Assessment of thermal comfort and energy savings in a field study on adaptive comfort with application for mixed mode offices

Abstract

The study of the thermal comfort of the occupants of a building represents an important challenge, due to its close relation with energy efficiency. Facing the application of set-point temperatures, the adaptive comfort model proposes the linking of the comfort temperature to the outdoor temperature which would potentially reduce the use of the HVAC system. Although there are studies that propose experimental adaptive models, few verify their effectiveness. In the current study an adaptive comfort algorithm for hybrid buildings is experimentally validated based on a 17-month field study in office buildings in Spain. The implementation of the algorithm in the HVAC control system, both during the cooling and the heating period, allowed for the evaluation of the energy consumption, obtaining savings of 27.5% and 11.4% respectively. The percentage of thermal sensation votes in comfort evolved from 94% (prior to implementing the comfort algorithm) to 87.5% (once implemented) for the summer season and from 79.5% to 81.6% for the winter season. The results demonstrate that the adaptive model is effective for the optimization of HVAC systems, and that it is possible to achieve energy savings without impairing the comfort of its occupants for the type of climate and buildings considered.

Keywords: thermal comfort; mixed mode; energy savings; baseline

1. Introduction

The thermal comfort (TC)-energy efficiency (EE) dilemma represents a major challenge in the operation and management of buildings [1]. In the area of thermal comfort, many field studies have been carried out in buildings of different nature and in zones with different climate [2]. Firstly, most of them were based on the Predicted Mean Vote until numerous subsequent studies demonstrated that this steady state approach failed as it was discussed in Peeters, L. et al. [3] based on several references that support such sentence. People, by nature, are able to adapt to the changing conditions of the thermal environment, which forms the basis of the adaptive thermal comfort approach: *if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort*. The indoor temperature where most people are comfortable is known as neutral or comfort temperature. Nicol and Humphreys [4] proposed that this temperature was closely correlated with the outdoor temperature and they also suggested that an algorithm could be defined to determine the optimum indoor temperature as a linear function of the mean outdoor temperature for free running (FR) buildings.

The results of field studies on adaptive models have important implications for energy consumption [2]. Applying the adaptive comfort temperature as a room temperature set-point potentially reduces the use of the HVAC system. The savings are mainly due to the acceptance of higher indoor temperatures than those recommended in summer periods and lower than those recommended in winter periods [5]. In situations or places where the use of the HVAC system is unavoidable, a greater acceptability range of the thermal environment will lead to lower energy consumption [6,7].

In the area of energy efficiency, the application of energy conservation measures (ECMs) in buildings can lead to a substantial reduction in energy consumption [8,9] and although to date, several studies have faced the implementation of energy conservation measures, most of these measures do not focus on the set-point temperature of HVAC systems and cover other aspects [2,10,11].

Therefore, it is common for TC-related problems to be addressed separately to EE-related problems, so that, in the literature, studies can be found in the two fields but there is a smaller amount of research integrating both concepts. Although in [12], both objectives were simultaneously contemplated obtaining an experimental adaptive comfort algorithm (ACA) and quantifying up to 30% of energy savings without impairing the comfort of the occupants, few follow-up studies have followed this approach. Those studies which are based on adaptive comfort approach, in the case of implementing the obtained algorithm, opt for either the verification of the energy saving [13,14] or the verification of the comfort of the users [15]. There are also studies that quantify the energy savings based on the change of the set-point temperature in a static way [16,17] and there are a large number of references based on modelling and simulation in which it is necessary to emphasize that the own methods used implicitly carries some uncertainty since it is not possible to incorporate all the factors that are contemplated in the field studies and that can affect the obtained results [5,18,19].

Another issue to be highlighted in relation to energy efficiency is the quantification of energy savings. Initially one of the major obstacles was the lack of basis to establish a baseline energy consumption (hereinafter referred to as baseline), which is necessary to determine improvements in energy efficiency. Due to the importance of quantifying the savings, numerous efforts have been made to develop standard protocols to verify it [20]. In 1997 the Efficiency Valuation Organization (EVO) published the

International Performance Measurement and Verification Protocol (IPMVP) [21] where standardized methods for the measurement and verification of savings were developed and in 2002 ASHRAE published its guidelines for energy measurement and saving demand [22]. Both organizations are considered to be the main international benchmarks for measuring and verifying energy savings [23].

One of the fundamental aspects that they face is the standardization of the evaluation and verification of savings based on the basis that these can't be measured directly, since the savings represent a decrease compared to a previous situation that does not occur simultaneously. The savings should therefore be determined by comparing the measured consumption after the implementation of an improvement (verification period) and the prevision of the energy consumption of the baseline (obtained in the model period) before it [24,25]. Likewise, Reichl and Kollmann [26] highlighted the need for a formalization of the baseline development process.

