Build Simul (2020) 13: 51–63
https://doi.org/10.1007/s12273-019-0560-2

# A comparative study on energy demand through the adaptive thermal comfort approach considering climate change in office buildings of Spain

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## Abstract

In Spain, the current Building Technical Code (referred to as CTE in Spanish) establishes restrictive setpoint temperatures that ensure high levels of thermal comfort but at the expense of high energy demands. However, the strategy to achieve thermal comfort in offices tends towards the adaptive approach, since users manually open windows, control the operation of the air-conditioning systems, and perform adaptation actions in order to achieve adequate levels of well-being. This research develops the adaptive comfort control implemented model (ACCIM), which dynamically handles the setpoint temperatures based on the limits of adaptive comfort, in three representative climatic zones of the Spanish territory, in both the present scenario and future scenarios. This is carried out by following a methodology based on the phases of (i) analysis of climatic zones, (ii) model construction, (iii) data collection, (iv) simulations in the present scenario, (v) simulations in future scenarios, and (vi) analysis of the results of a theoretical model and of a real-life model. Not only do the results indicate that it is possible to reduce the energy demand, by using adaptive setpoint temperatures, up to 69.91% for the least restrictive category and of 31.34% in the category that has the highest level of expectation of the users, but they also show the variations in demand that would occur in possible future climatic scenarios. The application of the study in a real-life case achieves minimum differences of between 3% and 10%, thereby validating the prediction model.

## Keywords

adaptive comfort,
energy demand,
performance simulation,
climate change

## Article History

Received: 25 February 2019
Revised: 12 May 2019
Accepted: 16 May 2019

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## 1 Introduction

Climate change is an area in which governments and other institutions have shown a growing interest in recent years. According to data from the Fifth Assessment Report (AR5) of the United Nations Intergovernmental Panel on Climate Change (IPCC), in 2010, 32% of global primary energy was employed in buildings, which produced 19% of global emissions. In 2008, in order to reduce the overall temperature increase and therefore mitigate the effects of climate change, the agreement of the 2020 Climate and Energy Package (European Commission 2008) was signed, and, in the year 2013, the period of action was extended until 2030 (European Commision 2014).

In 2002, the Energy Performance of Buildings Directive (EPBD) (European Commision 2002) was applied in Spain by means of the Building Technical Code (CTE) (Gobierno de España 2006), and consequently the Regulations on thermal installations in buildings (RITE) (Gobierno de España 2007) came into force. Recently, Directive 2018/844 (European Union 2018) has stated the need for European countries to establish energy renovation strategies for existing building stock in order to provide efficient buildings before 2050, which led to a change in the Basic Document 'DB HE Energy Saving' of the CTE in 2018 (Decreto 2018). The current Spanish construction regulations divide the Spanish territory into different climatic zones and classifies them according to their climatic severity in winter (from A, with the least severity, to E, with the greatest severity) and to their climatic severity in summer (from 1, with the least severity, to 4, with the greatest severity). Therefore, the nomenclature of each of these climatic zones is composed of one letter and one number. Based on this classification, the current regulation establishes limitations on the maximum thermal transmittance

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of the building envelope. However, the values become more restrictive only with the growing tendency of the climatic severity of winter, and not with that of summer. In this way, the high levels of thermal discomfort and/or the consequent high energy consumption are not being considered in areas with hot weather.

On the other hand, static setpoint temperatures with very restrictive values are considered as the low setpoint temperature of 20 °C and the high setpoint temperature of 25 °C in accordance with the CTE, which would ensure thermal comfort for people, whereby a comfort model was applied based on the Predicted Mean Vote (PMV) (Fanger 1967). The current Spanish construction regulations, however, fail to take into account the high consumption required to maintain the internal operative temperature within such a restrictive temperature range. In contrast, research into the application of adaptive comfort models is booming (de Dear and Brager 2002; McCartney and Nicol 2002), whereby people are considered to have a perception of the comfort temperature, which varies with the outside temperature.

The main difference between the models of adaptive comfort and those based on the PMV is that the former consider that the neutral temperature depends on the variations of the average temperature outside, while the latter consider that the neutral temperature is independent of the outside temperature. In addition, adaptive models not only contemplate the possible adaptation of the individual to the variation of temperatures through behavioural actions, such as opening or closing windows (Rijal et al. 2007), donning or removing clothes (Morgan et al. 2002; Parsons 2002), and consuming hot or cold food or drink (Damiati et al. 2016), but also take into account the psychological adaptation to the temperatures, in which the expectations of the occupant intervene through the effect called weather memory (Luo et al. 2018). However, the models based on the PMV were developed in offices, in which the occupants had to wear highly regulated clothing and had no access to windows or thermostats and, therefore, had no opportunity for adaptation.

Adaptive comfort models are applicable under certain limitations. One of these limitations states that, for its application, there should be no cooling system, and if a heating system does exist, it should not be in operation, so that the only way to condition the indoor air is through natural ventilation. However, recent research studies the extension of the adaptive approach to the use of air conditioning and the use of mixed mode (Sánchez-García et al. 2019). This extension is based on the use of daily setpoint temperatures assigned to the neutral temperature (i.e. the temperature at which the highest percentage of acceptability is reached) to maintain the indoor temperature within the daily limits of adaptive comfort, and, in the case of mixed mode, prioritize the use of natural ventilation when the outside conditions are favourable, or use the air conditioner when they are not. These methods carry a high potential for energy saving: the fact of establishing the heating and cooling setpoint temperatures at 20 °C and 26 °C enabled a 45% reduction in energy consumption to be achieved (Spyropoulos and Balaras 2011). In another study, energy savings of between 32% and 73% are obtained; these depend on the climatic zone and involve the adjustment of the heating and cooling setpoint temperatures to 18.3 °C and 27.8 °C, respectively. However, although the setpoint temperatures used in these studies are less restrictive than conventional setpoint temperatures, they remain static. In this line of research, there are studies in which dynamic setpoint temperatures are applied in order to maintain the operating temperature within the adaptive comfort zone: the use of the lower limit of the adaptive comfort model developed for the Netherlands (van eer Linden et al. 2006), established in the ISSO74 standard (Arets 2004) as heating set point, allows a reduction of 74% in the energy consumption to be attained (Kramer et al. 2015). To date, very little research has been carried out in this field located in Spain. In one of the studies, the adaptive model of the ASHRAE standard 55-2017 (ANSI/ASHRAE 2017) is applied by means of the simplified method, that is, using comfort limits based on the monthly average temperature, and therefore, these limits varied monthly (Sánchez-Guevara Sánchez et al. 2017). In this way, setpoint temperatures based on these limits also varied monthly. The results showed reductions in energy demand for heating and cooling of 20% and 80%, respectively. In another investigation, having previously developed a thermal comfort model for mixed-mode buildings (Barbadilla-Martín et al. 2017), the comfort limits of the model are used as setpoint temperatures. Subsequently, the energy demand is compared with the use of the conventional temperatures (average of 23.5 °C in cooling and 22.3 °C in heating) with those based on the adaptive comfort model (average of 24 °C in cooling and 21 °C in heating), and reductions of 27.5% and 11.4% in cooling and heating respectively are observed (Barbadilla-Martín et al. 2018). Finally, the process of using setpoint temperatures based on the adaptive comfort model is automated through the implementation in a domestic system (Aparicio-Ruiz et al. 2018) carried out in an office building, whose results showed reductions of 27% in cooling consumption and of 11% in heating with the application of an algorithm of adaptive comfort. In another study, the implementation of setpoint temperatures based on adaptive models is studied in buildings that operate solely with air conditioning, reaching cooling values between 2 °C and 5 °C above the previously used setpoint temperature of 23 °C (Yun et al. 2016).

