RAPIDLY-DEPLOYABLE, SELF-TUNING, SELF-RECONFIGURABLE NEARLY-OPTIMAL CONTROL DESIGN FOR LARGE SCALE NONLINEAR SYSTEMS
AGILE

FP7-ICT-2009.3.5: Engineering of Networked Monitoring and Control Systems

Optimization-based Active Techniques for Energy Efficient Building Control

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SEVENTH FRAMEWORK PROGRAMME

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International Conference on Buildings Energy Efficiency and Renewable Energy Sources 2014

Outline

- Part I: Optimization Algorithms (sketch)
  - Building Optimization and Control (BOC)
    - Active techniques
    - Objective function (performance)
  - The PCAO BOC
    - Basic architecture
    - Model-based
    - Fully-adaptive
    - Interfacing:
      "Plug-n-Play" nature

Outline

- Part II: Real-life Experimental Results (more emphasis on this part)
  - Test Case1, Chania, Greece
    - 10 offices
    - EnergyPlus (inaccurate) model
    - Cooling with A/C
  - Test Case 2, Kassel, Germany
    - 22 offices
    - TRNSYS (validated) model
    - Heating with concrete activation slabs

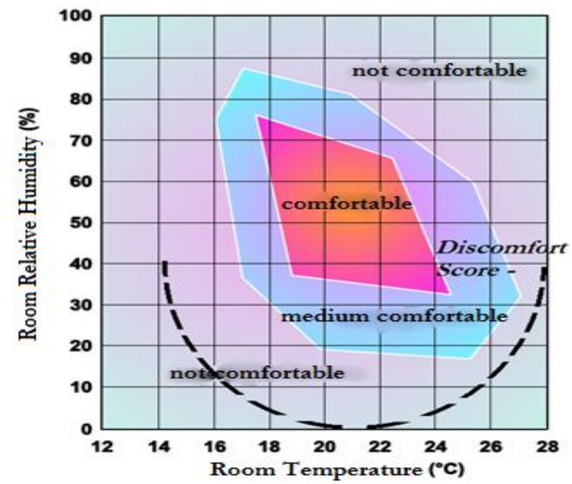
Part I: Optimization Algorithms

How to measure performance: example, cooling problem

- Optimize cooling energy demands, while keeping comfort conditions between satisfactory levels

$$Total_{score} = t*Energy_{score} + (1-t)*Comfort_{score}$$

- $Energy_{score}$ is
  - energy absorbed from the electric grid=energy consumption (in absence of any renewable sources) or
  - effective energy absorbed from the electric grid grid≠energy consumption (in the presence of renewable sources)
- $Comfort_{score}$ is
  - Fanger index (many sensor required) or
  - Other comfort standards (typically require only zone temperature and humidity)
- Comparisons: with simple strategies, called Base Case Scenario (BCS) or Rule-Based Controller (RBC), e.g.
  - HVAC setpoint at 24 °C and 25 °C during office hours



German Comfort standard

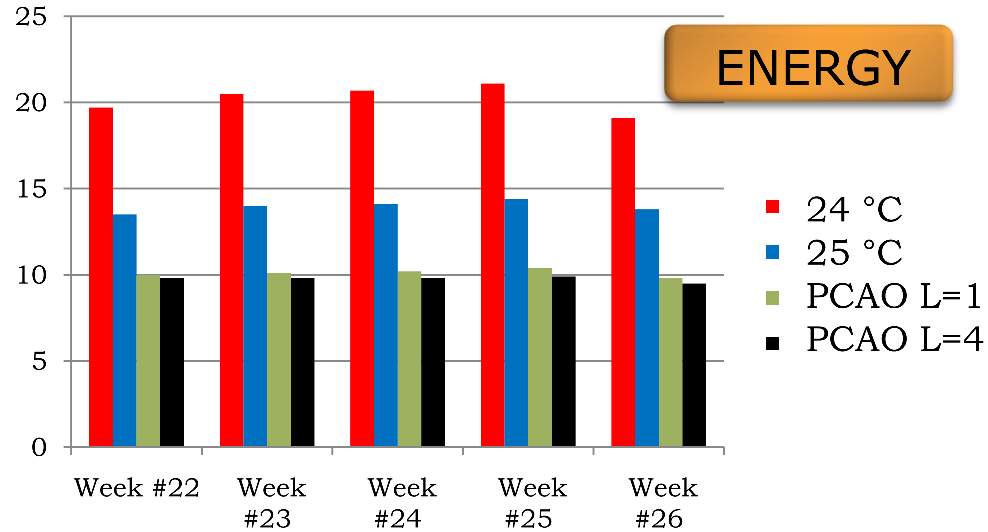
Energy and Comfort score is much more than a simple trade-off

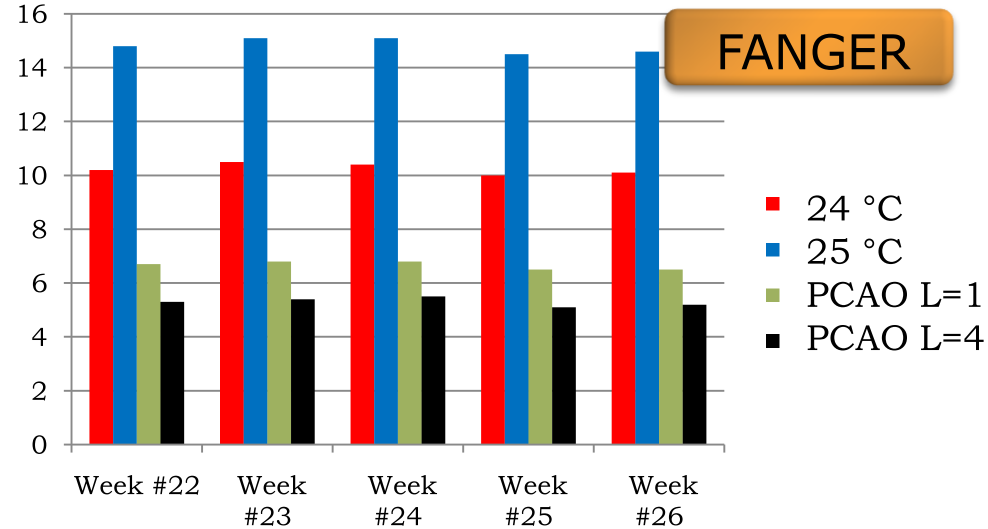
Table. PCAO simulation results (1 week)

