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Adaptive comfort opportunities under mechanically conditioned environment

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Abstract

Despite being provided by mechanical ambient conditioning systems or not, all building have to a certain extent a degree of adaptation. Studies have shown that with either a weak or strong dependency to outdoor conditions there always are adaptive opportunities that might have a significant impact on comfort perception. Changes on building design have also affected occupant's expectations and the way they perceive thermal comfort.
Based on the current usage of cooling systems this paper intend to derive how adaptive the systems already are and what possibilities are to heed to a more adaptive pattern.
In this paper are compared spaces conditioned with different cooling systems, from all air HVAC systems to mixed-mode rooms with split units. The adaptability to variable conditions and occupant's expectations are studied as a function of the type building through field studies.

Keywords: adaptive comfort, adaptive opportunities, mixed-mode buildings, HVAC systems, controllers

1. Introduction

During the 20th century thermal comfort became a product supplied by heating, ventilation and air conditioning (HVAC) devices running on cheap energy. With air conditioning, openable windows became superfluous or even counterproductive, and as a result, office building facades turned into a fully sealed protection shield between the inside and the outside environment. The people's attitude towards comfort was influenced dramatically and research focused on defining optimum environments for thermal comfort (Raymond J. Cole et al., 2008). Fanger's indexes of PMV (Predicted Mean Vote) and PPD (Percentage of People Dissatisfied) still is currently used by heating and air-conditioning engineers, to predict for any type of activity and clothing the thermal environments for which the largest possible percentage of a given group of people experience thermal comfort (Van Hoof, 2008). Temperatures were regarded as an ideal constant value for a given set of occupancy. His model remains in the principal standard on thermal comfort like the EN15251(CEN, 2007) and the ASHRAE 55(ASHRAE, 2010).

However, building's reality is forcing to rethink the existent comfort models and indexes, analysing their gaps and suitability to new type of buildings (Cole et al., 2008). The push for energy efficiency on the building sector has led to an increasing diversity of building design and operation of HVAC systems. It's likely nowadays to find buildings suited with more adaptive opportunities, although provided with conventional HVAC systems. Moreover, trend is to reduce or minimize the use of mechanical cooling for economic reasons. Therefore, building and comfort research is now in need for contextualizing the comfort/energy potential in a climate dependent relationship between occupancy, building and local outdoor environment (Nicol, 2007).

Humphreys work in the 80's already indicated a possible dependency to the outdoor weather based on the results for field studies on buildings with cooling and/or heating systems (Humphreys, 1981). The same trend is clear in more recent studies about an overall large sample of mechanically conditioned buildings (Humphreys et al., 2013). These results have shown that even in a small degree, generally speaking, heated and cooled buildings are also adaptive in some way.

Based on both energy and comfort guidelines and standards, HVAC systems are used in a constant manner. Even the more dynamic kind of systems, like the variable flow and variable speed systems are set up to a constant value of temperature that is considered as the comfort temperature. This value is supposed to remain constant whenever the systems are used. Yet, the building is at the same time interacting with other dynamic features, like heat gains and natural ventilation that result on a drift from the set point temperature. The systems' dead band should control those deviations narrowing the range of temperature allowed in a room. However, there is no reason why the system itself could operate in a more adaptive way. Although it's true that people's perception of comfort varies from naturally to mechanically conditioned buildings, it is also true that there are room for adaptive action in such buildings. Those opportunities could be behavioural, physiological psychological adaptions (Brager and de Dear, 1998). If the adaptive comfort, similar to the naturally conditioned buildings, is accepted by the occupancy then a significant reduction of the energy intensity of buildings could be explored. So it is important to assess how adaptive the different cooled/heated buildings already are and how they can become more adaptive.

Studies have shown that the perceive control by the occupants play a major role in their tolerance and acceptability of their thermal sensation (Deuble and de Dear, 2012a). Among the findings of Deuble and de Dear study it was found that occupants' acceptance of the same combination of thermal conditions was dependent on the building's mode of operation (Deuble and de Dear, 2012b). Detailing the use of some adaptive actions in mixed-mode buildings Rijal et al. concluded that occupants controlled the building to provide substantial seasonal variation in the indoor temperature (Rijal et al., 2009). Also field studies have shown that when available people take an active role adjusting their environment through technical and behavioural measures(Liu et al., 2012).

Although there is an increasing interest in the design of mixed-mode buildings, it comes with additional challenges that need to be considered regarding the use of the adaptive opportunities they bring the rooms. Classical thermal comfort studies are still in need (de Dear et al., 2013). This paper will provide additional evidence, from mechanically cooled buildings, suggesting that there is an interesting potential for adaptive comfort. It will also approach the possibility of these buildings follow similar patterns to the ones specified locally for naturally cooled buildings, in this case the, according to the EN15251.

2. Methodology

In this paper will study five buildings provided with five different mechanical conditioning systems. Traditional office buildings are already equipped with some adaptive opportunities, and these buildings are representatives of the common practice in Portugal. All cases could be considered as mixed-mode buildings as they are able to resort both to natural ventilation and mechanical cooling. The main objective is comparing the comfort and temperature profiles and assess if there is any influence of the conditioning systems and the adaptive features they have.

The field study lasts for about 8 week covering the months of July and half August and September. The two buildings with a controllable central cooling system, P4 and P5, were interviewed for 2 additional weeks during September. During the second half of August buildings were almost empty due summer leave, therefore the comfort campaign was interrupted these weeks. All buildings were interviewed under their usual operating mode. The temperature dead-band was partially controlled by the central systems and by the local thermostats of room or terminal units. Therefore it was expected relaxed dead-bands. With this was tested the thermal acceptability to more variable conditions.