The use of setpoint temperatures based on the adaptive

comfort approach could lead to a new definition of energy demand: adaptive energy demand, which could be defined as the useful energy needed to maintain interior thermal conditions within the adaptive comfort zone. This new definition of energy demand could in turn generate a new definition of energy poverty, to which adaptive comfort models can be applied (Sánchez-Guevara Sánchez et al. 2017, 2018; Pérez-Fargallo et al. 2017) and for which the influence of climate change presents a field of major interest (Pérez-Fargallo et al. 2018).

The objectives of this research involve the quantification of the energy demands coming from the use of an adaptive comfort control system (ACCIM, adaptive comfort control implemented model) for office buildings in three representative climatic zones of the Spanish territory in the three categories established in the EN 15251 standard (CEN 2007). In addition, the resulting demands will be contrasted with those corresponding to the application of the model based on the PMV; trends from the effect of climate change will be analysed for the years 2050 and 2080 and the prediction model will be compared with a real-life case.

This paper is divided into four sections. In the previous section, the introduction and the objectives of the study were exposed. Secondly, the methodology followed by this research is described. Thirdly, the results are discussed. This section is in turn divided into three parts: (i) a comparative study of the evolution of energy demand in a base case; (ii) the influence adaptive comfort levels considering energy demand in a base case, and (iii) the analysis of energy demand and the influence of climate change in an actual case. Finally, the main conclusions of results are presented.

## 2 Methodology

This study is carried out using a methodology based on the phases of: (i) the analysis of climate zones; (ii) model construction; (iii) data collection; (iv) simulations in the present scenario; (v) simulations in future scenarios; (vi) the application to a real-life case; and (vii) the analysis of results (Fig. 1).

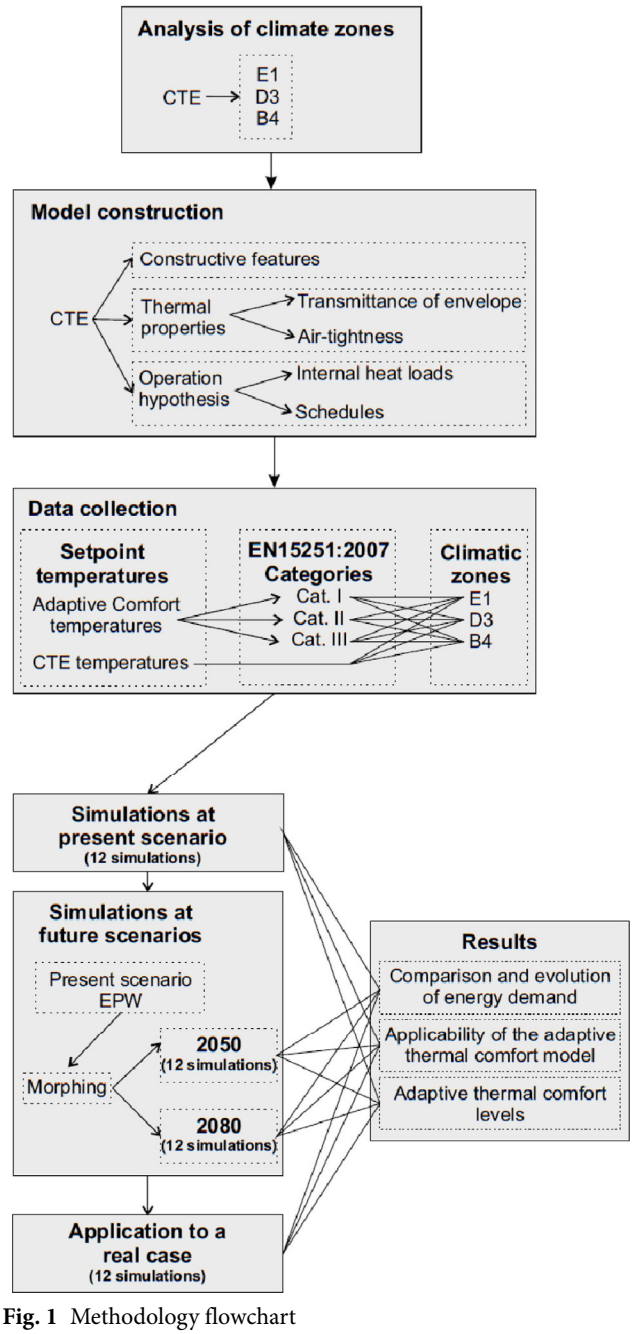



**Fig. 1** Methodology flowchart

### 2.1 Analysis of climate zones

In Spain, the DB HE Reference climates (Código técnico de la Edificación 2015) (Basic Document 'DB HE Energy Saving of the CTE) establish various climatic zones with the combination of a winter climatic severity (A, B, C, D, or E) together with a summer climatic severity (1, 2, 3, or 4). E indicates the coldest climate in winter and 4 indicates the hottest climate in summer. In the Iberian Peninsula, this combination gives rise to the following types of climatic zones: A3, A4, B3, B4, C1, C2, C3, C4, D1, D2, D3, and E1.

In the present study, the three most representative climatic zones of the Spanish territory have been considered: climatic zone B4, (which corresponds to the Csa class according to the Koppen-Geiger classification (Rubel and Kottek 2010)) with its Mediterranean climate of mild winters and dry and very hot summers, in which the city of Seville is located; climatic zone D3, (which corresponds to the BSh class) with its semi-arid cold climate with moderately cold winters and hot summers, in which the city of Madrid is located; and climatic zone E1, (which corresponds to the CSB class) with its continental Mediterranean climate with mild summers and cold winters, in which the city of Avila is located.

## 2.2 Construction of the theoretical model

The case study prototype is defined as a "shoebox" and has the dimensions of 5 m × 5 m × 2.5 m, with a surface area of 20.3 m² and an occupied volume of 60.8 m³: these are architectonically defined according to Appendix D DB HE-1 CTE, whereby the characteristic envelope parameters depending on climate zone are considered.

The prototype represents a building for office use. The choice of this version is justified by two reasons: on the one hand, the model established in the EN 15251 standard is applicable to this type of building; on the other hand, although the building stock in Spain is principally formed of residential buildings, according to the statistical data of the Institute for Diversification and Energy Saving (IDAE), the electricity consumption of the residential sector in 2016 is 5,989,728 toe as compared to the consumption of 6,183,486 toe by the tertiary sector. This latter amount constitutes 30% of the total energy consumption of the country.