	Energy from the grid [kW]/ Improv.[%]	Total Discomfort/ Improv.[%]
RBC= 25°C	13.5/ **0**	14.8/ **0**
MB L=1	10.0/ **25.9%**	6.7/ **54.7%**
MB L=4	9.8/ **27.4%**	5.3/ **64.2%**
RBC= 24°C	19.7/ **0**	10.2/ **0**
MB L=1	10.0/ **49.2%**	6.7/ **34.3%**
MB L=4	9.8/ **50.2%**	5.3/ **48.0%**

- Energy improv. 25-50%
- Fanger improv. 35-60%

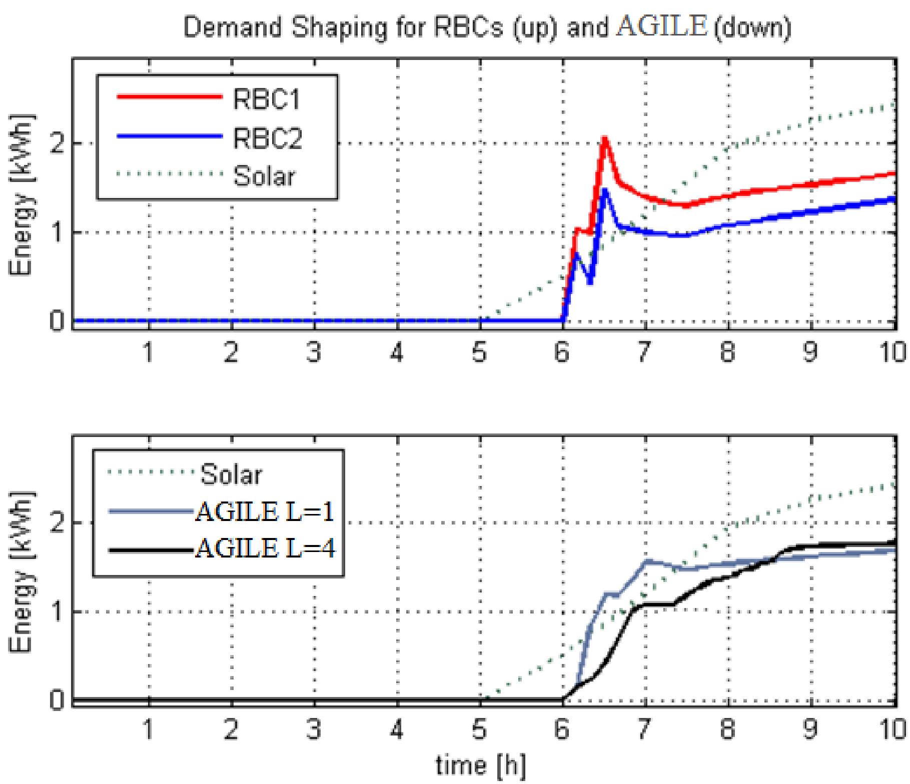
BOTH ENERGY AND COMFORT CAN BE IMPROVED!!

