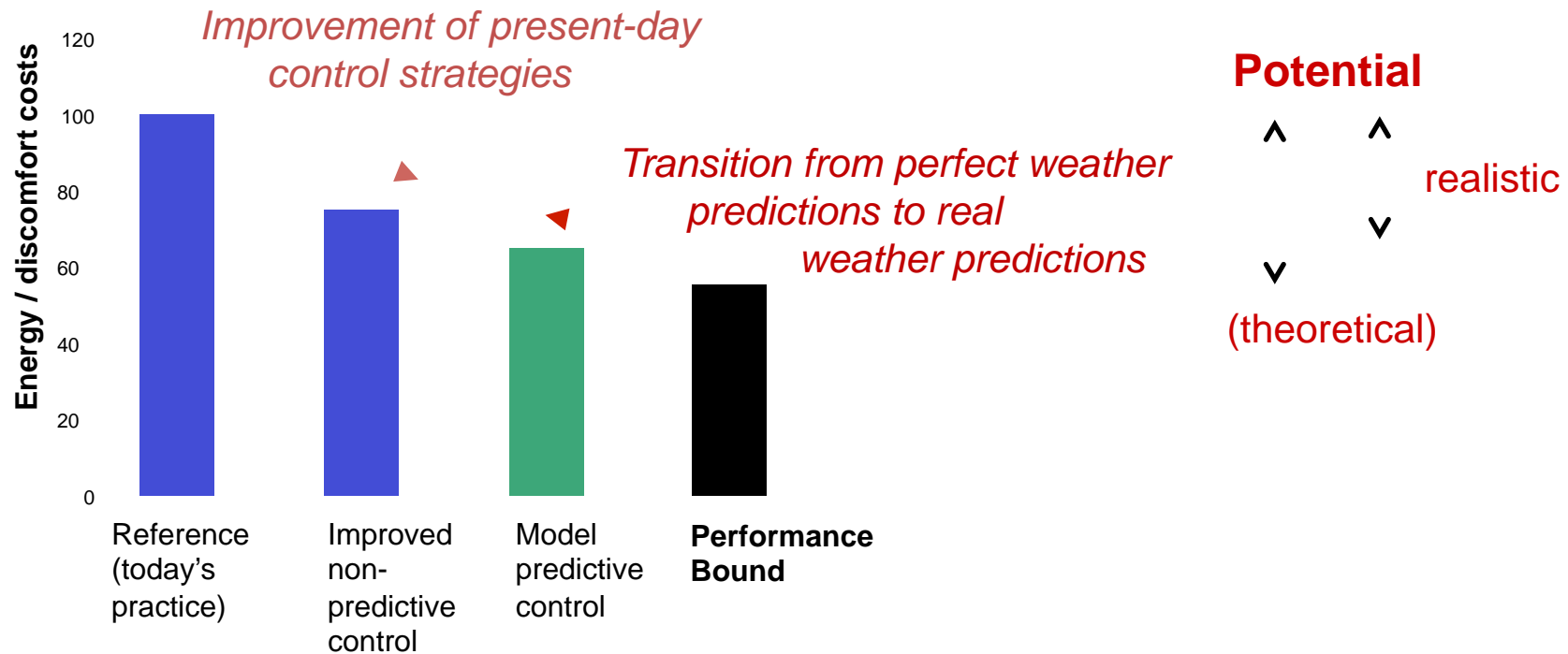
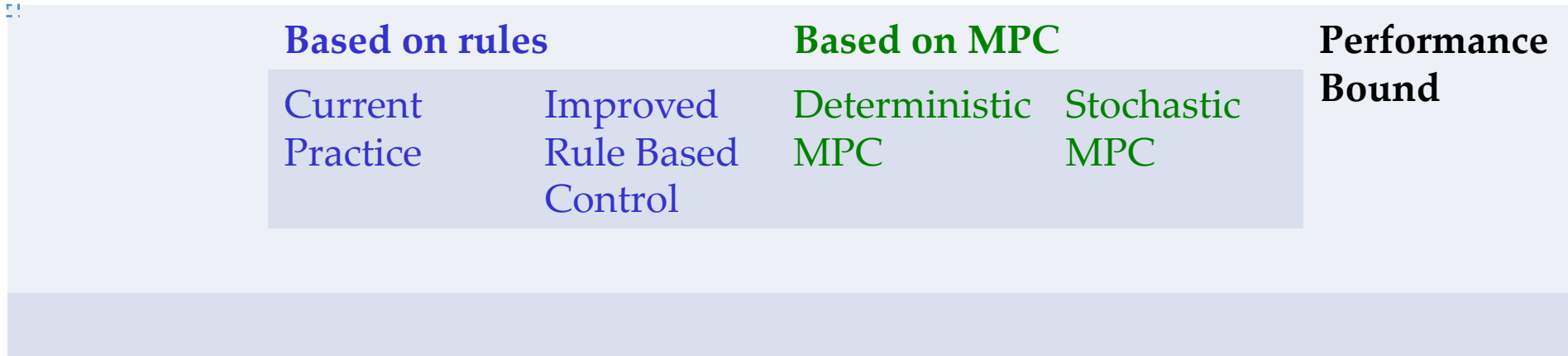
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realistic < > theoretical