In the proposed prototype, the percentage of adopted openings is 30% compared to the enclosure, and these are composed of PVC frames that form three vertical glass panels. The thermal transmittance of these elements is shown in Table 1.

On the other hand, the infiltration rate has been established at 0.739 ren/h for zone B4 and 0.907 ren/h for zones D3 and E1, whose the calculations are based on the documents "Technical conditions of the procedures for the evaluation of the energy efficiency of buildings" (Ministerio de Industria Energía y Turismo 2015) and Table 2.3 of the Basic Document HE Energy Saving (Código técnico de la Edificación 2013) according to the climatic zone (Table 2).

The internal loads are established for an 8-hour usage regime of office activity and for an average density (Fig. 2) according to Appendix C of the Basic Document (Código técnico de la Edificación 2013); the occupation load is 9.79 W/m², the lighting load is 9 W/m², the equipment is 4.5 W/m², and 4.04 W/m² for the ventilation. According to the standard UNE-EN ISO 12464-1, the minimum luminance level for office work is 300 lux. For indoor air quality (IAQ), office use corresponds to IDA 2 (good air quality). For this category, the minimum external airflow of ventilation must be set at 12.5 L/s per occupant (Ministerio de la Presidencia 2007).

**Table 1** Thermal envelope transmittance limit

| Limit transmittance of element (W/(m²·K)) | | Climate zones | | |
|---|---|---|---|---|
| | | B4 | D3 | E1 |
| Walls (Ulim) | | 0.82 | 0.66 | 0.57 |
| Floor (Ulim) | | 0.52 | 0.49 | 0.48 |
| Roof (Ulim) | | 0.45 | 0.38 | 0.35 |
| Windows (Ulim) (30% of openings) | Frame/dividers | 1.72 | 1.72 | 1.72 |
| | Glazing | 2.00 | 2.00 | 2.00 |

**Table 2** Air permeability (according to Table 2.3, Basic Document HE Energy Saving (Código técnico de la Edificación 2013))

| Parameter | Winter climate zone | | | | | |
|---|---|---|---|---|---|---|
| | α | A | B | C | D | E |
| Air permeability (m³/(h·m²)) | < 50 | < 50 | < 50 | < 27 | < 27 | < 27 |

## 2.3 Data collection

For the study of the applicability of the model, the EnergyPlus Weather (EPW) files of the climatic zones have been extracted in order to establish the setpoint temperatures in the adaptive model. The EPW files are the most widespread and suitable data for use with building energy simulations programmes. These files developed by ASHRAE, comprise hourly data of the most relevant parameters related with the climate of a specific location. And, the setpoint temperatures in the static model can be established in accordance with the CTE, which sets the limits of indoor temperatures from which the air-conditioning systems of the building begin to operate. In this code, the high-temperature set point is 25 °C and the low 20 °C throughout the year, regardless of the climatic zone, the external weather, and the thermal loads.

The procedure to ascertain the adaptive setpoint temperatures on an hourly basis is more complex: firstly, the average outdoor temperatures have to be calculated for 365 days a year of all three climatic zones under study, and the average outdoor temperatures of the previous 7 days are necessary.

$$\theta_{rm} = (\theta_{ed\text{-}1} + 0.8 \times \theta_{ed\text{-}2} + 0.6 \times \theta_{ed\text{-}3} + 0.5 \times \theta_{ed\text{-}4} + 0.4 \times \theta_{ed\text{-}5} + 0.3 \times \theta_{ed\text{-}6} + 0.2 \times \theta_{ed\text{-}7}) / 3.8$$

where:

$\theta_{rm}$: the prevailing mean outdoor air temperature,

$\theta_{ed\text{-}1}$: the average outdoor temperature of the previous day,

$\theta_{ed\text{-}2}$: the average outdoor temperature two days before, and so on and so forth.

The EN 15251 standard establishes temperature limits applicable to office buildings in which users perform mostly sedentary physical activities with metabolic values of 1.0 to 1.3; they can modify their clothes from 0.5 to 1.0 clo and the thermal conditions must be mainly regulated manually by users through the opening and closing of windows (CEN 2007).

The control model based on adaptive setpoint temperatures established by this standard is also composed of four categories of the indoor environment depending on

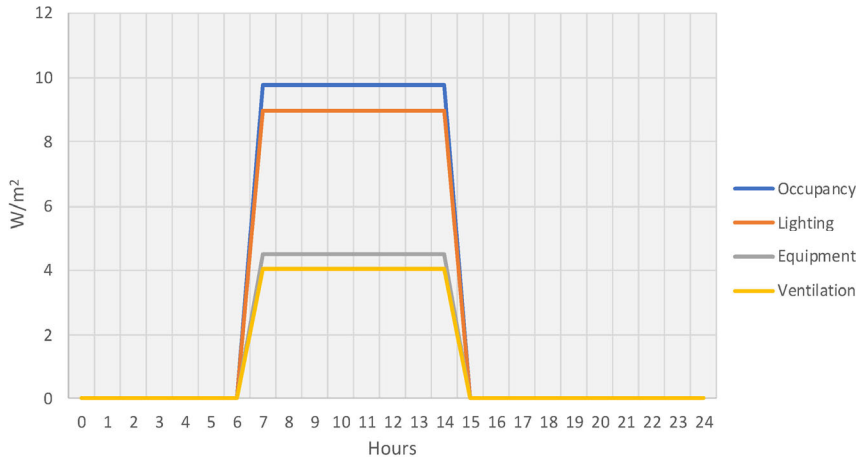



**Fig. 2** Internal load calendar

the level of expectations of users. These are summarized in Table 3.

In order to determine the comfort zone (Fig. 3) it is necessary to obtain, on the one hand, the indoor operative temperatures ($\theta_i$) for 365 days a year using the following formula:

$$\theta_i = 0.33 \times \theta_{rm} + 18.8$$

On the other hand, it is also necessary to evaluate these indoor operating temperatures within the limits of categories I, II and III (Table 4) whose relationship establishes the comfort zone.

