Comfort control in buildings using solar energy

UNED – Departamento de Informática y Automática
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Área de Ingeniería de Sistemas y Automática

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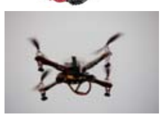
Automatic control, Robotics and Mechatronics

- Modeling and control of solar plants
- Modeling, control and robotics in agriculture
- Energy efficiency and comfort control in buildings
- Modeling and control of photobioreactors
- Education in Engineering
- Autonomous vehicles and robots
- Design of robots
- Vehicle dynamics
- Vibration analysis



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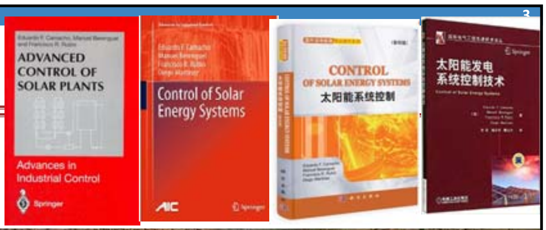
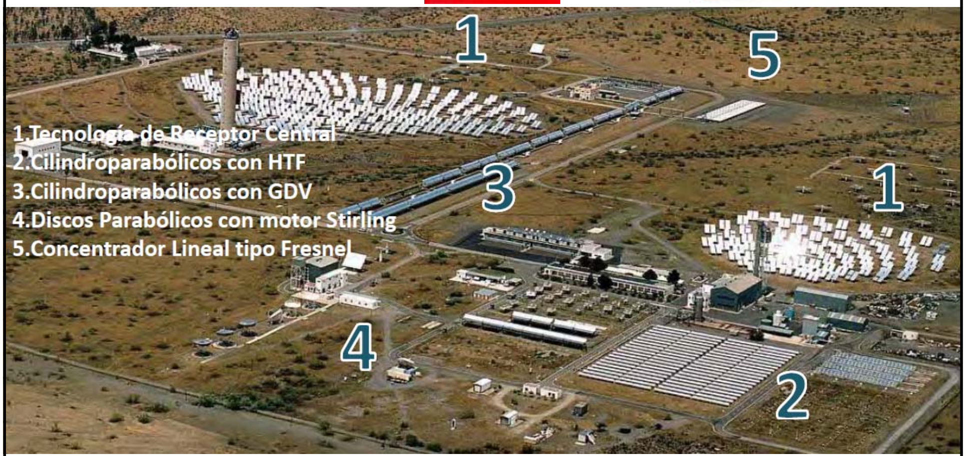
ARM
AUTOMÁTICA, ROBÓTICA Y MECATRÓNICA

- **Modeling & Control of solar energy systems**





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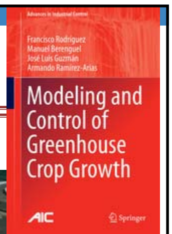
- **Control in agriculture**



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ARM
Solar energy and energy efficiency
Comfort Control in Buildings
Control of distributed collectors
Solar cooling
Comfort & energy control in buildings
Other applications of solar energy
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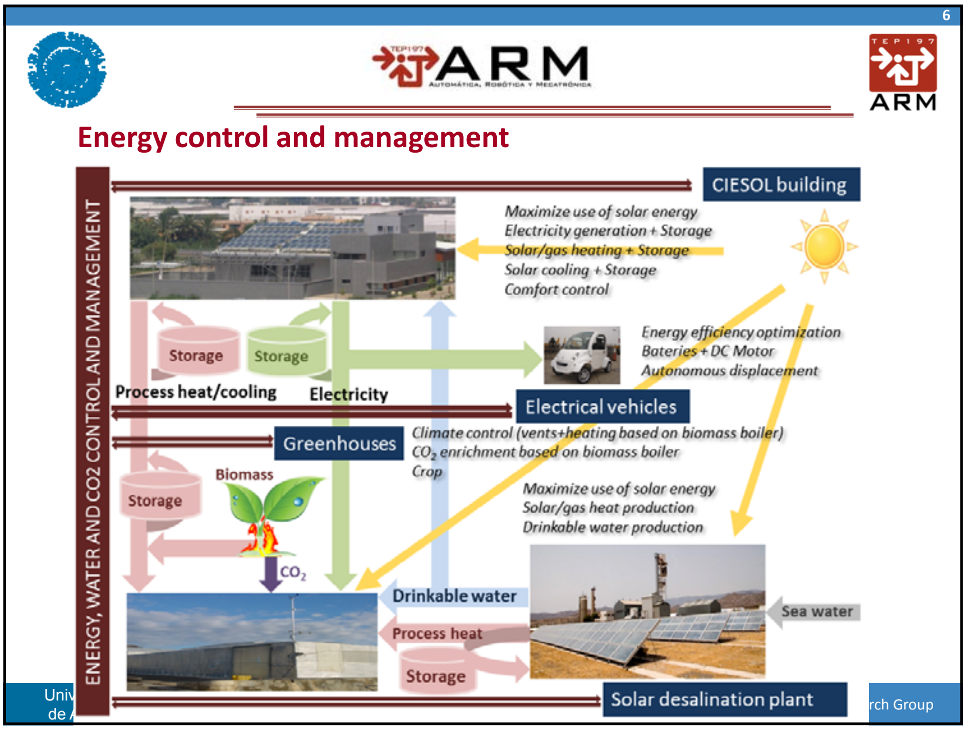
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ARM
Energy control and management
ENERGY, WATER AND CO2 CONTROL AND MANAGEMENT
CIESOL building
Maximize use of solar energy
Electricity generation + Storage
Solar/gas heating + Storage
Solar cooling + Storage
Comfort control
Storage
Storage
Process heat/cooling
Electricity
Energy efficiency optimization
Bateries + DC Motor
Autonomous displacement
Electrical vehicles
Greenhouses
Climate control (vents+heating based on biomass boiler)
CO_2 enrichment based on biomass boiler
Crop
Biomass
Storage
Maximize use of solar energy
Solar/gas heat production
Drinkable water production
CO_2
Drinkable water
Process heat
Storage
Sea water
Solar desalination plant
rch Group

Disturbances forecast

Basic characteristics of solar radiation forecasting

Forecasting horizon:	Short-term	Long-term
Purpose (spatial nature):	Local	Global
Kinds of model:	Physics-based models	Statistical models

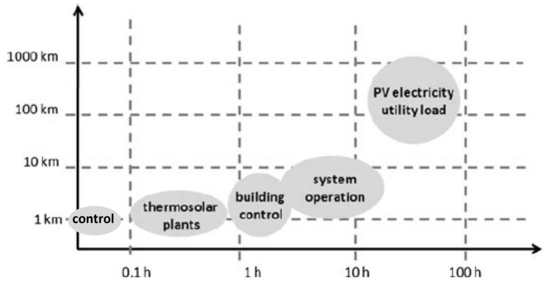

Fig. 2.2 Spatial and temporal scales of target applications, [175]

Ingredients: Solar energy is a disturbance and the main source of energy

Short-term forecast (15 minutes) useful for predictive control

A. Pawlowski, J.L. Guzmán, M. Berenguel, F. Rodríguez, J. Sánchez. Application of time-series methods to disturbance estimation in predictive control problems. **International Symposium on Industrial Electronics ISIE'10**, 409-414, Bari, Italy, **2010**.

A. Discrete Kalman Filter
B. Discrete Kalman Filter with Data Fusion
C. Exponentially Weighted Moving Average
D. Double Exponential Smoothing

$$S_k = \alpha z_k + (1-\alpha)(S_{k-1} + b_{k-1})$$

$$b_k = \gamma(S_k - S_{k-1}) + (1-\gamma)b_{k-1}$$

z_k measurement
S_k unadjusted forecast
b_k estimated trend
α smoothing parameter for data (0,1)
γ smoothing parameter for trend (0,1)

can be obtained via optimization techniques

The one-period-ahead forecast is given by:

$$\hat{x}_{k+1} = S_k + b_k$$

The m–periods-ahead forecast is given by:

$$\hat{x}_{k+m} = S_k + m b_k$$

NIST. (2006) Engineering statistics handbook. [Online]. Available: http://www.itl.nist.gov/div898/handbook/index.htm

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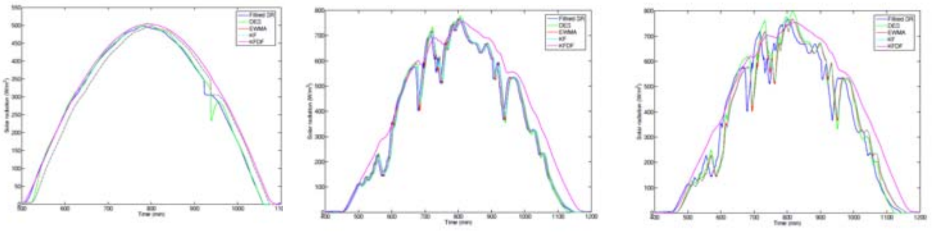
Short-term forecast (15 minutes) useful for predictive control



Results for a clear day with a 15-samples horizon

Results for a day with passing clouds and a 5-samples horizon

Results for a day with passing clouds and a 15-samples horizon

Alternative: "lazy man" weather approach

The same approach can be used for other disturbances (temperature, wind, …)

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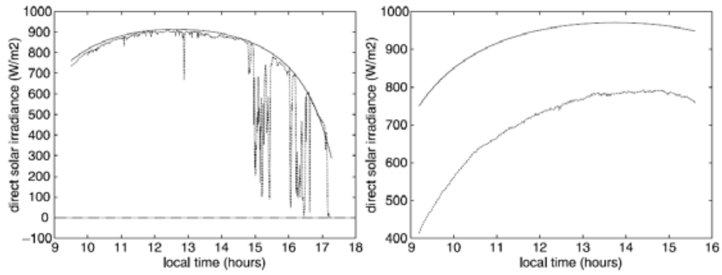
Ingredients: Solar energy is a disturbance and the main source of energy

Clear day prediction

Extraterresterial Radiation on Horizonal Surface: $I_{ho}(h,J) = I_{SC}\epsilon_o \cos\theta_{ZS}$

where $I_{ho}I$ is the instant solar radiation, h is the local time, J is the day number in Julian calendar, I_{SC} is the solar constant, ϵ_o is the distance between sun and earth, and θ_{ZS} is the sun zenithal distance.

Similar models for direct beam irradiance



(a) November 26th, 1990 (b) September 19th, 1991

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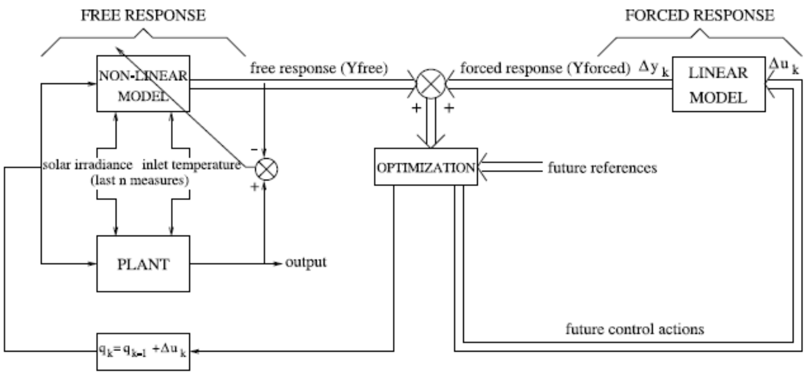
Clear day prediction



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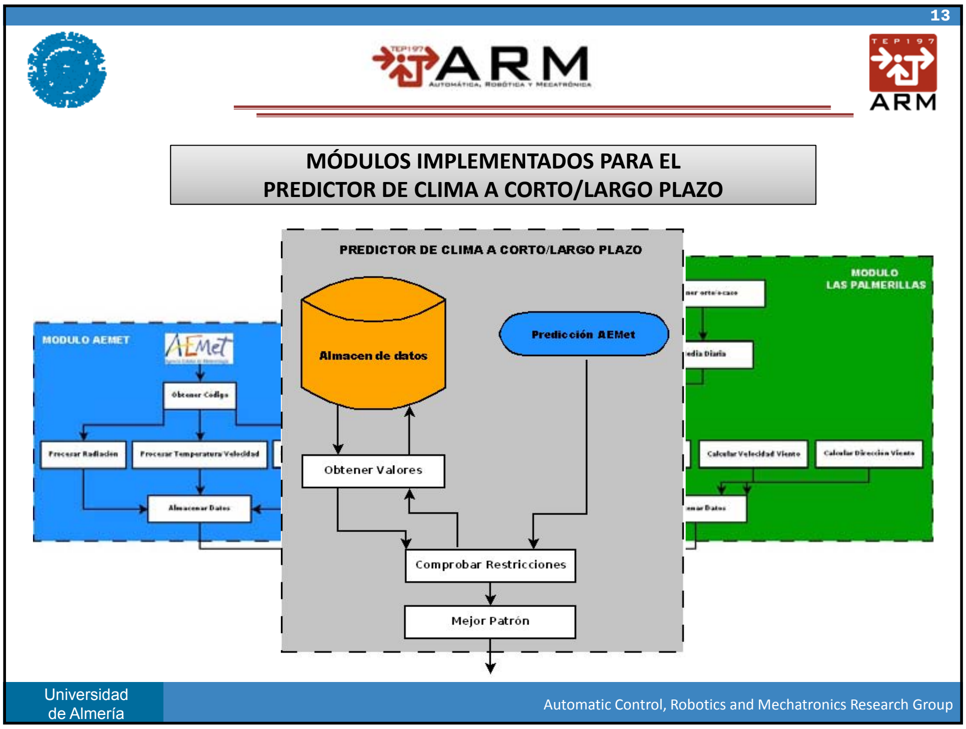
Ingredients: Solar energy is a disturbance and the main source of energy