A classical comfort field study was undertaken in every building simultaneously. The polling strategy was based on the repeated transverse approach. All occupants were invited to participate in the study by answering an online comfort survey. The questionnaire was designed to be compact and quick. Therefore it was based on the SCATS's and COMMONCENSE longitudinal survey. People were asked about their thermal feeling, preference and acceptability, their actual clothing and activity. Additionally, the survey included questions about the active controllers and the use of thermostats. Occupants were free to answer the surveys up to twice a day, though the entire population were visited and sampled once a week.

Together with the questionnaires air temperature and relative humidity were measured continuously, using a reading time step of 15min. The indoor air velocity and the mean radiant temperature were measured during a week in every month. For the first one was used a hot sphere anemometer and for the last one a globe thermometer. Outdoor temperature was collected locally using the campus weather station. Running mean temperature was calculated from these records.

3. Description of the case studies

The experimental work took place during the summer season from July till September inclusive. August was also included in the monitoring although responses were scars due to the vocational season. Five case studies were selected and are described below. Over 190 people were interviewed and over 1300 answers were collected. All case studies are considered as air conditioned buildings (AC) for they are mainly controlled through mechanical cooling. However, they have access to both mechanical and natural cooling.

3.1 P1 - FEUP - 2nd floor:

This is the second floor of a 4 storey building (Figure 1). The building is used for the administrative services and is configured for open offices and individual offices. This building follows the conventional constructive characteristics in Portugal, double brick walls, and double glazed fenestration.

The offices are all suited with openable windows, local lighting control and single packaged units cooling systems (conventional split systems), also locally controlled. Some occupants have local fans. For the fresh air, the offices have a mechanical ventilation system providing a minimum rate without any cooling. Besides, occupants are able to increase fresh air rates by opening the windows.

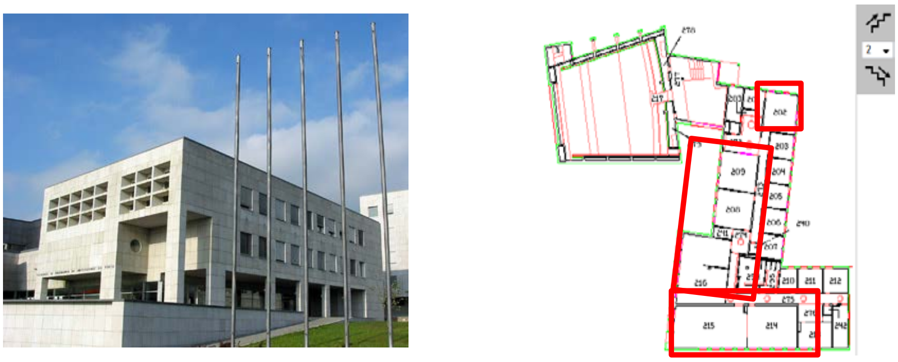


Figure 1. FEUP’s administrative second floor and layout

There are no constant patterns regarding the indoor set points and usage frequency as the systems are used as another adaptive opportunity of the space. However, air velocity is roughly constant and below 0.25 m/s.

In this case study 39 participants were pooled, with a range of ages of 20’s to 40’s, reporting 305 answers. The occupancy schedule begins at 8am until 6pm, with a lunch break from 12am to 2pm.

3.2 P2 - Basement FEUP

This building corresponds to a partially buried floor, highly occupied, dedicated for the administrative services. The basement layout consists in 2 large open offices and 2 individual offices. Windows can be opened, though for security reasons they usually remain closed.

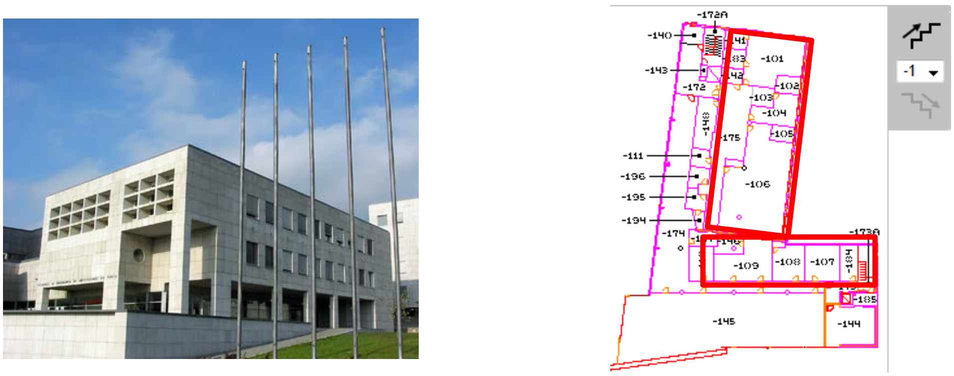


Figure 2. FEUP’s basement floor and layout

In this case study 32 participants were pooled, with a range of ages of 20’s to 50’s, reporting 414 answers. The occupancy schedule begins at 8am until 6pm, with a lunch break from 12am to 2pm.

The case study is suited with an advanced chilled beam system. A central chiller provides cool water to a set of chilled beam panel scattered through the ceiling. An air handling unit (AHU) provides pre-cooled fresh air to the terminal units. There is a single thermostat for each room controlled by the occupants. However the AHU is set automatically by the building management system.

3.3 P3 - Library FEUP

This building is an 8 floors building, with a partially buried floor. The building has a mixed use of conventional office and library. Staffs are located on the basement, ground, fifth and sixth floors and compose the subjects interviewed in this thesis, since it is focused on permanent occupancy. The location of the occupants is identified at Figure 3. All rooms are open office layouts, shared with 3 or more people, with openable window at the 5^{th} and 6^{th} floors.