## 2.4 Simulation

### *2.4.1 Simulations in the present scenario*

In order to determine the influence that the application of the adaptive model has on the static model in the energy demand, we use building energy simulation software, DesignBuilder, which integrates the EnergyPlus calculation

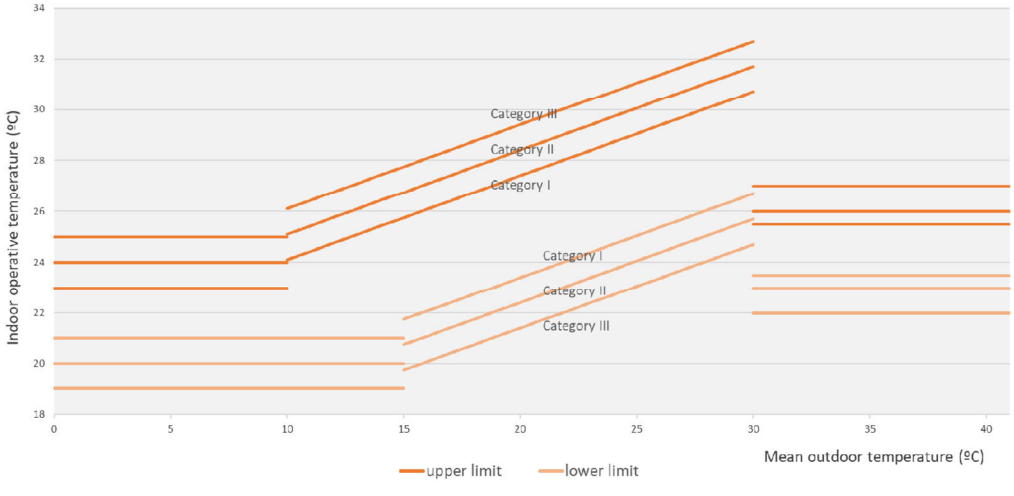



**Fig. 3** Definition of the comfort zone according to the limits established in each category

**Table 3** Expectation categories addressed in the EN 15251 standard

| Category | Detail |
|---|---|
| I | High level of expectation; this is recommended for spaces occupied by very sensitive and fragile people with special requirements, such as the handicapped, sick, elderly, and very young children |
| II | Normal level of expectation; this should be used for new and renovations |
| III | Acceptable and moderate level of expectation; it can be used in existing buildings |
| IV | Values outside the criteria of the preceding categories; this category should only be accepted during a limited period of the year |

engine. Through this software, it is possible to develop advanced dynamic simulations in real time, by using hourly climate data files on the case study "shoebox" that refer to the use of a local office. In addition to the input on climate data, construction characteristics and internal loads, the adaptive setpoint temperatures are also incorporated in accordance with Table 4. For this study, an air-conditioning system VRF (Variable Refrigerant Flow) has been proposed, a heat pump air-air batteries comprising heating and cooling direct expansion (DX) with an EER (Energy Efficiency Ratio) of 3.0 and 3.1 COP (Coefficient Of Performance). This equipment is programmed to operate during the occupancy schedule.

#### 2.4.2 *Simulations in future scenarios*

In this study, we also evaluate the degree of incidence of the model, based on adaptive setpoint temperatures in future climate scenarios. To this end, the CCWorldWeatherGen tool of the Hadley Centre Coupled Model 3 HadCM3 UK Met Office is used, which, through a morphing process, generates meteorological files adapted to climate change from any location in the world and creates files compatible with the majority of simulation programs for the energy performance of buildings (Jentsch et al. 2013).The "morphing" of the three current climate files has been made for scenario A2 of greenhouse gas emissions in accordance with the IPCC, which has resulted in 3 climate scenario files for 2050 and another 3 files for 2080. Energy demand data related to heating and cooling can then be extracted from each simulation. In total, 48 simulations will be carried out: 36 correspond to the base model (3 climatic zones × 3 climatic scenarios × 4 categories) and 12 correspond to a real-life case (one climatic zone B4 × 3 climatic scenarios × 4 categories).

### 2.5 Application to a real-life case

The current simulation model is an office building of 312.4 $m^2$ of built-up land located in Mairena del Aljarafe (Seville), which corresponds to a temperate climate zone with mild winters and extremely hot summers.

#### 2.5.1 *Data collection and fieldwork*

The energy simulation program, DesignBuilder, is again employed and the same setpoint temperature settings used in the prototype have been considered. Only those parameters characteristic of the envelope, internal loads, and periods of use and occupancy of this building are modified. The data is collected from its architectural project, interviews with the occupants, onsite visits, and from the monitoring temperatures and energy consumption, as shown in Table 5.

The data regarding the envelope and the properties of the HVAC system is extracted from the architectural project. The building has a façade composed of prefabricated pieces of GRC (Glassfibre Reinforced Concrete), a non-ventilated air chamber, thermal insulation of rock wool, and an interior lining with a laminated gypsum panel. This façade has a thermal transmittance of 0.76 W/($m^2$·K); the windows have 6 + 12 + 6 glass panes, of 2.82 W/($m^2$·K) transmittance, and aluminium frames of 4.72 W/($m^2$·K). As for the air-conditioning system, this is a VRF system, with EER and COP values of 4.42 and 4.95, respectively. The mechanical ventilation system provides a constant airflow of 0.386 $m^3$/s.

The periods of occupation and the use of the facilities are determined through interviews with the occupants and visits to the building. The occupation schedule is of 8 hours, distributed from 9:00 AM to 2:00 PM and 4:00 PM to 7:00 PM, during which the facilities (lighting, office equipment and computers, as well as the HVAC system) are in operation, except at weekends, when the office remains unoccupied and the equipment is turned off. The occupation was determined by counting the number of people who were in each room.

In order to validate the simulation model and ensure that the results are reliable and accurate, the temperature and energy consumption are monitored. The indoor conditioned temperatures, indoor non-conditioned temperatures, and outdoor temperatures, corresponding to the 4th, 14th and 2nd floors, respectively, are all monitored (Fig. 4). The monitoring process started on 11/29/2016 and ended on 06/20/2017, measuring the indoor and outdoor temperatures each day for 1-hour intervals, thereby generating a total

**Table 4** Comfort temperature ranges per category in regards to prevailing mean outdoor air temperature ($\theta_{rm}$) (the EN 15251 standard)

| Category – Limit | | Prevailing mean outdoor air temperature $\theta_{rm}$ - comfort temperature | | | |
|---|---|---|---|---|---|
| | | $\theta_{rm} < 10$ °C | 10 °C ≤ $\theta_{rm} < 15$ °C | 15 °C ≤ $\theta_{rm} \leq 30$ °C | $\theta_{rm} > 30$ °C |
| I | Upper comfort limit $\theta_{imax}$(UI) | 23.0 | 0.33×$\theta_{rm}$+18.8+2 | 0.33×$\theta_{rm}$+18.8+2 | 25.5 |
| | Lower comfort limit $\theta_{imin}$ (LI) | 21.0 | 21.0 | 0.33×$\theta_{rm}$+18.8−2 | 23.5 |
| II | Upper comfort limit $\theta_{imax}$(UII) | 24.0 | 0.33×$\theta_{rm}$+18.8+3 | 0.33×$\theta_{rm}$+18.8+3 | 26.0 |
| | Lower comfort limit $\theta_{imin}$ (LII) | 20.0 | 20.0 | 0.33×$\theta_{rm}$+18.8−3 | 23.0 |
| III | Upper comfort limit $\theta_{imax}$(UIII) | 25.0 | 0.33×$\theta_{rm}$+18.8+4 | 0.33×$\theta_{rm}$+18.8+4 | 27.0 |
| | Lower comfort limit $\theta_{imin}$ (LIII) | 19.0 | 19.0 | 0.33×$\theta_{rm}$+18.8−4 | 22.0 |