Long-term prediction

INM MINISTERIO DE MEDIO AMBIENTE

Ejido, El (80 m) - ALMERÍA — Elaborado: 01.09.2004 07:50 (hora local peninsular)

Fecha	Miércoles 01 a.m.	Miércoles 01 p.m.	Jueves 02 a.m.	Jueves 02 p.m.	Viernes 03 a.m.	Viernes 03 p.m.	Sáb 04	Dom 05	Lun 06	Mar 07
Estado del cielo										
Probabilidad de precipitación (%)	0		10		20		25	15	20	15
T. Máxima (ºC)	32		30		29		31	32	31	31
T. Mínima (ºC)	19		19		19		20	21	20	20
Viento (Km/h)	Calma	7	11	11	7	Calma	Calma	11	7	7
Índice UV Máximo	7		8		8					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MÓDULOS IMPLEMENTADOS PARA EL
PREDICTOR DE CLIMA A CORTO/LARGO PLAZO
PREDICTOR DE CLIMA A CORTO/LARGO PLAZO
Almacen de datos
Predicción AEMet
Obtener Valores
Comprobar Restricciones
Mejor Patrón
MODULO AEMET
Obtener Codigo
Procesar Radiacion
Procesar Temperatura/Velocidad
Almacenar Datos
MODULO
LAS PALMERILLAS
Calcular Velocidad Viento
Calcular Dirección Viento
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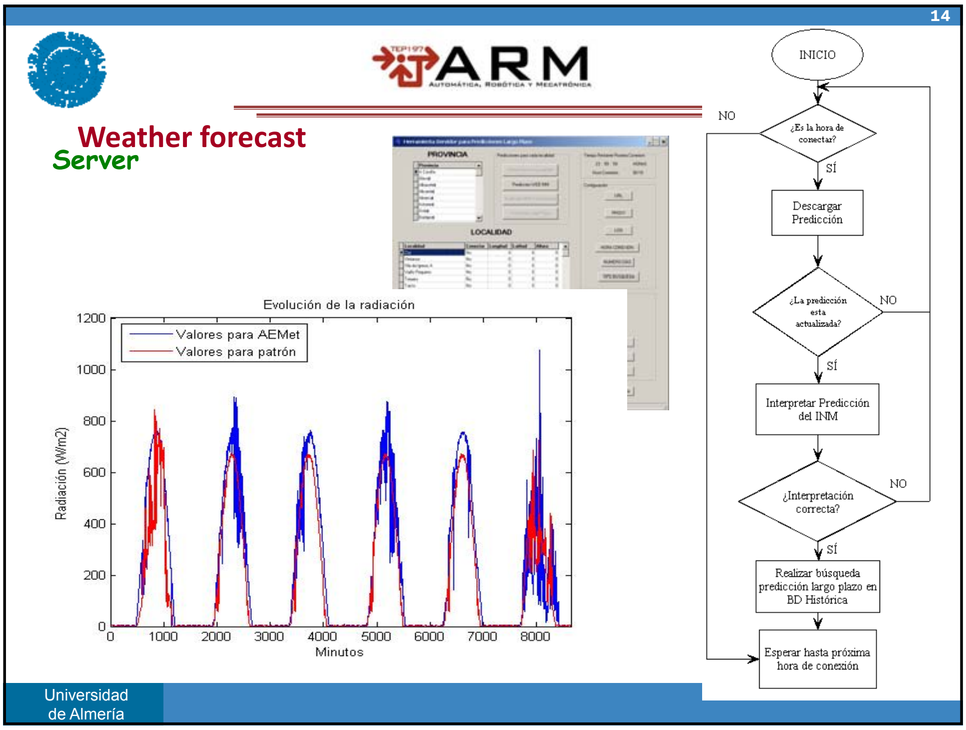
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Weather forecast
Server
Evolución de la radiación
Valores para AEMet
Valores para patrón
Radiación (W/m2)
Minutos
INICIO
¿Es la hora de conectar?
NO
SÍ
Descargar Predicción
¿La predicción está actualizada?
NO
SÍ
Interpretar Predicción del INM
¿Interpretación correcta?
NO
SÍ
Realizar búsqueda predicción largo plazo en BD Histórica
Esperar hasta próxima hora de conexión
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Motivation and main objectives

Motivation

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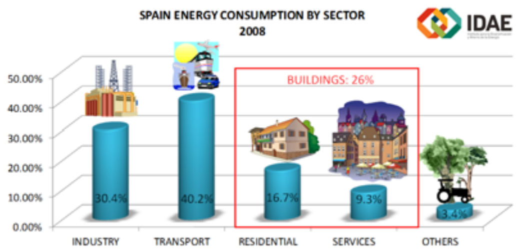
- Energy consumption in buildings represents about 40% of total world energy consumption, more than half used by HVAC (Heating, Ventilation and Air Conditioning) Systems. Moreover, they are also responsible of approximately 35% of CO_2 emissions.

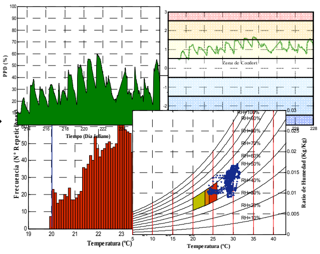
Energy Efficiency

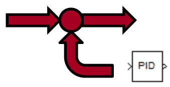


- MAIN OBJECTIVE
  - To provide comfortable environments with the minimum possible energy consumption.

Main objectives

1. To study and analyze users' comfort inside a building from both thermal comfort and indoor air quality points of view.
2. Development of a methodology for design, calibration and validation of physical models with unknown parameters.
3. Study, analysis and development of advanced control techniques for the comfort control problem.
4. Test and integration in a control architecture of the developed strategies in order to analyze its behaviour.





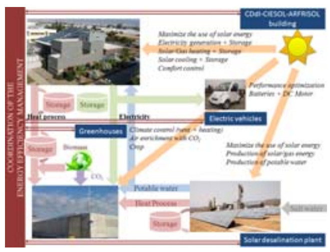
Scope of the research

PSE-ARFRISOL research project (M. Rosario Heras – CIEMAT)

- It is a singular strategic project about bioclimatic architecture and solar cooling.

POWER+ENERPRO research projects (Francisco Rodríguez+Manuel Berenguel)

- Supervision and control strategies for the integrated management of installations inside energy efficient environments.



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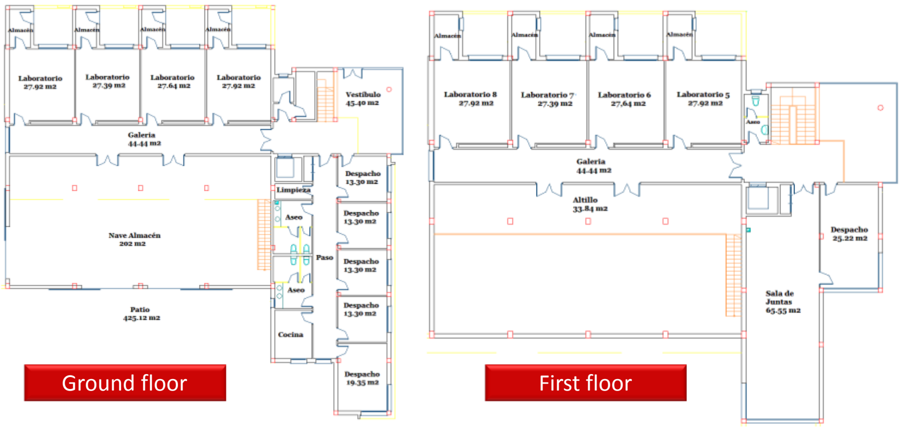
CIESOL building

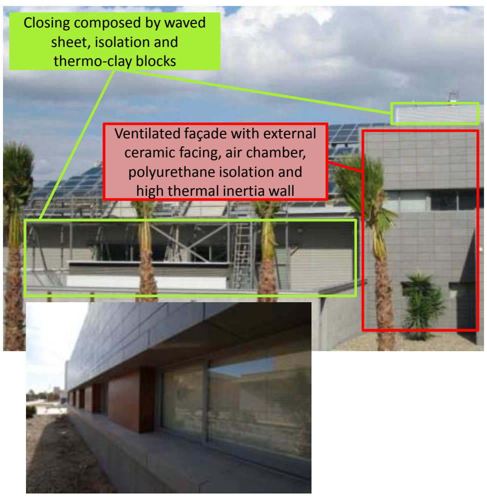
Passive strategies

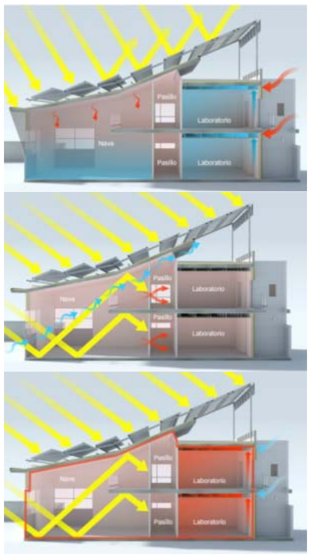
CIESOL building



CIESOL building

Passive strategies





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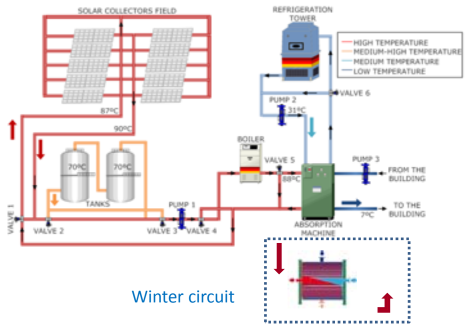
CIESOL building

Active strategies: Solar cooling installation

- This research centre was built following a bioclimatic architecture criteria, where HVAC systems are based on solar cooling using a solar collectors field, a hot water storage system, a boiler, and an absorption machine with its refrigeration tower.



