Advanced Control Strategies For The Modulation of Solar Radiation In Buildings: MPC-enhanced Rule-based Control

Speaker:

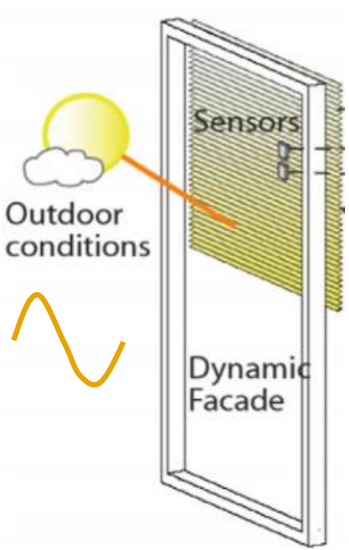
Fabio Favoino
Marco Savino Piscitelli

Politecnico di Torino, Dipartimento Energia,
TEBE research group

Authors:

Marco Savino Piscitelli, Politecnico di Torino
Silvio Brandi, Politecnico di Torino
Giovanni Gennaro, Politecnico di Torino
Alfonso Capozzoli, Politecnico di Torino
Fabio Favoino, Politecnico di Torino
Valentina Serra, Politecnico di Torino

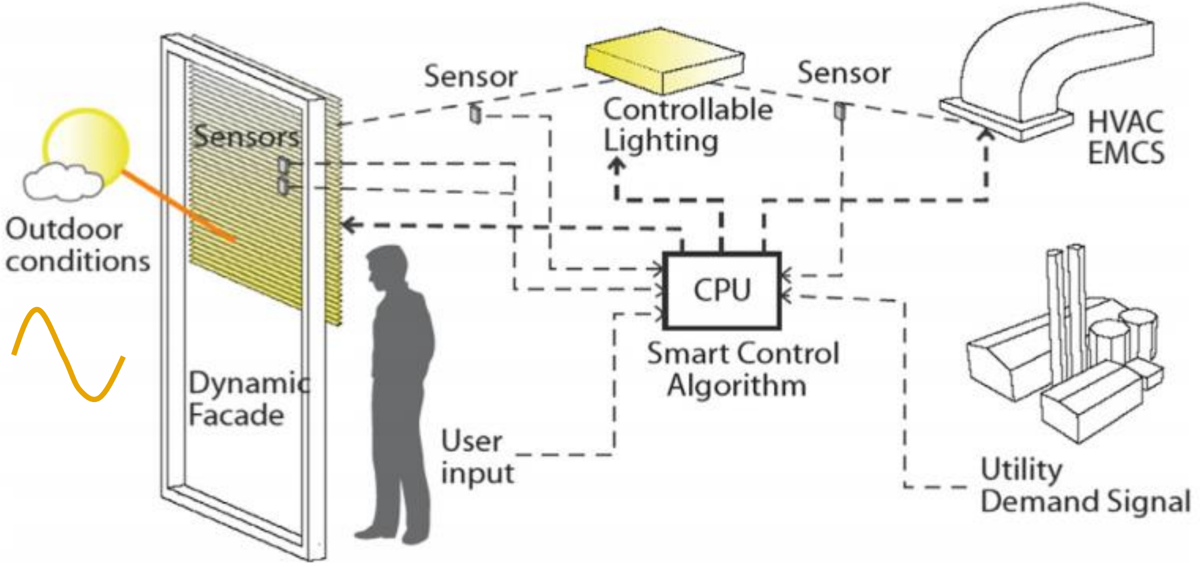
Control of solar radiation w/ adaptive facades



Building Envelopes which are capable to **adapt** their physical properties (i.e. thermal, optical, structural, etc.) in a **reversible** way as a **response** to and/or to adjust to **transient boundary conditions** (either external, such as climate, or internal, such as occupants' requirements), in order to respond to **changing priorities** (i.e. minimizing the building energy use, maximizing the use of natural light, maximising privacy, etc.)

[Maria Konstantoglou, Aris Tsangrassoulis, Dynamic operation of daylighting and shading systems: A literature review, Renewable and Sustainable Energy Reviews, Volume 60, July 2016, Pages 268-283, ISSN 1364-0321, http://dx.doi.org/10.1016/j.rser.2015.12.246]

Control of solar radiation w/ adaptive facades



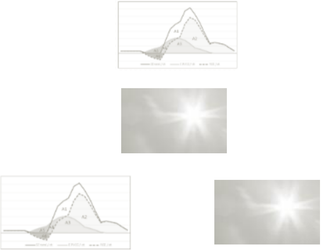
[Maria Konstantoglou, Aris Tsangrassoulis, Dynamic operation of daylighting and shading systems: A literature review, Renewable and Sustainable Energy Reviews, Volume 60, July 2016, Pages 268-283, ISSN 1364-0321, http://dx.doi.org/10.1016/j.rser.2015.12.246]

Building Envelopes which are capable to **adapt** their physical properties (i.e. thermal, optical, structural, etc.) in a **reversible** way as a **response** to and/or to adjust to **transient boundary conditions** (either external, such as climate, or internal, such as occupants' requirements), in order to respond to **changing priorities** (i.e. minimizing the building energy use, maximizing the use of natural light, maximising privacy, etc.)

