THERMAL COMFORT PREDICTIVE CONTROL STRATEGIES FOR A SOLAR ENERGY RESEARCH CENTER

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1. Introduction

Energy efficiency and energy consumption management inside of buildings are topics which are currently receiving a great interest, where companies and research centres are putting special attention. (Kolokotsa et al., 2000). According to a recent study, energy consumption in buildings represents about 40% of total world energy consumption, more than half used by HVAC (Heating, Ventilating and Air Conditioning) systems, (Yang et al., 2003). For this reason, appropriate control strategies on HVAC systems which must be able to provide comfortable environments from a thermal, visual, and indoor-air quality points of view, are desirable in order to minimize HVAC energy consumption (Hernández, 2000).

In (Castilla et al., 2011) a comparison among several control strategies in order to maintain users' thermal comfort was performed. This work presents a more deeper study about the best control strategy obtained from (Castilla et al., 2011), that is, a classical Model Predictive Control (MPC) strategy, which allows to obtain a high thermal comfort level taking into account energy costs. Therefore, the main goal of this work is to choose an appropriate cost function for the MPC controller, achieving a tradeoff between the use of the HVAC system and users' thermal comfort for a long period of time (summer), even with extreme climate conditions.

Several cost functions for the MPC are tested in order to choose the most appropriated one. These cost functions have been specifically developed according energy reduction and zero PMV (*Predicted Mean Vote*) objectives. Finally, the advanced controllers has been tested in an existing building at the University of Almería, the energy research centre CDdI-CIESOL-ARFRISOL, although the results obtained with this control system can be extrapolated to any building with a suitable sensors network and a HVAC system.

2. Case study description

The experiences described in this work have been carried out in the building CDdI-CIESOL-ARFRISOL (Fig. 1). This building has two plants with a total surface of 1071.91 m2 and it is located inside the Campus of the University of Almería (South-Eastern of Spain). This research centre contains a HVAC based on solar energy use by one stage absorption cooling machine (Pasamontes et al., 2009). Overall building energy performance is being monitored having some of its rooms (Fig. 2) specifically dedicated to the study of comfort conditions and to the study of additional actuation capabilities (Ferre et al., 2009).There is a meteorological station placed on the roof of the building, which is monitoring outside temperature, relative humidity, CO2 level, solar radiation, and wind speed and direction.

The CDdI-CIESOL-ARFRISOL building is one of the five buildings (CDdI: "Research – demonstrator collector") studied in the project ARFRISOL (http://www.arfrisol.es), which is a singular strategic project of the Spanish R&D plan 2004-2011 financed by EU-ERDF funds and by the Spanish Ministry of Science and Innovation (MICINN). This project is headed by the Energy Efficiency Unit of CIEMAT and relies on the participation of research centres such as CIEMAT, the University of Almería or the University of Oviedo, the most important Spanish construction companies, and some of the Spanish solar technological companies.

Fig. 1: Outdoor CDdI-CIESOL-ARFRISOL building

Fig. 2: Sensors and actuators in a typical office

The five CDdIs studied within this project are located in Spain, at the University of Almería (South-East), Plataforma Solar de Almería (South-East), in CIEMAT-Madrid (Center), in Barredo-Asturias Foundation (North-West), and in CEDER-CIEMAT-Soria (North-East), respectively. Among other objectives, this project aims to establish a network of building being monitored under common and standardised specifications and to provide suitable building and climatic operation data sets for the elaboration of energy performance assessment procedures (Jiménez et al., 2010; Jiménez et al., 2011).

3. Thermal comfort

In accordance with the most part of international standards, such as (ISO 7730, 1994) and (ashrae55, 1992), thermal comfort can be defined as: *"That condition of mind which expresses satisfaction with the thermal environment"* (Fanger, 1973). This definition emphasizes that comfort is a cognitive process influenced by several kind of processes, i.e: physical, physiological or even psychological (Ashrae, 2009).

The estimation procedure of comfort conditions in a certain environment have been studied by many authors (Dear and Brager, 2001; Hoof, 2008; Orosa, 2009; Sherman, 1985; Wan et al., 2009). However, the most used index is the PMV (*Predicted Mean Vote*), which predicts the mean response about thermal sensation of a large group of people exposed to certain thermal conditions for a long time (IDAE, 2007). The value of this index is a seven-point thermal sensation scale that is shown in Tab. 1. Besides, to ensure thermal comfort conditions in a certain environment, different standards recommend to maintain the PMV index value at level 0 with a tolerance of ±0.5 (Liang and Du, 2005).