# Controller approaches

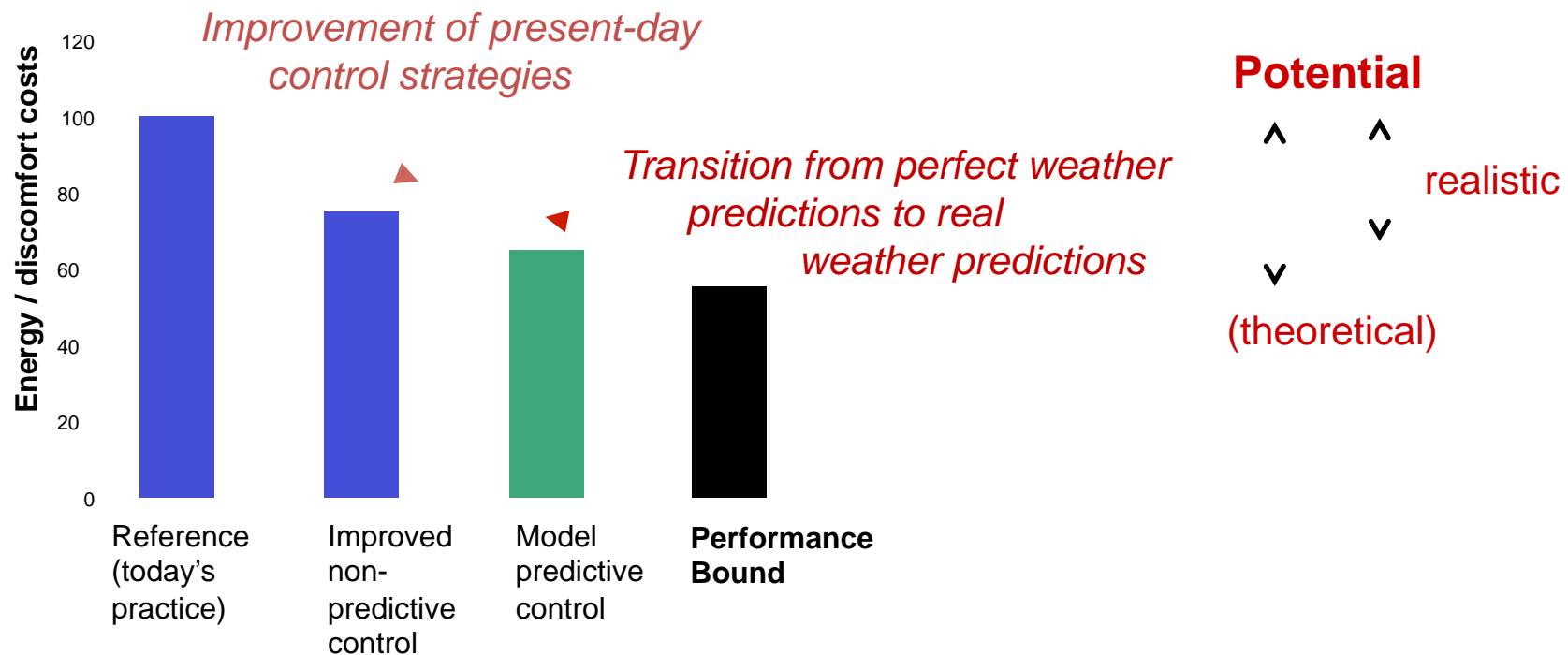
realistic < > theoretical



# Controller approaches

realistic < > theoretical

	Based on rules		Based on MPC		Performance Bound
	Current Practice	Improved Rule Based Control	Deterministic MPC	Stochastic MPC	
Model based	no	no	yes	yes	yes
Weather pred.	none	none	realistic	realistic	perfect