Control vs performance

Actuator(s) → **Sensor(s)** → **Control algorithm(s)**

possible glazing states



Static Glazing

Min Energy

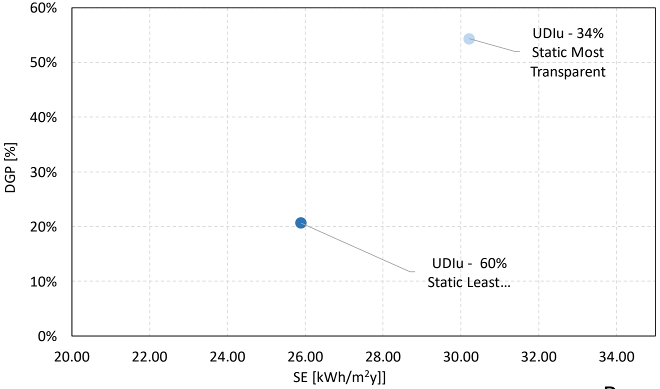
Min Glare

Min Energy & Glare

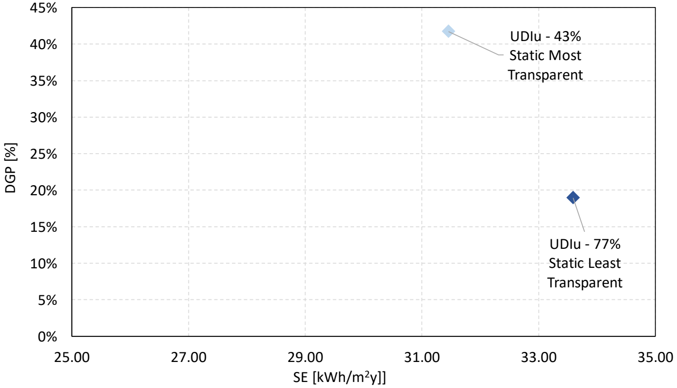
Favoino F., Francesco Fiorito F., Cannavale A., Ranzi G., Overend M. Optimal control and performance of photovoltachromic switchable glazing for building integration in temperate climates.Applied Energy, Volume 178, 15 Sept 2016, Pages 943–961