Tab. 1: Thermal sensation scale

PMV index value	Sensation
+3	Hot
+2	Warm
+1	Slightly warm
±0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

PMV is defined by six variables that are shown in Tab. 2. The most part of these variables can be obtained in a simple way by means of specific sensors (Tse and Chan, 2008). However, clothing insulation and metabolic rate are not estimated variables, that is, they are determined by the user situation when PMV index is estimated. Thus, if this situation is known, the values of these variables can be found in different standards (Ashrae55, 1992; ISO 7730, 1994).

Tab. 2: Variables which define PMV index

Parameter	Symbol	Range	Unit
Metabolic rate	M	0.8 – 4	met, $(W \cdot m^{-2})$*
Clothing insulation	I_{cl}	0 – 2	clo, $(m^2 \cdot {}^oC \cdot W^{-1})$**
Air temperature	y_T, (t_a)	10 – 30	ºC
Mean radiant temperature	$\bar{t}_r$	10 – 40	ºC
Air velocity	v_a	0 – 1	$m \cdot s^{-1}$
Relative humidity	y_{RH}	30 – 70	%

*** 1 met = 58.15 W/m^2**
**** 1 clo = 0.155 $m^{2o}C/W$**

Furthermore, human thermal sensation is strongly related with the thermal balance of the body, considering this a whole entity, where the human body is in a heat balance situation, for example, the heat produced by metabolism must be equal to the amount of heat lost by the human body. Thus, when the human body is in this balance situation, he/she is in ideal conditions of comfort and the PMV index is equal to 0 (IDAE, 2007). The PMV index can be estimated according to this balance and the six previous variables just as (eq. 1).

$$y_{PMV} = [0.303\exp(-0.036M) + 0.028]\cdot L \qquad (eq.1)$$

$$L = (M-Q) - 0.0014\cdot M\cdot(34-y_T) - 3.05\cdot 10^{-3}\cdot[5733-6.99\cdot(M-Q)-p_a] - 0.42\cdot(M-Q-58.15)$$
$$-1.72\cdot 10^{-5}\cdot M\cdot(5867-p_a) - 39.6\cdot 10^{-9}\cdot f_{cl}\cdot[(t_{cl}+273)^4-(\bar{t_r}+273)^4] - f_{cl}\cdot h_c\cdot(t_{cl}-y_T) \qquad (eq.2)$$

where

- Q: external work [W·m^{-2}], that is, the developed work performed by muscles doing a certain task.
- y_T: air temperature [ºC].
- p_a: partial water vapour pressure in the air [Pa]. Relative humidity, y_{HR}, is the relation, expressed in percentage, between partial water vapor pressure in the air and saturated water vapor pressure from a temperature.
- t_{cl}: clothing surface temperature [ºC].
- h_c: convective heat transfer coefficient [m^2·ºC·W^{-1}].
- I_{cl}: clothing insulation [m^2·ºC·W^{-1}].
- f_{cl}: clothing area factor [–].
- v_a: air velocity [m·s^{-1}]

In previous equations, *L* is the thermal load in the human body [W·m^{-2}], defined as the difference between the internal heat production and the heat lost which occurs when the person is in a thermal situation, and *M* is the metabolic rate [W·m^{-2}]. The procedure to estimate PMV index and the t_{cl}, h_c and f_{cl} variables is widely described in (Castilla et al., 2010b, 2011).

4. Control system architecture

In (Castilla et al., 2010a) several comfort analyses of CdDI-CIESOL-ARFRISOL building were done. In accordance with these analyses, it has been concluded that it is necessary to develop a specific control system, which allows to obtain a tradeoff between HVAC system energy consumption and users' thermal comfort. More specifically, the system developed in this work consists in a classical Model-based Predictive Control (MPC) architecture (Castilla et al., 2010b). The main control objective is to maintain users' thermal comfort inside the comfort zone defined by the PMV index, (eq. 1).