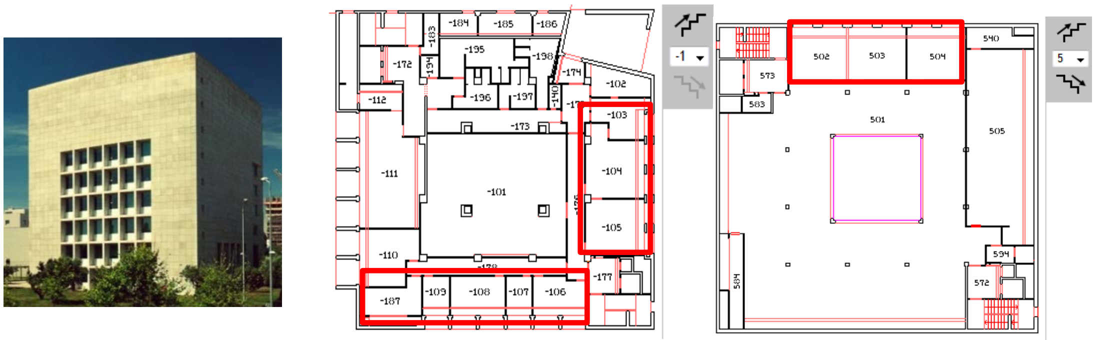


Figure 3. FEUP's library and layout

The building is completely served by a traditional HVAC system. It is cooled by two chillers, 81kW each, which provide cool water to a set of Air Handling Units (AHU) throughout the building, with some units treating only fresh air. The system is controlled by a building management system (BMS) at a central facility of the Faculty.

The control system is limited. The AHU that serve the interviewed rooms are set for an ambient temperature of 23 ºC and are always on during the working hours. However AHUs with fresh air only do not have indoor temperature sensor to control the rooms. Thus, units are controlled with estimates of supply air temperature. From the occupant's point of view the available controls are for lighting, fan coils although not very used, and in some cases windows. Ground floor and basement are occupied floors without operable windows, while at the top floors people are able to open their windows.

In this case study 29 participants were pooled, with a range of ages of 20's to 50's, reporting 183 answers.

3.4 P4 - INESC 1

This building is a research facility mainly characterized for open spaces and individual offices. The open plan areas were the subject for this thesis. The building has 4 floors with this configuration, from which floors 1 to 3 were studied. The glazing area is considerably large in the open offices and windows are openable (Figure 4).

Figure 4. INESC façade of old building and layout

The building is equipped with an all air centralized system, consisting on a central production of cool water with thermal storage and air handling units per storey. Additionally it has fan coils located at the periphery of the spaces. Occupants have also installed local fan to increase the air velocity.

In this case study 46 participants were pooled, with ages of 20-30's, reporting 175 answers. The large majority of the occupants were students and young researchers.

3.5 P5 - INESC 2

This building is also a research facility with a similar layout as the previous case study (Figure 5). From this building were collected data from the 4 office floors. Windows are openable by vertical or horizontal axis. At the time of the campaign the building was partially occupied.

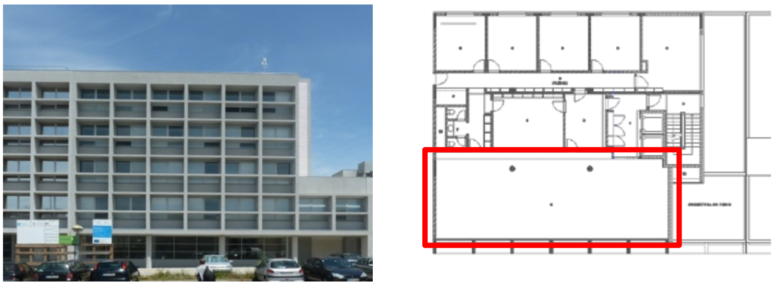


Figure 5. INESC façade of new building and layout

Since it is a newer building the air conditioning system is different from previous case. The centralized system keeps the same configuration. Yet, terminal unit were added at the ceiling level to fine tune temperatures. The thermostat controls all terminal units in the room. Diffusers on the ceiling are alternate between the central AHU and the terminal unit creating a homogeneous distribution of the temperature.

In this case study 32 participants were pooled, with a range of ages of 20's to 30's, reporting 414 answers. The large majority of the occupants were young researchers.

Summarizing the sampling of the comfort surveys Table I indicates per case study the number of participants and answers collected.

Table I - Summary of samples per case study

Building	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**
AC System	Packaged units (Splits)	Pre-cooler AHU + Chilled beams	General AHU + local fan coils	General AHU + local fan coils	General AHU + local fan coils	General AHU + local rooftops
AC Control	Local	Central + Local	Central + Local	Central + Local	Central + Local	Central + Local
Operable Windows	Yes	Yes	No	Yes	Yes	Yes
Participants	39	32	19	10	46	47
Surveyed area (m^2/oc)	10,6	6,5	9,7	12,6	13,3	8,9
Observations	305	414	137	46	175	241
Top Mean (ºC)	25,7	25,0	24,0	24,4	24,9	25,7
Top SD	1,2	0,9	1,2	1,6	1,2	1,2
Tout Mean (ºC)	23,2	23,5	24,6	23,2	22,9	23,2
Tout SD	4,5	3,8	5,7	5,9	3,3	4,5

4. Temperature profiles

4.1 Comparing temperatures to EN 15251

On a first analysis to the thermal behaviour of the case studies the temperature was plotted against time. Records were obtained continuously for the summer season and during the days of the comfort campaign. Figure 6 reports the daily average of the indoor air temperature only during the occupied days and hours. Temperature measurements took place at several locations on each building simultaneously, so the values shown represent the spatial average considering that the profiles were similar.