Min Glare ↓

London



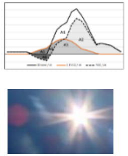
Rome

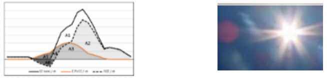


← **Min Energy**

Control vs performance

Actuator(s) possible glazing states → **Sensor(s)** → **Control algorithm(s)**



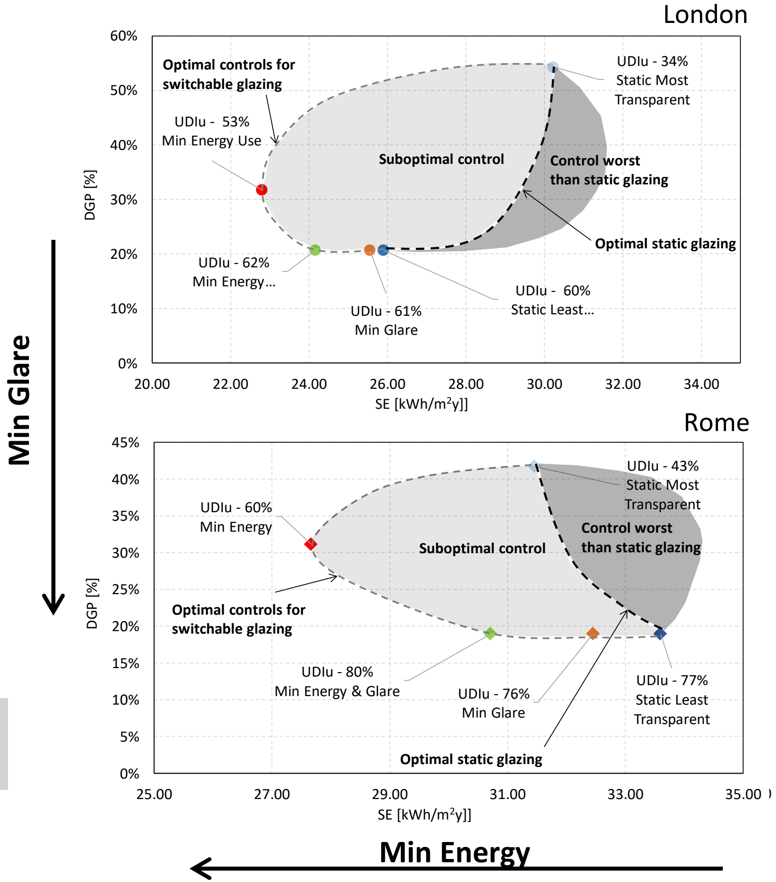


Static Glazing

Min Energy

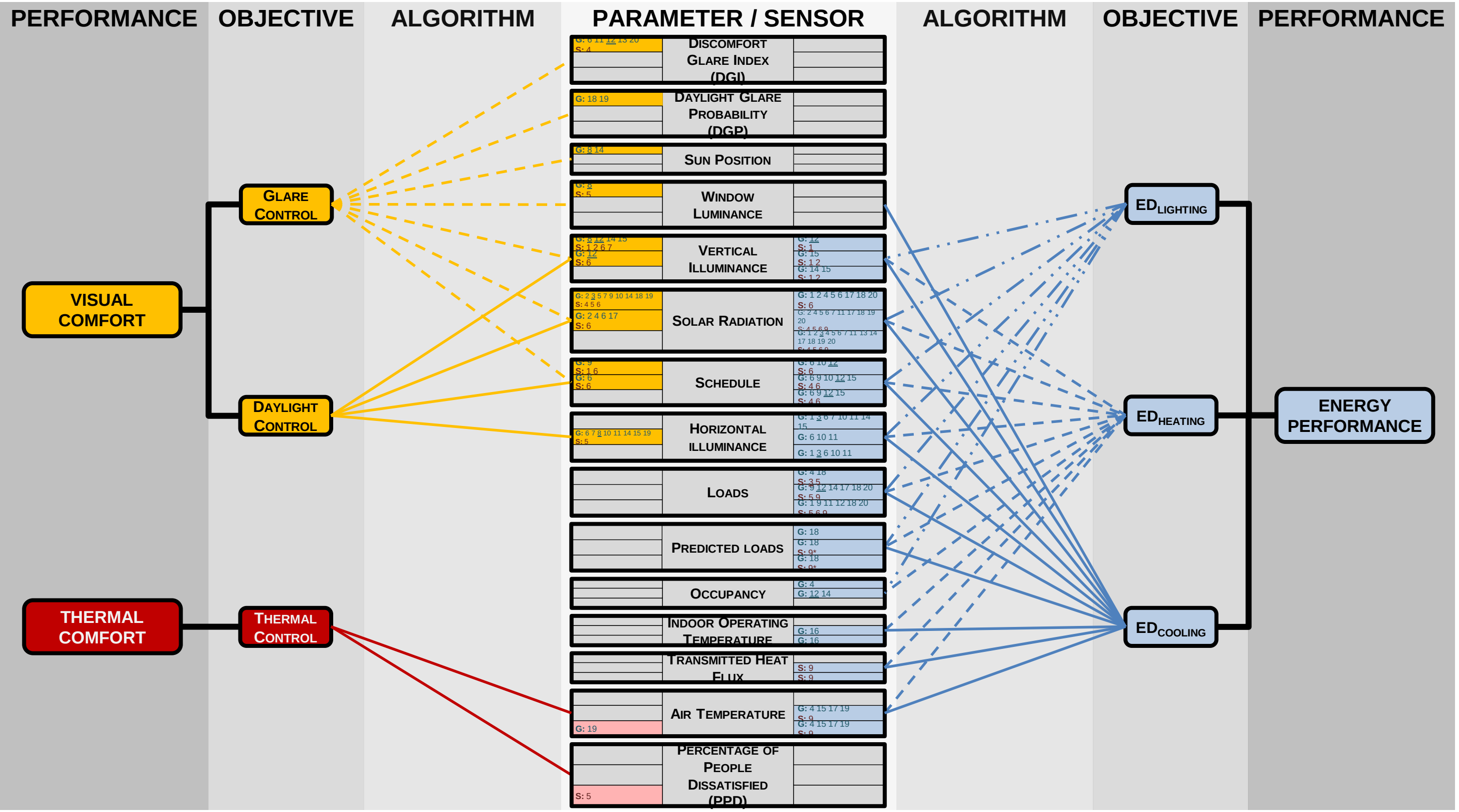
Min Glare

Min Energy & Glare

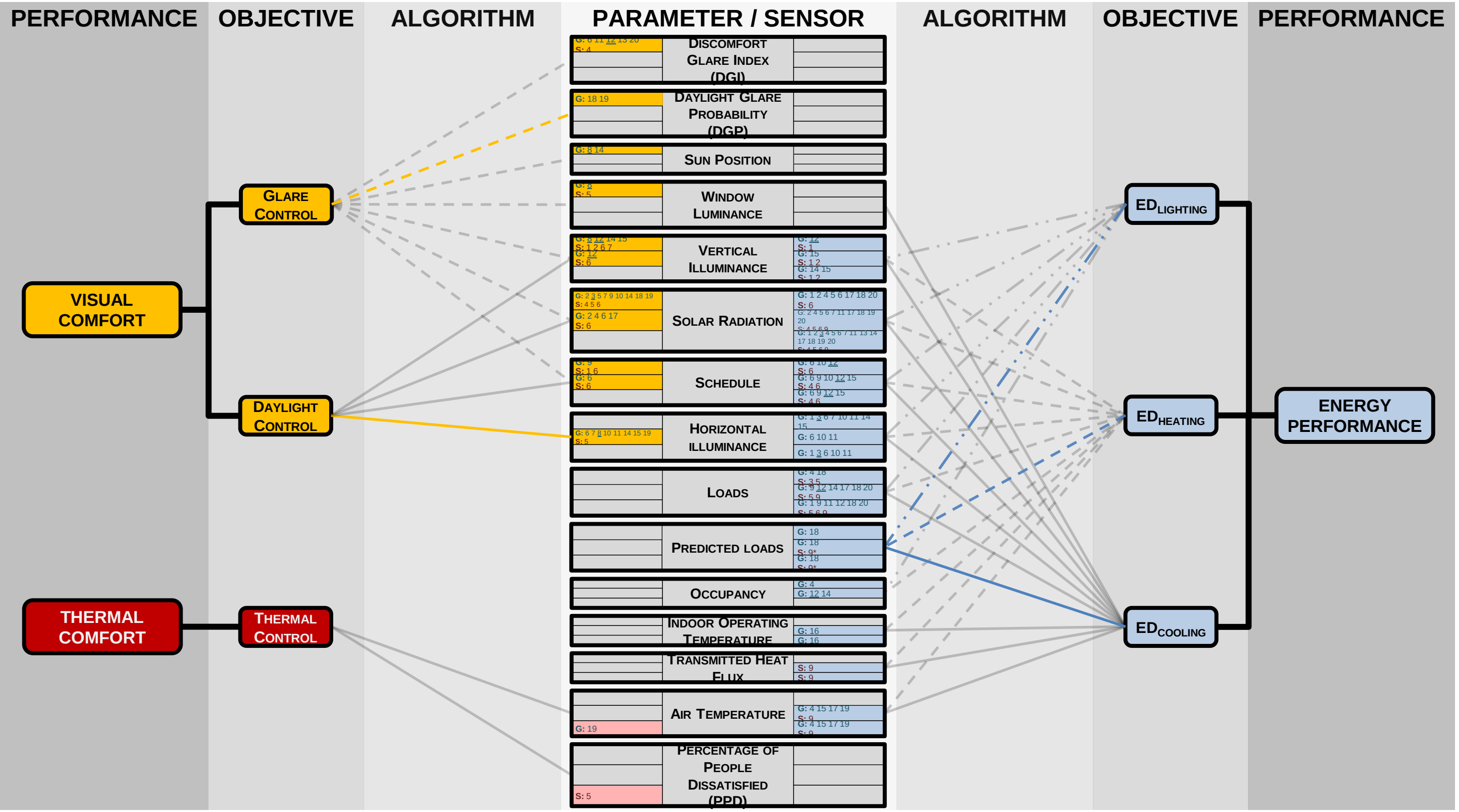


Favoino F., Francesco Fiorito F., Cannavale A., Ranzi G., Overend M. Optimal control and performance of photovoltachromic switchable glazing for building integration in temperate climates.Applied Energy, Volume 178, 15 Sept 2016, Pages 943–961