To the development of this control system, it has considered that there is only one actuator available inside the CdDI-CIESOL-ARFRISOL building to control thermal comfort, the HVAC system based on solar cooling (Pasamontes et al., 2009). The HVAC system is characterized by having two operation modes: summer and winter. For each of them, a nominal linearized model around an operation point, which represents air temperature dynamics (ºC) as a function of fan-coil velocity (%), has been obtained by means of classical identification techniques (Rivera and Jun, 2000). Moreover, to identify the models associated with each operation mode of HVAC system (summer and winter) Pseudo-Random Binary Signals (PRBS) were used. In (eq. 3), the continuous-time transfer functions in the Laplace variable s of these linearized models are shown:

$$G(s) = \frac{Y_T(s)}{U(s)} = \frac{k}{\tau s+1};\begin{cases} summer: & k = -0.037, \tau=41.67 \\ winter: & k = -0.0755, \tau=44.17 \end{cases}$$

where the static gain of each model, *k*, is expressed in ºC/% and the time constant, τ, is in minutes. These transfer functions relate the changes in the mass flow air supplied by the HVAC system with changes in the indoor room temperature. Although, they are very simple Linear-Time Invariant (LTI) models, they have a correct performance, in the sense that, different uncertainties associated with the process does not affect system behaviour in closed loop. However, in future works, models based on first principles will be developed. Besides, these models will include external climate prediction models, since in this work, disturbances have been considered as a constant equals to its actual value along temporal horizon defined in the framework of the MPC algorithm.

This control system depends on the relations between PMV index and the indoor temperature (static relationship (eq. 1 – 2)) and the indoor temperature with fan-coil velocity (discrete time versions of models described by (eq. 3) using a sample time of $T_s = 5$ min).

4.1. Model-based Predictive Control (MPC)

Model-based Predictive Control is one of the most used techniques in comfort control (Castilla et al., 2011; Donaisky et al., 2007; Freire et al., 2006; Freire et al., 2008). The importance of this technique lies in the use of a model (of the system, the noises and the disturbances) to make predictions of the future outputs. Furthermore, these predictions are included inside a cost function which establishes a relationship between the close-loop behaviour of the system and the control effort. Subsequently, this cost function is minimized taking into account the constraints of the problem. Finally, a receding horizon strategy is implemented, that is, only the first control signal value obtained is applied to the system, and in the next sample time, new measurements are obtained and the algorithm is repeated.

More specifically, in (Castilla et al., 2011), a comparison between a hierarchical and a classical Model Predictive Control strategy is done. The main objective of that work was to obtain the strategy with a better behaviour inside the CDdI-CIESOL-ARFRISOL building during a short period of time and with not very extreme climate, the month of September. The results showed that the best result was obtained with a classical Model Predictive Control. Therefore, in this work, that strategy is applied for a long period of time (summer) with the purpose of demonstrating that it is capable to maintain thermal comfort even with extreme climate conditions, since Almería (the place where the CDdI-CIESOL-ARFRISOL building is located) is characterized by having a Mediterranean arid climate with a maximum mean temperature during summer around 31 ºC.

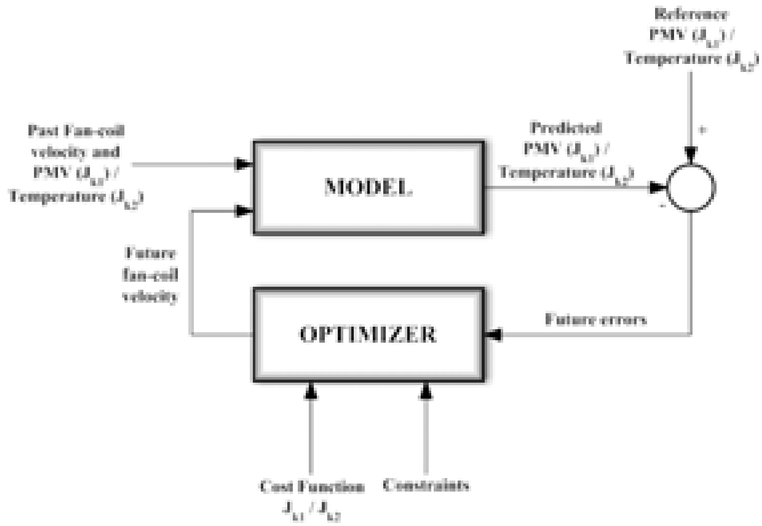

Fig. 3: Classical predictive control system architecture

This strategy has been tested inside the CdDI-CIESOL-ARFRISOL building, where two different cost functions have been used, see Fig. 3. Therefore, the optimization problem is represented by (eq. 4), and the two cost functions by (eq. 5) and (eq. 6).