**Table 5** Envelope features, HVAC system and internal loads

| Envelope characteristics | Layers | Thickness (mm) | *U*-value (W/(m²·K)) |
|---|---|---|---|
| Façade | GRC Stud frame panels | 100 | 0.76 |
| | Air chamber | 70 | |
| | Mineral wool insulation | 40 | |
| | Plasterboard | 13 | |
| Openings | Glazing: 6+12+6 mm | — | 2.82 |
| | Aluminium frame | — | 4.72 |
| Ceiling/floor | Plasterboard suspended ceiling | 15 | 1.38 |
| | Enclosed air chamber | 450 | |
| | Concrete slab | 300 | |
| | Enclosed air chamber | 150 | |
| | Steel-clad particleboard raised floor | 30 | |
| | HVAC systems | Schedules | Setpoint |
| | Heating | 9am to 2pm and 4pm to 7pm | 23 °C |
| | Cooling | | 25 °C |
| | Ventilation | | 0.386 m³/s |
| | Loads | Schedules | (W/m²) |
| Occupancy | Offices | 9am to 2pm and 4pm to 7pm | 6.2 |
| | Open workspaces | | 5.6 |
| Lighting | Offices | 9am to 2pm and 4pm to 7pm | 12.1 |
| | Open workspaces | | 10.9 |
| Equipment | Offices | 9am to 2pm and 4pm to 7pm | 4.6 |
| | Open workspaces | | 4.2 |

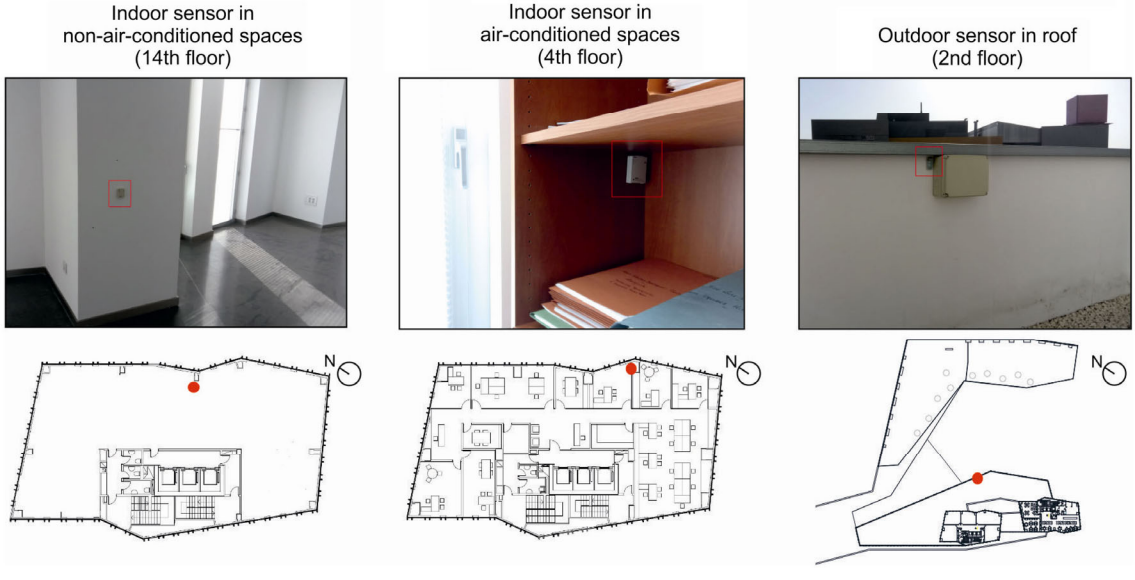



**Fig. 4** Temperature sensor positions in a real-life building

of 14,616 records. The indoor temperature was measured using HOBO U12-012 sensors and the outside temperature using a HOBO Pendant data logger sensor 8K-UA-002-08, both with an accuracy of ± 0.7 °C. The sensors were previously calibrated to reduce errors in the measurement process, and were positioned based on the indications of ASHRAE Standard 55-2017, Section 7.3.2, Physical measurement positions within the building (ANSI/ASHRAE 2017), which prevented them from receiving external heat sources, and at a height of 1.1 metres from the ground. The information related to energy consumption was obtained through electricity bills provided by the occupants.

#### 2.5.2 *Validation of the simulation model*

The indoor and outdoor temperatures and the simulated energy consumption are compared with those measured. In relation to temperatures, the recommendations of the ASHRAE Guideline 14-2014 standard are followed (ANSI/ASHRAE 2014). A certain variance is observed, mainly in the indoor conditioned temperature and the outdoor temperature. In the case of the indoor conditioned temperature, the measured temperatures are respectively lower and higher than those simulated in winter and summer, whereas in the case of the outdoor temperature, the measured temperature is higher than that simulated during the summer.

However, this variance is not significant, since the Mean Bias Error (MBE) and the Coefficient of Variation of the Root Mean Square Error (CV (RMSE)) satisfy the limits of 10% and 30%, respectively (Table 6). Therefore, the simulated data is reliable and no further adjustments are necessary to calibrate the model.

**Table 6** Simulation model validation based on temperature and energy consumption

| | | MBE | CV(RMSE) |
|---|---|---|---|
| Temperature | Outdoor | 7.4% | 21.9% |
| | Conditioned indoor | −3.2% | 8.7% |
| | Non-conditioned indoor | 1.4% | 9.0% |
| | | Measured (kWh/year) | Simulated (kWh/year) |
| Energy consumption | Year 2015 | 365,683 | 334,408 |
| | Year 2016 | 356,086 | |

## 3 Results and discussion

### 3.1 Comparison and evolution of energy demand

The total energy demand (heating plus cooling) of the case study in the 3 separate climatic zones (B4, D3, and E1) are compared in Fig. 5 while considering both the different models of setpoint temperatures (CTE, Cat. I, Cat. II, Cat. III) and the Climate scenarios (Present, 2050, and 2080). A reduction in the current scenario of the EN 15251 standard can be observed in all the categories with respect to the CTE for zones B4 and D3; however, for zone E1 there is an increase in Cat. I compared to the CTE of 13.66 kWh/(m$^2$·year) because the heating setpoint temperature corresponding to Cat. I is 21 °C, which is higher than the temperature of the Heating set point of 20 °C of the CTE.

Based on the results obtained regarding the influence of climate change, it can be observed that the increase in demand is more abrupt in the CTE model than in the EN 15251 standard. The general trend is an increase in total demand due to the significant increase in cooling. For the E1 zone, specifically in the period 2050, a decrease in total demand can be observed. This is because the increase in temperatures caused by climate change has an apparent and temporary favourable effect due to the fact that a greater number of hours are recorded within the comfort limits and, at these hours, less energy is required to reach the setpoint temperature. This trend occurs only temporarily from the current scenario until 2050, since, in 2080, the temperatures begin to exceed the upper limit of applicability, and hence the conditioning systems are activated, and consequently the energy demand grows. This favourable characteristic is only local, corresponding to the E1 zone, and its benefit is very small (around 15% reduction) compared to the other harmful effects that climate change has on the environment, such as a greater risk of fires, lack of drinking water, and floods.