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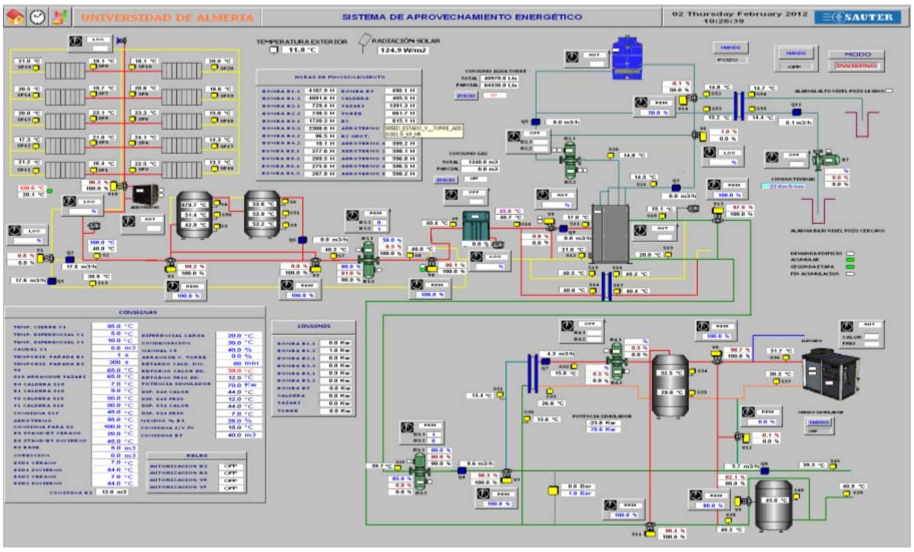
CIESOL building



CIESOL building

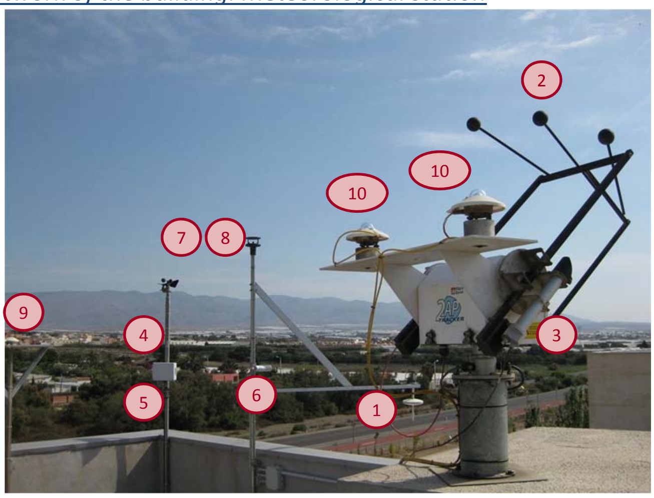
Other active strategies




CIESOL building

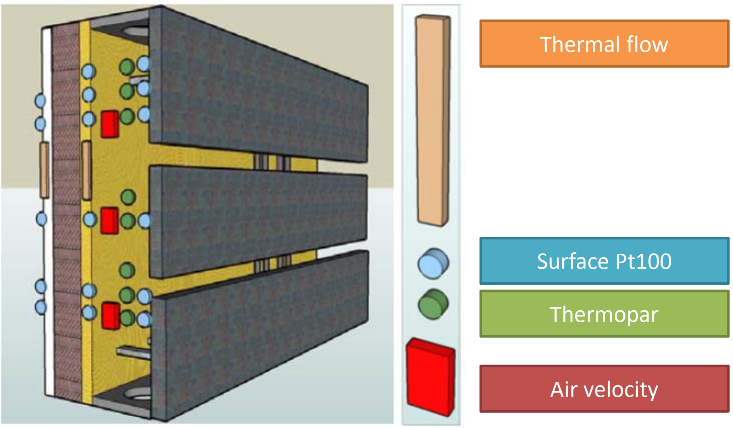
Sensors network of the building: Meteorological station

1. Atmospheric pressure
2. Solar tracking
3. Pyrheliometer
4. Air temperature
5. Relative humidity
6. CO2 concentration
7. Wind velocity
8. Wind direction
9. Pyrgeometer (infrared radiation)
10. Pyranometer (direct and diffuse irradiances)



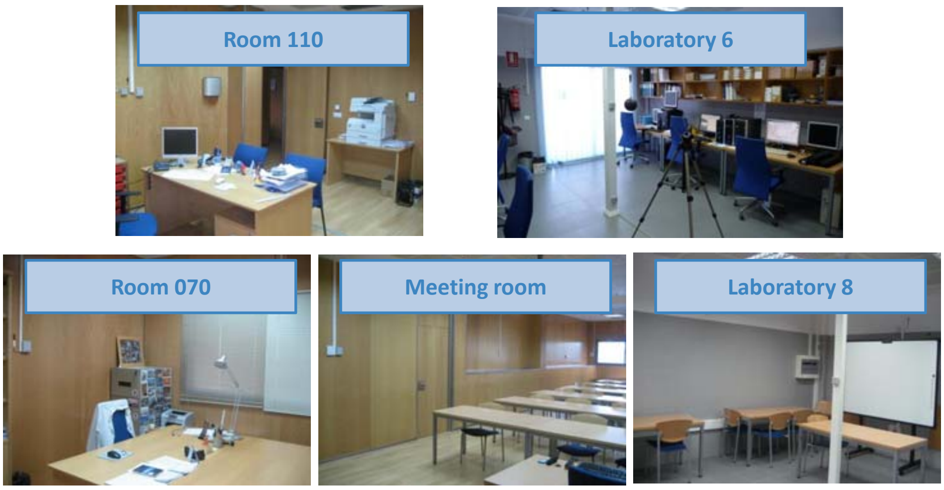
CIESOL building

Sensors network of the building: Ventilated façade



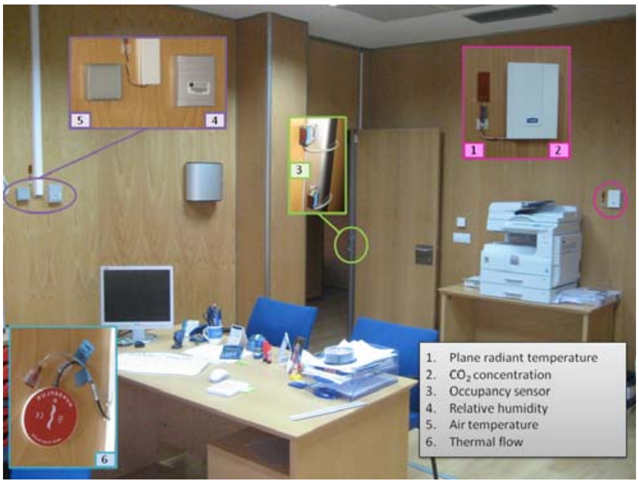
CIESOL building

Sensors network of the building: Representative rooms of the building



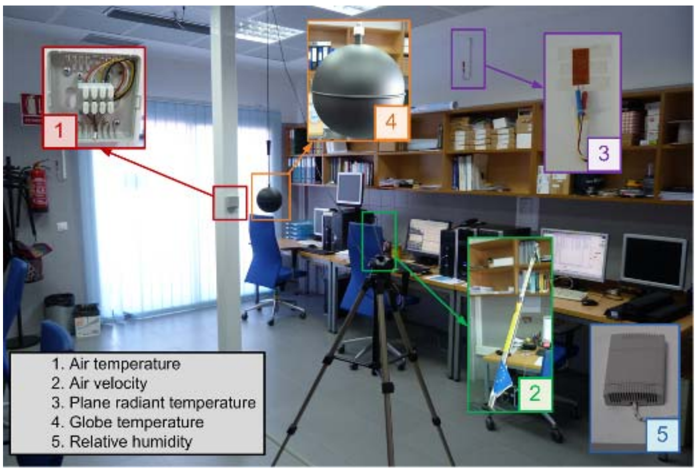
CIESOL building

Sensors network. A characteristic room of the building



CIESOL building

Sensors network of the building: Representative rooms of the building



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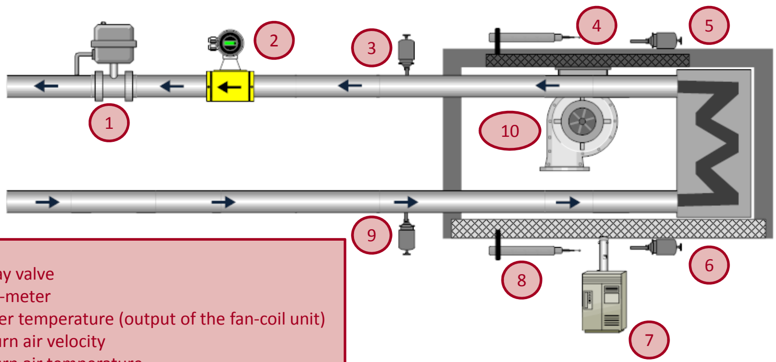
CIESOL building

Sensors network of the building: fan-coil units



1. 2-Way valve
2. Flow-meter
3. Water temperature (output of the fan-coil unit)
4. Return air velocity
5. Return air temperature
6. Impulse air temperature
7. Impulse relative humidity
8. Impulse air velocity
9. Water temperature (input of the fan-coil unit)
10. Fan (0 – 33 – 66 – 100%)

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CIESOL building

Sensors network of the building: Room occupation system

Also with Xbox Kinect

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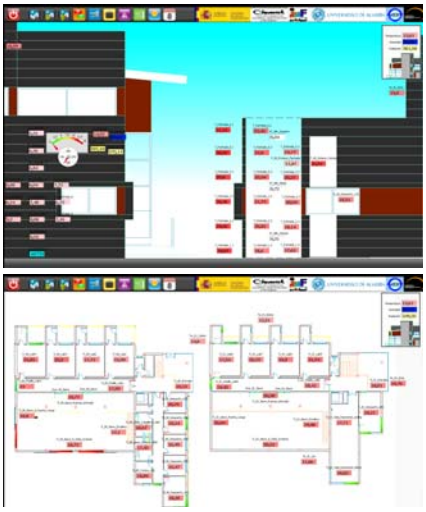
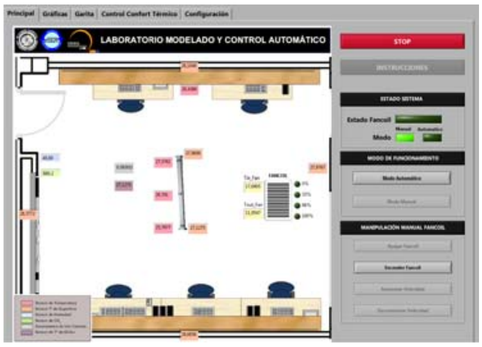
CIESOL building





Monitoring and acquisition applications: around 400 sensors and actuators integrated via OPC using a dedicated Ethernet network

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Thermal comfort

Thermal Comfort?

ISO 7730 — International Organization for Standardization

ASHRAE 55

"That condition of mind which expresses satisfaction with the thermal environment"

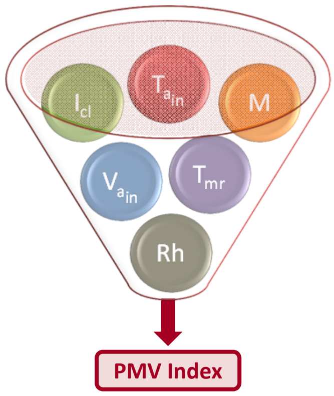
"Comfort is a cognitive process which depends of different kinds of processes, such as, physical, physiological or even psycological"

Thermal comfort

Predicted Mean Vote (PMV) Index

- This index is able to predict the average response about thermal sensation of a large group of people exposed to certain thermal conditions for a long time.

+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold



Thermal comfort

Predicted Mean Vote (PMV) Index

Classical approach

- The PMV index can be estimated as a function of the six previous variables just as:

$$PMV = [0.303\exp(-0.036M) + 0.028]L$$

where

M : *Metabolic rate*

L : *Thermal load in the human body*

$$L = (M - W) - 0.0014 \cdot M \cdot (34 - T_{a_{in}}) -$$
$$-3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M - W) - p_{a_{in}}] -$$
$$-0.42 \cdot (M - W - 58.15) -$$
$$-1.72 \cdot 10^{-5} \cdot M \cdot (5867 - p_{a_{in}}) -$$
$$-39.6 \cdot 10^{-9} \cdot F_{cl} \cdot [(T_{cl} + 273)^4 - (T_{mr} + 273)^4] -$$
$$-F_{cl} \cdot h_c \cdot (T_{cl} - T_{a_{in}})$$

Acronym	Meaning
W	Effective mechanical power
$T_{a_{in}}$	Air temperature
$p_{a_{in}}$	Partial water vapor pressure in the air
F_{cl}	Clothing area factor
T_{cl}	Clothing surface temperature
T_{mr}	Mean radian temperature
h_c	Convective heat transfer coefficient

Función no lineal de otras variables (si no se miden) o valores tabulados

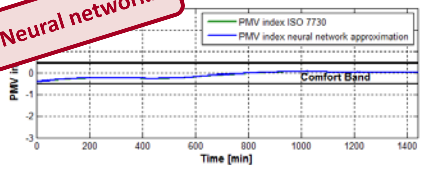
Thermal comfort

Predicted Mean Vote (PMV) Index

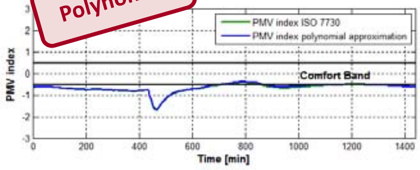
PMV index approximations

- To reduce computational costs and price of sensors network in order to estimate PMV index different black box models based on neural networks and polynomial approximations has been obtained.