Control of solar radiation w/ adaptive facades



Control of solar radiation w/ adaptive facades



Requirements for active control of solar radiation by means of MPC:

- Calibrated building models;
- Weather prediction;
- Endogenous loads predictions;
- Large number of sensors;
- Computational power;
- Higher costs than RBC;
- More difficult to ensure performance;

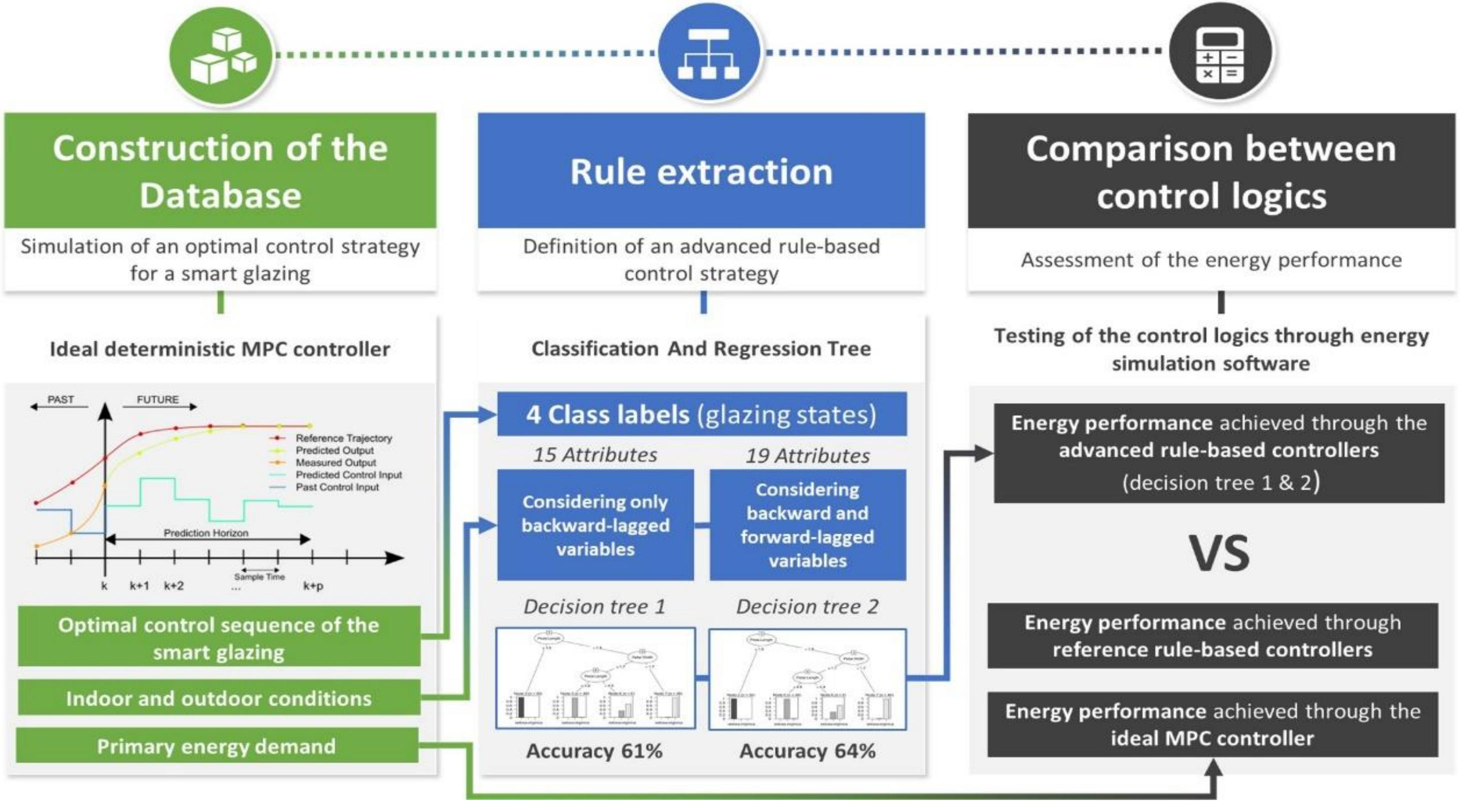
Objectives of the study

1 **reduce the complexity** of smart glazing MPC controls by extracting simpler IF-THEN rules that can be adopted in operation to mimic optimal control, with a relatively low decrease of operational performance.