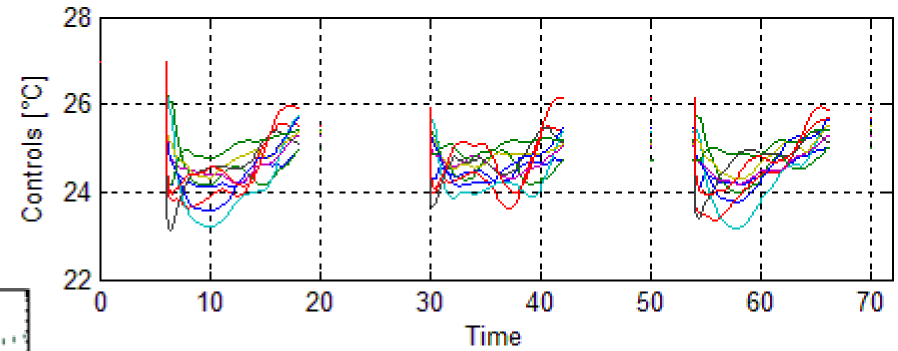




How to improve performance? Example, demand shaping

DEMAND SHAPING

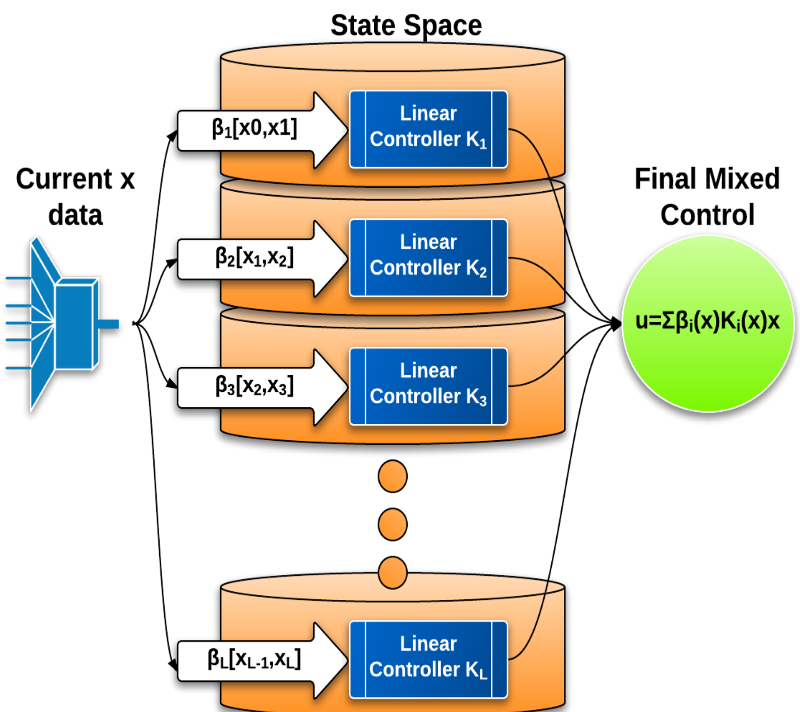




HVAC Set points

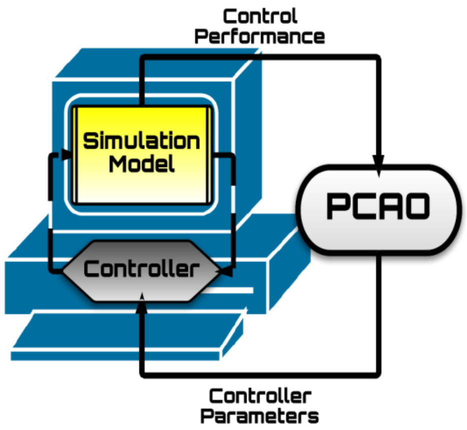
- Pre-actively schedule the HVAC so as to minimize the energy requirements from the grid
- We can play with the HVAC set points in an energy/comfort efficient way

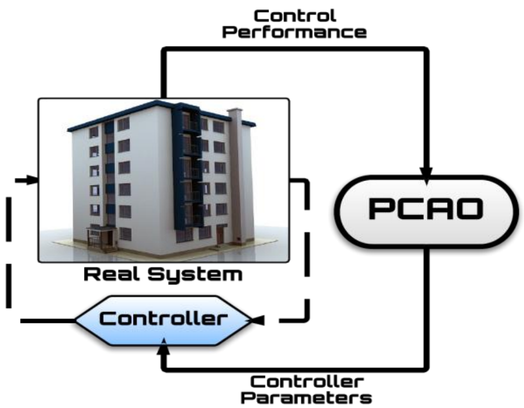
PCAO basic architecture: switching linear controllers



- How to select the number of switching controllers:
  - From a theoretical point of view the larger the number, the better is the performance
  - Interestingly, in practice we verified that such a number does not to have to be large to achieve a good performance.
  - It suffices to "intelligently" design the switching strategy (i.e., when to switch from one linear controller to another) in order to achieve a good performance with a small number of switching linear controllers.
  - In our examples, we select at maximum 4 controllers, depending on the external temperature

Two version of PCAO: Model-based and Fully Adaptive

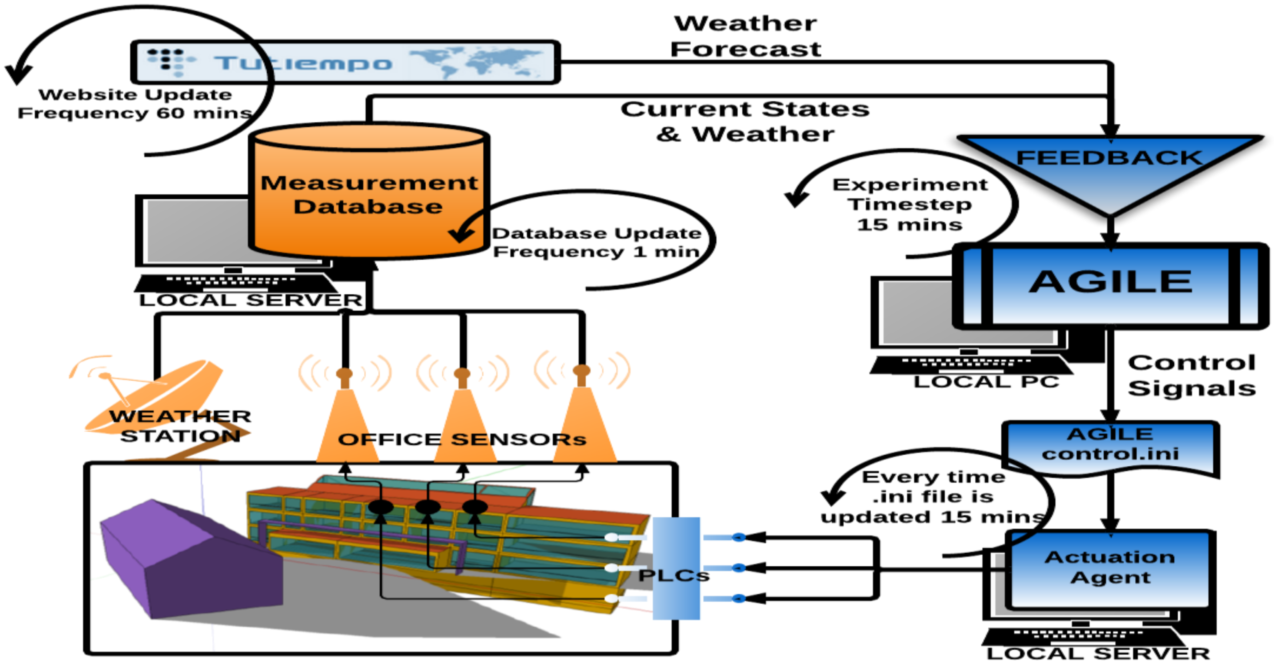




- *Model-based:* it uses a Building Energy model to predict the future effect of the control action

- *Fully-Adaptive:* it learns on-line the optimal control policy (it can be very robust to modelling errors)

Interfacing PCAO to Test Cases: "Plug-n-Play" nature



- Straightforward, plug-n-play interconnection (input/output data from the building)