Neural networks

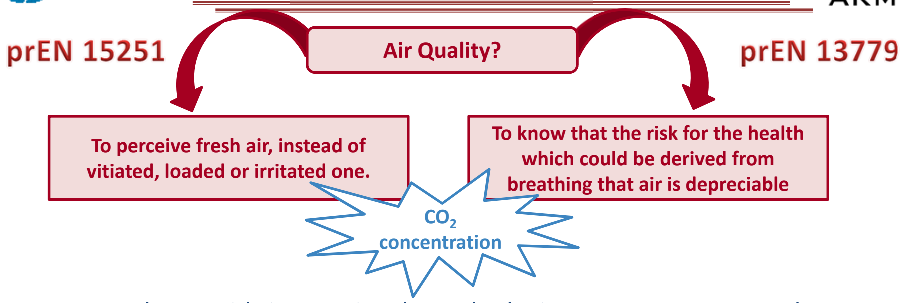


Polynomial



	RMSE			
Model	VA1a	VA1b	VA2a	VA2b
ANN	0.0117	0.0079	0.0145	0.0123
Polynomial	0.0065	0.0357	0.0296	0.0528

Air quality



- In accordance with international standards, just as prEN 13779 and prEN 15251, indoor air quality could be classified by CO_2 concentration since it is the main bioeffluent from human respiratory

Category	Description	Typical range	Default value
IDA 1	High indoor air quality	≤400	350
IDA 2	Medium indoor air quality	400 – 600	500
IDA 3	Moderate indoor air quality	600 – 1000	800
IDA 4	Low indoor air quality	> 1000	1200

Air quality

Indoor Air Quality (IAQ) Index

- This index allows to classify indoor air for occupied rooms, where smoking is not allowed and pollution is caused mainly by human metabolism, according to the four indoor air quality categories.

$$IAQ = 0.001 \cdot CO_{2_{in}} - 0.5$$

IAQ ≤ 0	High indoor air quality (IDA 1)
0 < IAQ < 0.1	Medium indoor air quality (IDA 2)
0.1 ≤ IAQ < 0.5	Moderate indoor air quality (IDA 3)
0.5 ≤ IAQ ≤ 1	Low indoor air quality (IDA 4)

- To guarantee indoor air quality in a certain environment, it is recommended to maintain a CO_2 concentration level between 500 ppm and 600 ppm, that is an IAQ index value at 0 with a tolerance of 0.1.

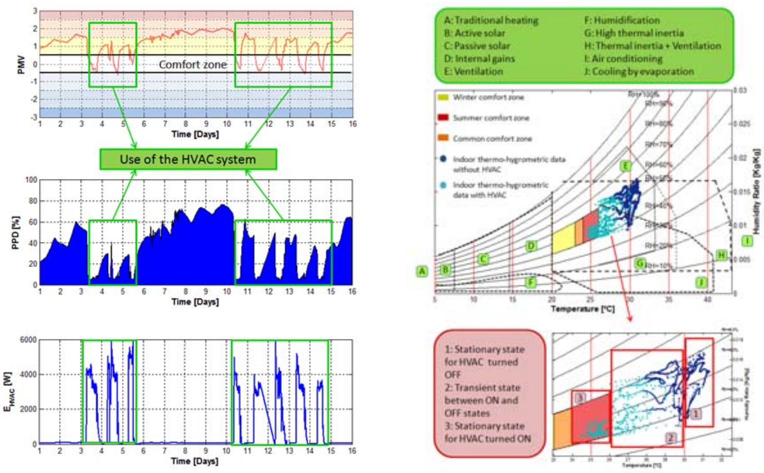
Comfort analysis

- The main objective of this study is to evaluate the performance of the passive bioclimatic strategies of the CDdI-CIESOL-ARFRISOL building without the use of any control strategy.
- As the building does not have a fixed work schedule, the following assumptions has been established:
  - o Saturdays and Sundays are considered periods of non occupation, that is, the building is supposed to be empty.
  - o Within the occupation periods (from Monday to Friday) it is established a night time period that comprise from 21:00 PM to 07:00 AM.

Almería characteristic climate	Summer	Winter	Autumn
Maximum mean air temperature [ºC]	30.7	17.7	20.4
Minimum mean air temperature [ºC]	22	8.8	12.0
Mean relative humidity [%]	65	68	70
Average precipitation days [-]	0	3	3
Mean monthly sunshine hours [-]	312	191	187

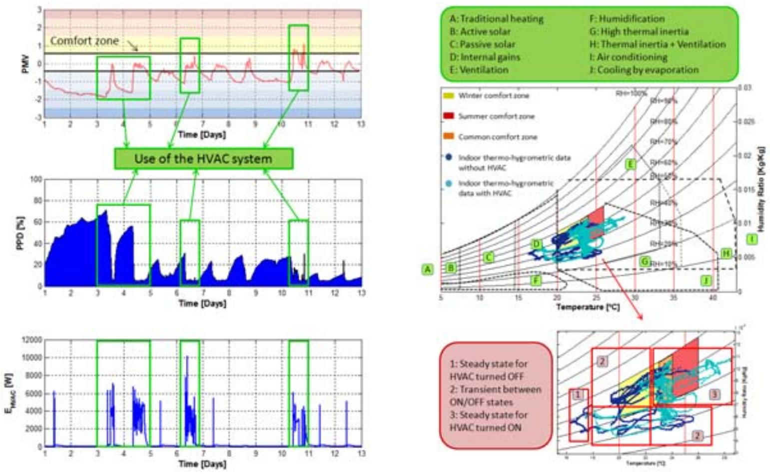
Comfort analysis

Thermal comfort analysis. Summer period
From 1st (Saturday) to 15th (Saturday) of August 2009.



Comfort analysis

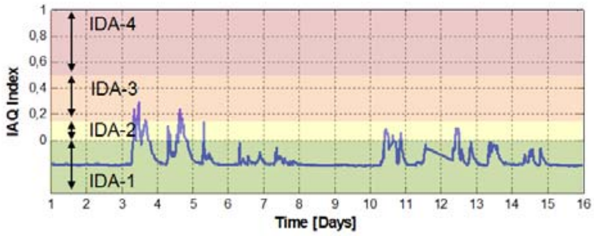
Thermal comfort analysis. Winter period
From 13th (Saturday) to 24th (Wednesday) of February 2010



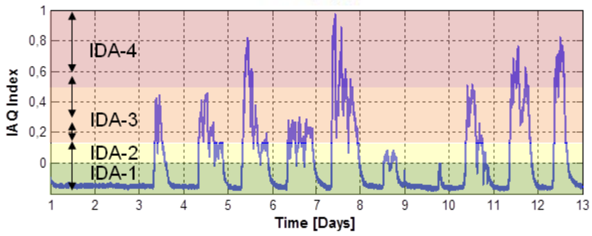
Comfort analysis

Indoor air quality

- Summer



- Winter



Comfort analysis

Main conclusions of the comfort analysis

- For both summer and winter periods, it is necessary the use of a HVAC system to cool in summer, and to heat in winter.
- The existence of a significant percentage of data outside the comfort zone during summer and winter periods allows to consider two hypothesis which are not strictly exclusive:
  - Insufficiency of manual control that was implemented in the HVAC system.
  - Existence of subjective factors in the evaluation of both thermal comfort and indoor air quality.
- As a function of this comfort analysis, it has reached the conclusion that it was necessary to develop a specific control system which allows to maintain environmental conditions of the building inside a comfort zone for the user minimising, at the same time, energy consumption.

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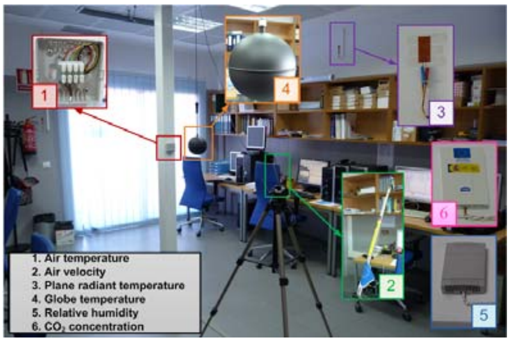
Indoor climate model of a room

Models allow to obtain important information about systems, and thus, they represent a key factor in order to design control strategies and solve optimization problems.

A typical CDdI-CIESOL-ARFRISOL office room

- Room location: second floor of the building.
- Total volume: 4.96 x 5.53 x 2.8 m^3
- North orientation
- Number of windows: 1
- Window surface: 2.15 x 2.09 m^2
- Window location: north wall
- Actuators:
  - o Window opening/closing system
  - o Shading opening/closing system
  - o HVAC fan power
  - o HVAC water flow valve

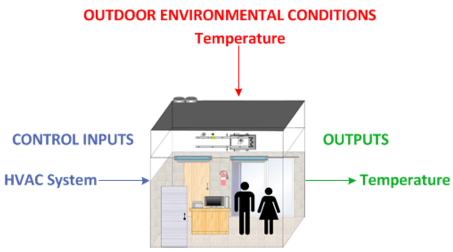


Indoor climate model of a room

A Linear Time-Invariant (LTI) temperature model

Assumptions:

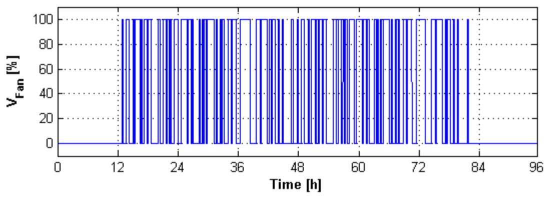
- The state variable of the system is the indoor air temperature.
- There exist only one element which interact with the indoor air temperature: the external air.
- As control variable, it was supposed that there was only one actuator available, the fancoil unit, which allows to control indoor air temperature by means of its fan velocity.
- It is considered that all the variables of the process are homogenously distributed.



Indoor climate model of a room

A Linear Time-Invariant (LTI) temperature model

- PRBS Signal: Pseudo – Random Binary Signal



- ARX Model: AutoRegressive model with eXogeneus input

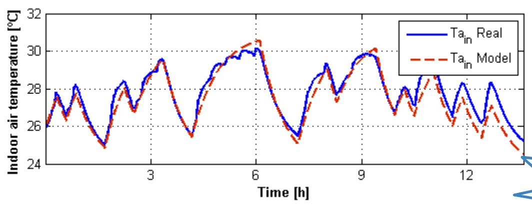
$$y(t)+a_1y(t-1)+\ldots+a_{na}y(t-na)=b_1u(t-nk)+\ldots+b_{nb}u(t-nk-nb+1)$$

where *na* is the number of poles, *nb+1* is the number of zeros and *nk* is the delay of the system if it exists.

Indoor climate model of a room

A Linear Time-Invariant (LTI) temperature model

- Cross validation results for the LTI indoor temperature model



NMAE = 10%

$$y(t)-0.9417y(t-1)-0.2779y(t-2)-0.008656y(t-3)+0.06594y(t-4)+$$
$$+0.1009y(t-5)+0.06291y(t-6)=0.0001126u(t)$$

At present, grey-box models considering simplified balances (R,C circuits) so that only a few parameters have to be identified.

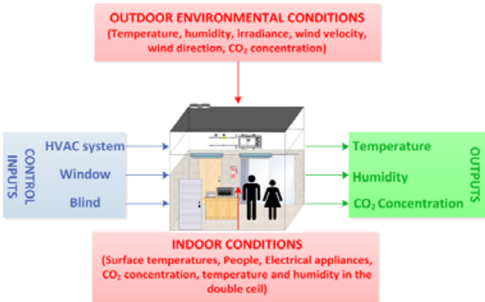
Indoor climate model of a room

A first principles model of a room

- The first principles model of a room is composed of three submodels which describe the indoor air temperature, the indoor air relative humidity and the indoor CO_2 concentration dynamic behaviour. Hence, it can be represented by a system of differential equations given by:

$$\frac{dX}{dt} = f(X, U, D, V, C, t) \text{ with } X(t_i) = X_i$$

where *X*, *U*, *D*, *V* and *C* are vectors of the state variables, control inputs variables, disturbances, system variables and system constants, respectively, *t* is the time, X_i is the known initial state at the initial time t_i, and *f* is a nonlinear function based on mass and heat transfer balances.



Indoor climate model of a room

A first principles model of a room

Assumptions:

- It is supposed that the room is composed by seven elements: indoor air, walls, windows, shading system, HVAC system, people and electrical appliances.
- The state variables of the model are: indoor air temperature, indoor relative humidity and CO_2 concentration.
- The *control inputs* of the system are: the natural ventilation, expressed as a function of the window opening, the blind, and the forced ventilation by means of a fancoil unit.
- The *disturbance inputs* of the system are: the outside air temperature, humidity and CO_2 concentration, wind speed and its direction, direct, diffuse and reflected irradiance, the plane radiant temperatures of all surfaces of the room, indoor air velocity, number of people inside the room and the electrical appliances that are connected at each moment.
- The physical characteristics of the different elements (walls, windows, etc.) such as density or specific heat are considered constant. However, the physical characteristics of the air inside the room are estimated as a function of indoor air temperature.