Several approaches to determine baseline consumption can now be found in the literature [25,27,28]. Although one of the most commonly used approaches for baseline determination is the direct application of regression methods [25], it implies the need for a subsequent calibration and given that the uncertainty of the savings measured using such method is a widely discussed issue today [29,30] the model proposed in the current field study is based on the application of transfer functions. There are several reasons that justify the use of transfer function models versus generalized linear models. The relationship is almost instantaneous and established a priori. Also, the input variables influence the output variables but not vice versa and it is not necessary to calibrate the model afterwards. Although currently models based on transfer functions are used in all scientific fields to evaluate dynamic responses, the first precedent of this method is in the field of construction [31].

Due to the fact that an important development in EE-TC research should be the quantification of energy savings and the evaluation of the real impact on occupants' satisfaction, the objective of the current study is empirically verifying that the adaptive control algorithms lead to equivalent comfort conditions with reduction in energy consumption comparing with a fixed set point temperature.

The following sections detail the proposed methodology for it, based on adaptive thermal comfort approach, including the analysis of the results (both in terms of thermal comfort and energy consumption) and the main conclusions.

2. Methodology

Four main phases can be identified in the proposed methodology. Phase 1 involves a field study on thermal comfort and the methods to obtain an experimental adaptive comfort algorithm. Phase 2 of integration comprise the implementation of the ACA in the control system of a building. Phase 3 involves the measurements of the energy savings. Phase 4 involves the validation of the ACA in terms of thermal comfort and energy savings. Although the attainment of the experimental adaptive comfort algorithm is not developed in the present article (phase 1), the essential information related to it is shown in order to easily analyse and understand all the results.

2.1 Field study (phase 1)

2.1.1 Evaluation of thermal comfort

Phase 1 involves a field study based on the adaptive thermal comfort approach [12,32,33]. For this purpose, 11 office spaces were selected with 54 workers in three non-residential buildings and located in the Southwest region of Spain, in Seville (37°N, 5°W). Most of the rooms had similar dimensions and they were homogeneous in terms of occupancy and use. All the spaces dated from the 90's, had double glass windows and blinds that could be opened and closed manually with NE/SE, NE and E orientation. Two of the three buildings were classified as mixed mode or hybrid (MM) buildings and operated by switching from the natural ventilation mode to the conditioned/heated mode [11].

The climate in Seville is characterized by variable rainfall, dry and very hot summers and mild and humid winters. **Table 1** shows the mean and standard deviation of the average monthly outdoor temperature (T_{mean}), the mean and standard deviation of the maximum monthly outdoor temperature (T_{max}) and the mean and standard deviation of the average monthly outdoor relative humidity (HR_{mean}) during 2016.

Table 1. Outdoor climate

Variables		Jan	Feb.	March.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
$T_{mean}(°C)$	m	12.7	12.9	13.0	16.5	19.8	25.8	29.4	29.5	25.8	21.3	14.3	12.8
	s.d	2.1	2.6	1.8	2.3	2.7	2.6	1.6	1.3	3.5	2.3	2.8	1.9
$T_{max}(°C)$	m	16.9	17.8	19.8	22.2	25.8	33.7	37.3	37.5	33.5	27.1	19.2	17.3
	s.d	1.9	2.6	2.0	3.1	4.6	3.5	2.8	1.8	4.6	3.7	3.3	1.9
$HR_{mean}(\%)$	m	81.4	70.2	65.1	66.7	58.9	43.0	41.8	41.5	48.7	66.6	74.1	80.9
	s.d	8.6	12.2	11.2	12.0	18.6	10.3	10.8	8.2	11.7	11.6	11.7	6.7

The complete field study was carried out for one year and five months, from October 2015 to March 2017. About 6.376 thermal sensation data, more than 1.000.000 data sets of sensors and almost 100.000

sets of system operating HVAC data were collected during that time. To measure the indoor thermal environment experienced by occupants, standalone data loggers were used (including air temperature, relative humidity, globe temperature, air velocity, surface temperature, $C0_2$ concentration and luminosity) at 15 minutes intervals throughout the whole monitoring period (17 months). The instruments were placed on users' desks or as close to them as possible and away from external heat sources. Outdoor temperature was measured by a weather station available in the buildings.

In order to evaluate the thermal comfort of the occupants, a longitudinal survey and two additional weekly questionnaires were elaborated. For the thermal sensation vote (TSV) two thermal sensation scales were used based on ASHRAE scale. Additionally, the Nicol scale of five points of thermal preference (TP) was used as well as a binary scale to evaluate the acceptability of the indoor environment. **Table 2** shows the scales used in the field study as well as the implementation period of each one.