2 **reduce the need for a calibrated building model** and on-line optimisation during building operations

3 **reduce the number of variables** needed for implementing optimal control strategies

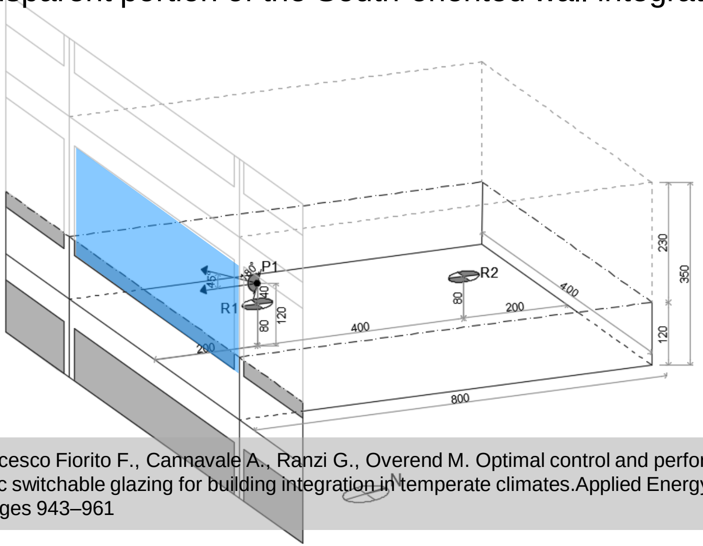
Methodological framework of the analysis

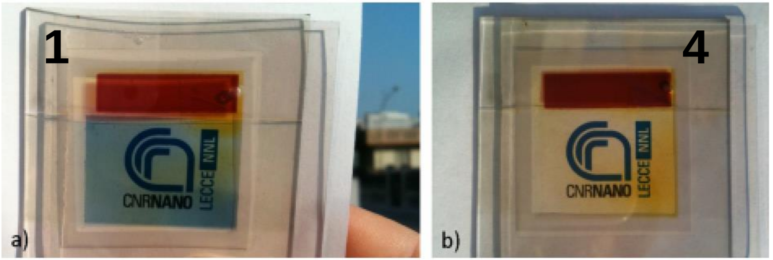


Case study

The virtual test case building is a reference **enclosed office room** (4 m wide x 8 m deep x 3.5 m high) in a heating dominated climate (i.e. **London**), with a Window-to-Wall-Ratio of 60% on the South-oriented façade.

- The opaque portion of the façade is a **typical curtain wall construction**, and concrete slab for the horizontal partitions;
- The transparent portion of the South-oriented wall integrates a PVC **smart glazing**





State	τ_{VIS} [-]	g-value [-]
4	0.595	0.508
3	0.446	0.396
2	0.341	0.325
1	0.238	0.238

Favoino F., Francesco Fiorito F., Cannavale A., Ranzi G., Overend M. Optimal control and performance of photovoltachromic switchable glazing for building integration in temperate climates.Applied Energy, Volume 178, 15 Sept 2016, Pages 943–961

Case study: Reference control strategies

1

RBC – Passive: this is based on the amount of incident solar radiation on the façade

2

RBC – Opt Hourly: the smart glazing adopts a state, at 1-hour intervals, which minimizes the total building loads (sum of heating, cooling and lighting loads).

3

MPC: the smart glazing is actively controlled at 1-hour intervals, such that its control sequence minimizes the total site energy use of the building over a certain time horizon.

State selection RBC

State 4	State 3	State 2	State 1
0-100 [W/m^2]	100-250 [W/m^2]	250-700 W/m2	>= 700 W/m2

Optimization problem RBC. opt

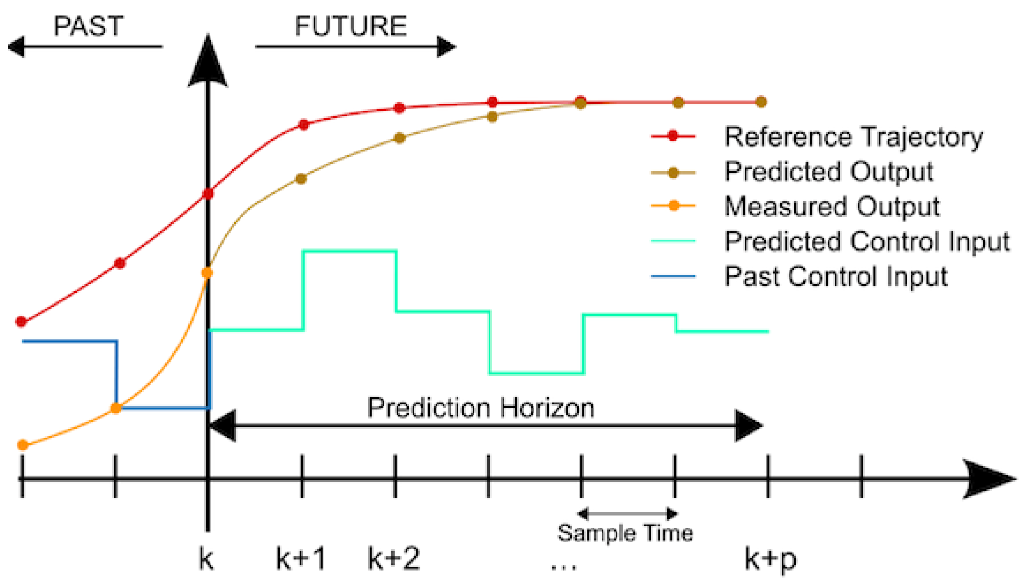
$$min \begin{cases} f(X) = \dot{Q} = \dot{Q}_{heat} + \dot{Q}_{cool} + \dot{Q}_{ligh} \left[\frac{kW}{m^2 y}\right] \\ X(t) = (g - value\ (t)\,[-], \tau_{vis}\ (t)\,[-]) \end{cases}$$

Optimization problem MPC

$$min \begin{cases} f(X) = SE = SE_h + SE_c + SE_l \left[\frac{kWh}{m^2 y}\right] \\ X(t) = (g - value\ (t)\,[-], \tau_{vis}\ (t)\,[-]) \end{cases}$$

Construction of the database

The first stage is aimed at simulating an optimal control strategy obtained by means of an **ideal model predictive control (MPC)**



The simulated predictive controller minimises the total energy use of the room over the prediction horizon (i.e., cooling, heating, lighting), selecting **hour by hour the optimal discrete state of the smart glazing.**

one-year dataset of optimal hourly control signal with other influencing variables

Favoino F., Francesco Fiorito F., Cannavale A., Ranzi G., Overend M. Optimal control and performance of photovoltachromic switchable glazing for building integration in temperate climates.Applied Energy, Volume 178, 15 Sept 2016, Pages 943–961

Rule extraction from MPC simulated data

The second stage of the analysis is aimed at **extracting from the MPC control logic, a set of decision rules** capable to:

(i) **reduce the complexity** and the computational cost in implementing the glazing controller,

(ii) achieve an energy **performance close to the** reference **optimal solution**,

(i) **increase** the control logic **interpretability**.