Indoor climate model of a room

TEP197 ARM

A first principles model of a room

Temperature model

$$m_a \cdot C_{p_a} \cdot \frac{dT_{a_{in}}}{dt} = \overbrace{Q_{conv}}^{\text{Convection}} + \underbrace{Q_{glass}}_{\text{Window}} + \overbrace{Q_{fv}}^{\text{Forced Ventilation}} + \underbrace{Q_{nvnt}}_{\text{Natural ventilation}} + \overbrace{Q_{inf}}^{\text{Infiltrations}} + \underbrace{Q_{iGain}}_{\text{Internal gains}}$$

Humidity model

$$V_{a_{in}} \rho_{a_{in}} \frac{dW_{a_{in}}}{dt} = \overbrace{M_{w_p}}^{\text{People}} + \underbrace{M_{w_{fv}}}_{\text{Forced ventilation}} + \overbrace{M_{w_{inf}}}^{\text{Infiltrations}} + \underbrace{M_{w_{nvnt}}}_{\text{Natural ventilation}}$$

CO_2 concentration model

$$V_{a_{in}} \frac{dCO_{2_{in}}}{dt} = \underbrace{MCO_{2_p}}_{\text{People}} + \overbrace{MCO_{2_{nvnt}}}^{\text{Natural ventilation}} + \underbrace{MCO_{2_{fv}}}_{\text{Forced ventilation}} + \overbrace{MCO_{2_{inf}}}^{\text{Infiltrations}}$$

Indoor climate model of a room

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A first principles model of a room

Calibration and Validation methodology

Main problem: an important set of unknown parameters

- Data of the climate variables to model, the disturbances and the actuators state are measured and stored in a database, thus, the main parameters estimation and *the calibration problem can be divided into three submodels calibration processes*.
- Some of the processes which are involved in each one of the balance equations do not have any influence in determined periods of a day or they are not coupled. Thus, *all the parameters of a single submodel do not have to be estimated simultaneously*.
- Some processes have to be modelled in different forms based on determined situations.
- Some controlled experiments tests can be performed into the room in order to estimate the parameters associated with the actuators.

Indoor climate model of a room

A first principles model of a room

Calibration and Validation methodology

- The proposed methodology consists of a two steps calibration process:
  - First step. To determine a search space by means of an iterative search by performing single experimental tests for each one of the involved processes.
  - Second step. To obtain the final value for each one of the unknown parameters by means of genetic algorithms.

$$J(x) = \min \sum_{i=1}^{N} \left| x(i) - \hat{x}(i,\Psi) \right|^2 =$$

$$= \min \sum_{i=1}^{N} \sum_{k=1}^{3} \left| x_k(i) - \hat{x}_k(i,\Psi) \right|^2$$

where N is the number of samples and k is the number of models which are going to be calibrated.

Indoor climate model of a room

A first principles model of a room

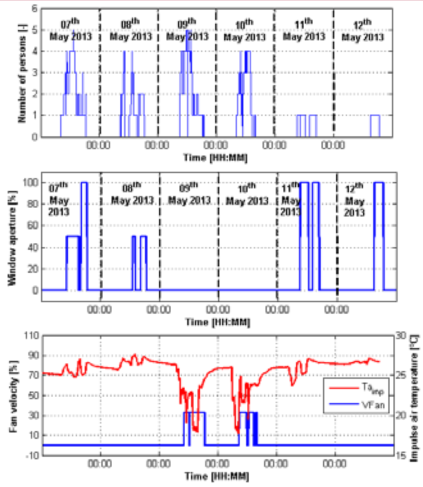
Calibration and Validation methodology

- Test 1. Empty room and blind closed (5).
- Test 2. Empty room and blind open (1).
- Test 3. Empty room and blind in several positions (6).
- Test 4. Empty room and using forced ventilation (1).
- Test 5. Empty room and using natural ventilation (1).
- Test 6. Occupied room (1).
- Test 7. Occupied room and using natural ventilation (2).
- Test 8. Validation of the selected unknown parameters (10).

Indoor climate model of a room

A first principles model of a room

Validation of the first principles model
Summer period. From 7th to 12th May 2013



Room occupation

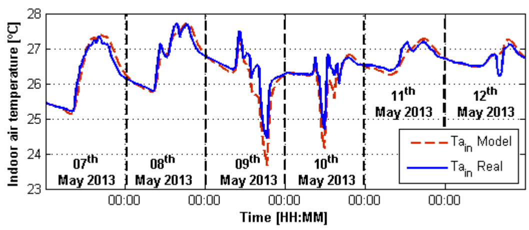
Window aperture

Fancoil use

Indoor climate model of a room

A first principles model of a room

Validation of the first principles model
Summer period. From 7th to 12th May 2013



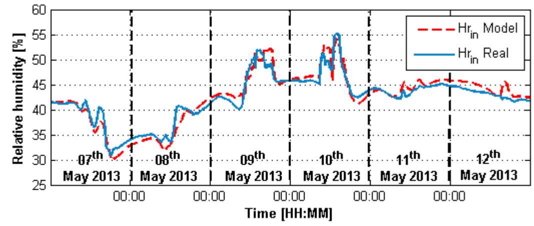
Parameter	Validation Test 3
Interval	[24.43 – 27.72]
Rng	3.29ºC
N	51840
MAE	0.15
MRE	0.005
S_N	0.68
NMAE	4.55%

Indoor climate model of a room

ARM

A first principles model of a room

Validation of the first principles model
Summer period. From 7th to 12th May 2013



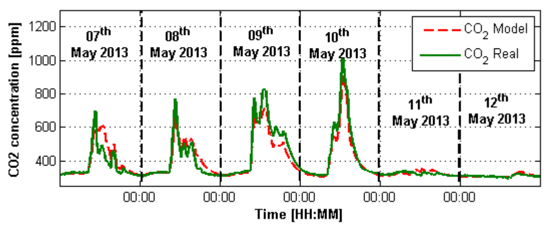
Parameter	Validation Test 3
Interval	[30.80 – 55.31]
Rng	24.51%
N	51840
MAE	1.07
MRE	0.03
S_N	5.14
NMAE	4.36%

Indoor climate model of a room

ARM

A first principles model of a room

Validation of the first principles model
Summer period. From 7th to 12th May 2013



Parameter	Validation Test 3
Interval	[296.44 – 1014.60]
Rng	718.12 ppm
N	51840
MAE	22.58
MRE	0.05
S_N	110.49
NMAE	3.14%

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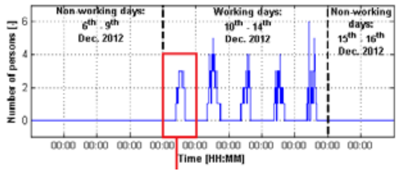
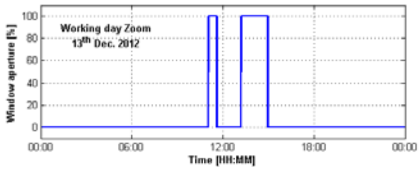
Indoor climate model of a room

Validation of the first principles model
Winter period. From 6th to 16th December 2012

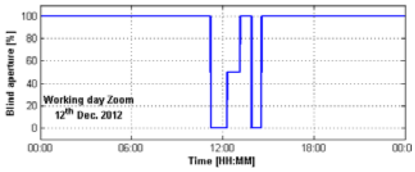
Room occupation



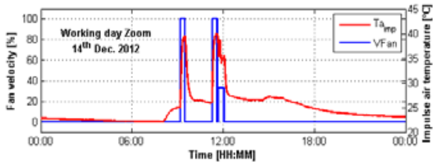
Window aperture



Blind aperture



Fancoil use



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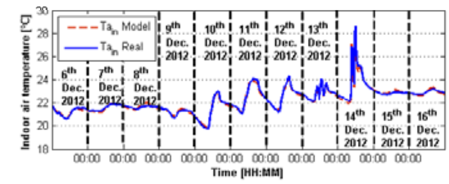
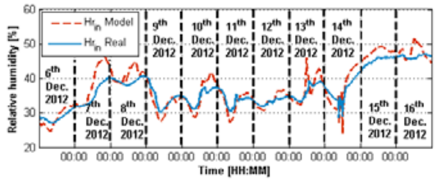
Indoor climate model of a room

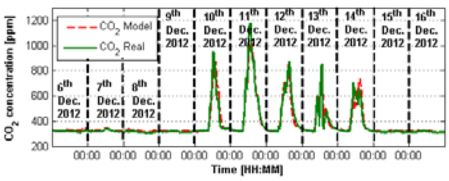
Validation of the first principles model
Winter period. From 6th to 16th December 2012



Parameter	Validation Test 1
Interval	[19.74 – 28.59]
Rng	8.85ºC
N	94973
MAE	0.16
MRE	0.01
S_N	0.94
NMAE	1.80%



Parameter	Validation Test 1
Interval	[26.97 – 46.92]
Rng	19.94%
N	94973
MAE	2.89
MRE	0.08
S_N	4.68
NMAE	14.49%



Parameter	Validation Test 1
Interval	[302.98 – 1182.25]
Rng	879.56 ppm
N	94973
MAE	35.39
MRE	0.08
S_N	107.37
NMAE	4.02%

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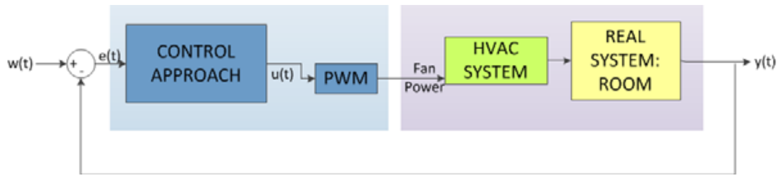
Linear controllers for users' thermal comfort

- Main objective. To obtain a high thermal comfort level taking energy costs into account.

- To do that, it has been considered that there is only one actuator available inside the CDdI-CIESOL-ARFRISOL building in order to control thermal comfort, the HVAC system.

- Two different approaches are presented:
  - A hierarchical predictive control strategy.
  - A classical Model Predictive Control (MPC) strategy.



Thermal comfort control inside a room

Generalized Predictive Control Algorithm

Controller Auto-Regressive Integrated Moving-Average (CARIMA)

$$A(z^{-1})y(t) = z^{-d}B(z^{-1})u(t-1) + C(z^{-1})\frac{e(t)}{\Delta}$$

$$\Delta = 1 - z^{-1}$$

$$A(z^{-1}) = 1 + a_1 z^{-1} + a_2 z^{-2} + \dots + a_{na} z^{-na}$$

$$B(z^{-1}) = b_0 + b_1 z^{-1} + b_2 z^{-2} + \dots + b_{nb} z^{-nb}$$

$$C(z^{-1}) = 1 + c_1 z^{-1} + c_2 z^{-2} + \dots + c_{nc} z^{-nc}$$

Quadratic Cost Function

$$J = \sum_{j=N_1}^{N_2} \delta(j)[\hat{y}(t+j \mid t) - w(t+j)]^2 + \sum_{j=1}^{N_u} \lambda(j)[\triangle u(t+j-1)]^2$$

- D.W. Clarke, C. Mohtadi and P.S. Tufts. *Generalized predictive control I. The basic algorithm*. Automatica, 23, 137-148, 1987
- E.F. Camacho, C. Bordóns. Model Predictive Control. Springer, 2012.
- One of the most popular MPC algorithm in both industry and academy.

Thermal comfort control inside a room

Generalized Predictive Control Algorithm

Obtaining the GPC Control Law

- The predicted outputs, $\hat{y}(t+k|t)$, are calculated using the prediction model ($C(z^{-1})=1$):

$$A(z^{-1})y(t) = z^{-d}B(z^{-1})u(t-1) + C(z^{-1})\frac{e(t)}{\Delta} \;\Rightarrow\; \mathbf{y} = \underbrace{\mathbf{Gu}}_{\text{forced response}} + \underbrace{\mathbf{f}}_{\text{free response}}$$

- Substitute the compact prediction values in the cost function, *J*.

$$J = \sum_{j=N_1}^{N_2} \delta(j)[\hat{y}(t+j \mid t) - w(t+j)]^2 + \sum_{j=1}^{N_u} \lambda(j)[\Delta u(t+j-1)]^2 \;\Rightarrow\; J = (\mathbf{Gu} + \mathbf{f} - \mathbf{w})^\top(\mathbf{Gu} + \mathbf{f} - \mathbf{w}) + \lambda \mathbf{u}^\top \mathbf{u}$$

- Minimize *J* with respect to $\Delta \mathbf{u}$ where an analytical solution is obtained for the unconstrained case:

$$\mathbf{u} = -\mathbf{H}^{-1}\mathbf{b} = (\mathbf{G}^\top\mathbf{G} + \lambda\mathbf{I})^{-1}\mathbf{G}^\top(\mathbf{w} - \mathbf{f}) \;\Rightarrow\; u(t) = u(t-1) + \mathbf{K}(\mathbf{w} - \mathbf{f})$$

Thermal comfort control inside a room

Generalized Predictive Control Algorithm

Obtaining the GPC Control Law (future predictions):

$$\mathbf{y} = \underbrace{\mathbf{Gu}}_{\text{forced response}} + \underbrace{\mathbf{f}}_{\text{free response}}$$

The prediction outputs, *y(t+j)*, must be obtained for $j \geq N_1$ and $j \leq N_2$. The horizons can be set as $N_1=d+1$, $N_2=d+N$, $N_u=N$. Thus, *N*-ahead predictions will be used in the optimization process.