The comparative analysis of annual cooling and heating energy demand data in both models (CTE and adaptive) shown in Fig. 6, indicates a considerable reduction in cooling demand in the three climatic zones under study through the establishment of adaptive setpoint temperatures, which are additionally resilient to climate change. However, regarding the annual heating demand, this reduction in category I with respect to the CTE model is not achieved in any of the climatic zones, mainly due to the high level of requirements that this category presents.

Table 7 shows the annual demand values for heating and refrigeration, whereby the reduction percentages with respect to the CTE model are represented as negative, and the percentages of increase are represented as positive. In the heating demand, we find that zone B4 for category I shows the highest value of increase with respect to the demand obtained with the CTE of 47% in the current scenario and 127% in 2018.

In the context of climate change, the demand for refrigeration presents an incremental trend due to the increase in temperatures for the three climatic zones, most notably in the E1 zone. Conversely, there is a decrease in the heating demand in the three zones, whereby up to a 95% reduction for category III is reached in zone B4 between the present day and 2080.

Results are directly applicable only to Spanish climate. This methodology could be applicable to similar climate conditions considering that there might be differences regarding the minimum thermal performance of the envelope and energy performance of the HVAC systems according to the regulations in each country. Thermal expectations and adaptation opportunities of the occupants might differ between countries as well, and so this could have an influence on thermal comfort levels and energy consumption.

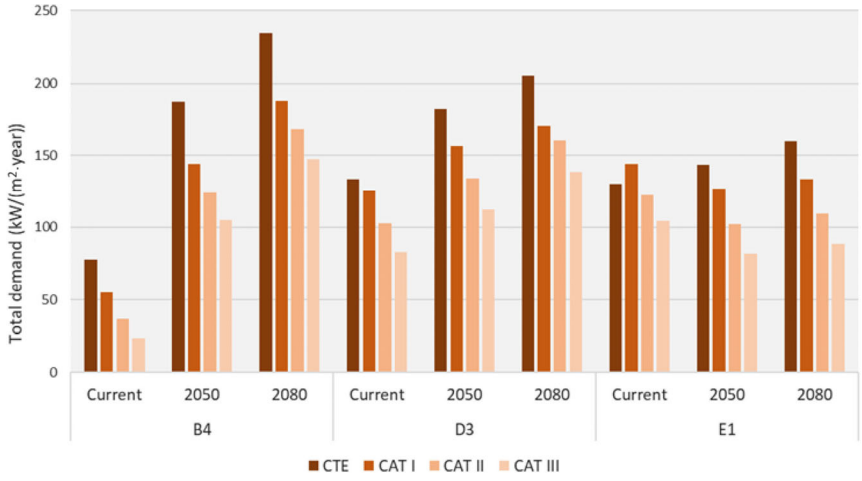



**Fig. 5** Variation in total demand in the context of change for each of the three climate zones under study

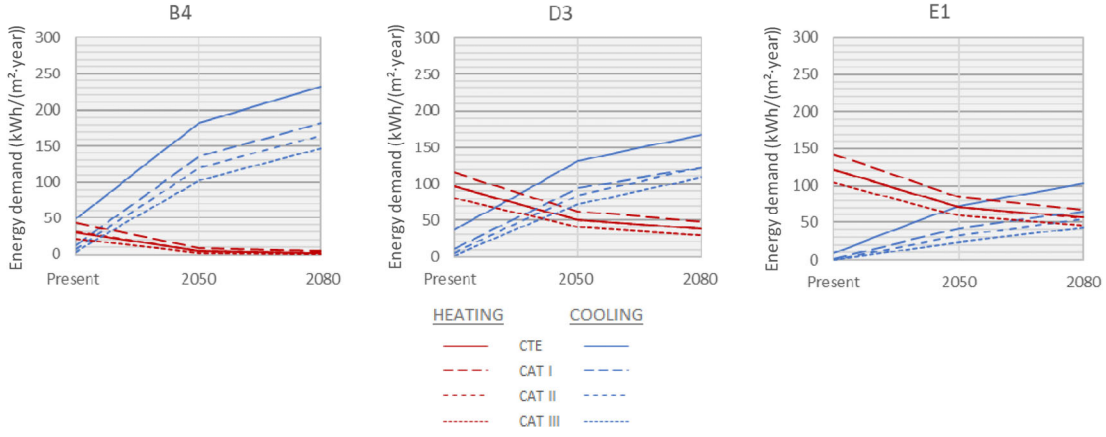



**Fig. 6** Variation in heating and cooling demand in the context of climate change

**Table 7** Percentage of variation in the demand for heating and cooling with respect to the CTE

| | Heating | | | COOLING | | |
|---|---|---|---|---|---|---|
| B4 | Current | 2050 | 2080 | Current | 2050 | 2080 |
| CAT I | 47% | 85% | 127% | −75% | −26% | −21% |
| CAT II | 4% | 1% | 5% | −86% | −35% | −29% |
| CAT III | −31% | −51% | −58% | −93% | −44% | −37% |

| | Heating | | | Cooling | | |
|---|---|---|---|---|---|---|
| D3 | Current | 2050 | 2080 | Current | 2050 | 2080 |
| CAT I | 19% | 23% | 26% | −71% | −28% | −27% |
| CAT II | 0% | −1% | 0% | −84% | −36% | −27% |
| CAT III | −17% | −22% | −23% | −93% | −45% | −35% |

| | Heating | | | Cooling | | |
|---|---|---|---|---|---|---|
| E1 | Current | 2050 | 2080 | Current | 2050 | 2080 |
| CAT I | 17% | 19% | 20% | −81% | −42% | −37% |
| CAT II | 0% | 0% | −1% | −95% | −57% | −48% |
| CAT III | −15% | −17% | −19% | −99% | −68% | −58% |

The current EN 15251 standard establish comfort limits only for the present scenario. Thus, as there is no adaptive comfort model for future scenarios, the current EN 15251 standard has been applied in future scenarios as well. This could imply a limitation because the acceptability and comfort ranges could change as the human beings adapt to the increase in temperature. Human adaptation to the increasing temperatures in future scenarios is unknown, however it might be considered that the temperature that human being would consider as comfortable (that is neutral temperature) would gradually approach to air temperature. This might result in an improvement of the potential of energy savings, as setpoint temperatures might increase as well, and so, energy consumption would decrease.

Energy policies and technology evolution have an impact on energy consumption. As a response to climate change, there could be some changes in the future regarding the energy policies, and the COP and EER of air-conditioning systems might increase as a result of the improvement in technology. Thus, this could lead to some inaccuracies in the results, as these factors are unknown in the future and

have not been considered in this study.