$$u = min_u \, J_{k\{1,2\}} \quad (eq. 4)$$

where

$$J_{k1} = \sum_{j=0}^{N-1} y_{PMV}(k+j|k)^2 + \lambda \sum_{j=0}^{N-1} u(k+j|k)^2 \quad (eq. 5)$$

$$J_{k2} = \sum_{j=0}^{N-1} (w(k+j|k) - y_T(k+j|k))^2 + \lambda \sum_{j=0}^{N-1} u(k+j|k)^2 \quad (eq. 6)$$

In (eq. 4 – 6), N is the prediction horizon, λ is a weighting factor, and $y_{PMV}(k+j|k)$, $y_T(k+j|k)$ and $u(k+j|k)$ are the predictions PMV index, indoor temperature, and control signal (fan-coil velocity) respectively, estimated at sample time $k+j$ with the information available at sample time k. Besides, $w(k+j|k)$ is the future reference estimated for the indoor temperature.

The first control law defined by (eq. 4) and (eq. 5) tries to find out the best future control sequence, $\boldsymbol{u}$, which is able to minimize the PMV index within the prediction horizon (in this case the PMV index reference in the Fig. 3 is equal to zero, since it is the desired value). Notice that, at the same time, the cost associated with the control action is penalized. Remember that, the first part of the cost function defined by (eq. 5) can be related to the control action by means of the static non-linear relation between PMV index and the indoor temperature, (eq. 1 – 2), and the discrete time version of the transfer functions (eq. 3) which relate indoor temperature and fan-coil velocity.

In the second control law, (eq. 4) and (eq. 6), a two-step optimization algorithm is used. In a first stage, an indoor temperature reference is estimated, $w(k)$, through the resolution of a non-linear optimization problem based on (eq. 1 – 2), where using the current climate variables, the problem is solved looking for a PMV value equal to zero. Afterwards, an indoor temperature reference array of length N, $\boldsymbol{w}$, is built with all its elements equal to this value of indoor temperature, $w(k)$. Then, in a second stage, the MPC strategy, based on the cost function defined by (eq. 6) tries to minimize the future temperature tracking error, that is, it tries to minimize the difference between the future estimated indoor temperature ($\boldsymbol{y_T}$) and the reference indoor temperature ($\boldsymbol{w}$). Furthermore, at the same time, the action control required to reach this reference indoor temperature is penalized through the weighting factor λ. The main difference with the first control law is that, in this case, the first part of the cost function (eq. 6) represents the error between reference indoor temperature and the estimated indoor temperature, instead of the PMV index associated with the estimated indoor temperature.

Besides, the optimization problem is subject to several system constraints given by (eq. 7) and (eq. 8). The first constraint provides the lower limit (y_{Tmin}) and the upper limit (y_{Tmax}) of the output variable. The second constraint makes reference to the physical constraints of the HVAC system, in other words, it takes the fan-coil saturation [u_{min}, u_{max}] into account.

$$y_{T_{min}} \leq y_T(k+j|k) \leq y_{T_{max}} \qquad \forall j = 0,\ldots,N-1 \quad (eq.7)$$

$$u_{min} \leq u(k+j|k) \leq u_{max} \qquad \forall j = 0,\ldots,N-1 \quad (eq.8)$$

Finally, independent of the selected cost function, problem (eq. 4) is solved as a MPC non-linear optimization where a control action sequence, $\boldsymbol{u}$, is calculated and only the first value of the obtained control signal is applied to the system (receding horizon strategy). Then, in the next sample time, new measurements are acquired and the algorithm is repeated.

4.2. Pulse Width Modulation of the continuous control signal

At each sample time the previous optimization algorithm provides a fan-coil velocity value that has to be provided by the actuator (within the range 0 – 100%). However, the usual industrial fan-coils are implemented through discrete on/off actions. Therefore, it is necessary to transform the computed fan-coil velocity in such a way that the control action can be provided by means of the discrete actuator. The usual way of doing this is through a PWM (*Pulse Width Modulation*) signal (Salsbury, 2002). In this case, the PWM signal is characterized by having a cycle time, C, equals to five minutes, an internal sample time of a second, a minimum time for which the control signal is equal to 100%, T_{on} = 5 min, and a minimum time for which the control signal is equal to 0%, T_{off} = 2 min. Besides that, a neutral zone of 0.25 ºC has been defined to avoid oscillations around the setpoint.