Table 2. Scales in the field study

Scales		Period
Thermal sensation_I	warm (w), slightly warm (sw), neutral (n), slightly cool (sc), cool (c)	12 months (October 2015-October 2016)
Thermal sensation_II	hot (h), warm (w), slightly warm (sw), neutral (n), slightly cool (sc), cool (c), cold (cd)	5 months (October 2016-March 2017)
Thermal preference (Nicol scale)	much cooler (mc), a bit cooler (bc), no change (nc), a bit warmer (bw), much warmer (mw)	17 months (October 2015-March 2017)
Acceptability (binary scale)	unacceptable (uc), acceptable (ac)	17 months (October 2015-March 2017)

The Griffith method was used to calculate the comfort temperature or neutral temperature proposed by EN15251 [34] and for evaluating the relationship between the comfort indoor temperature and the outdoor, the running mean temperature (T_{rm}) was used. Eq. (1) represents the relationship between the comfort temperature and the running mean temperature in the form of an adaptive comfort algorithm based on the experimental data. For the better understanding of the current study, the procedure for obtaining the proposed ACA for hybrid buildings is not explained in detail and can be consulted in [35].

$$T_{comfort\_MM} = 0.24\, T_{rm} + 19.3 \qquad (n=3739, R^2=0.41, p<0.001) \qquad (1)$$

2.1.2 Evaluation of energy consumption

In order to evaluate the sensitive heat capacity delivered by the HVAC system, Eq. (2) was used.

$$\dot{Q} = \dot{m}\, C_{p\,air}\, |\Delta T| \qquad (2)$$

Where $\dot{Q}$ is the sensitive heat capacity delivered, $\dot{m}$ the airflow of the fan-coil, $C_{p\,air}$ the specific heat of air and $|\Delta T|$ the drop of the air temperature of the fan-coil, that is to say, its difference in air temperature. The drop of the air temperature was measured by two sensors installed for this purpose, one in the air inlet and the other one in the air outlet of each of the fan coils in the rooms under study. The air velocity of each fan coils was monitored by the Building Management System and the fan coils' technical specifications were consulted to know the proportional airflow rate.

The energy consumption was calculated based on Eq. (3).

$$C = \dot{Q} / \bar{\zeta}_{seasonal} \tag{3}$$

Where C is the energy consumption, $\dot{Q}$ the sensitive heat capacity delivered by the HVAC system and $\bar{\zeta}_{seasonal}$ the seasonal efficiency ($SEER$ or $SCOP$ for the cooling or heating period respectively). Focusing the Eq. (3) for heating and cooling periods Eq. (4) was obtained.

$$Cooling: C = \dot{Q} / SEER \quad ; \quad Heating: C = \dot{Q} / SCOP \tag{4}$$

Eq. (3) and Eq. (4) show that reductions in demand and consumption are proportional for the whole period (both in the cooling season and in the heating season).

2.2 Integration (phase 2)

2.2.1 Building management system

In phase 2 the comfort algorithm obtained (Eq. (1)) was integrated in the building management system. The implementation of the ACA and the verification of energy savings and thermal comfort were carried out in one of the three buildings considered in phase 1, specifically one of the MM buildings where eight offices were selected with a daily occupation both in the morning and in the afternoon and always occupied by the same users. The choice of the building was due to the fact that there was a possibility of integrating the algorithm into its control system.

The building had a centralized four-pipe operation HVAC system with a chiller and a heat pump that provided heating and air conditioning throughout the building. All the variables related to the operation of the HVAC system were centrally managed through a single platform that integrated all the data and allowed the establishment of logical rules. The temperature was also centrally set by a fixed base set-point for both the warm season and the cold season.

Each room in the building had one or more fan-coils for heating and air conditioning on demand. The fan-coils were controlled by the users of each room using a thermostat located onsite. The variables under the occupants' control were fan-coil (on/off) status, the driving force and the environmental temperature within a range of +/- 3 degrees relative to the base set-point set in the system.

2.2.2 Integration of the adaptive comfort algorithm

The implementation of the adaptive comfort algorithm was carried out both during a winter season and during a summer season. Most important milestones are shown in the **Table 3**.

Table 3. Milestones in the study

Milestone		Date
M.1	Beginning of the first campaign (set-point period)	October 2015
M.2	Implementation of ACA-summer season (ACA period)	July 2016 (14/07/2016)
M.3	Beginning of the second campaign (set-point period)	October 2016
M.4	Implementation of ACA-winter season (ACA period)	February 2017 (06/02/2017)
M.5	Ending of the field study	March 2017

During the period hereinafter referred to as "set-point", the centrally established set-point was maintained, while during the period hereinafter referred to as "ACA", an indoor temperature according to the adaptive comfort algorithm which was obtained experimentally (Eq. (1)) was applied. The environmental variables of the rooms were monitored as well as the thermal perception of the users, which was obtained through surveys on their thermal satisfaction. The actual energy consumption of the fan-coils was also quantified by sensors installed for this purpose.