To this purpose a decision tree algorithm (i.e., CART) has been employed.

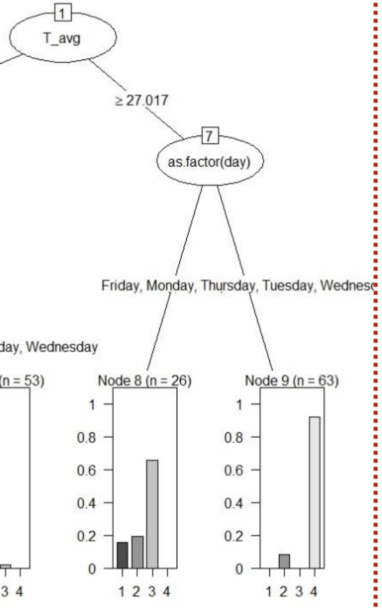
Classification And Regression Tree (CART)

The objective of a classification model consists in learning a function or a set of rules, which allows to **predict** for a new unlabeled statistical object its **class membership**.

Model development

1. Starting from the **root node**, at each node of the tree model, the data are successively splitted.
2. At each split the model identify which variable, and threshold value, better discriminate data according to impurity measures.
3. The splitting process ends when **stopping criteria are satisfied** (e.g., max depth)

Classification Tree



Classification And Regression Tree (CART)

In this study, **two different trees have been trained and tested** assuming different pools of input variables.

The first tree is fed **only** using **backward-lagged variables**	The second tree is fed **also** using **forward-lagged variables**

The optimal size was assessed through a cost-complexity process, searching for a **trade-off between the misclassification error** of the predicted discrete states of the glazing and the number of decision rules extracted.

Accuracy

$$A_{dt} = \frac{n^\circ_{correct}}{n^\circ_{tot}}$$

Complexity parameter

$$R(t) = r(t)p(t)$$

$$R(T_t) = \sum R(i) \; for\ i = leaves\ in\ the\ subtree\ rooted\ at\ t$$

$$\alpha = \frac{R(t) - R(T_t)}{N_T - 1}$$

Sets of input variables for decision tree 1 & 2

D.tree	Variable	Description	Backward lag [hrs]	Forward lag [hrs]
1	$T_{int,h}$	Hourly Indoor zone temperature [°C]	-1	-
	$T_{est,h}$	Hourly outdoor temperature [°C]	-21, -37, -42	-
	SR_h	Hourly solar radiation [W/m^2]	-1, -8, -13, -23, - 24, -33, -36, -37, -42	-
	$T_{est,day}$	Daily average outdoor temperature [°C]	-	-
	hour	Hour of the day	-	-
2	$T_{int,h}$	Hourly Indoor zone temperature [°C]	-1	-
	$T_{est,h}$	Hourly outdoor temperature [°C]	-3, -42	+3
	SR_h	Hourly solar radiation [W/m^2]	-1, -10, -12, -13, -17, -24, -37, -41	0, +1, +2, +3, +4
	$T_{est,day}$	Daily average outdoor temperature [°C]	-	-
	hour	Hour of the day	-	-

Fabio Favoino & Marco Savino Piscitelli, Politecnico di Torino, Dipartimento Energia, TEBE research group

Rule extraction and testing of the control strategies

Open loop test

In the open loop test the classification accuracy A_{dt} of the decision trees, has been employed as performance measure suitable for evaluating their capability in **reproducing the MPC control sequence**