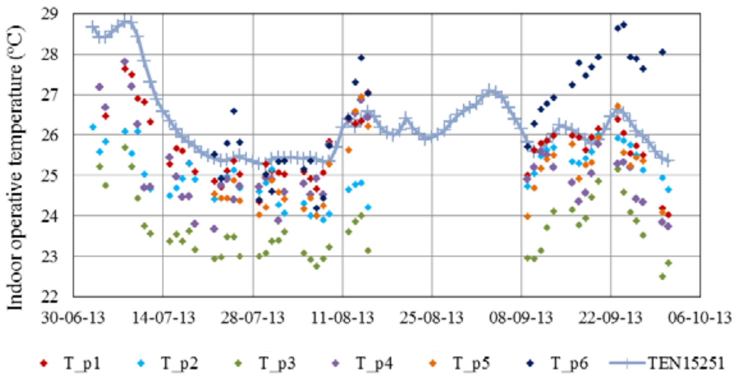


Figure 6. Representative temperature distribution on time for each case study

The EN15251 trend line is included in Figure 6 as function of time. Although it refers to naturally conditioned buildings (NV) it is used as benchmark for the case studies. It is interesting to note how all buildings follow a similar pattern as the one intended for NV. Note that all buildings should be considered as air conditioned buildings (AC), for they are provided with HVAC systems. The type of cooling system is different in every building, and this might affect how they adapt to outdoor. The most sealed building is P3 and it shows the highest offset from EN15251 reference. However, the same building at the upper floors, P4, where windows could be open the metered temperatures were more similar to the other buildings, which also have the same opportunities. The variations and peaks along time are similar in all cases.

That there is an adaptive process to weather is further evident in the Figure 7. In this figure the average indoor temperature during the occupied hours is plotted against the running mean outdoor temperature.

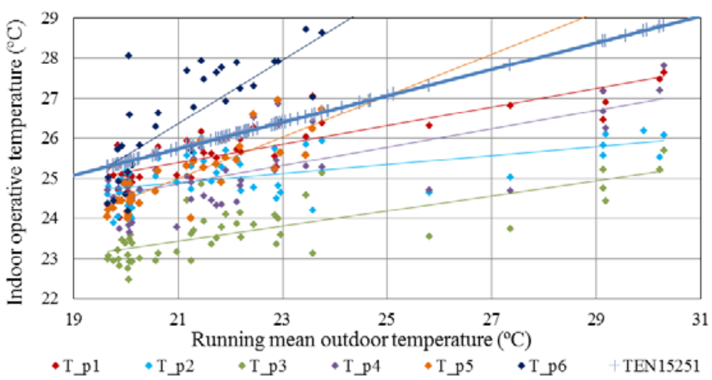


Figure 7. Average temperature dependence to outdoor weather by building

The temperatures above don’t mean to report the actual comfort temperatures. Instead, they reveal the normal operating mode of the systems and the usual temperatures they provide. It shows that even AC buildings behaviour is dependent to the outdoor weather. They don't provide a constant environment detached from the outside. Even case P3, which consist in rooms without any window is clearly a function of weather.

Also, there is a great population of samples above the reference comfort values provided in the national regulations, 25ºC in Portugal. It seems that even the mechanical conditioned buildings don't keep lower set point according to PMV.

There is a clear distinction with the cases P5 and P6 that reveal higher temperature slopes. Their trend lines reveal higher slopes than other buildings. Although Figure 7 reports daily average temperatures of a continuous monitoring, it's worth to mention that 80% of the votes are within the comfort zone vote.

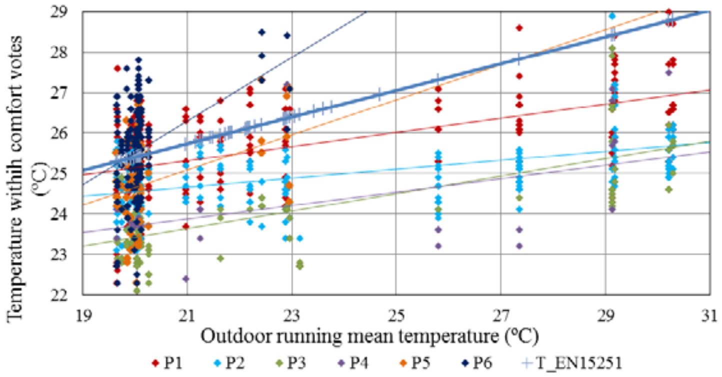
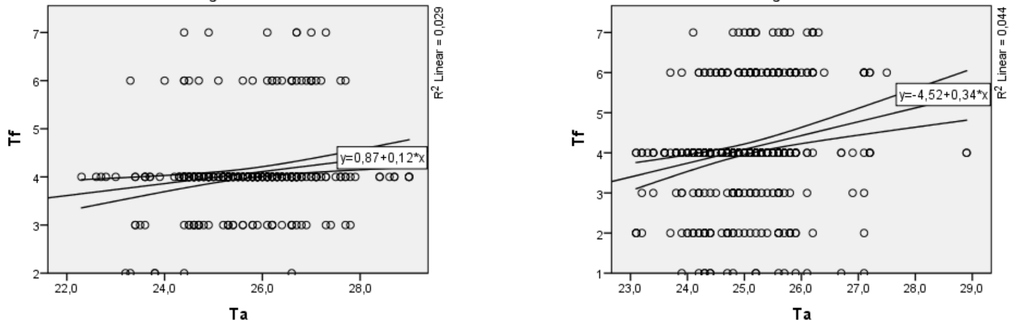


Figure 8. Temperature for comfort zone by system

Figure 8 shows filtered results for the temperature where the participants voted within the comfort zone range. Here are no average values, instead is used the raw data for the votes 3 to 5 on the comfort sensation 7-point scale. It is not conclusive how comfort trend might be affected by the type of cooling system. For instance, cases P5 and P6 could also be regarded as mixed-mode buildings (MM), for they have local control of the HVAC plus operable windows, and this cases show the highest slope on the trend lines. On the other hand, case P1, which is the most similar case to MM buildings (local AC only and windows), has one of the lowest slopes, similar to P3 which is not MM.

4.2 Finding a temperature correlation to outdoors

This section describes the temperature correlation for the comfort votes. For each building was calculated a linear trend line using the full data available. Note that the data contains votes for a wide temperature range despite being AC buildings. Figure 13 reveals that the temperature range varies around 22-28ºC.