# Outline

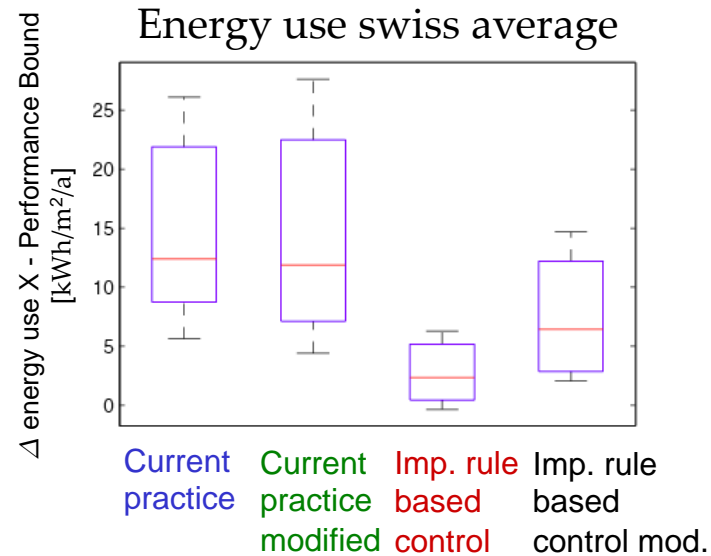
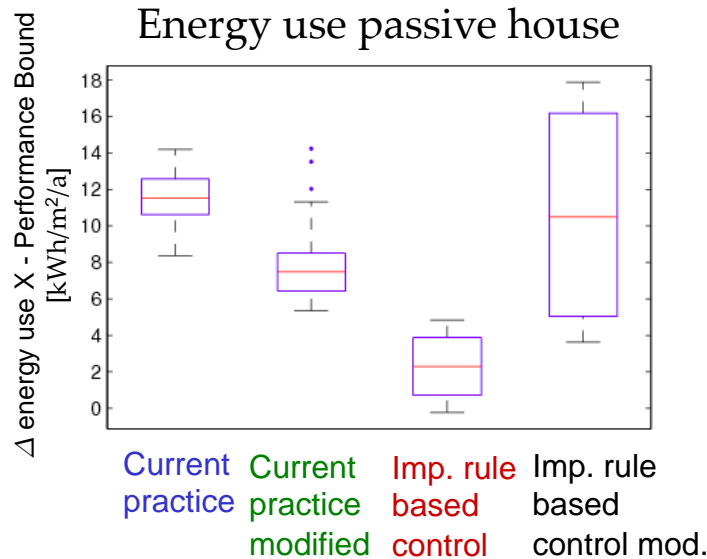
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# Potential analysis

## - Example 1: Importance of blind control

	Current Practice	Current Practice modified (more blind freedom)	Improved Rule Based Control (more info)	Imp. Rule Based Control modified (blinds hourly)
avail. position	open, 50%,closed	continuous	continuous	continuous
movement frequency	hourly	continuous	continuous	hourly
measurements used	current	current	current + past	current + past