The integration of the algorithm into the building system was carried out by the use of rules and logic gates in the control module available in the building management system.

2.3 Measurement and validation (phase 3)

In the current study, the energy savings were evaluated once the adaptive control algorithm (ECM) was implemented, being the approach for baseline determination based on the application of transfer functions.

Eq. (5) represents the generic model for the determination of the baseline based on transfer functions [36]:

$$f(t) = \sum_{i=0}^{m} a_i \; Y_i(t-i) + \sum_{i=1}^{n} d_i \; f(t-i) \tag{5}$$

Where $f(t)$ is the target variable, Y_i are the independent variables or excitations, a_i are the adjustment coefficients of each variable Y_i at the current moment and in the past and d_i show the relation of the target variable with the past instants, that is to say, the dynamic inertia.

As can be seen in all the manuals for the evaluation of building behaviour [37], the evolution of the indoor temperature and the consumption are linked. In order to know one, the other is required and vice versa. The proposed model, in contrast to tendencies of published material, combined two inverse characterization models.

Based on Eq. (6), the particularized model for the characterization of the consumption and for the determination of the baseline is defined in Eq. (6) [37].

$$CI(t) = \sum_{i=0}^{m} a_i^c \cdot \Delta T(t-i) + \sum_{i=1}^{n} d_i^c \cdot CI(t-i) \tag{6}$$

Where $CI(t)$ is the hourly consumption. We opted for an hourly model as it is more precise than the daily models. Likewise, the hourly model allowed us to adjust quite accurately the consumption during the model period.

$\Delta T(t) = T_{FR}(t) - T_{INT}(t)$ is the difference between average temperature of indoor air when the system is off (and the building operates as a free running building) and the average temperature of the indoor air when the HVAC system is on. This variable showed the effect of the HVAC system in the temperature of the room.

m and n depend on the inertia of the model and represent the way the current instant is affected by the previous instants.

a_i^c y d_i^c are coefficients of the consumption model unknown a priori. They were identified during the model period (based on the experimental data) applying the room air weighting factor procedure of ASHRAE [36-38].

The periods of cooling and heating were distinguished, obtaining a different model for each of them. **Table 4** shows the coefficients and the R^2 for both periods.

Table 4. Coefficients of the consumption model and the free running temperature model

Variables	Cooling period	Heating period
a_{12}	-4.5	1.5
a_{11}	7.9	-0.2
a_{10}	-2.0	-4.3
a_9	-2.5	4.6
a_8	1.5	-3.2
a_7	0.6	3.2
a_6	3.9	-3.0
a_5	-10.2	3.9
a_4	7.0	-5.2
a_3	-3.3	3.0
a_2	6.6	2.4
a_1	-6.0	-5.7
a_0	1.2	2.7
d_1	0.5	0.5
R^2	0.91	0.84

Eq. (7) (model for the free running temperature) is the particularization of Eq. (5) for temperatures.

$$T_{FR}(t) = \sum_{i=0}^{m} a_{1i}^{T_{FR}} \cdot T_{EXT}(t-i) + \sum_{i=o}^{m} a_{2i}^{T_{FR}} \cdot RAD(t-i) + \sum_{i=1}^{n} d_i^{T_{FR}} \cdot T_{FR}(t-i) + K \qquad (7)$$

Where T_{EXT} is the average outdoor temperature and RAD is the average global horizontal irradiance. These variables were considered model variables and allowed baseline identification during the reference period. Likewise, the exploitation of the model as baseline entailed knowing both climatic conditions and indoor temperatures.

It should be emphasized that although the effect of irradiance is usually condensed with the effect of the outdoor temperature for a more balanced temperature, in Mediterranean climates the effect of irradiance can be especially critical. In the current work it was equally weighted to the outdoor temperature in order to obtain a more realistic model.

K is related to internal gains in the room and represents the increase of the temperature due to internal sources. These internal sources were assumed constant and invariant so that they could be considered as a fixed parameter in the reference period for obtaining the baseline since the spaces considered, being tertiary buildings, presented a very stable use (there was an average period of the day in which the HVAC system was in used).

$a_{1i}^{T_{FR}}$, $a_{2i}^{T_{FR}}$ y $d_i^{T_{FR}}$ are the coefficients particularized for the free running temperature model. They were calculated using the same procedure for calculating the coefficients of the consumption model.