The predictions could be done just from the CARIMA model:

$$\hat{y}(t+d+j|t) = (1-a_1)\hat{y}(t+d+j-1|t) +$$

$$+(a_1 - a_2)\hat{y}(t+d+j-2|t) + \cdots + a_{na}\hat{y}(t+d+j-n_a-1|t) +$$

$$+b_0\Delta u(t+j-1) + \cdots + b_{nb}\Delta u(t+j-n_n b-1)$$

This is really done using a Diophantine Equation.

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Thermal comfort control inside a room

Generalized Predictive Control Algorithm

Dealing with constraints:
Typical Quadratic Programming (QP) Problem:

$$J = \frac{1}{2}\mathbf{u}^T\mathbf{H}\mathbf{u} + \mathbf{b}^T\mathbf{u} + \mathbf{f}_0$$

$$\mathbf{R}\mathbf{u} \leq \mathbf{c}$$

$$\mathbf{E}\mathbf{u} = \mathbf{g}$$

$$J = \frac{1}{2}\mathbf{x}^\top\mathbf{H}\mathbf{x} + \mathbf{f}^\top\mathbf{x}$$

$$\mathbf{R}\mathbf{x} \leq \mathbf{c}$$

$$\mathbf{E}\mathbf{x} = \mathbf{g}$$

Minimization of a quadratic function with linear constraints. Example: **quadprog** function of *Matlab*.

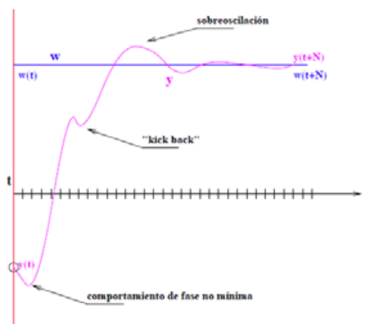
```
QUADPROG Quadratic programming.
   X = QUADPROG(H,f,A,b) attempts to solve the quadratic programming
   problem:

            min 0.5*x'*H*x + f'*x   subject to:  A*x <= b
             x
```


Thermal comfort control inside a room

Generalized Predictive Control Algorithm

Dealing with constraints:
Different types of constraints:

- o ***Physical or security constraints:*** process limitations.
- o ***User-defined constraints***: to force derided output.
- o ***Input:*** typical saturation constraints.
- o ***Output:*** operation conditions.



All of them must be defined based on control increments Δu (**u**).

$$\mathbf{R}\mathbf{u} \leq \mathbf{c}$$

$$\mathbf{E}\mathbf{u} = \mathbf{g}$$

Thermal comfort control inside a room

Generalized Predictive Control Algorithm

Dealing with constraints:

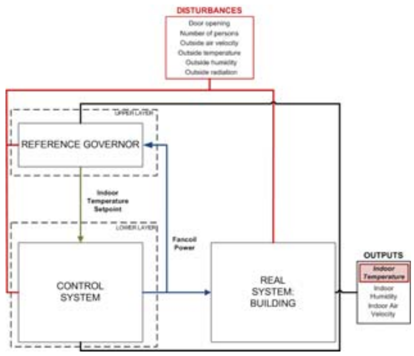
Table 1. Constraints in GPC. The GPC treatment of constraints is conceptually simple and can be included systematically during the design process. This table shows the main constraints within the scope of the GPC technique.

Variable	Linear constraint
Control signal amplitude (U) $u_{min} \leqslant u(t) \leqslant u_{max}$	$\Gamma u_{min} \leqslant \Upsilon \Delta u + u(t-1)\Gamma \leqslant \Gamma u_{max}$
Control signal increment (DU) $\Delta u_{min} \leqslant u(t) - u(t-1) \leqslant \Delta u_{max}$	$\Gamma \Delta u_{min} \leqslant \Delta u \leqslant \Gamma \Delta u_{max}$
Output signal amplitude (Y) $y_{min} \leqslant y(t) \leqslant y_{max}$	$\Gamma y_{min} \leqslant G\Delta u + f \leqslant \Gamma y_{max}$
Envelope constraints (Y Band) $y_{min}(t) \leqslant y(t) \leqslant y_{max}(t)$	$G\Delta u \leqslant \mathbf{y}_{max} - f;\ \mathbf{y}_{max} = [y_{max}(t+1) \ldots y_{max}(t+N)]$ $G\Delta u \leqslant \mathbf{y}_{min} - f;\ \mathbf{y}_{min} = [y_{min}(t+1) \ldots y_{min}(t+N)]$
Output overshoot $y(t+j) \leqslant \gamma w(t);\ j = N_{o1} \ldots N_{o2}$	$G\Delta u \leqslant \Gamma \gamma w(t) - f$
Output monotone behavior $y(t+j) \leqslant y(t+j+1)$ if $y(t) < w(t)$ $y(t+j) \geqslant y(t+j+1)$ if $y(t) > w(t)$	$G\Delta u + f \leqslant [(0^T/G')]\Delta u + [(y(t)/f')]$ G' and f' are the result of eliminating the last row of G and f.
Limit inverse response (NMP) $y(t+j) \leqslant y(t)$ if $y(t) > w(t)$ $y(t+j) \geqslant y(t)$ if $y(t) < w(t)$	$G\Delta u \geqslant \Gamma y(t) - f$
Final state $y(t+N+1) \ldots y(t+N+m) = w$	$\mathbf{y}_m = [y(t+N+1) \ldots y(t+N+m)]^T$: $\mathbf{y}_m = G_m \Delta u + f_m.\quad G_m \Delta u = w_m - f_m$
Output integral $T_m \sum_{t+1}^{t+N_i} y(t) = I$	$\Gamma^T \begin{bmatrix} y(t+1) \\ \vdots \\ y(t+N_i) \end{bmatrix} = G_i \Delta u + f_i \geqslant I$

Linear controllers for users' thermal comfort

A hierarchical predictive control strategy

- This structure is based on a traditional control scheme with a reference governor in a top layer, that by means of a nonlinear optimizer is able to generate a indoor temperature reference.



$$\Delta w_T = \min_{\Delta w_T} J_{k\{1,2\}}$$

$$J_{k1} = \sum_{j=1}^{N} \hat{y}_{PMV}(k+j|k)^2 + \lambda \sum_{j=1}^{N_u} \Delta w_T(k+j-1)^2$$

$$J_{k2} = \sum_{j=1}^{N} \hat{y}_{PMV}(k+j|k)^2 + \lambda \sum_{j=1}^{N_u} \Delta u(k+j-1)^2$$

$$w_{T\,min} \leq w_T(k+j-1) \leq w_{T\,max} \quad \forall j = 1, \ldots, N_u$$

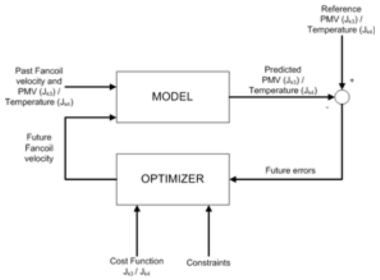
$$u_{min} \leq u(k+j-1) \leq u_{max} \quad \forall j = 1, \ldots, N_u.$$

Linear controllers for users' thermal comfort

A classical MPC strategy

- This technique uses a model of the system to make predictions of the future outputs. They are included inside a cost function which establishes a relationship between the close loop behaviour of the system and the control effort. This cost function is minimized taking into account the constraints of the problem. Finally, a receding horizon strategy is implemented.

$$\Delta \mathbf{u} = \min_{\Delta \mathbf{u}} J_{k\{3,4\}}$$



$$J_{k3} = \sum_{j=1}^{N} \hat{y}_{\mathrm{PMV}}(k+j|k)^2 + \lambda \sum_{j=1}^{N_u} \Delta u(k+j-1)^2$$

$$J_{k4} = \sum_{j=1}^{N} (\hat{y}_T(k+j|k) - w_T(k+j))^2 + \lambda \sum_{j=1}^{N_u} \Delta u(k+j-1)^2$$

$$w_{T\,\min} \le w_T(k+j-1) \le w_{T\,\max} \quad \forall j = 1, \ldots, N_u$$

$$u_{\min} \le u(k+j-1) \le u_{\max} \quad \forall j = 1, \ldots, N_u.$$

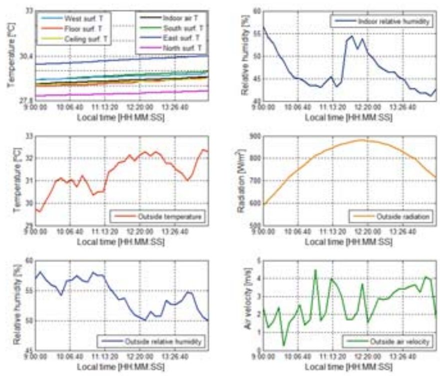
Linear controllers for users' thermal comfort

Selection of weighting coefficients for the cost functions

- It is almost impossible to find different days with identical conditions, since these variables are non controllable. Thus, a typical day for the analyzed period has been chosen to compare different strategies through simulations.

Strategy	Lambda (λ)	ISE Criterion
(A): J_{k1}	0.1	20.01
	0.3	33.46
(B): J_{k2}	0.0065	27.29
	0.008	33.37
(C): J_{k3}	0.001	19.77
	0.00355	33.53
(D): J_{k4}	0.012	27.83
	0.2	58.53

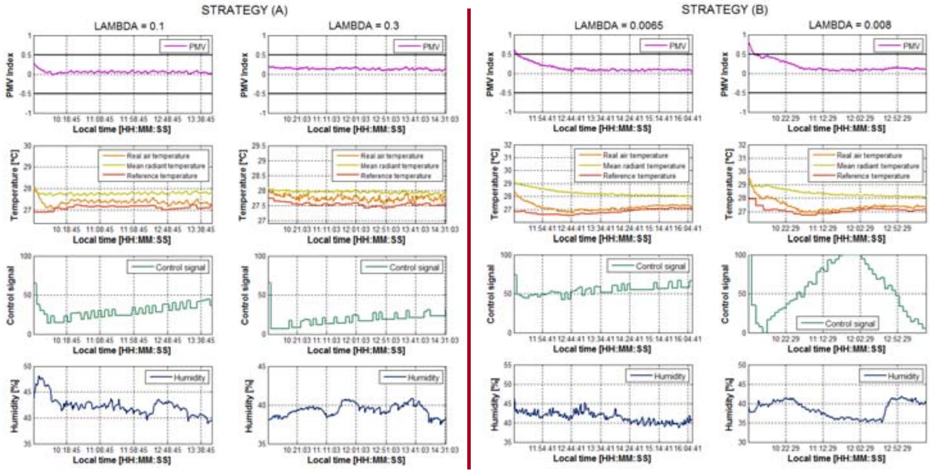
$$ISE = \int_0^{\infty} e(t)^2 \, dt$$



Linear controllers for users' thermal comfort

ARM

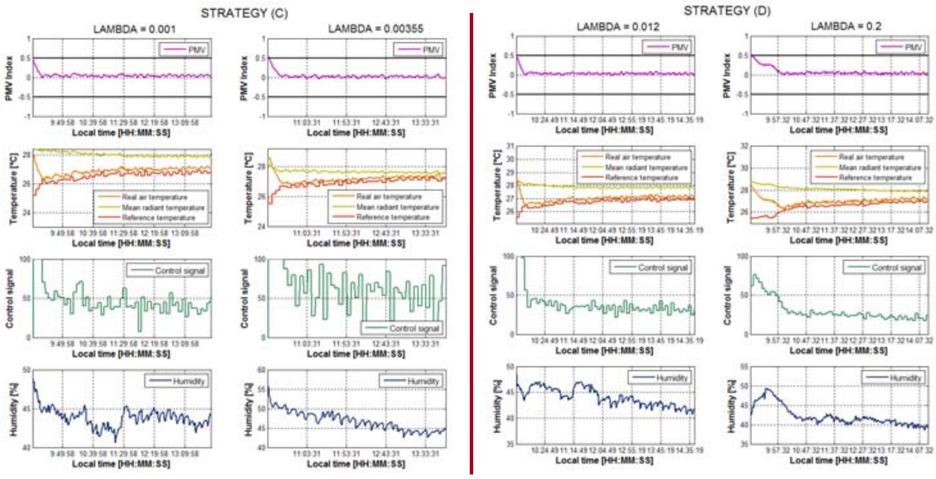
Results from the hierarchical predictive control strategy



Linear controllers for users' thermal comfort

ARM

Results from the classical MPC strategy



Linear controllers for users' thermal comfort

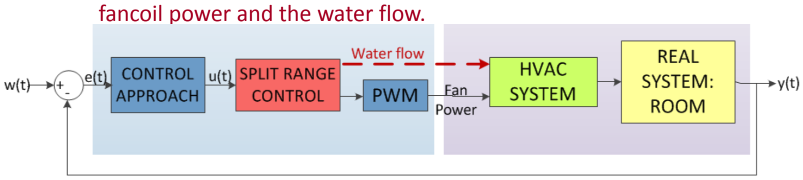
Results

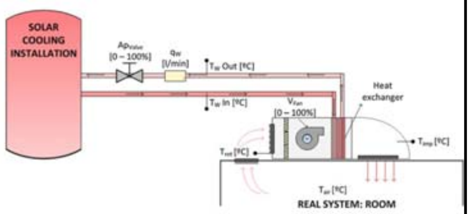
- A comparison among different strategies have been performed as a function of several indexes:
  - Index 1: Mean number of changes per hour [-].
  - Index 2: Percentage of total time in which the HVAC system is connected [%].
  - Index 3: Average energy consumption per hour [W].