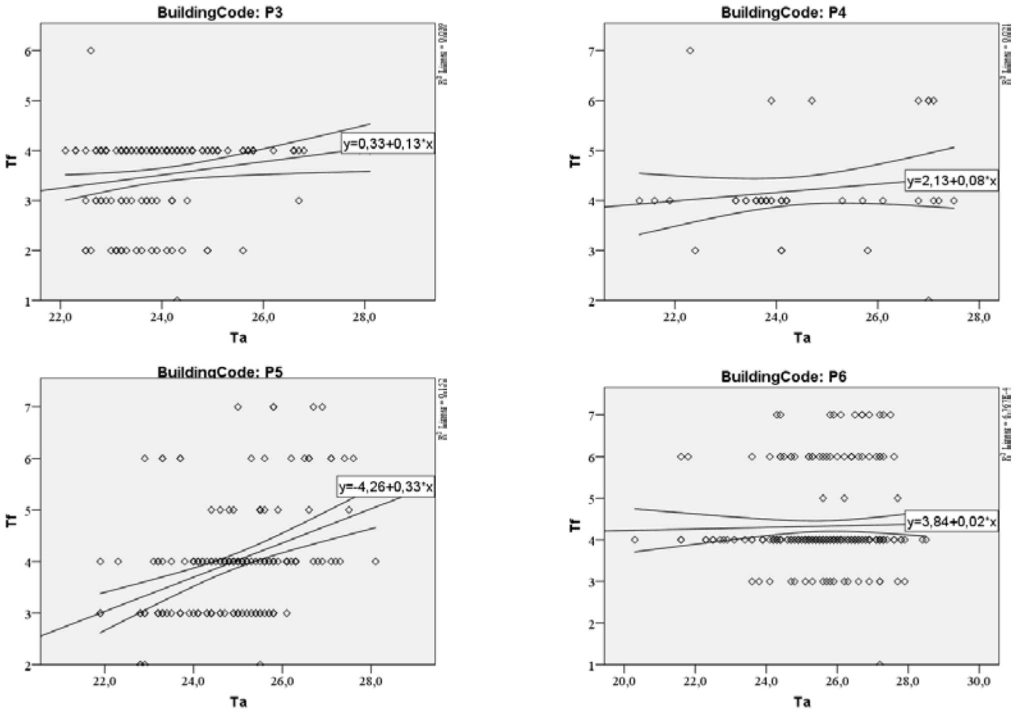


Figure 9. Trend lines for the temperature vs vote correlation. Temperature range is similar for neutral vote in all buildings

The resultant slope coefficients for each case are summarized on Table II. The data collects 50 to 70% of the votes within a comfort scale of 3 to 5. The accuracy of these graphs could be increased by a normalization process using temperatures differences to the daily averages instead of the raw data. However, daily data for these cases was scarce and do not allow accurate results by this mean.

When dealing with observations of longitudinal surveys within a day lap, it is likely to have scarce samples that affect considerably the confidence of the results. Humphreys et al reported that for 10 to 20 observations the standard error is estimated from 0,4K to 0,8K (Humphreys et al., 2013).

The Griffith method is particularly useful for small samples, like the ones on a daily base analysis. This method uses a constant coefficient equivalent to the linear regression slope (Griffiths, 1990). Instead of using values derived from climate chamber, will be used an slope of 0,5K^{-1} obtained from field studies. It could be assumed that almost no adaption occurs during a day. Therefore, daily averages of the indoor temperature comfort were used to estimate the comfort temperature.

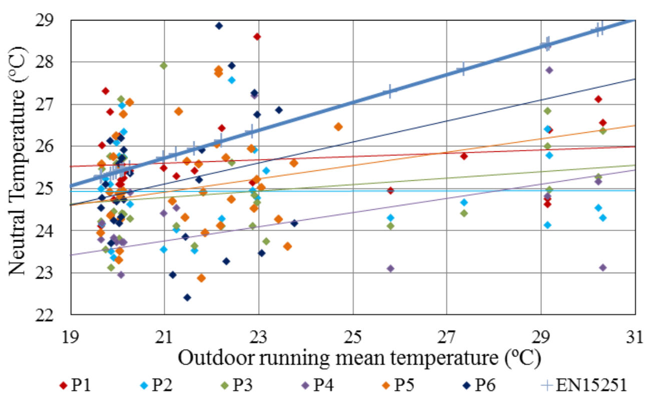


Figure 10. Comparison of neutral temperatures by Griffiths' method

After applying the Griffith method, the daily neutral temperatures were plotted on Figure 9. One of the cases didn't reveal any correlation to the outdoor temperature. In previous figures it was also the case with the lowest slope. Nevertheless, it could be said that there are different comfort patterns than the reported in the standards for mechanically cooled buildings, and that those patterns approach to the NV correlation of the EN15251 in different ways that might be affected by the type of cooling systems they have.

The slopes for each case are compared against the EN15251 in Table VIII.

Table II. Summary comfort results by building

		P1	P2	P3	P4	P5	P6	Average
	Average Tn (ºC)	25,7	25	24,6	24,2	25,0	25,1	24,9
Griffith	**Slope coeff**	0,039	0,002	0,076	0,169	0,157	0,248	0,115
	Constant	24,79	24,89	23,20	20,22	21,63	19,90	22,44
Linear Regression	**Slope coeff**	0,12	0,34	0,13	0,08	0,33	0,02	0,17
	Constant	0,87	-4,52	0,33	2,13	-4,26	3,84	-0,268

The adaptive behaviour in these buildings occurred under they usual behaviour. By concept, a mechanically cooled building should be controlled to retain a constant temperature. Yet, all cases reveal variable temperatures because of the adaptive actions occupants were able to take. Even the more limited case does so. Therefore, there is no reason why a building might not achieve comfort if its central systems are also controlled in an adaptive way.