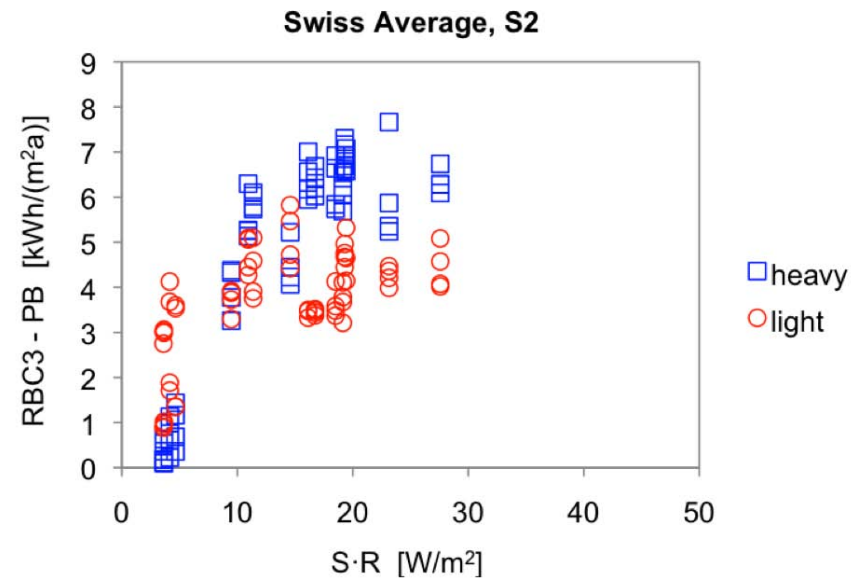
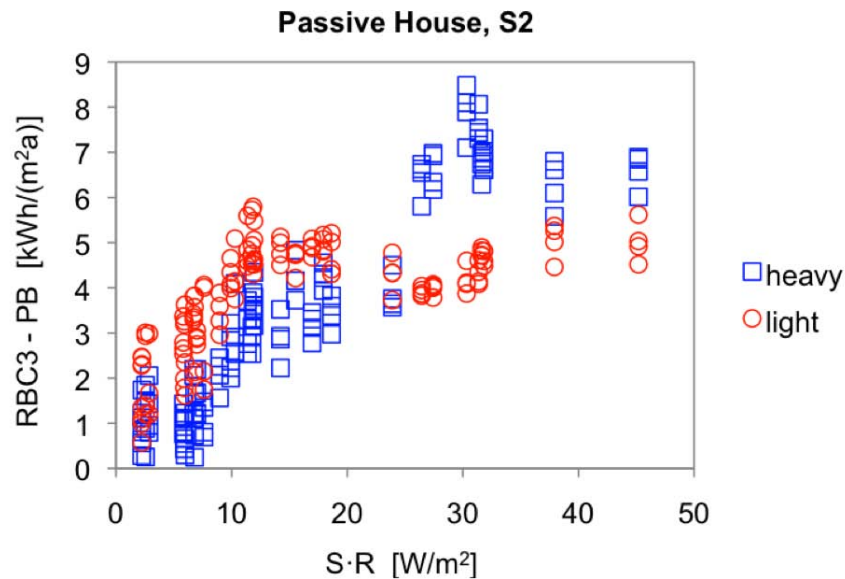


# Importance of solar gain area

## Specific solar gain area

$$S = \frac{g \cdot A_{win}}{A_{floor}}$$

R = annual average of vertical global radiation components



## Large savings potentials:

- with high solar gains and heavy building
- with low solar gains and light building