Part II: Real-life Experimental Results

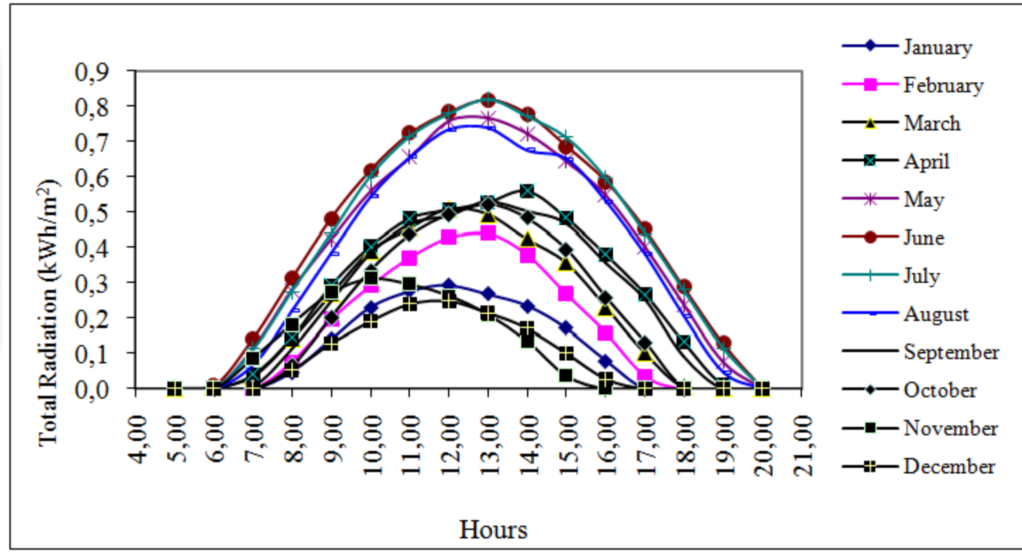
Considerations for Buildings

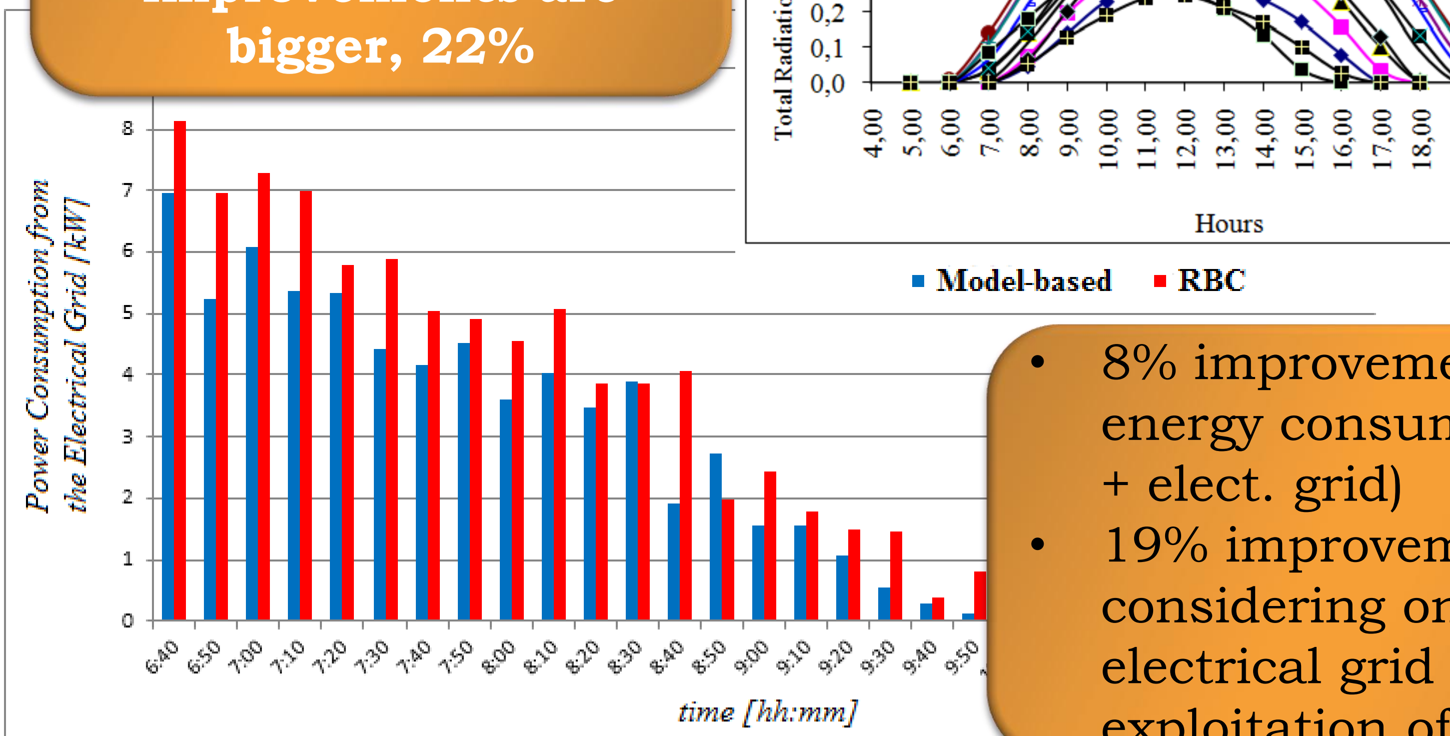
- Test Case 1 (Poorly Insulated Building)

- Both *Model-based* and *Fully-Adaptive* have been tested
  - vs. Rule Based Control (RBC)
- The RBC 25°C was used
  - emphasis on energy consumption reduction

Model-based PCAO with demand shaping

Outdoor temperature was 0.5 °C hotter during the PCAO experiment → the real improvements are bigger, 22%





- 8% improvement in total energy consumption (PV + elect. grid)
- 19% improvement considering only the electrical grid → Good exploitation of PV

Set of experiments in summer 2012-2013 (8 weekends of experiments)

- 9 experiments selected for evaluation (based on similar comfort conditions)

Table 1: 2012 Experiments (RBC vs AGILE)