In relation to the indices of both models (Eq. 6 and Eq. 7) it should be pointed out that, although ASHRAE [37] suggests fixing $n = 1$ and $m = 3$, Ciulla et al [31] propose using higher values of m and n due to the fact that on an hourly basis the variables that affect indoor temperature and consumption (sun protection status, window closure/opening) are unknown. The lack of awareness of these variables is balanced out by increasing the number of previous instants considered in the model.

Due to the above, for both the consumption model and the free running temperature model, the values $n = 1$ and $m = 12$ were used. So that although the proposed model is based on transfer functions, such increase in the indexes makes it shift away towards ARMAX models [39].

3. Verification and analysis of results (phase 4) and discussion

The fourth phase contemplated both, the validation of the comfort level of users and the quantification of energy savings, once the adaptive comfort algorithm was implemented. For this, the data of the environmental variables monitoring and the thermal sensation of the occupants were analysed. In terms of thermal comfort, the evolution of the thermal sensation and thermal preference data, the thermal acceptability data and the evolution of the indoor temperature in the room were considered. In relation to energy efficiency, the actual measures once the ACA was implemented were considered in comparison with the values predicted by the baseline.

As the comfort algorithm was implemented during the summer season and during the winter season, both comfort and energy performance are shown independently for the cooling period and for the heating period. Although the baseline was referenced on an hourly basis, both the comfort level and the savings verification are represented as aggregates on a daily basis and accrued per campaign for a better understanding.

3.1. Cooling period

In order to show the effect of the ACA on the indoor temperature, in **Fig. 1** the evolution of the indoor temperature for one of the rooms under study during a sample period (one month) of the cooling season is shown, as well as the average daily outdoor temperature and the running mean temperature. In the "set-up" period, the standard set-point was implemented in the control system (average set-point: 22.3 °C). In the "ACA" period, the comfort algorithm was implemented in the system (average set-point: 24 °C), being observed how the adaptive set-point led to the establishment of higher indoor temperatures.

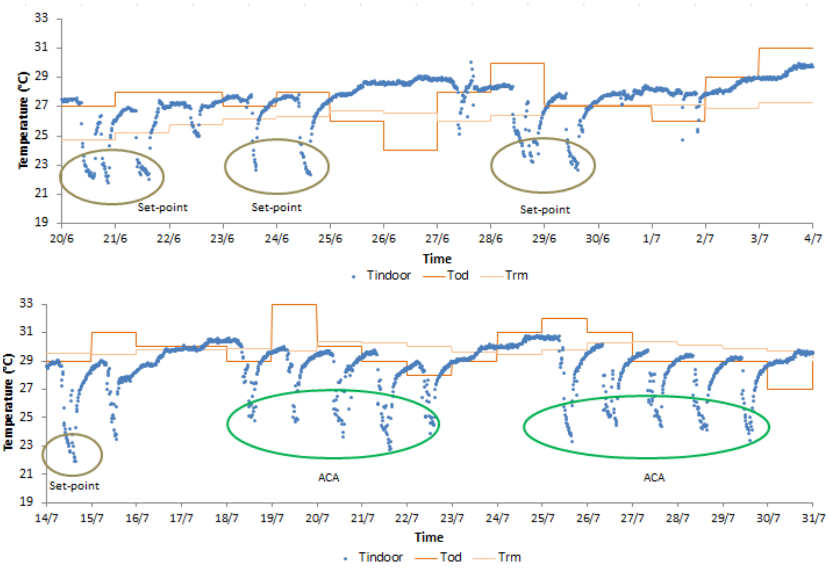

Fig. 1. Evolution of the indoor temperature-cooling period

3.1.1. Comfort evolution

Table 5 shows the evolution of the thermal sensation votes, the thermal preference votes and the votes casted on the scale of thermal acceptability by the occupants for the full cooling period (from April 2016 to September 2016) and all the selected rooms (eight). The occupants were not aware of changes in the room operation mode.

Table 5. Distribution of TSV, TP and acceptability votes-cooling period

Votes		TSV					TP					Acceptability	
Range		-2	-1	0	1	2	-2	-1	0	1	2	-1	1
Set-point	n	13	146	437	95	30	25	83	538	69	6	76	645
	%	1.8	20.2	60.6	13.2	4.2	3.5	11.5	74.6	9.6	0.8	10.5	89.5
	%	1.8	94.0			4.2	3.5	95.7			0.8	10.5	89.5
ACA	n	8	57	214	94	44	47	84	259	24	3	54	363

	%	1.9	13.7	51.3	22.5	10.6	11.3	20.1	62.1	5.8	0.7	12.9	87.1
	%	1.9	87.5			10.6	11.3	88.0			0.7	12.9	87.1

Analysing the evolution of the TSV, it can be observed that the percentage of neutral votes (zero) softly decreased, with an incremental trend in slightly warm votes (1) and warm votes (2). The percentage of comfort votes (which is considered in most studies as the temperature range in which users emit thermal sensation votes between -1 and 1 if thermal sensation neutral is renumbered as zero) was maintained in a similar magnitude range once the ACA was implemented. The sample size of the votes in comfort was representative, considering the number of votes available. It has been verified that the sample size was representative with a confidence level of 95%.