# Potential analysis

## - Example 2: Potential for advanced control

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**Goal:**

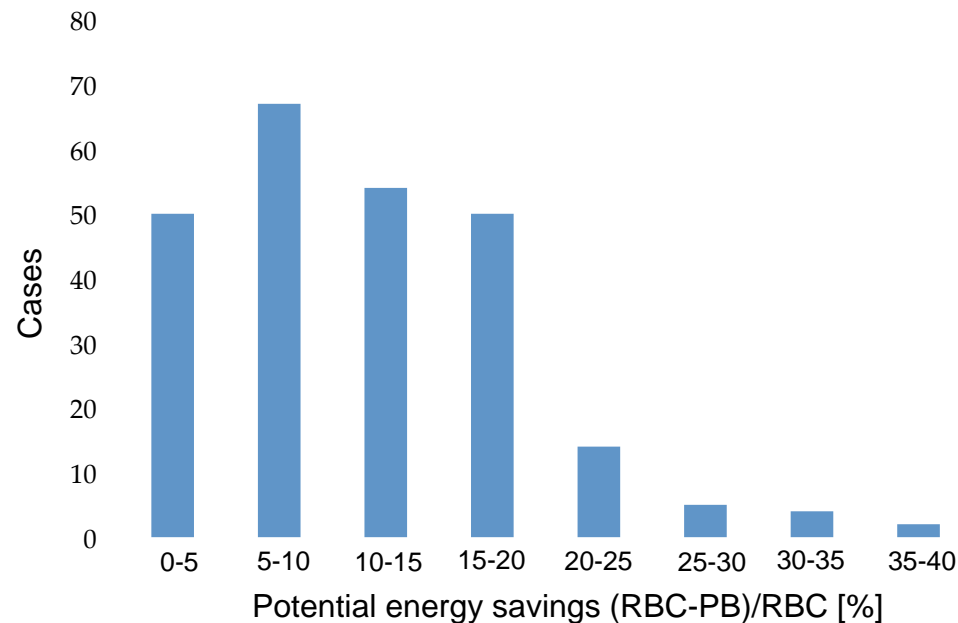
Isolate effect of advanced control

**Comparison:**

Performance Bound vs. Improved Rule Based Control

- Blind control perfect (continuous)

- 250 cases considered



→ Even with Improved Rule Based Control and perfect blind control:  
Large potential in many cases!

# Potential analysis

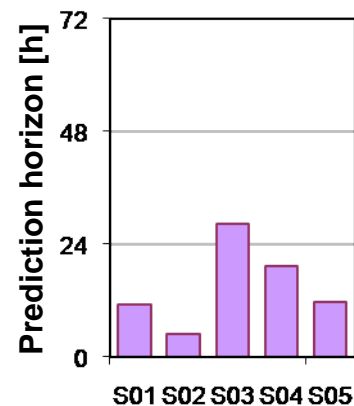
## - Example 3: Prediction horizon length

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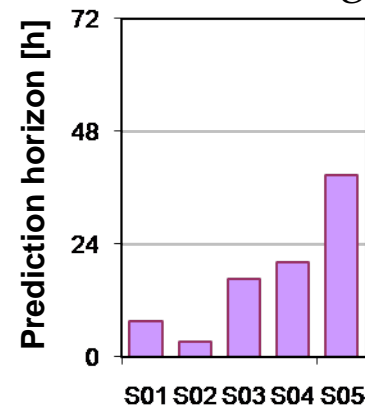
**Goal:** Choose horizon length, get error to Performance Bound to 5%

**Comparison:** Performance Bound vs. Performance Bound with shorter horizon lengths

Passive house



Swiss average



→ In the following investigations we use a horizon of 24h.

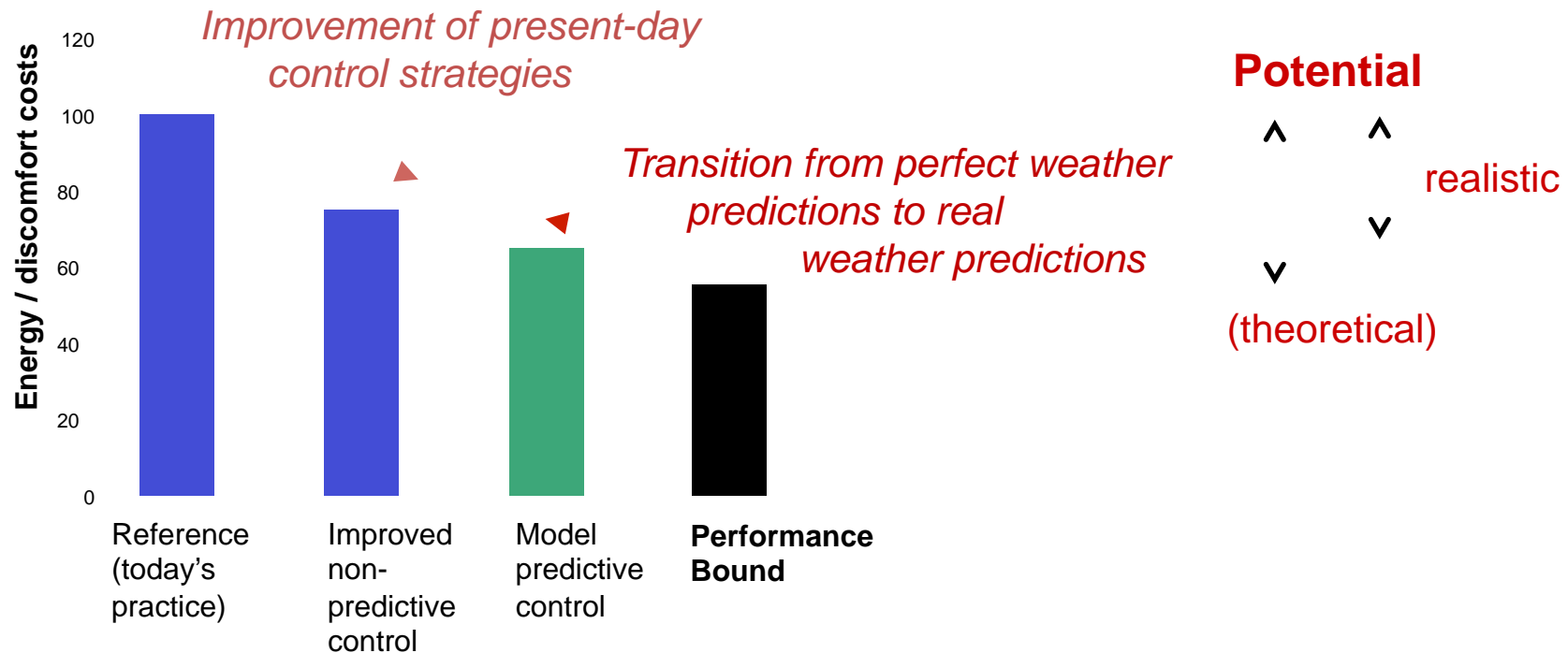
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# Controller approaches