### 3.2 Adaptive thermal comfort levels vs. energy demand

Through hourly temperature data, an analysis of adaptive thermal comfort has been carried out for the three climatic zones under study in the current period and its influence in the context of climate change, while taking 2050 and 2080 as scenarios. In Fig. 7, the results of adaptive cooling and heating demand are plotted, as are the indoor operative temperatures based on the average outdoor temperature, in addition to the limits of applicability and comfort limits according to the EN 15251 standard for Category II, which corresponds to new or renovated buildings.

In Fig. 7, the operative interior temperature can be observed along the left-hand-side ordinate axis; on the right-hand-side ordinate axis, this id the energy demand; and on the abscissa axis, the average outdoor temperature is given.

The grey cloud of points shows the indoor operative temperature for each hour of the year. The energy demand is represented by red or blue dots, depending on whether the requirement is heating or cooling. These points correspond to those indoor temperatures that exceed the comfort limits and therefore raise the energy demand to achieve the desired indoor temperature.

On the other hand, the increase of cooling demand and decrease of heating demand for the future climatic scenarios becomes visible as a consequence of global warming. In relation to Fig. 7, we have obtained the data relative to the number of hours of requirement or non-requirement of air conditioning (Table 8), thus obtaining that the climatic zone B4 is the zone with the highest percentage of hours when no air conditioning is required.

In the current period, most of the demand is attributed to heating; this is due to the high index of hours that lie outside the limit of applicability, in which the outdoor temperatures are lower than 10 °C. Furthermore, the indoor operative temperature limit set at 20 °C for Cat. II is not reached, and hence the indoor operative temperature is the temperature that comes closest to this limit.

Zone D3 presents the greatest number of hours of air-conditioning requirement due to its arid-dry climate with hot summers and cold winters in which indoor operative temperatures exceed the highest setpoint temperatures in the cooling season and fail to reach the lower setpoint temperatures in the heating season.

On the other hand, in Table 8, it can be observed that the increase in the number of cooling hours produced in 2080 will carry much more weight than the reduction in the number of heating hours occurring in the same period.

### 3.3 Case study: analysis of the energy demand and the influence of climate change

Figure 9 shows the results of the simulations carried out in the current scenario and in the base model from which the

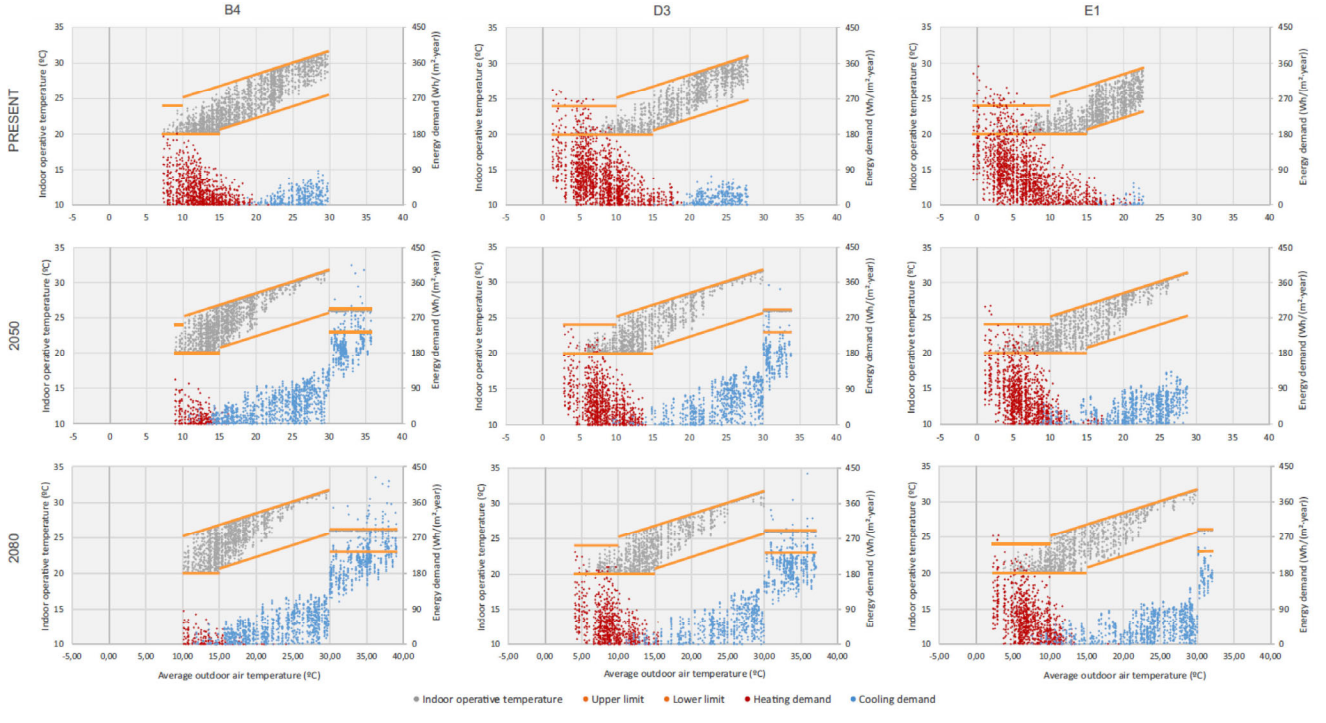



**Fig. 7** Operative temperature, prevailing mean outdoor air temperature and energy demand scatter plot for the different climatic zones in present and 2050 according to EN 15251 Cat. II

**Table 8** Number of hours of heating and cooling requirement for the current scenario, 2050, and 2080 according to the EN 15251 standard Cat. II regarding the hours of operation of the building

| | | B4 | | | D3 | | | E1 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Hours | % | kWh/(m²·year) | Hours | % | kWh/(m²·year) | Hours | % | kWh/(m²·year) |
| Present | Heating | 807 | 27.64% | 30.17 | 1338 | 45.82% | 97.00 | 1488 | 50.96% | 122.07 |
| | Not required | 1789 | 61.27% | — | 1288 | 44.11% | — | 1394 | 47.74% | — |
| | Cooling | 324 | 11.10% | 6.77 | 294 | 10.07% | 5.80 | 38 | 1.30% | 0.45 |
| 2050 | Heating | 228 | 7.81% | 4.87 | 872 | 29.86% | 49.97 | 1031 | 35.31% | 70.91 |
| | Not required | 1429 | 48.94% | — | 1120 | 38.36% | — | 1150 | 39.38% | — |
| | Cooling | 1263 | 43.25% | 119.09 | 928 | 31.78% | 83.93 | 739 | 25.31% | 31.44 |
| 2080 | Heating | 170 | 5.82% | 2.39 | 722 | 24.73% | 38.07 | 863 | 29.55% | 55.86 |
| | Not required | 1310 | 44.86% | — | 1161 | 39.76% | — | 1148 | 39.32% | — |
| | Cooling | 1440 | 49.32% | 165.52 | 1037 | 35.51% | 121.95 | 909 | 31.13% | 53.85 |