There was a slight increase of 6% in the votes for dissatisfaction due to the heat (2) that do not suppose a substantial increase with respect to the initial value. It should also be noted that this was reflected in the scale of acceptability with an increase in the percentage of votes that considered the thermal environment to be unacceptable by only 2%, going from 89.5% to 87.1% which is still a high value. The same tendency was observed in the evolution of TP votes.

The average thermal sensation vote confirmed the previous conclusion, since it was within the range of comfort in both periods and close to thermoneutrality. An initial predisposition of the thermal preference on the part of the occupants to neutral environments, with some tendency to cold environments was initially observed. This trend continued and increased slightly during the ACA period. The acceptability average responses also remained in the same order of magnitude (**Table 6**).

Table 6. Mean and standard deviation of votes-cooling period

Period	Variables	TSV	TP	Acceptability
Set-point	Mean	0.08	-0.18	0.77
	S.D.	0.82	0.69	0.64
ACA	Mean	0.26	-0.35	0.74
	S.D.	0.90	0.79	0.67

3.1.2. Evolution of energy consumption

Of the eight spaces selected for the implementation of the ACA, the results shown refer to the savings in the energy demand of one of the rooms, being considered representative of the rest in dimensions as well as in occupation and use of the space.

Due to the fact that the baseline had to be defined and its accurate required the acquisition of as many points of measure as possible, the model period for obtaining the baseline ranged from June 1 (2016) to July 14 (2016). The verification period ranged from July 15 (2106) to October 2 (2016), operating the system on a timetable from Monday to Friday from 9:00 a.m. to 9:00 p.m.

Due to the characteristics of the selected building, the rooms were not occupied in the month of August, therefore there was no use of the HVAC system or associated consumption. This month was therefore removed from the savings verification period.

Table **7** shows the cumulative energy (measured and predicted) for the entire model period and its mean and standard deviation.

Table 7. Energy consumption, mean and standard deviation during the model period (cooling)

Variables	Cooling-measured (model period)	Cooling-baseline (model period)
Energy consumption (kW)	863.28	826.44
Mean energy consumption (kW)	27.62	26.46
S.D. (kW)	15.30	16.65

Fig. 2 shows the evolution of the baseline and the real energy consumption during the verification period. The savings due to the implementation of the ACA can be observed.

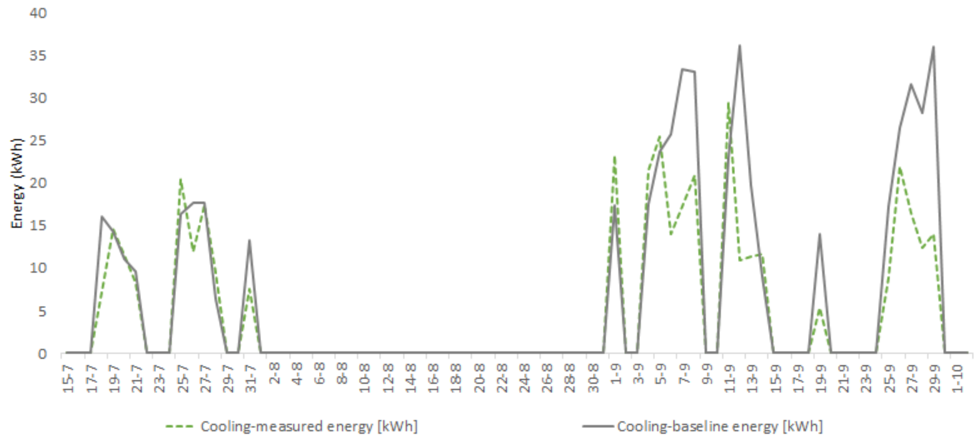

Fig. 2. Evolution of the consumption during the verification period (cooling)

Table **8** shows the cumulative energy (measured, predicted and saved) for the entire verification period (once the ACA is implemented) and its mean and standard deviation.

Table 8. Energy consumption, mean and standard deviation during the verification period (cooling)

Variables	Cooling-measured (verification period)	Cooling-baseline (verification period)	Savings
Energy consumption (kW)	372.95	514.62	141.67
Mean energy consumption (kW)	14.34	19.79	5.45
S.D. (kW)	6.28	8.73	8.80

Based on the above values the reduction in the consumption of cooling energy during the period from July 15 to October 2 amounts to 27.53% +/-4%, since according to Eq. (3) a reduction of the energy delivered is proportional to the consumption of energy, provided $\bar{\zeta}_{seasonal}$ is supposed to be constant.