realistic < > theoretical



# Simulations

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## Tradeoff curve

### energy vs. violations

- comfort level can be adjusted
- standards: 70Kh/a

Energy use [kWh/m<sup>2</sup>]  
^

70Kh/a

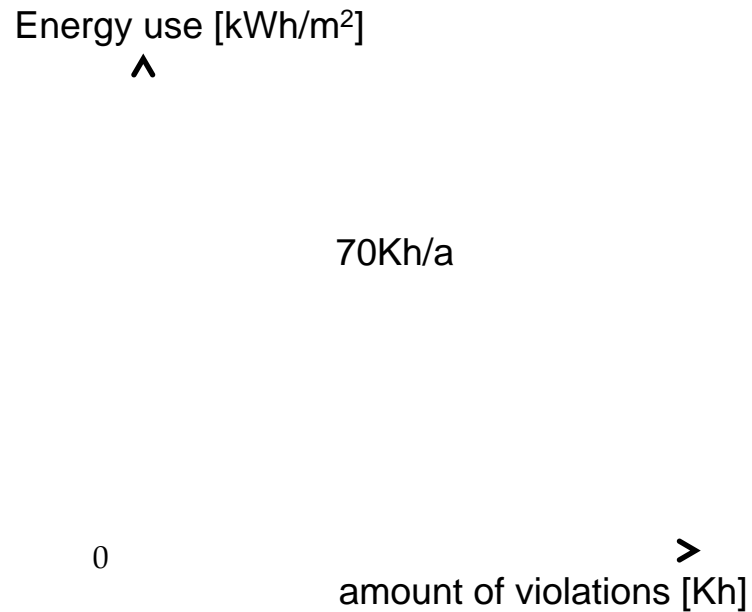
0

>  
amount of violations [Kh]