5. Results and discussion

The control strategy described in Section 4 has been implemented inside the CdDI-CIESOL-ARFRISOL building during summer 2010. The different weighting coefficients (λ) have been selected to provide a similar performance and the obtained results have been analyzed from a thermal comfort and energy consumption points of view.

More specifically, with the main objective of analyze the effect of the weighting coefficient in the system behaviour and the associated costs, two different weighting coefficients have been determined for each strategy. To compare the different strategies among them, it is necessary that each variable which affects thermal comfort is the same in different tests including the number of people inside the room. However, it is almost impossible to find different days with identical conditions, since these variables are not controllable. The room selected for the tests is located on the second floor of the CdDI-CIESOL-ARFRISOL building, and it is characterized by having North orientation, a total surface of 27.78 m^2 and a typical number of occupants equal to five. Thus, apart from real tests, a typical day from the analyzed period, which is shown in Fig. 4, has been chosen to compare different strategies through simulations. On the other hand, in these simulations, indoor air velocity has been considered as a constant and equivalent to that achieved when the HVAC system is operating, and also that the room being studied has five occupants during the tests.

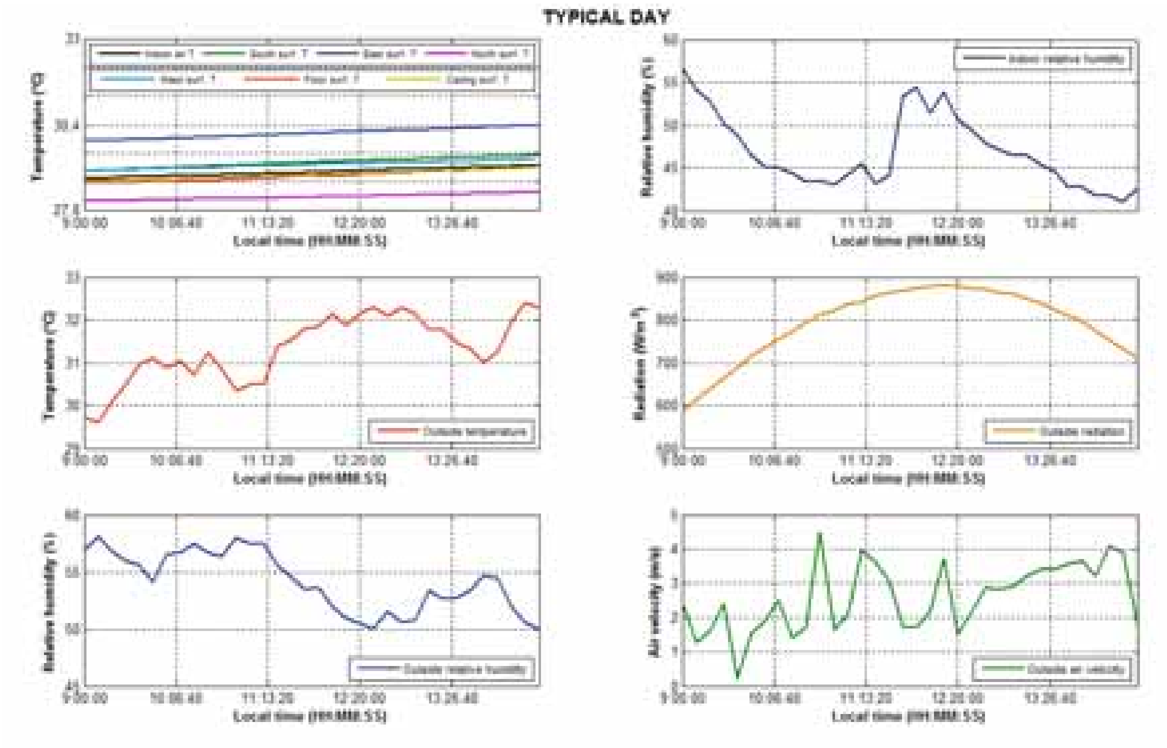

Fig. 4: Climate variables of the typical day

Therefore, several simulations have been carried out during a typical day in order to estimate equivalent weighting coefficients based on a comparison criterion: the Integral Square Error (ISE) criterion. In (eq. 9) its mathematical formulation can be observed, where *e(t)* is the error between the real and the simulated responses.

$$ISE=\int_0^\infty e(t)^2 dt \quad (eq.9)$$

Tab. 3: Lambda (λ) choices as a function of ISE criterion

Strategy	Lambda (λ)	ISE Criterion
(A): J_{k1}	0.002	21.24
	0.00355	33.53
(B): J_{k2}	0.005	20.20
	0.014	33.06