The estimation of the baseline and therefore the energy savings consists of a value (27.53%) with an associated uncertainty (+/- 4%), which is determined by the average difference between the baseline and the consumptions measured during the model period.

3.2 Heating period

Fig. 3 shows the evolution of the indoor temperature for one of the rooms studied during a sample period of the total heating period, as well as the average daily outdoor temperature and running mean temperature. It can be seen how the adaptive set-point led to the establishment of lower indoor temperatures (the average set-point was 23.5 °C before the implementation of the ACA and 21.5 °C after it).

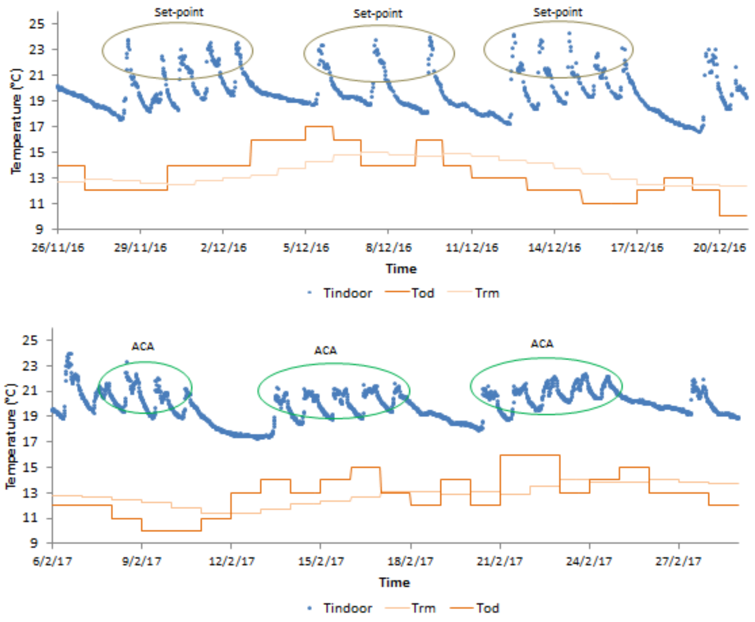

Fig. 3. Evolution of the indoor temperature-heating period

3.2.1. Comfort evolution

Table 9 shows the evolution of the thermal sensation votes, the thermal preference votes and the votes casted on the scale of thermal acceptability by the occupants for the full heating period (from October 2016 to March 2017) and all the selected rooms. The occupants were not aware of changes in the room operation mode.

Table 9. Distribution of TSV, TP and acceptability votes-heating period

Votes		TSV							TP					Acceptability	
Range		-3	-2	-1	0	1	2	3	-2	-1	0	1	2	-1	1
Set-point	n	25	112	202	327	147	26	11	12	70	464	220	84	163	687
	%	2.9	13.2	23.8	38.5	17.3	3.1	1.3	1.4	8.2	54.6	25.9	9.9	19.2	80.8

	%	16.1		79.53			4.4		1.4	88.7			9.9	19.2	80.8
ACA	n	2	37	113	40	47	6	0	0	4	88	133	20	43	202
	%	0.8	15.1	46.1	16.3	19.2	2.4	0.0	0.0	1.6	35.9	54.3	8.2	17.6	82.4
	%	15.9		81.6			2.4		0.0	91.8			8.2	17.5	82.4

Analysing the evolution of the TSV, it can be observed that the percentage of neutral votes (zero) decreased and there was an incremental tendency in the slightly cold votes (-1) and in the cold votes (-2). The percentage of comfort votes increased once the ACA was implemented and the percentage of votes for dissatisfaction due to the cold remained constant. The sample size of the votes in comfort was representative, considering the number of votes available. It has been verified that the sample size was representative with a confidence level of 95%.

This same tendency was maintained in the TP votes, increasing the percentage of votes that would wish for a slightly higher indoor room temperature, although the acceptability of the thermal environment was maintained (from the 80.8 % of votes that considered acceptable the thermal environment before implementing the ACA to 82.4% after its implementation).

It can be observed that the average thermal sensation vote was within the range of comfort in both periods and close to thermoneutrality. In the heating season, a preference for slightly warmer environments was observed. This trend continued and increased during the ACA period although the temperature remained acceptable by most occupants based on the average vote on the acceptability/unacceptability scale which increased slightly (**Table 10**).

Table 10. Mean and standard deviation of votes-heating period

Period	Variables	TSV	TP	Acceptability
Set-point	Mean	-0.32	0.35	0.62
	S.D.	1.16	0.82	0.79
ACA	Mean	-0.55	0.69	0.65
	S.D.	1.06	0.64	0.76

3.2.2. Evolution of the energy consumption

The model period for obtaining the baseline ranged from January 16 (2017) to February 6 (2017). The verification period ranged from February 7 (2107) to March 9 (2017). The system operated on a timetable from Monday to Friday from 9:00 a.m. to 9:00 p.m.