# Simulations

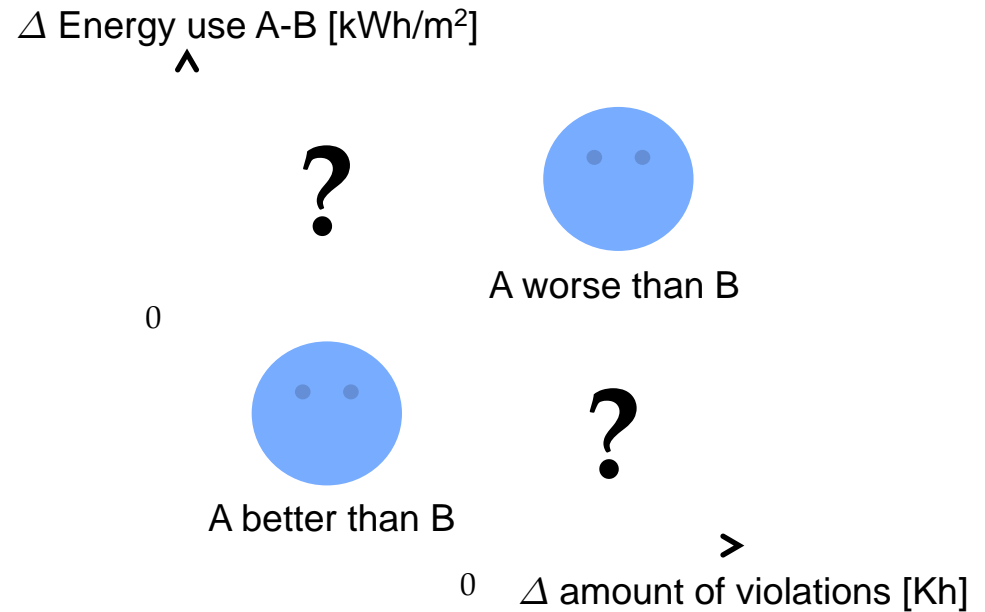
## Tradeoff curve energy vs. violations

- comfort level can be adjusted
- standards: 70Kh/a



## Comparison of controllers A and B

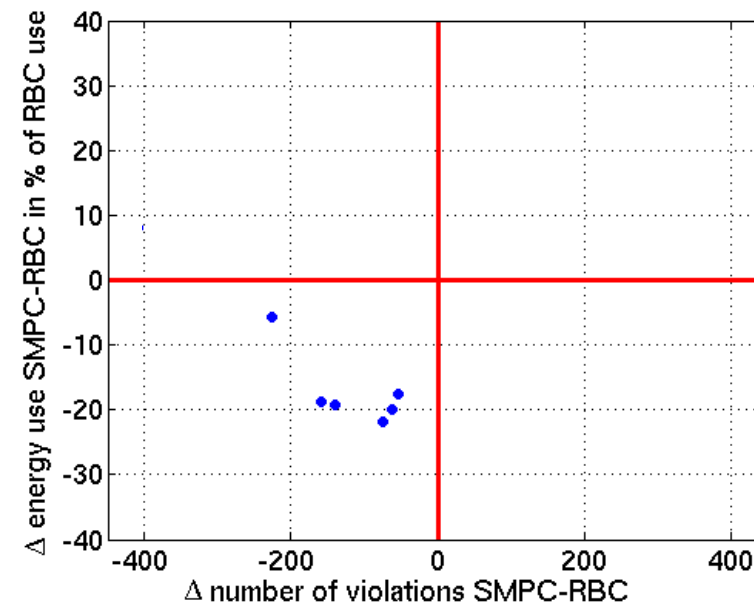
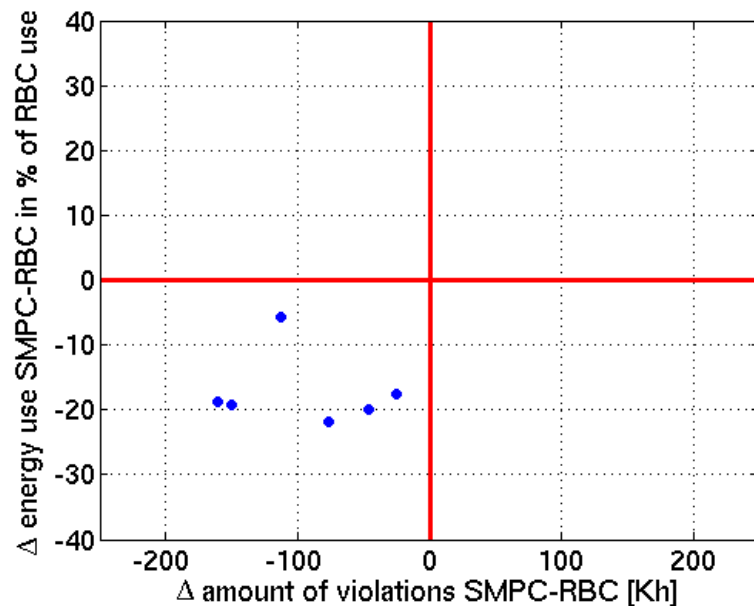
- 4 possible cases
- 2 cases undetermined (controller need to be tuned to be comparable)



# Simulation results

**Goal:** Investigate improvement with Stochastic MPC  
**Comparison:** Stochastic MPC vs. Improved Rule Based Control with hourly blind movement

- Difference in energy use as % savings of improved rule based control
- Difference in violations (amount & number) as absolute values



→ Stochastic MPC outperforms Improved Rule Based Control!