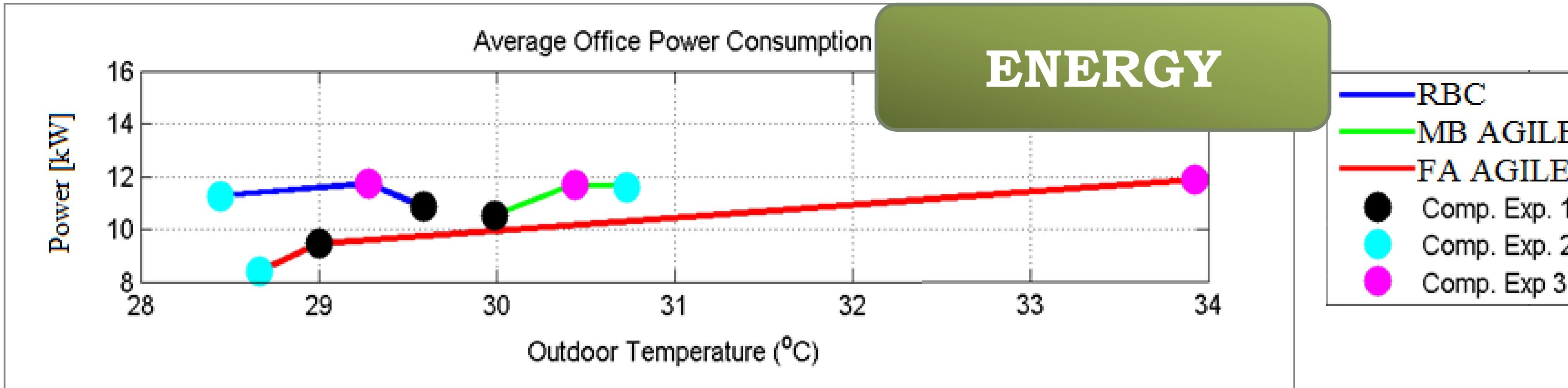
Weekend	Saturday	Sunday
1	July 28 (RBC)	July 29 (AGILE)
2	August 11 (RBC)	August 12 (AGILE)
3	August 18 (AGILE)	August 19 (RBC)
4	August 25 (AGILE)	-

Table 2: 2013 Experiments (RBC vs AGILE)

Weekend	Saturday	Sunday
5	June 29 (RBC)	June 30 (AGILE)
6	July 6 (RBC)	July 7 (RBC)
7	July 13 (AGILE)	July 14 (AGILE)
8	July 20 (AGILE)	-

- 3 groups of 3 experiments each (1 RBC, 1MB, 1 FA)

Model-based and Fully-adaptive AGILE with no demand shaping

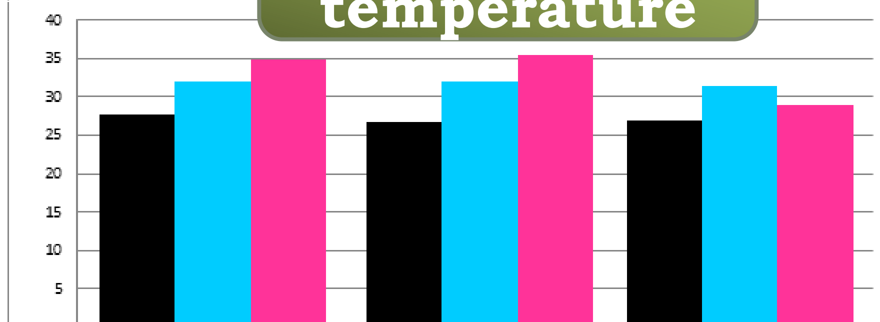


COMFORT

Temperature reduction

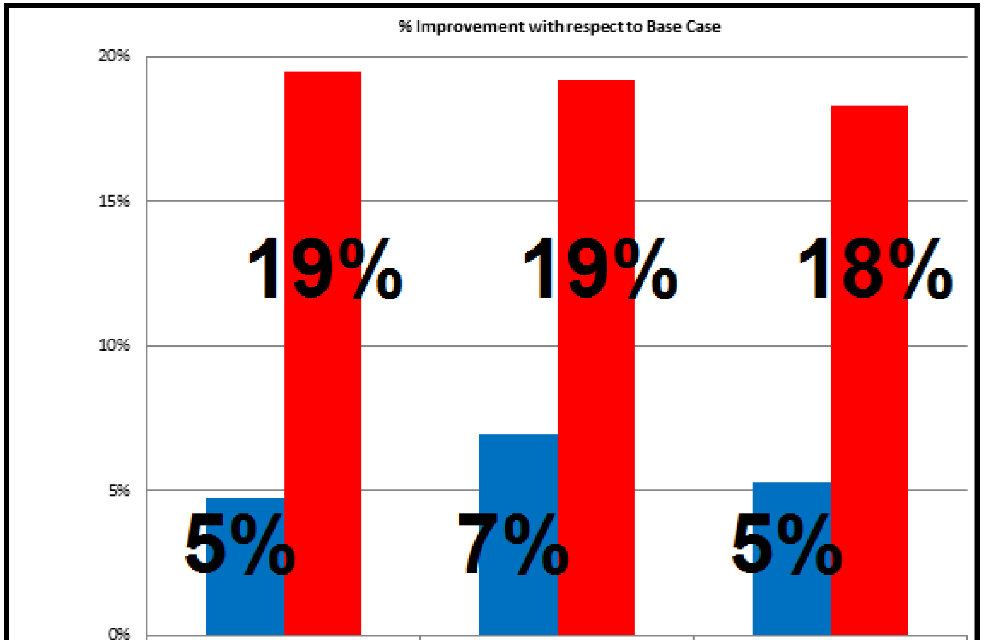
	Base Case	Model based	Fully Adaptive
1	0.525	0.54	1.81
2	3.046666667	3.063333333	3.05
3	2.06	2.05	2.14

Initial temperature



	Base Case	Model based	Fully Adaptive
1	27.7	26.645	27
2	31.97333333	31.97	31.36666667
3	34.92333333	35.5	28.93333333