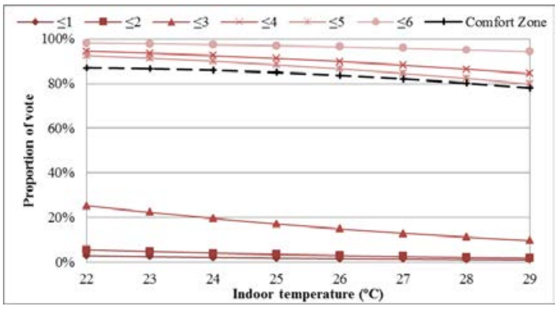
4.3 Comfort proportions

In this section are compared the comfort zones in all case studies. Using logit lines the seven-point comfort scale the proportions of each vote are highlighted. The lines are obtained using the logit function (1) plotting the proportion as a function of indoor temperature (2). The linear regression keeps the same slope coefficient for every category considering that it cannot be overlaps of comfort categories, i.e., thermal sensation do follow the sequence of the comfort scale. So, one person could not feel comfortable, then too hot and after slightly hot, in a progressive temperature raise.

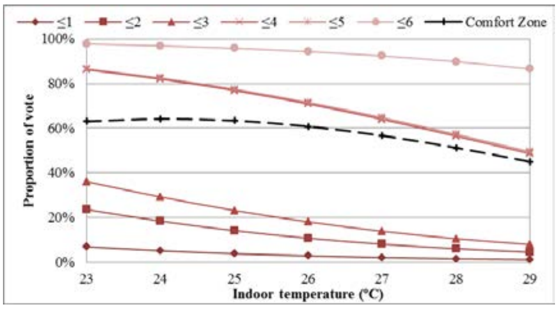
$$Logit(p_c) = \log\left(\frac{p_c}{1-p_c}\right) = a + bT \qquad (1)$$

$$p_c = \frac{e^{a+bT}}{1+e^{a+bT}} \qquad (2)$$

The probit analyses for each case are reported on Figure 10. Each line gives the proportion of having a vote or less of a give point in the comfort scale. Therefore the comfort zone includes the proportions between voting 5 or less minus voting 3 or less.



P1



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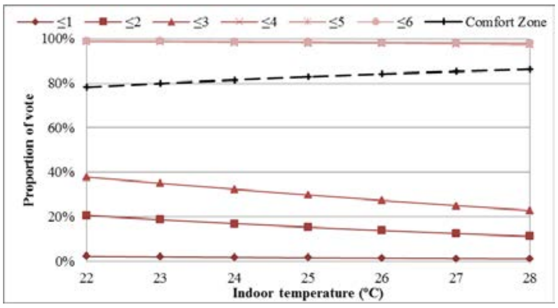
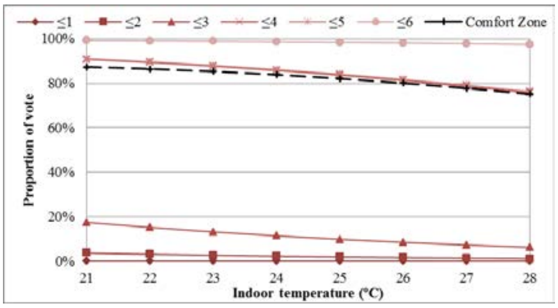
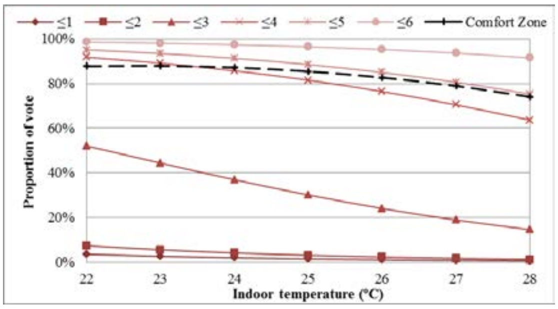


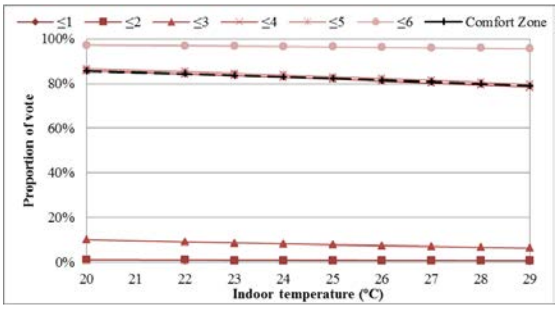
P3



P4



P5



P6

Figure 11. Probit analysis of comfort proportion due temperature per case study

The area until the black dashed line should represent the comfort zone. There is a risk on using an entire block of data from a survey that contains several buildings and long periods (Humphreys et al., 2013). As it is shown on the cases above, the day-to-day variations affect the shape of the bell-curve of the comfort zone. Ideally daily bell curves will reflect accurately the thermal sensitivity of the occupancy.

In this study the overall performance was compared. Hence, a single chart per case was built. Although, the comfort lines are quite flat this could indicate the thermal tolerance within the range “comfortable” and “comfortably warm”. The effect of the adaptive actions over time is embedded in these charts. They suggest that high proportions of about 80% might be achieved through a temperature range from 22 to 29 ºC. When asked about how acceptable the thermal environment was for the occupant, in all case studies over 85% of the samples votes as acceptable or very acceptable, and this share keeps roughly constant along the temperature range.

5. Adaptive opportunities

The case studies in this paper could be considered as mixed-mode buildings, as they are able to use the HVAC system as an adaptive opportunity by means of local control and can resort to natural ventilation.

5.1 Frequency

It is not uncommon to see mechanically cooled buildings in Europe that are also suited with operable windows and thus capable of combining the best features (Deuble and de Dear, 2012b). They, in theory, should make use of natural ventilation whenever possible and mechanical cooling as backup.

Table summarizes the frequency of use of the adaptive features available. Percentages are shown relative to the number of observations per building.