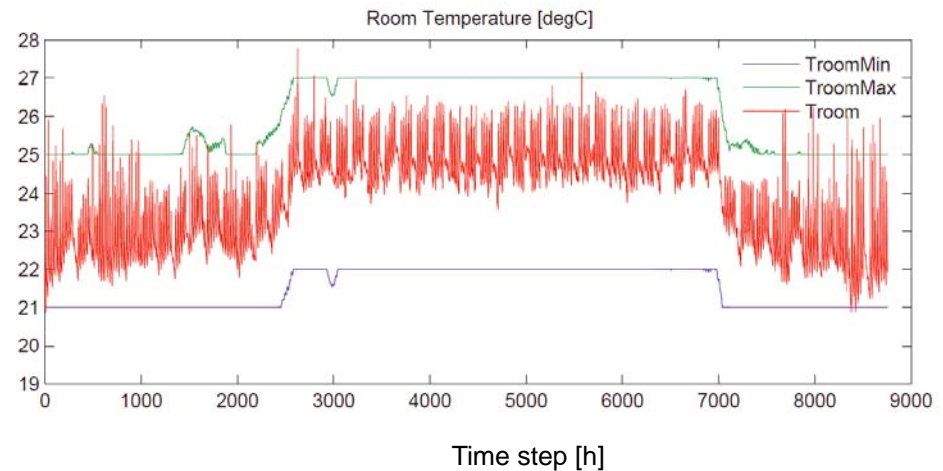
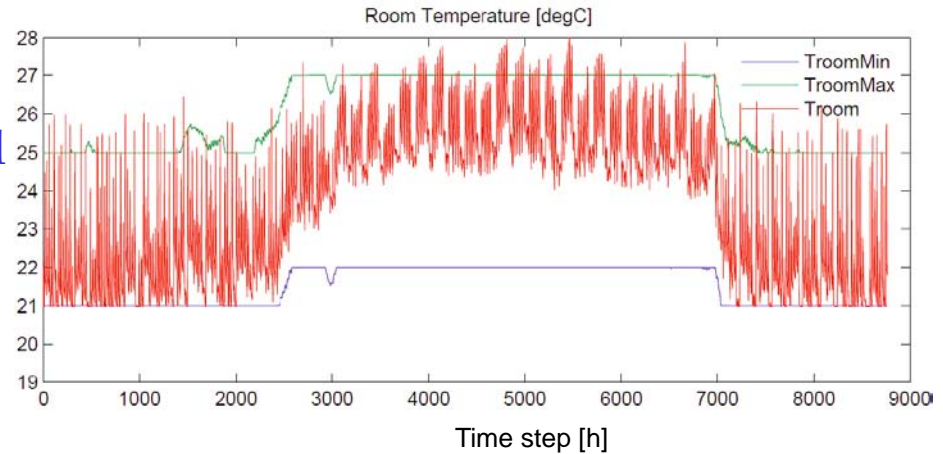
# Simulation results

## Room temperature behavior

- Energy saving with Stochastic MPC: up to 22%
- Violation savings with Stochastic MPC: up to 160Kh

Improved rule-based control (current and past measurements, hourly blind movement)

Stochastic MPC



→ Diurnal temperature variations are more favorable with Stochastic MPC!

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*Dimitrios Gyalistras & Markus Gwerder (Eds.)*

## Use of Weather and Occupancy Forecasts For Optimal Building Climate Control (OptiControl): Two Years Progress Report

Reporting Period May 2007–April 2009

Available December 2009!

*Terrestrial Systems Ecology ETH Zurich  
R&D HVAC Products, Building Technologies Division, Siemens Switzerland Ltd., Zug*

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**ETH**  
Eidgenössische Technische Hochschule Zürich  
Swiss Federal Institute of Technology Zurich

 Schweizerische Eidgenossenschaft  
Confédération suisse  
Confederazione Svizzera  
Confederaziun svizra  
**MeteoSwiss**

**EMPA**   
Materials Science & Technology

**SIEMENS**

swiss**electric**  
research

  
ccem.ch

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# Summary

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- **Large-scale simulation studies** carried out
- **Large potential** for advanced control strategies in many cases
- **Stochastic MPC** can significantly **improve performance**
- **Hybrid MPC** solution for **hierarchical control** can significantly **improve performance**