Once the weighting coefficients have been determined, see Tab. 3, real test for each strategy with its associated weighting coefficients have been realized inside the CdDI-CIESOL-ARFRISOL building. To be able of compare these strategies among them, several tests have been performed looking for those days with the most similar weather conditions. Notice that all the tests have been carried out with the same number of people inside the room (five people), although with several uncontrollable disturbances due to short variations in this number. Real results from experiments performed in CdDI-CIESOL-ARFRISOL building for each strategy can be observed in Figs. 5 – 6.

More specifically, the results of the real experiments figures can be divided in two parts: the left side contains the results for the day in which the lower value of λ of each strategy has been used, while the right side shows the results for the day in which the higher value of λ has been tested. Besides, each column shows the PMV index evolution, the indoor, outdoor and mean radiant temperatures, the fan-coil velocity (control signal), and the indoor relative humidity. A comparison among different strategies can be observed in Tab. 4. This comparison is based on three performance indexes: (i) first index is useful to determine if the actuator is over-actuated, since it expresses the mean number of changes in HVAC state (on/off) per hour, (ii) the second index determines the percentage of time the actuator is used, and (iii) the third index shows the mean energy consumption per hour associated with the use of the actuator.

Tab. 4: Summary of the results obtained for each strategy

Strategy	Lambda (λ)	Index 1*	Index 2**	Index 3***
(A)	0.002	124	53.18	69
	0.00355	77	29.78	39
(B)	0.005	67	74.33	97
	0.014	92	31.27	41

*** Average number of changes per hour [–]**
**** Percentage of total time in which the HVAC system is connected [%]**
***** Average energy consumption per hour [W]**