The Validation Case: Summary of Results



	1	2	3
Model-based	5%	7%	5%
Fully Adaptive	19%	19%	18%

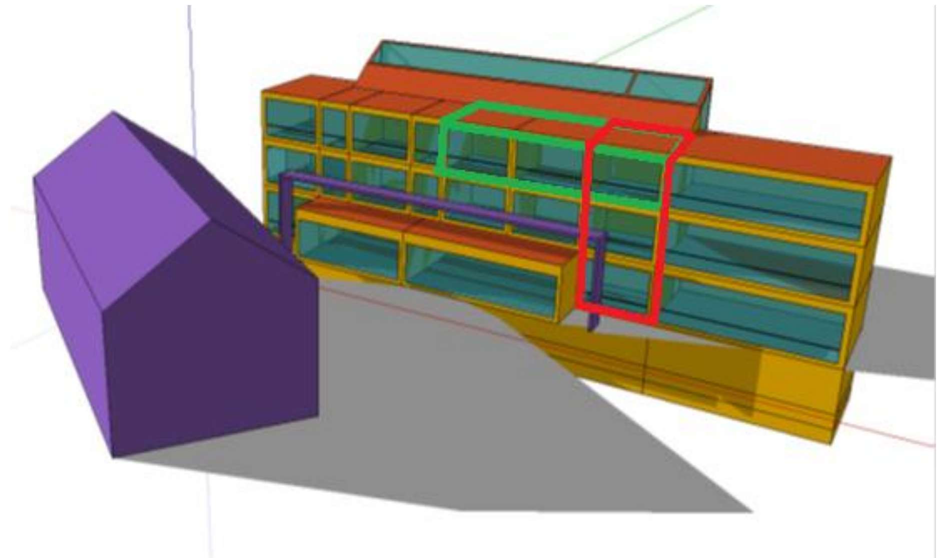
- Poorly Designed Building
- Model-based ~5% (similar comfort conditions with Base Case)
- Fully Adaptive >20% (similar or better comfort conditions than Base Case)

Considerations for Buildings

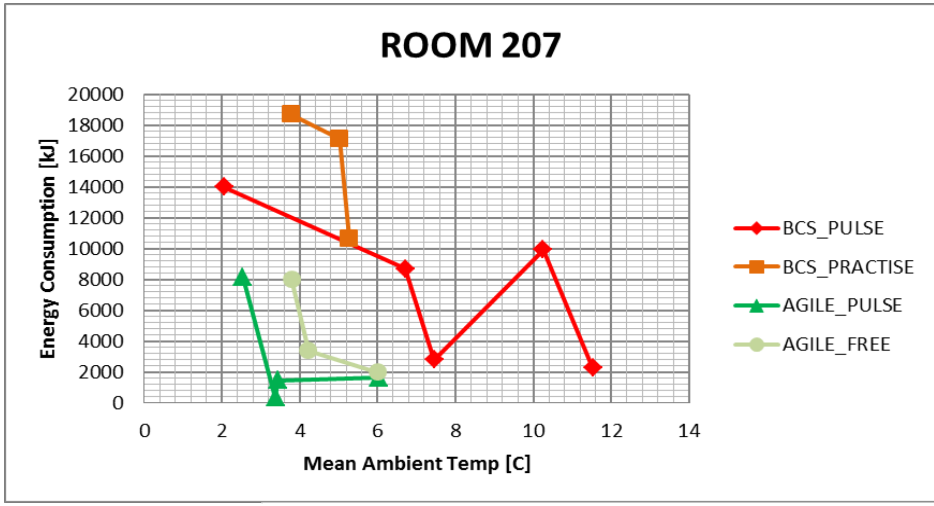
- Test Case 2 (Very Well Designed Building)