Strategy	Lambda (λ)	ISE Criterion	Index 1	Index 2	Index 3
(A): J_{k1}	0.1	20.01	30	30.13	40
	0.3	33.46	62	18.20	24
(B): J_{k2}	0.0065	27.29	58	42.50	56
	0.008	33.37	84	37.74	50
(C): J_{k3}	0.001	19.77	42	42.14	55
	0.00355	33.53	35	29.39	39
(D): J_{k4}	0.012	27.83	47	33.26	44
	0.2	58.53	57	41.61	55

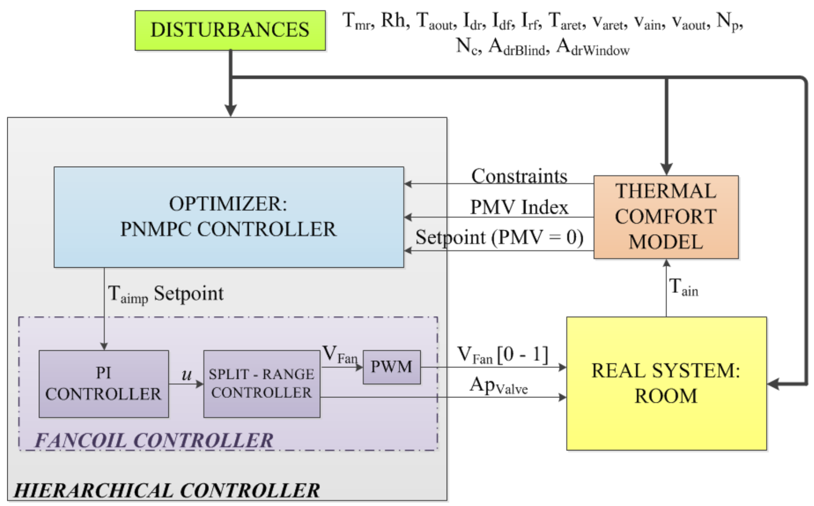
A nonlinear controller for users' thermal comfort

- Main objective. To obtain a high thermal comfort level trying to reduce energy consumption.
- Main differences of this approach with the linear control approaches:
  - The use of a nonlinear first principles model which accurately reflects the dynamics of the room climate and takes into account the main disturbances.
  - It has been considered that the HVAC system has two degrees of freedom, the fancoil power and the water flow.





A nonlinear controller for users' thermal comfort



A nonlinear controller for users' thermal comfort

Optimization layer: A nonlinear MPC approach

- In general, MPC control algorithms, as Generalized Predictive Control (GPC), are applied to linear systems that are characterized by the use of a predicted output data vector, **Ŷ**, throughout a prediction horizon, *N*, as a function of a vector which contains changes in the control action, **Δu**:

$$\hat{Y} = F + G \cdot \Delta u$$

where the system free response vector, **F**, and the matrix **G** are estimated by means of different methods depending of the selected algorithm.

- In this case, the PNMPC strategy is used to compute both **F** and **G** from the non-linear model explained previously.

$$\hat{Y} = F + G_{PNMPC} \cdot \Delta u$$

$$F = f(y_p, \Delta u_p, \Delta v_p) \qquad G_{PNMPC} = \frac{\partial \hat{Y}}{\partial \Delta u}$$

Thermal comfort control inside a room

A Practical Non-Linear Model Predictive Control (PNMPC) approach

$$\hat{Y} = F + G_{PNMPC} \cdot \Delta u$$

$$F = f(y_p, \Delta u_p, \Delta v_p) \qquad G_{PNMPC} = \frac{\partial \hat{Y}}{\partial \Delta u}$$

$$\mathbf{G} = \begin{bmatrix} \frac{\partial \tilde{y}(k+1)}{\partial \Delta u(k)} & 0 & \cdots & 0 \\ \frac{\partial \tilde{y}(k+2)}{\partial \Delta u(k)} & \frac{\partial \tilde{y}(k+2)}{\partial \Delta u(k+1)} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial \tilde{y}(k+N_2)}{\partial \Delta u(k)} & \frac{\partial \tilde{y}(k+N_2)}{\partial \Delta u(k+1)} & \cdots & \frac{\partial \tilde{y}(k+N_2)}{\partial \Delta u(k+N_u-1)} \end{bmatrix}$$

Thermal comfort control inside a room

A Practical Non-Linear Model Predictive Control (PNMPC) approach

- The control law is obtained using techniques similar to the used in classical MPC algorithms.

$$\hat{Y} = F + G_{PNMPC} \cdot \Delta u$$

$$F = f(y_p, \Delta u_p, \Delta v_p) \qquad G_{PNMPC} = \frac{\partial \hat{Y}}{\partial \Delta u}$$

  - Cost function

$$J = \sum_{j=1}^{N} \delta(j)\left[\hat{Y}(k+j\,|\,k) - w(k+j\,|\,k)\right]^2 + \sum_{j=1}^{N_u} \lambda(j)\left[u(k+j-1)\right]^2$$

  - Constraints

$$\Delta u_{\min} \le \Delta u(k+j\,|\,k) \le \Delta u_{\max} \qquad \forall j = 0, \cdots, N_u - 1$$

$$u_{\min} \le u(k+j\,|\,k) \le u_{\max} \qquad \forall j = 0, \cdots, N_u - 1$$

$$\hat{Y}_{\min} \le \hat{Y}(k+j\,|\,k) \le \hat{Y}_{\max} \qquad \forall j = 0, \cdots, N - 1$$

Thermal comfort control inside a room

A Practical Non-Linear Model Predictive Control (PNMPC) approach

- To estimate **F** and $\mathbf{G}_{PNMPC}$ at each sample time it is necessary to use the following algorithm:
  - 1. Obtain $\hat{\mathbf{Y}}^0$ vector with a length of *N*. To do that, it is necessary to execute the model using past inputs, outputs and measurable disturbances, and with $\Delta\mathbf{u} = [0\ 0\ \ldots\ 0]^T$.

$$\hat{\mathbf{Y}}^0 = \mathbf{F}$$

  - 2. Estimate the first column of the $\mathbf{G}_{PNMPC}$ matrix. The model has to be executed using past inputs, outputs and measurable disturbances, and, in this case, with $\Delta\mathbf{u} = [\varepsilon\ 0\ \ldots\ 0]^T$ where ε is a very small value, such as, u(k-1)/1000.

$$\mathbf{G}_{PNMPC}(:,1) = (\hat{\mathbf{Y}}^1 - \hat{\mathbf{Y}}^0) / \varepsilon$$

  - 3. Estimate the second column of the $\mathbf{G}_{PNMPC}$ matrix. The model has to be executed using past inputs, outputs and measurable disturbances, and, in this case, with $\Delta\mathbf{u} = [0\ \varepsilon\ \ldots\ 0]^T$.

$$\mathbf{G}_{PNMPC}(:,2) = (\hat{\mathbf{Y}}^2 - \hat{\mathbf{Y}}^0) / \varepsilon$$

  - 4. Continue with the remainder columns of $\mathbf{G}_{PNMPC}$ matrix until the last column where $\mathbf{Y}^{Nu}$ vector is obtained executing the model with past inputs and outputs, and with $\Delta\mathbf{u} = [0\ 0\ \ldots\ \varepsilon]^T$ where *Nu* is the control horizon.

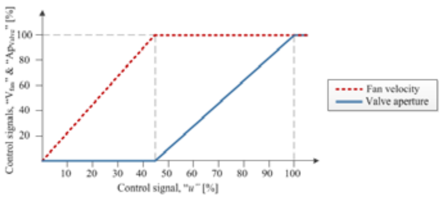
$$\mathbf{G}_{PNMPC}(:,Nu) = (\hat{\mathbf{Y}}^{Nu} - \hat{\mathbf{Y}}^0) / \varepsilon$$

A nonlinear controller for users' thermal comfort

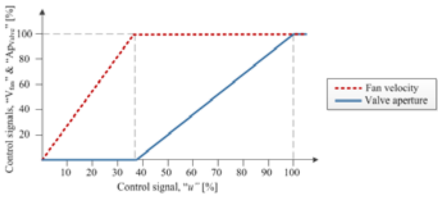
Control layer: Fancoil MISO Controller

- The fancoil unit available in the CDdI-CIESOL-ARFRISOL building allows to change the impulse air temperature by the regulation of the water flow through it, and/or the return air velocity.
- To do that, a discrete PI with antiwindup combined with a split-range control strategy has been used.

Winter

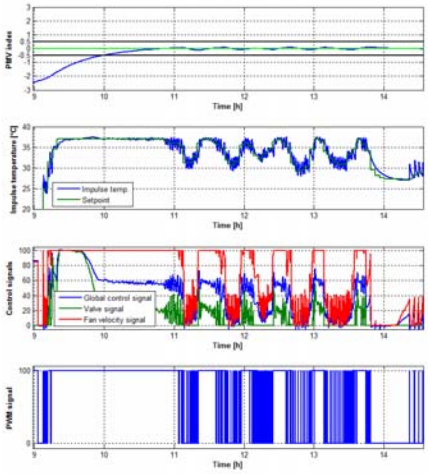


Summer



A nonlinear controller for users' thermal comfort

Results. Winter period

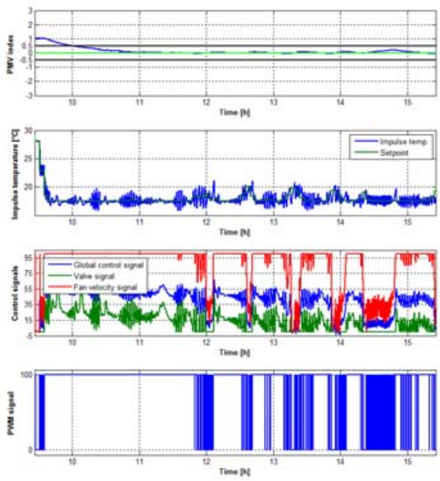


Linear approach	Nonlinear approach
22.83 (kW/h)	10.65 (kW/h)

Energy saving 53%

A nonlinear controller for users' thermal comfort

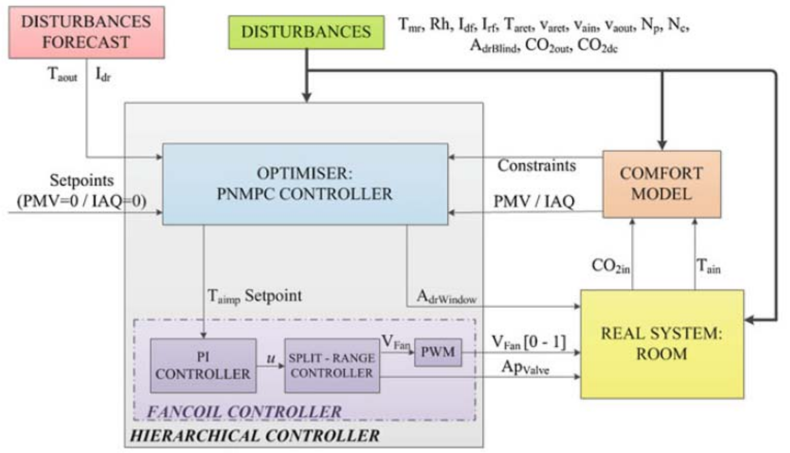
Results. Summer period



Linear approach	Nonlinear approach
35.39 (kW/h)	20.42 (kW/h)

Energy saving 42%

A multivariable nonlinear control for users' thermal comfort and indoor air quality



A multivariable nonlinear control for users' thermal comfort and indoor air quality