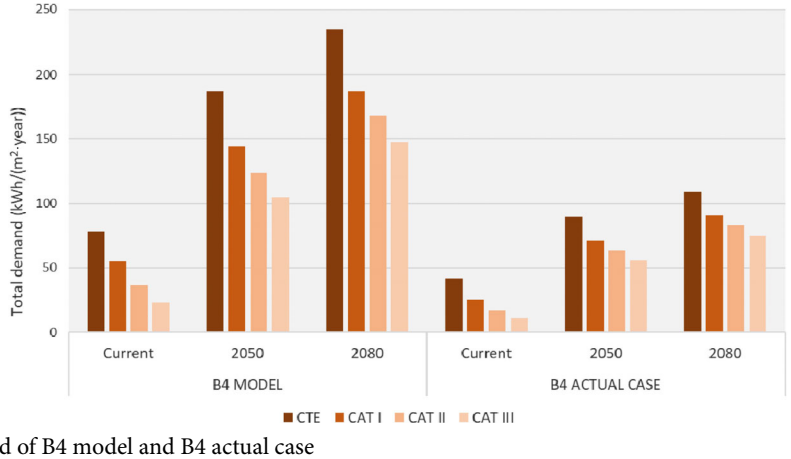



**Fig. 8** Total energy demand of B4 model and B4 actual case

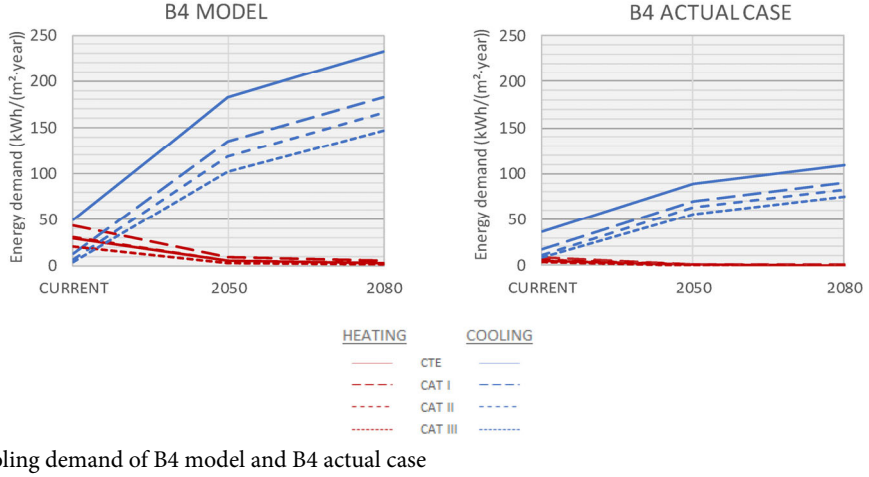



**Fig. 9** Heating and cooling demand of B4 model and B4 actual case

lines referring to cooling and heating arise.

In the current case, there is a significant reduction in energy demand with respect to the results obtained with the prototype, mainly due to the fact that they have different internal loads and different parameters of the envelope. Despite the difference in demand values, both models follow a similar trend as regards global warming.

Although we find decreases in the total demand of the simulated real-life case study with respect to the prototype, as shown in Fig. 8, when the demand for cooling and heating are studied separately (Fig. 9), the results obtained for the current climate scenario in particular reveal a reduction in the demand for heating in the current model, both CTE and in the different categories, between 80% and 85% but,

on the other hand, in the cooling demand only reductions are achieved with the CTE model and there is an increase in the current case of 34% in Cat. I, 65% in Cat. II, and 130% in Cat. III.

It should be noted that, in the study of the demand made in possible climate scenarios, we find reductions in both models (CTE and adaptive), although the reduction trend continues to be greater in the heating demand, whereby a 100% reduction is reached with respect to only 53% obtained in cooling demand.

The variation in energy demand resulting from the application of adaptive setpoint temperatures has been evaluated in B4 MODEL and B4 ACTUAL CASE in order to ascertain the deviation between the theoretical model and the current case. Based on this question, Table 9 is presented, which relates the reduction obtained in categories I, II and III with respect to the CTE model for both the Base Case and the Actual Case. This table demonstrates the similarity of these two cases as being the percentages of difference between 3% and 10%, which are attributable to the variation of the characteristics of the envelope, the schedule, and occupancy density. Therefore, based on the results, we can deduce that the base model can provide reliable results in its application in current cases.

**Table 9** Degree of relationship between B4 model and B4 actual case for the current scenario, 2050 and 2080

| Relation | | Scenario | | |
|---|---|---|---|---|
| | | Present | 2050 | 2080 |
| CAT I/CTE | B4 Model | 29% | 23% | 20% |
| | B4 Actual case | 39% | 20% | 17% |
| | B4 Model - B4 actual case | −10% | 3% | 3% |
| CAT II/CTE | B4 Model | 53% | 34% | 28% |
| | B4 Actual case | 59% | 29% | 24% |
| | B4 Model - B4 actual case | −6% | 5% | 4% |
| CAT III/CTE | B4 Model | 70% | 44% | 37% |
| | B4 Actual case | 74% | 37% | 31% |
| | B4 Model - B4 actual case | −4% | 6% | 6% |

## 4 Conclusions

This research shows the results derived from the study of the energy demand in the CTE and EN 15251 standards made in a prototype that represents an office building located in different climatic zones of Spain (B4, D3, and E1). The influence of climate change has also been considered, as well as the behaviour of this base model in a current case.

Interesting results have been obtained since it has been possible to test the applicability of the adaptive comfort algorithm and its considerable reductions in demand with respect to the model based on static set points.

With the adaptive model, based on the EN 15251 standard for category II, a reduction in total demand is obtained with respect to the CTE model of 5.91% in the E1 zone, 22.86% for the D3 zone; and a reduction of 52.78% is reached in the B4 zone in the current period. The results also show that, for between 38% and 62% of the hours of operation, heating and cooling are not required.

In a climate change context, we observe that the total demand resulting from the application of adaptive setpoint temperature is also reduced with respect to the CTE model. The contribution of this study would pave the way for future standards more related with climate adaption instead of use fixed setpoints without considering outdoors climate conditions. Moreover, if we compare the evolution of demand in the current period with that of future scenarios, we can observe that there is a growing trend of this demand, which is a product of global warming. Despite the need in this research for the use of a simplified prototype due to the amplitude of the study volume, it has also been possible to prove the acceptability and application in current models, and to achieve satisfactory results, which drive the continuation of the study focused on pursuing a decrease in the demand for energy.

Although this study includes the analysis of future climate scenarios, it must be borne in mind that the EN 15251 standard was developed in 2007 and that the database for the use of this model in hot climates remains limited. In contrast, the adaptability that humans will develop to temperatures in 2050 and 2080 is unknown. For this reason, future research is needed in order to attain the generation of comfort models for each particular climate type and the integration with the national standard while considering the diversity of the climate zones.

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