$$A_{dt} = \frac{n°_{correct}}{n°_{tot}}$$

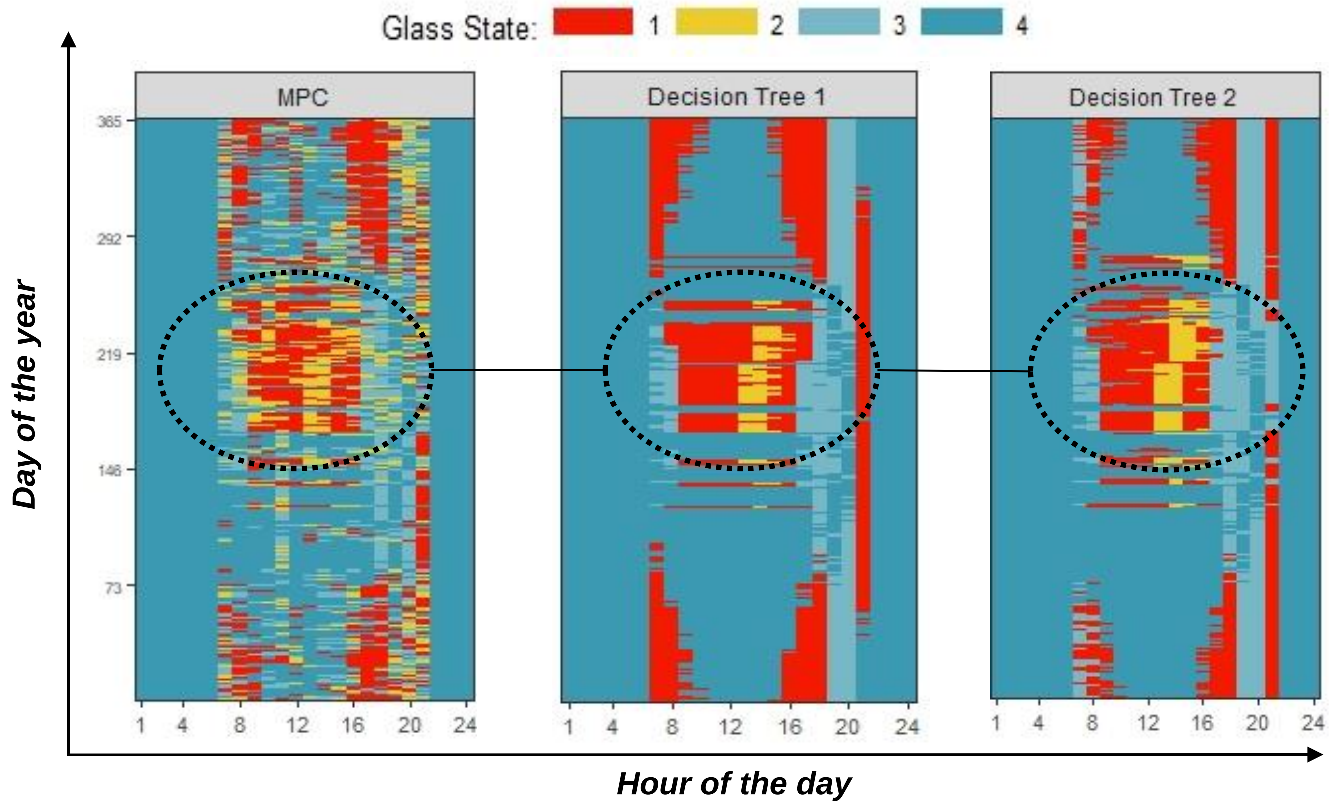
Closed loop test

The rule-based controllers are tested embedding them in the building energy model.

This case represents the closest approximation of the controller performance on a real automation system.

EnergyPlus

Results achieved in the open loop test



DT	Accuracy	n° rules	state change
1	**61%**	21	2039
2	**64%**	28	2293

-30% state changes

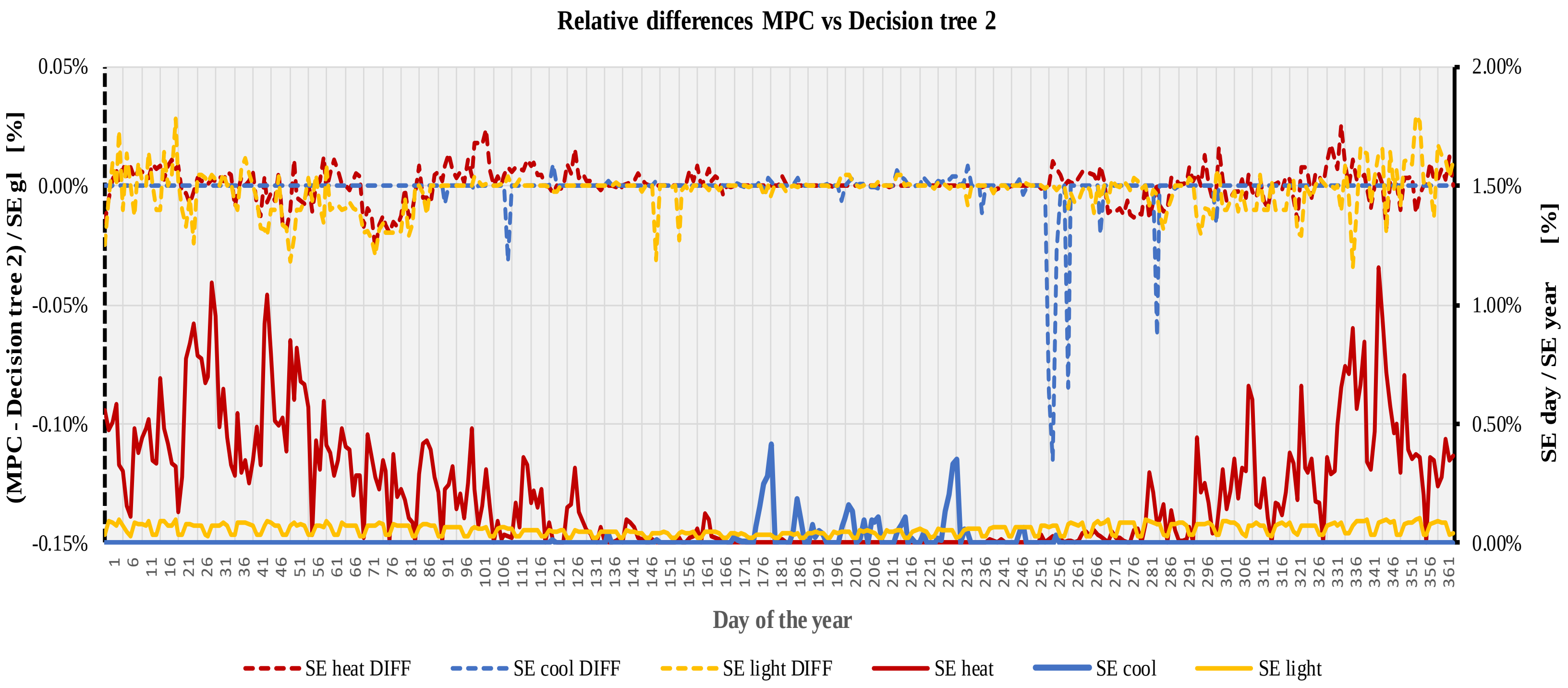
MPC state change
3153

The MPC puts too much effort in switching the glazing even though the impact of the control action is not so relevant.