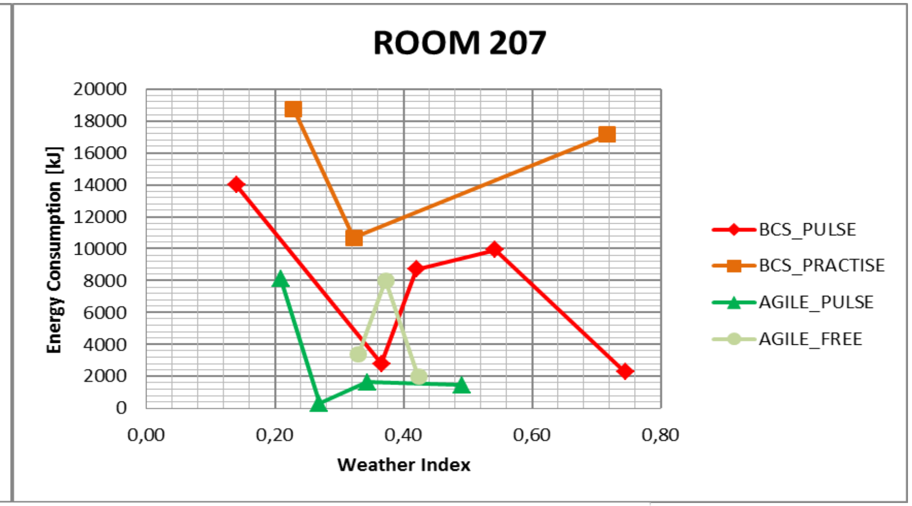
Test Case 2: Real System

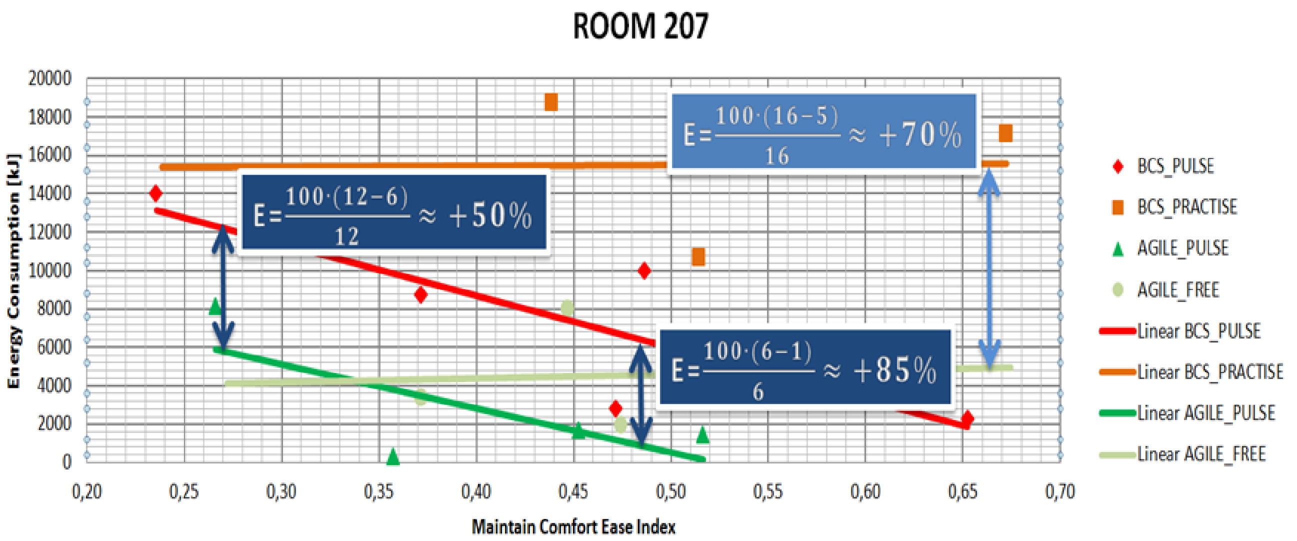
- Due to building management policy reasons and restrictions only three thermally similar zones were available for AGILE tests
- Available zones (green highlighted area) for the AGILE real life implementation were zones 205, 206, 207 all three located on the second floor.
- Tests took place during December 2013.



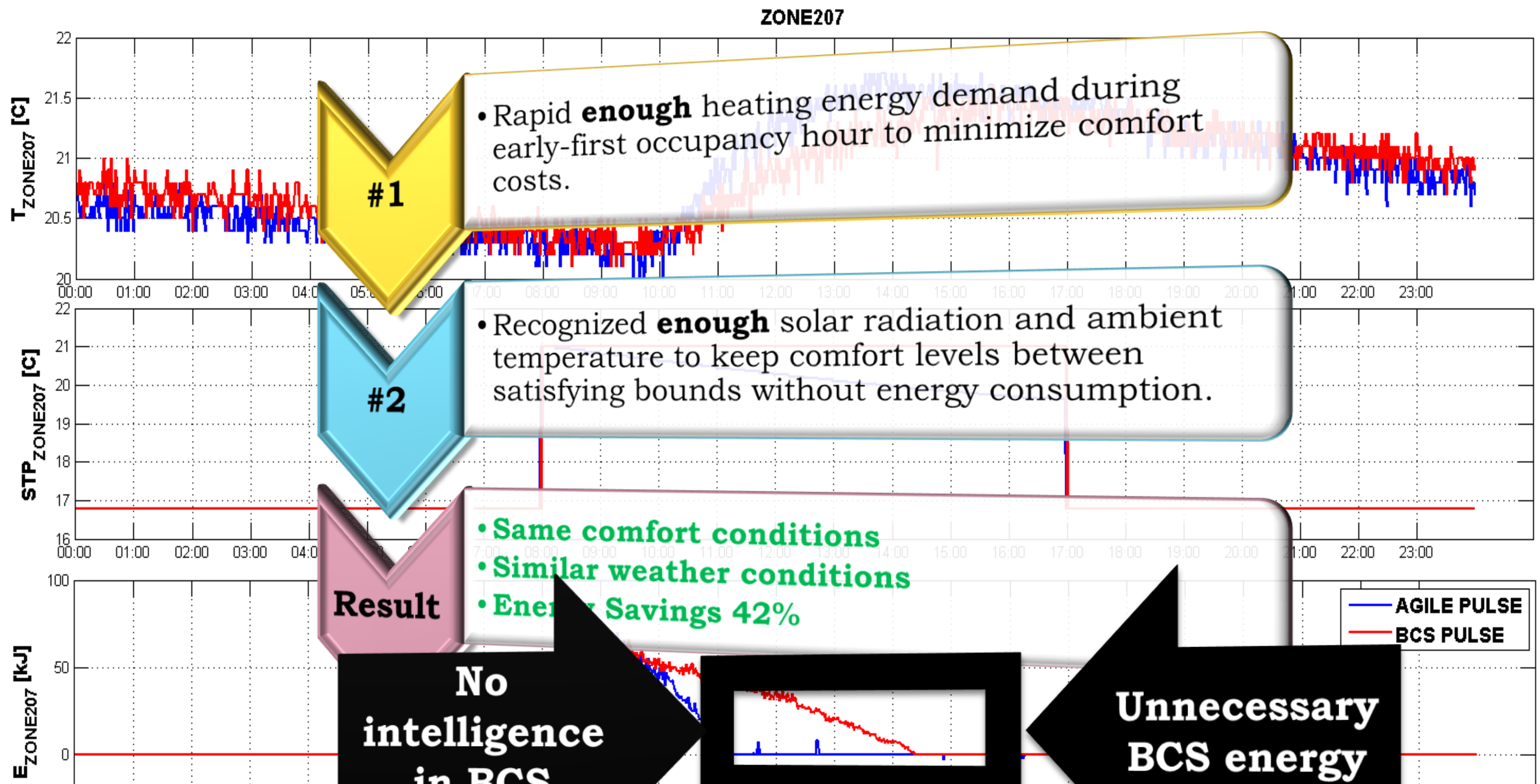
Test Case 2: Office 207 (model available)







Test Case 2: Sample Results



Experiment	Avg Zone T 8.00 - 17.00 [C]	Temp at 8.00	Day Total Energy [kJ]
AGILE_PULSE	21,06	20,30	8119,26
BCS_PULSE	20,90	20,40	13994,00