Table III. Frequency of use of the adaptive controllers

Building	Samples	Window	Blinds	Lights	Fans	AC
P1	*305*	30%	34%	61%	7%	57%
P2	*414*	29%	31%	60%	5%	57%
P3	*137*	15%	28%	69%	6%	72%
P4	*46*	22 %	28%	65%	7%	37%
P5	*175*	30%	29%	75%	7%	65%
P6	*241*	30%	38%	69%	10%	57%

In average the buildings made use of windows in about 30% of the votes, with except of case P3 that have very few windows available. They overall votes regarding the air conditioning represent 60% of the samples. Also, local control for lighting and blinds was always available and the participants reported almost 70% and 35% of usage respectively. This further supports that even AC buildings make reasonable use of other adaptive opportunities.

Following the same trend as reported by Rijal et al, in their study on mixed mode buildings (Rijal et al., 2009), the availability of AC control as adaptive opportunities reduces the use of natural ventilation considerably. Interesting to note that is their study they included buildings as AC with operable windows, and some of those cases had similar probabilities as MM buildings. The same is verified here, a total AC case as P3, with very few windows, reveals the same pattern of use of the MM buildings.

5.2 Combined use of AC

When available multiple actions may take place at the same time. Although there are other reasons than thermal comfort for using the available controllers, results, show that when AC is on, people kept their windows closed during about 90% of the time. Still some cases reached 15% of open windows. In these cases windows could have left open due dissatisfaction with the AC, or for air quality reasons.

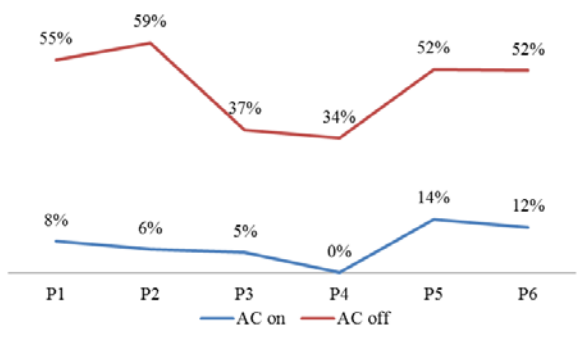


Figure 12. Percentage of open windows according to the AC condition

Figure 11 shows how occupants make use of both controllers as a changeover mixed-mode building. Windows are likely to be open when AC is off and when they are close indoor temperatures is also in free floating. Considering that the AC is on about 60% of the time, from which about 50% windows are open simultaneously, then the frequency when there are no active controllers is quite reduced, about 15 to 20% of the observations.

The use of fans is very low because in Portugal it is not usual buildings been design with local fans. The cases reporting its use refer to local fans placed by the occupants. Nevertheless, this feature was always used together with the air conditioning system. This might suggest that local ventilation to increase convective body heat losses could be a useful supplement to active controllers in mechanically cooled buildings.

Lighting and blinds are other mean of reducing heat gains in the buildings. On average, 65% of the votes when AC was on lightings were also on. Blinds as well were used about 35% of the times together with AC.

5.3 Use of mechanical cooling thermostat

All cases were suited with some degree of local control. Some had one thermostat per room. Others had control over their local fan coil units spread in every room. Comparing all cases it was found a common issue. Almost 10% of the responses claimed that there was no control of their mechanical cooling. Also, another 5 to 8% reported people using their thermostats while replying it was off.

This misinformation about their cooling systems might affect the effective use of their controllers. It is not rare finding occupants that do not know when their systems are running, under normal circumstances, and how to operate with their AC systems so they can perceive the effectiveness of their actions.

This goes in line with the feedback collected from the question "Have you adjusted you thermostat recently?" On average, from 80 to 90% of the answers said they didn't. This information was verified from interviews in each building, where the common response was that they don't usually use the thermostat.

5.4 Thermal perception and controllers

This section describes the usage of controllers relative to their thermal sensation and preference. The usage proportion of each controlled was calculated according to binned scales of the thermal sensation and preference. The new scale for the thermal feeling is shown on Table IV, and for the thermal preference on Table V. Additionally, the proportions consider the distributions of the sample on the comfort scale. A weighted average by point-scale was multiplied to the proportion as shown in the equation 3.

$$p = \frac{C_i}{\sum_{i=-1}^{1} ci} \cdot \frac{n_i}{\sum_{i=-1}^{1} n_i} \quad (3)$$

Here p is the proportion of having a controller C active at a given thermal sensation or preference. The number of observations per each point-scale of comfort is n, and "i" represents the points on the respective proportion scales shown below.

Table IV. Scale conversion for thermal sensation

Bedford Scale	Proportion Scale
1.Much too cool	-1.Uncomfortable
2.Too cool	
3. Comfortably cool	0. Comfortable
4. Comfortable	
5.Comfortably warm	
6.Too warm	1.Uncomfortable
7.Much too warm	

Table V. Scale conversion for thermal preference

Thermal Preference Scale	Proportion Scale
1.Much warmer	1. Warmer
2. A bit warmer	
3.No change	0. No change
4. A bit cooler	-1. Cooler
5. Much cooler	

The proportions for each controller available as function of the thermal feel and preference respectively on table and table.

Table VI.Use of controllers by thermal feeling

Building	Tf	Votes	Windows	Blinds	Light	Fan	AC
P1	-1	6	0,00	0,00	0,00	0,00	0,00
	0	265	0,79	0,78	0,77	0,67	0,75
	1	34	0,01	0,01	0,01	0,03	0,01
P2	-1	60	0,01	0,02	0,03	0,05	0,03
	0	257	0,45	0,40	0,37	0,40	0,36
	1	97	0,05	0,05	0,05	0,01	0,06
P3	-1	23	0,04	0,02	0,02	0,00	0,02
	0	113	0,62	0,72	0,74	0,82	0,71
	1	1	0,00	0,00	0,00	0,00	0,00
P4	-1	1	0,00	0,00	0,00	0,00	0,00
	0	38	0,74	0,41	0,66	0,83	0,58
	1	7	0,00	0,08	0,03	0,00	0,04
P5	-1	4	0,00	0,00	0,00	0,00	0,00
	0	151	0,73	0,76	0,75	0,73	0,76
	1	20	0,02	0,01	0,01	0,00	0,01
P6	-1	1	0,00	0,00	0,00	0,00	0,00
	0	197	0,72	0,73	0,68	0,78	0,66
	1	43	0,02	0,02	0,03	0,01	0,03

Being the proportions weighted with the frequency of the thermal sensation provides a sense of the most frequent set of thermal votes and use of the controller. It combines the effect of frequency of the comfort vote with the distribution of the controller status among the comfort scale.