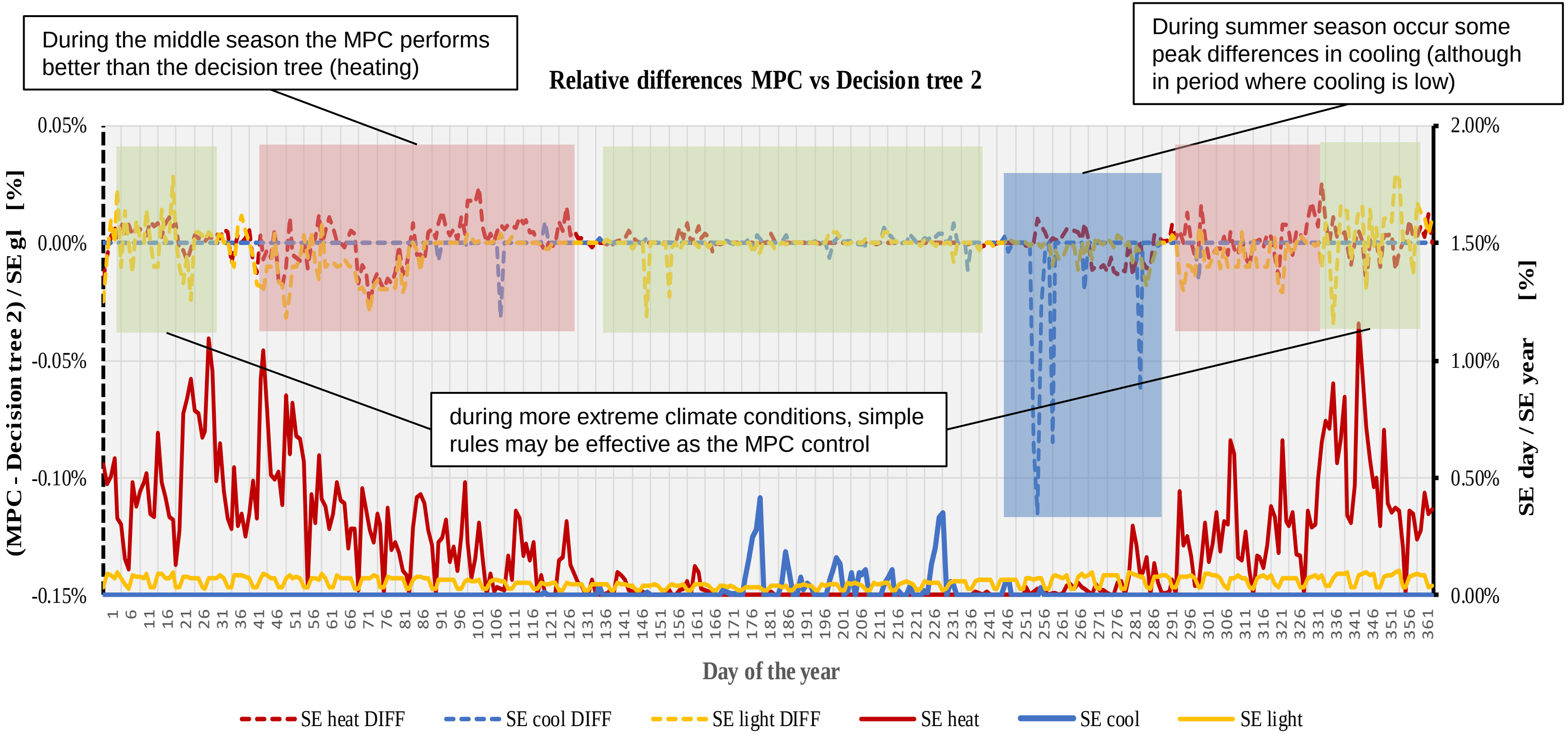
Results achieved in the closed loop test

Control type	Site Energy Uses *[kWh/m²y]*				Performance Reduction vs MPC				
	SE heat	SE cool	SE light	SE gl	N° state change [-]	SE heat [%]	SE cool [%]	SE light [%]	SE gl [%]
RBC - Passive	20.66	1.47	7.59	29.73	1428	-	-	-	-
H opt	19.17	1.22	8.14	28.52	743	-	-	-	-
MPC	18.96	1.09	5.29	25.33	3153	-	-	-	-
Decision tree 1	18.16	1.41	7.41	26.98	2039	4.19%	-29.70%	-40.12%	**-6.51%**
Decision tree 2	18.90	1.19	5.48	25.57	2293	0.30%	-9.33%	-3.71%	**-0.95%**

Results achieved in the closed loop test



Results achieved in the closed loop test



Conclusions

(i) Despite of only 61 - 64% model accuracy (open loop test), the CART was able to extract rules with a 5 - 1% performance difference with MPC (closed loop test);

(i) The rule extracted involve 5 input parameters based on the measurements of 3 sensors (i.e., T_{ext}, T_{int}, SR);

(ii) The number of state changes was reduced by 30% compared to MPC;

(iii) future works will be aimed at simulating the MPC and RBC controllers in a more realistic way (i.e., without perfect prediction of the disturbances);

(iv) generalizability (to other case studies) and scalability (from single window to an entire façade) of advanced RBC controllers will be subjects of further investigations

Fabio Favoino & Marco Savino Piscitelli, Politecnico di Torino, Dipartimento Energia, TEBE research group

BS 2019 2-4 SEPT ROME — 16th IBPSA INTERNATIONAL CONFERENCE AND EXHIBITION

INTERNATIONAL BUILDING PERFORMANCE SIMULATION ASSOCIATION

Advanced Control Strategies For The Modulation of Solar Radiation In Buildings: MPC-enhanced Rule-based Control

Questions and Comments

Speaker:

Fabio Favoino
Marco Savino Piscitelli

Politecnico di Torino, Dipartimento Energia,
TEBE research group

Contacts:

fabio.favoino@polito.it
marco.piscitelli@polito.it