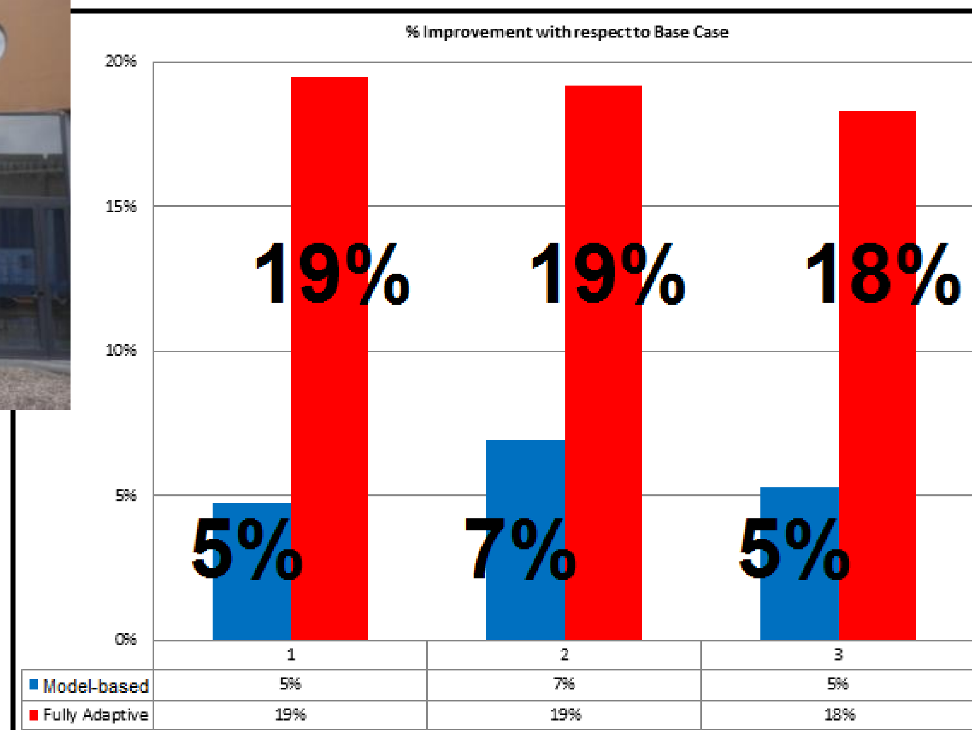
Test Case 2: Summary

- **Significant improvements**(see results evaluation presentation).
- **PCAO close-to-optimal control schedule cannot be easily described with cooperating rules** (when *exactly* to activate, for how long *exactly* to activate the heating devices, in order to save energy depend on highly nonlinear relationships between weather and system state conditions).
- Even **high complex RBCs** (more intelligent rules) **cannot catch close-to-optimal behavior**.
- Such **RBCs design might demand years of tests** and observations in the field for fine tuning.
- **PCAO requires few iterations** to end up with close-to-optimal fine tuned control.

Summary

Test Cases: Real-Life Experiments

Validation Case (Poorly-Designed Building)

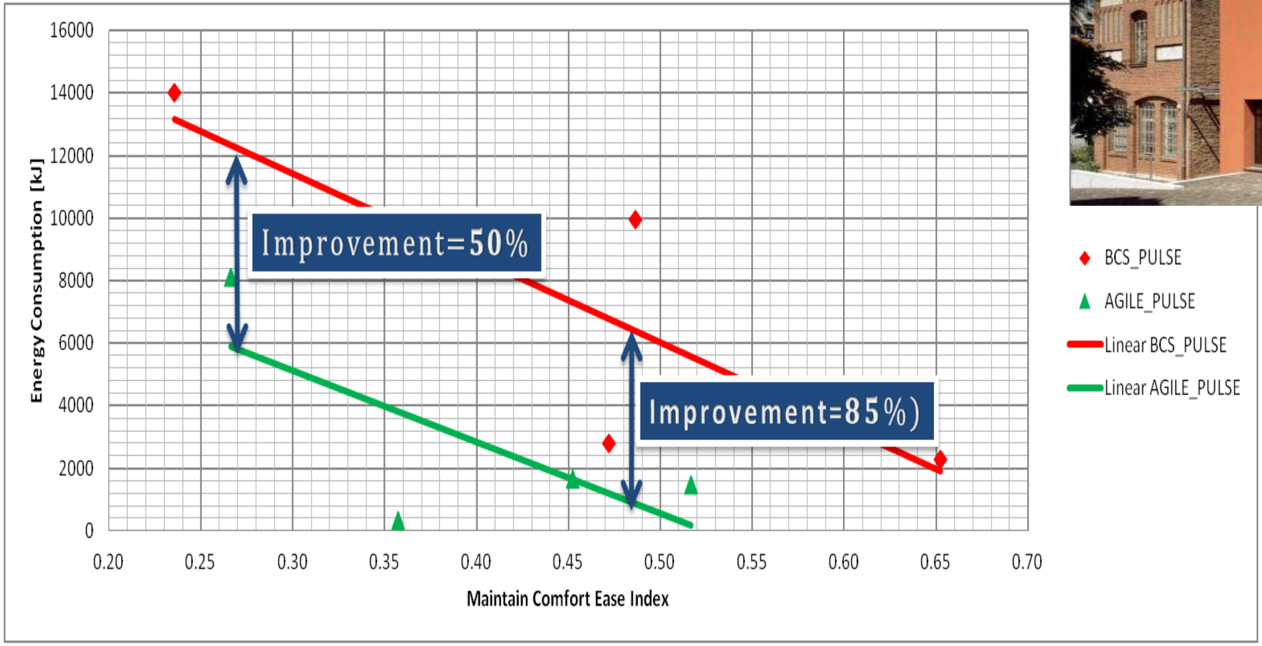


The Fully-Adaptive PCAO provided better comfort conditions than both Model-based PCAO (due to modelling errors)

Test Cases: Real-Life Experiments

Test Case 2 (Well-designed Building, very good model)

In the presence of a good model, the model based PCAO overcomes any possible Rule-based Control



Thank you for your attention
Question time