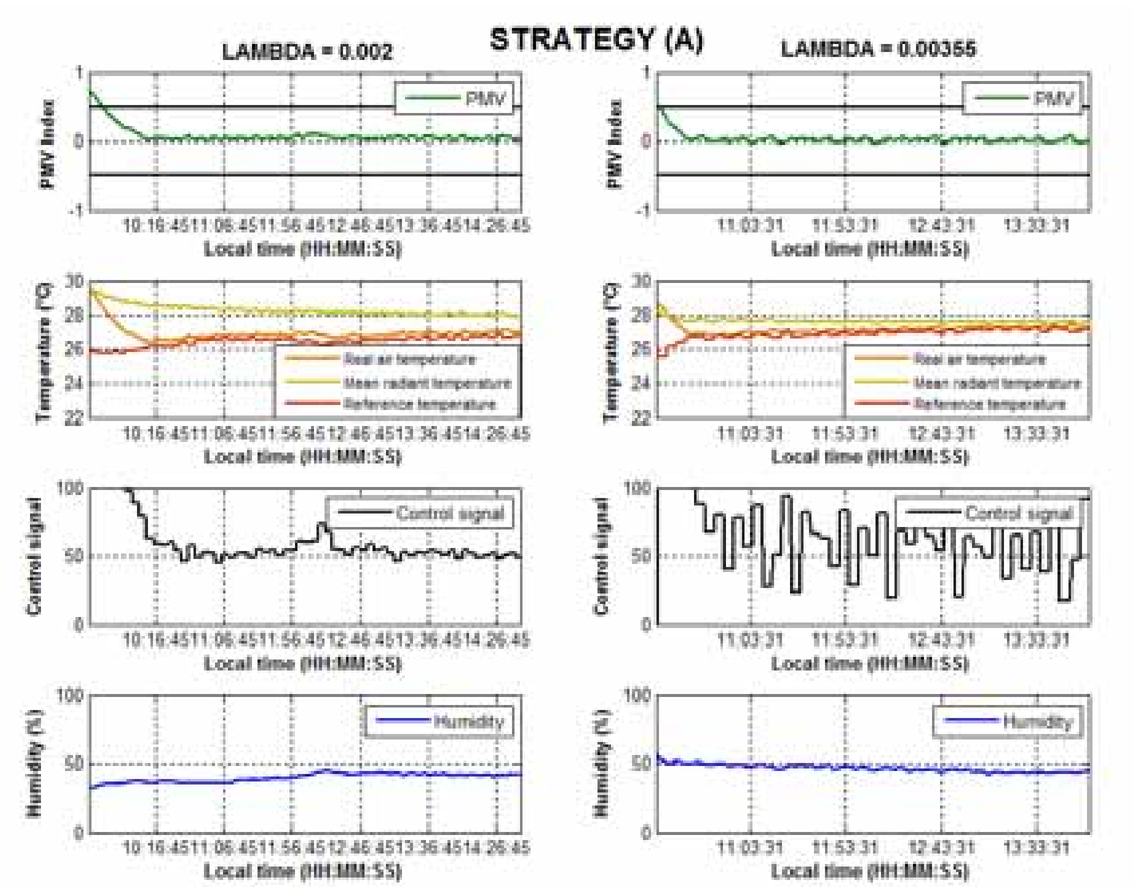

Fig. 5: Real results using strategy (A)

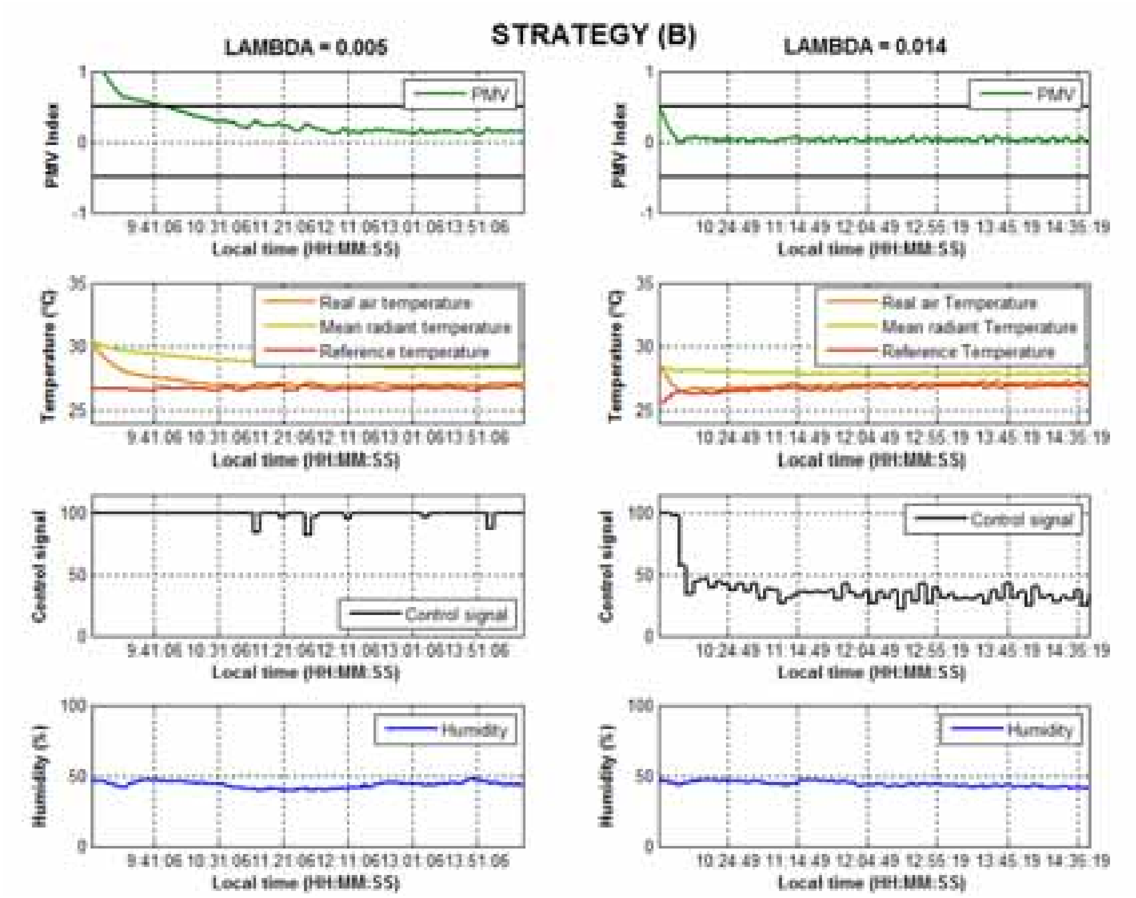

Fig. 6: Real results using strategy (B)

The results obtained for the strategy (A) are shown in Fig. 5 and the results for the strategy (B) are shown in Fig. 6. As commented previously, these tests have been performed along summer. Furthermore, in both strategies, the tests performed with a lower value of lambda were realized in the month of July, and the tests with a higher value of lambda were realized in September. Therefore, as a function of the commented before, and according to the ISE criterion, see Tab. 3, comparisons between strategy (A) with weighting coefficient equals to 0.002 and strategy (B) with weighting coefficient equals to 0.005, and between strategy (A) with weighting coefficient equals to 0.00355 and strategy (B) with weighting coefficient equals to 0.014, can be established.