A multivariable nonlinear MPC approach

- In this case, for the multivariable approach:

$$\begin{bmatrix}\hat{y}_1\\ \hat{y}_2\end{bmatrix} = \begin{bmatrix}f_1\\ f_2\end{bmatrix} + G_{PNMPC}\begin{bmatrix}\Delta u_1\\ \Delta u_2\end{bmatrix}$$

$$\hat{\mathbf{y}} = \mathbf{f} + \mathbf{G}\Delta\mathbf{u}$$

$$\mathbf{f}_i = f(\mathbf{y}_{i_p}, \Delta\mathbf{u}_{j_p}, \Delta\mathbf{v}_p)$$

$$\hat{\mathbf{y}} = \begin{bmatrix}\hat{\mathbf{y}}_1\\ \hat{\mathbf{y}}_2\end{bmatrix}$$

$$G_{PNMPC} = \begin{bmatrix}\frac{\partial \hat{y}_1}{\partial \Delta u_1} & \frac{\partial \hat{y}_1}{\partial \Delta u_2}\\ \frac{\partial \hat{y}_2}{\partial \Delta u_1} & \frac{\partial \hat{y}_2}{\partial \Delta u_2}\end{bmatrix}$$

$$\mathbf{f} = \begin{bmatrix}\mathbf{f}_1\\ \mathbf{f}_2\end{bmatrix}$$

$$J = \sum_{i=1}^{2}\sum_{j=1}^{N}\delta_i[\hat{y}_i(k+j|k) - w_i(k+j)]^2 + \sum_{c=1}^{2}\sum_{j=1}^{N_u}\lambda_c[\Delta u_c(k+j-1)]^2$$

$$\mathbf{G} = \begin{bmatrix}\mathbf{G}_{1,1} & \mathbf{G}_{1,2}\\ \mathbf{G}_{2,1} & \mathbf{G}_{2,2}\end{bmatrix}$$

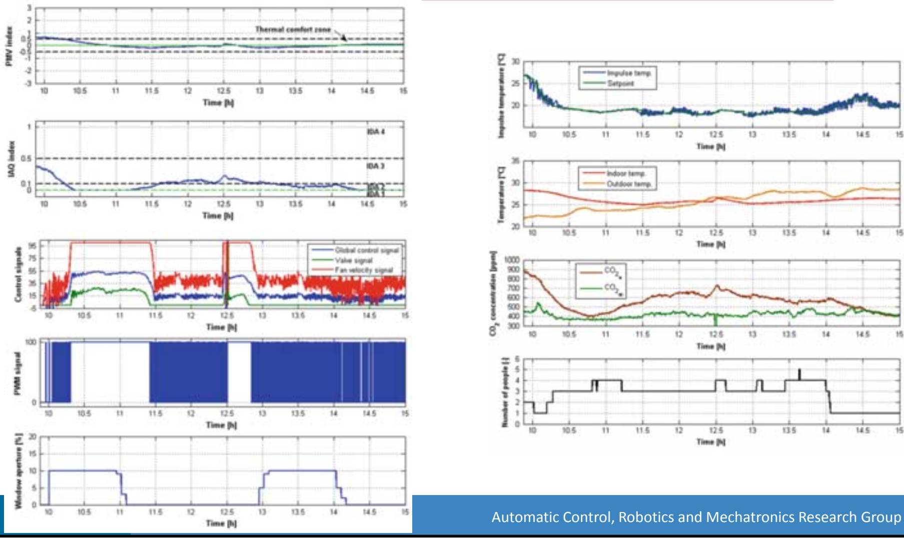
$$\begin{bmatrix}\Delta u_{1_{min}}\\ \Delta u_{2_{min}}\end{bmatrix} \le \begin{bmatrix}\Delta u_1(k+j-1)\\ \Delta u_2(k+j-1)\end{bmatrix} \le \begin{bmatrix}\Delta u_{1_{max}}\\ \Delta u_{2_{max}}\end{bmatrix} \quad \forall j = 1,\ldots,N_u$$

$$\Delta\mathbf{u} = \begin{bmatrix}\Delta\mathbf{u}_1\\ \Delta\mathbf{u}_2\end{bmatrix}$$

$$\begin{bmatrix}u_{1_{min}}\\ u_{2_{min}}\end{bmatrix} \le \begin{bmatrix}u_1(k+j-1)\\ u_2(k+j-1)\end{bmatrix} \le \begin{bmatrix}u_{1_{max}}\\ u_{2_{max}}\end{bmatrix} \quad \forall j = 1,\ldots,N_u.$$

A multivariable nonlinear control for users' thermal comfort and indoor air quality

MIMO controller simulation results

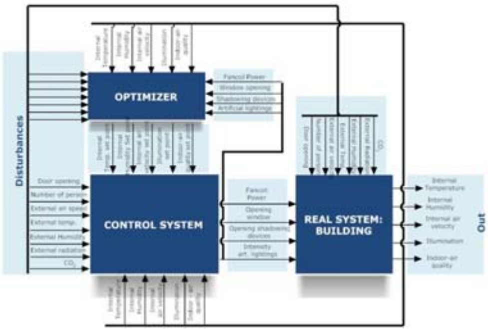


Index

Actual works

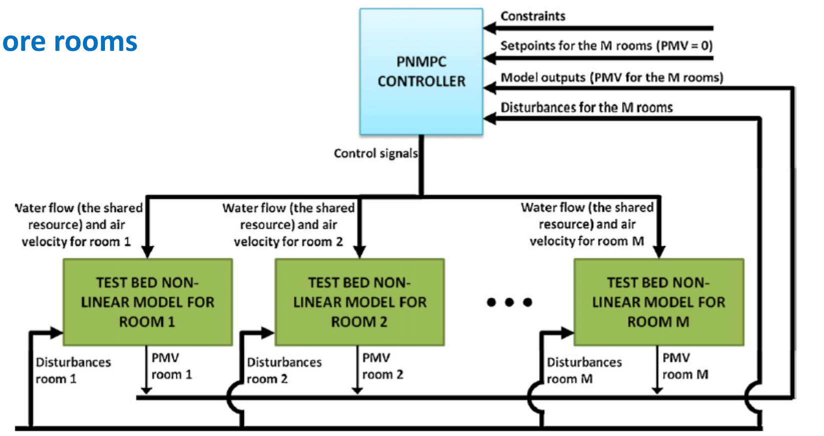
- Simplified modeling efforts
- Perform real tests of PNMPC approach in the building.
- Develop a distributed MPC controller.
- Obtain luminance and CO_2 concentration models for a typical room of the building.
- Develop a MIMO MPC/hierarchical controller in order to maintain users' comfort.

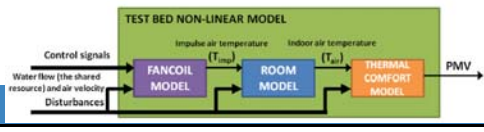
MIMO controller architecture



Actual works

More rooms





Actual works

More rooms

$$\sum_{i=1}^{M} u_i(t+j|t) \le a, \quad \forall j = 1, \ldots, N$$

$$\sum_{i=1}^{M} \dot{q}_{w_i} \le 60\ 1/\text{min},$$

$$N_i = 10 \quad N_{u_i} = 4$$

$$P(k): \ \min \ J(\Delta \mathbf{u}) = \frac{1}{2}\Delta \mathbf{u}^T \mathbf{H} \Delta \mathbf{u} + \mathbf{b}^T \Delta \mathbf{u} + f_0$$

$$\begin{aligned} \text{s.to}: \ & \mathbf{A}\mathbf{u} \le \mathbf{a} \\ & \Delta \mathbf{u}_{\min} \le \Delta \mathbf{u} \le \Delta \mathbf{u}_{\max} \\ & \mathbf{u}_{\min} \le \mathbf{u} \le \mathbf{u}_{\max} \\ & \hat{\mathbf{y}}_{\min} \le \hat{\mathbf{y}} \le \hat{\mathbf{y}}_{\max} \end{aligned}$$

$$-1\ 1/\text{min} \le \Delta \dot{q}_{w_i} \le 1\ 1/\text{min}$$

$$2\ 1/\text{min} \le \dot{q}_{w_i} \le 25\ 1/\text{min}$$

$$0.2\ \text{m/s} \le V_{\text{Fan}_i} \le 1.5\ \text{m/s}$$

$$-0.1\ 1/\text{min} \le \Delta V_{\text{Fan}_i} \le 0.1\ 1/\text{min}$$

$$4\lambda_{V_i} = \lambda_{q_i}$$

Actual works

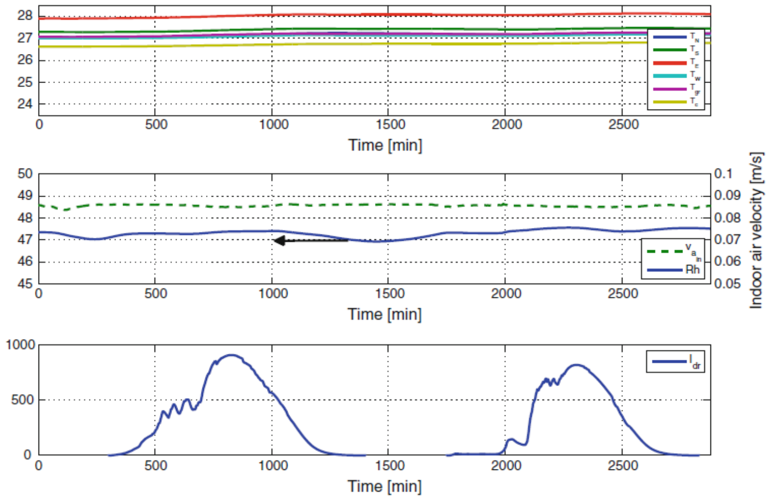


Fig. 5.41 Boundary conditions in the simulations. From *top* to *bottom*, *first graph* radiant temperatures (North, South, East, West, ceiling and ground), *second graph* indoor air velocity and indoor air humidity, and *third graph* direct solar irradiation (Álvarez et al. 2013)

Actual works

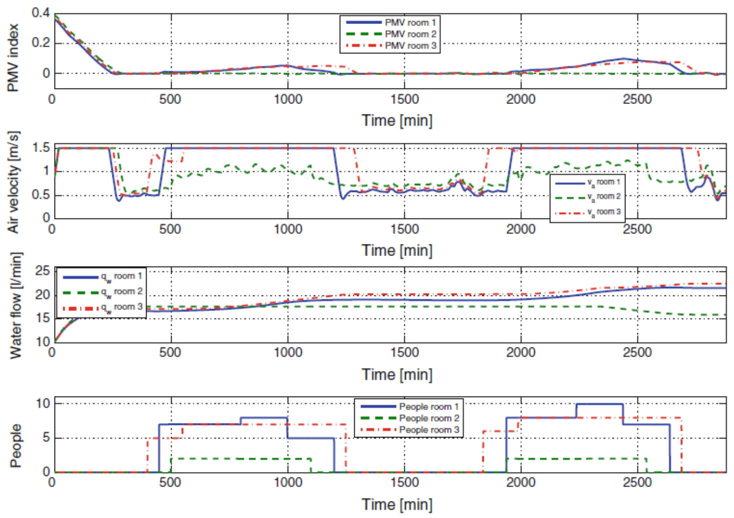
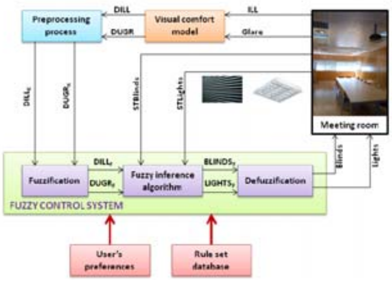
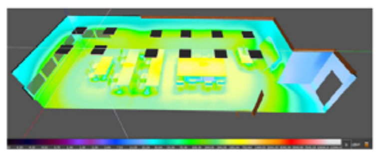


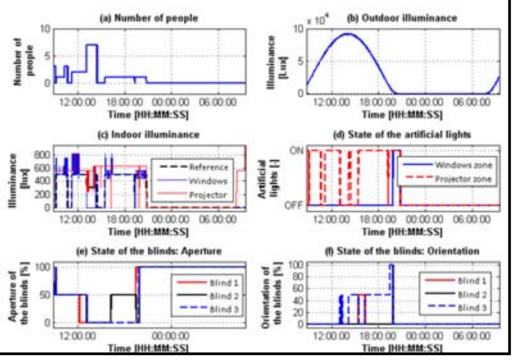
Fig. 5.42 Simulation test 1—results. From *top* to *bottom*, *first graph* PMV index, *second graph* fancoil air velocity, *third graph* water flow, and *fourth graph* number of people. Signals colour code, *solid blue* room 1, dashed *green* room 2, *dashed-dotted red* room 3 (Álvarez et al. 2013)

Actual works

Fuzzy Controller for Visual Comfort inside a Meeting-Room







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