Table VII.Use of controllers by thermal preference

Building	Tp	Votes	Windows	Blinds	Light	Fans	AC
P1	1	81	0,07	0,07	0,06	0,12	0,07
	0	198	0,43	0,41	0,43	0,27	0,44
	-1	26	0,01	0,01	0,01	0,01	0,01
P2	1	168	0,14	0,13	0,16	0,04	0,16
	0	165	0,22	0,17	0,14	0,18	0,15
	-1	81	0,02	0,05	0,05	0,09	0,04
P3	1	16	0,00	0,01	0,02	0,00	0,02
	0	80	0,44	0,28	0,34	0,44	0,34
	-1	41	0,07	0,12	0,09	0,07	0,08
P4	1	21	0,05	0,21	0,23	0,00	0,24
	0	22	0,38	0,22	0,21	0,48	0,23
	-1	3	0,01	0,01	0,00	0,00	0,00
P5	1	53	0,08	0,08	0,09	0,07	0,10
	0	99	0,34	0,35	0,32	0,35	0,33
	-1	23	0,02	0,01	0,02	0,02	0,01
P6	1	100	0,18	0,13	0,16	0,08	0,19
	0	130	0,29	0,34	0,31	0,37	0,26
	-1	11	0,00	0,00	0,00	0,01	0,00

Figure 12 compares the cases of window opening and cooling use splitting the effects of sample size and distribution. It corresponds to the thermal comfort zone in the new scales. Results show good correlation between AC usage and windows opening. People make use of both windows and AC together reducing the energy use. The dashed lines reflect how the comfort zone is wider relatively to the discomfort zone. There might be several reasons besides comfort for why a controller might remain active. Nevertheless, when the shares withdraw from midpoint it could imply that the controller is used more frequently, being while comfort is perceived and changing over when the perception does too. Comparing the windows with AC usage, one could confirm that windows are the first ones upon which occupants will take action, while the AC will take longer even collecting some discomfort votes. Further studies are needed with more case studies to correlate priorities of adaptive actions on AC, windows and others.

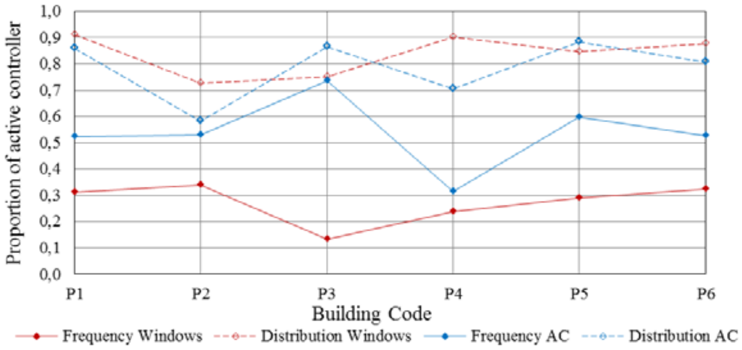


Figure 13. Effect of the number of votes per preference and votes of controllers per scale

Considering the share of active AC by thermal preference in all case studies were detected proportion from 0,6 to 0,8 of AC on while the thermal preference was “warmer”. One of the problems is the limitation of central control for adjusting to different desired temperatures. There is no feedback process that allows changing the status of the cooling system and therefore it might generate undercooling issues. This effect is further seen in the weighted proportions of Table VII. Discomfort is generally reported more for undercooling than for overheating.

6. Conclusions

Given the need for evidence on the behavior of AC buildings, this paper showed a contribution of 6 more samples where an adaptive behavior was evident. Some point resultant from the analyses presented in this paper could be drawn.

The cases used in this paper showed that it's possible that AC buildings operate under adaptive patterns. Results showed that the indoor temperature of buildings provided with AC could float similarly to the standard pattern of naturally ventilated buildings.

These buildings represent current trend on building/system design, as they were all built in the last 10 years. There is a wide variation of possible systems nowadays. However, is safe to say that almost all new buildings are able to use to sort of natural ventilation. The above increases the grey area on the definition of MM buildings and blurs the boundaries of the comfort metrics.

It was observed that even if buildings are mechanically cooled, controlled for a constant environment, the indoor temperature is quite dependent of weather conditions. Therefore, there is no reason why a building might not achieve comfort if its central systems are also intentionally controlled in an adaptive way.

The indoor-outdoor temperature relation in some cases showed that linear coefficient could be in some cases steeper than NV buildings. Tolerance might be increased because more actions are available for the occupants.

The analysis of the comfort scale proportions showed a very flat comfort area that could be the result of the adaptive process happening along the time scale of the data. However, this needs verified consistency with similar daily based studies. Nevertheless, the study showed there is an interesting potential for adaptive comfort in AC building, where system could adapt to their local indoor/outdoor correlation. Further studies are needed to test this assumption in different locations.

The analysis of the controllers showed that air conditioning is used as an adaptive opportunity, in combination with window opening. However, the misuse of the local control for the cooling systems reveals lack of information on how occupant should operate with their facilities. This factor could significantly reduce the efficacy perceived of the AC as an adaptive action.

Local fans when available were used roughly independently from the AC. This could indicate that on a summer scenario people might accept a trade-off between temperature and air movement if both controls are available locally.

This paper gives a preview of the potential of conventional AC buildings for becoming more adaptive. Further studies will be held contrasting the possibilities of constant against variable temperature profile in the same buildings.

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