More specifically, the test associated with strategy (A) and weighting coefficient equals to 0.002 was performed in the month of July, and as can be observed in the left side of Fig. 5, the initial PMV index value was above the comfort zone defined by the PMV index. However, the developed control strategy achieved that PMV index reaches a value almost equals to zero through the use of the fancoil. First, it is used at 100% of its capacity for about thirty five minutes, and then its use is reduced to 50%.

On the other hand, the results of strategy (B) with weighting coefficient equals to 0.005, which are shown in the left side of Fig. 6, were obtained in a too hot day in the month of July. As in the previous case, the initial PMV index value was situated outside the comfort zone, specifically, above this zone. Therefore, the strategy (B) tried to reach a PMV index value almost equals to zero, even although the fancoil was operating at 100% of its capacity the most part of the test, it only achieved to reach a PMV index value equals to 0.2, which, although it is not the optimal value, is inside the comfort zone.

Finally, the other tests were performed during September, hence, in both of them, as can be observed in the right side of Fig. 5 and Fig. 6, the initial value of PMV index was inside the comfort zone and approximately only a 50% of total fancoil capacity had to be used in order to reach a PMV index value almost equal to zero.

Therefore, as it is shown in Fig. 5 and Fig. 6, all the performed tests, except strategy (B) with weighting coefficient equals to 0.005, achieve an energy saving in the use of HVAC system in comparison with a traditional HVAC system, which is used approximately at 100% of its capacity along this period of time.

To compare strategy (A) with weighting coefficient equals to 0.002 and strategy (B) with a λ value of 0.005, it can be observed that under approximately similar conditions of number of occupants (five persons), indoor temperature, relative humidity and an initial value of PMV index situated outside the comfort zone, the PMV index is almost equal to zero with $\lambda = 0.002$, but in the case of strategy (B) with $\lambda = 0.005$ the PMV index is approximately equal to 0.2, even although the use of the fan-coil is very high.

Just like the previous comparison, these tests have been performed under similar conditions of number of occupants (five persons), indoor temperature, and relative humidity. Hence, the comparison between strategy (A) with $\lambda = 0.00355$ and strategy (B) with $\lambda = 0.014$ show that both strategies reach a PMV index value almost equal to zero. However, the time necessary to reach it is lower strategy (B), but it also has a greater use of the fan-coil actuator.

On the other hand, if the results shown in Tab. 4 for each strategy are compared, it can be observed that the strategy with lower mean energy consumption per hour is the strategy (A) with a weighting coefficient equals to 0.00355. Nevertheless, it can be observed that this strategy has a greater average number of changes per hour than strategy (B) with a weighting coefficient equals to 0.005. However, the previous strategy has the greatest mean energy consumption. Therefore, after an exhaustive analysis of the results, strategy (A) with a weighting coefficient equals to 0.00355 has been selected to use in future works. This strategy is characterized by having the minimum use of the actuator and energy consumption per hour and the second minimum mean number of changes. Besides, the existing difference between it and strategy (B) with weighting coefficient equals to 0.005 (strategy with minimum mean number of changes per hour) is not very significant in comparison to the other strategies.

6. Conclusions

In this work, several MPC controllers which provides a tradeoff between energy saving and users' thermal comfort has been presented. These advanced control techniques have been tested inside the CdDI-CIESOL-ARFRISOL building which is located in Almería, in the South-East of Spain. Almería is characterized by having hot and dry summers, since the MPC controllers have been tested from July to September in such a climate, it is possible to conclude that they are able to maintain users' thermal comfort even with extreme outside climate conditions. From the obtained results, it can be determined that the best strategy for the system is a MPC controller with a weighting coefficient equals to 0.00355.

Future works are aimed to use a complete indoor building climate model, an external climate prediction models and a people counting system in order to improve the current results. Finally, these results will be integrated in a multi-objective hierarchical control system able to guarantee users' comfort from a thermal, visual and indoor-air quality point of view, and, at the same time, able to achieve the greatest energy saving.

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