Table 11 shows the cumulative energy (measured and predicted) for the entire model period and its mean and standard deviation.

Table 11. Energy consumption, mean and standard deviation during the model period (heating)

Variables	Heating-measured (model period)	Heating-baseline (model period)
Energy consumption (kW)	292.11	261.12
Mean energy consumption (kW)	19.47	17.41
S.D. (kW)	9.69	7.29

Fig. 4 shows the evolution of the baseline and the real energy consumption during the verification period. The savings due to the implementation of the ACA can be observed.

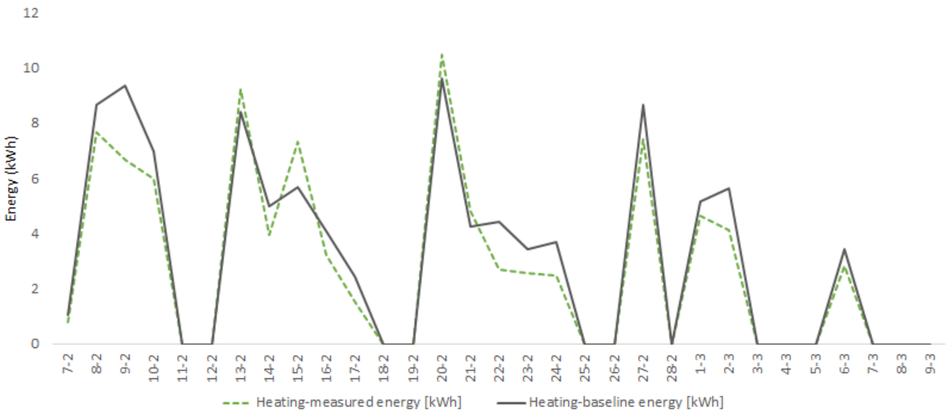

Fig. 4. Evolution of the consumption during the verification period (heating)

Table 12 shows the cumulative energy (measured, predicted and saved) for the entire verification period (once the ACA is implemented) and its mean and standard deviation.

Table 12. Energy consumption, mean and standard deviation during the verification period (heating)

Variables	Heating-measured (verification period)	Heating-baseline (verification period)	Savings
Energy consumption (kW)	88.91	100.30	11.40
Mean energy consumption (kW)	4.29	4.78	0.49
S.D. (kW)	3.32	3.31	1.05

Based on the above values, the reduction in the energy consumption during the heating period from February 7 to March 9 amounts to 11.36% +/-4%.

The results showed an energy savings of 27.5% during the cooling period (**Table 8**) and 11.4% during the heating period (**Table 12**). These results were in line with other studies where different ECM measures have been applied, in which savings of between 6% and 33.6% were obtained [6,15].

4. Conclusions

This paper reported the results from a field study carried out in office buildings in southwestern area of Spain (in Seville) focused on the following issues: 1) thermal comfort and 2) energy savings related with 3) the inclusion of an ACA in the HVAC system in MM office buildings. The results were based on the measures of the environmental variables and the thermal sensation votes, which amounted to more than

6.376 during the 17 months in which the field study was carried out. The following main conclusions can be drawn:

- A unique adaptive comfort algorithm was previously obtained for MM buildings located in an area characterized by mild winters and very hot summers.

-The acceptability of the occupants in terms of percentage of thermal sensation votes was empirically verified for a MM office building regarding the integration of the ACA in its HVAC system. During the heating period it rose slightly from 79.5% to 81.6%, being statistically equal the percentage of votes in comfort. During the cooling period, it decreased slightly from 94% to 87.5%, being a slightly difference statistically significant ($p<0.001$). It can be concluded that such percentage remained similar values before and after the inclusion of the ACA in the HVAC system.

-The energy savings were quantified for the same MM office building by comparing the values predicted by the baseline and the real values measured once the ACA was included in the HVAC system. The results showed an energy savings of 27.5% during the cooling period and 11.4% during the heating period. It was slightly higher for the cooling period but energy savings were also identified during the heating season.

-The results highlight the validity of an adaptive comfort algorithm for MM office buildings and show that it improves the HVAC system in terms of energy saving, while maintaining the comfort of the occupants. The proposed algorithm was validated in terms of comfort level and energy savings considering the experiment conditions (local climate, workers and analysed buildings), so it would be advisable to confirm such results taking into account a larger number of buildings and a wider sample of workers. Nevertheless it is also important to highlight that the obtained results are promising and similar achievements are expected even considering another type of building and climate.

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