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Assessment of the energy implications adopting adaptive thermal comfort models during the cooling season: A case study for Mediterranean nursing homes

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ABSTRACT

The growing demand in the use of cooling in buildings for the effects of climate change and the thermal comfort conditions requires the adoption of energy conservation measures. Implementing adaptive thermal comfort models can result in a significant decrease in energy consumption, especially in buildings where the users are groups of vulnerable people. However, no study has proposed a prediction of energy consumption from a comfort-based approach for nursing homes.

This article presents the development of adaptive consumption models to assess the energy implications of HVAC systems for the cooling season by measuring real data on energy consumption and environmental conditions. The adaptive consumption models are implemented in eight nursing homes located in two different climates (Mediterranean and Continental-Mediterranean). The findings reveal that adaptive thermal comfort control methods result in important energy savings in comparison to a fixed set point temperature. The study demonstrates a potential average energy savings of up to 9.9 % (8.1 % in Mediterranean climate and 11.7 % in the Continental-Mediterranean climate) for the analysed nursing homes.

The prediction of energy consumption from an adaptive comfort-based approach in nursing homes will enhance their energy efficiency ensuring the well-being of their vulnerable residents by maintaining optimal thermal comfort. These findings hold significant value for the effective energy management of buildings in future climate change scenarios and warrant careful consideration by nursing home facility managers.

1. Introduction

1.1. Overview

Increasing building energy efficiency is essential to achieve the European Green Deal target of carbon neutrality by 2050 [1], since buildings are responsible for approximately 36 % of CO_2 emissions and about 40 % of the European Union's energy usage [2]. A relevant part of the increase in energy consumption is due to the growing demand in the use of heating, ventilation, and air conditioning systems to achieve thermal comfort levels in the built environment adapted to the effects of climate change. The major energy end-use in industrialised countries is often HVAC systems, which accounts for nearly half of all energy used in buildings, notably non-domestic buildings [3–5]. Along these lines, numerous studies have recently focused on the challenge of improving the buildings' energy efficiency without compromising the users' thermal comfort.

1.2. Background

Over the past few decades, the research on thermal comfort models has focused on two approaches [6]. For predicting and evaluating indoor thermal comfort in buildings, Fanger [7] developed a heat balance steady-state method consisting on the Predicted Mean Vote (PMV) and Percentage People Dissatisfied (PPD) indices based on laboratory studies. Later, aiming at explaining inconsistencies between the projected thermal sensation using PMV-PPD indices and the actual thermal sensation in free-moving indoor climates, as discussed in Peeters et al. [8], regression-based adaptive thermal comfort models were developed taking into account human adaptive actions based on field investigations. The basis of international thermal comfort guidelines and standards, such as ISO 7730 [9], ASHRAE 55 [10] and EN 15251 [11]

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(current EN 16798 [12]) were established by both the traditional heat balancing and regression-based adaptive techniques.

It is worth noting the importance of adaptive thermal comfort models for older people, as one of the group most influenced by the effects of climate change. Conducted studies have shown that older adults experience different thermal perceptions than younger adults [13–17]. As stated by Barquero et al. [18] the elderly has less ability to regulate their body temperature and less ability to notice changes in their body temperature. In this regard, results obtained by Forcada et al. [19–21] demonstrated that residents' comfort levels in the Mediterranean environment are higher than those of caretakers. Moreover, extreme environmental events such as the heat waves of 1995 in Chicago [22], 2003 in England [23] and France [24], which caused excess mortality of the old people, highlight their vulnerability. This interest in enhancing the quality of life for older people has led researchers to develop and assess adaptive thermal comfort models for different climate regions [18–21,25–31].

In terms of improving buildings' energy efficiency, the adoption of energy conservation measures can result in a significant decrease in energy consumption [32,33]. Several studies have focused on the application of energy-saving measures in buildings, but few of them have addressed the challenge of improving energy efficiency by achieving optimal levels of occupants' thermal comfort. Generally, these studies are based on simulations and modelling using optimization algorithms and AI-based models. Some examples of latest studies are Ascione et al. [34] who applied a simulation and optimization-based framework for a model predictive control of space cooling systems is an existing nearly zero energy building (nZEB) located in South Italy achieving energy cost savings around 28 %. And for a Japanese older adults home with air conditioning, Kainaga et al. [26] conducted a field study of thermal comfort and building energy simulation. Their findings indicated that because the reduction in heating load offset the rise in cooling load, the overall heat load might not change considerably.

As pointed by Barbadilla-Martin et al. [35], very few studies deal with the adaptation of the HVAC systems set-point temperature to the corresponding adaptive thermal comfort model as an energy conservative measure. The majority of these studies' base energy prediction savings on simulations and modelling. For instance, Bienvenido-Huertas et al. [36] assessed the influence of using three different adaptive thermal comfort models (EN 15251:2007, EN 16798–1:2019 and ASHRAE 55–2017) in an office building located in 65 cities in Spain and Portugal, under three different climate scenarios. Their findings demonstrated that larger energy savings were obtained when adaptive set-point temperatures based on the EN 16798–1:2019 model were used. Aside from that, it was found that the areas with the highest cooling energy usage also had the most energy savings. In accordance with the NOM-008-ENER-2001 Mexican standard, López-Perez et al. [37] conducted a comparative analysis of energy savings in an air-conditioned educational building in a tropical climate using three AI-based models and two linear models to calculate the comfort temperature following an adaptive thermal comfort approach. Results showed annual cooling load savings ranging from 43.7 % to 15.1 % with AI-based models, whereas using linear models savings ranged from 15.6 % to 3.2 %. Moreover, the idea of adaptive energy consumption was introduced by Sanchez-García et al. [38]. The authors implemented an adaptive comfort model in a mixed mode office building in three scenarios and simulated the energy demand and energy consumption for three scenarios. Energy savings were obtained by comparing, for all scenarios, the energy demand and consumption for current operation mode with adaptive set-point temperatures. For the current scenario, the results reveal that when the adaptive comfort model is used, energy demand and energy consumption are reduced by 74.6 % and 59.7 %, respectively. To the authors knowledge, only Barbadilla-Martin et al. [35] analyses the impact of applying adaptive thermal comfort models on the building energy performance by measuring real data on energy consumption. In their study, the authors implemented an adaptive comfort algorithm in the HVAC control system in eleven office spaces during cooling and heating periods to validate that, in comparison to a fixed set point temperature, adaptive control methods result in equal comfort levels with lower energy use. In the study, energy savings were obtained by comparing the predicted baseline with the measured energy consumption. They obtained energy saving during the cooling and the heating periods, respectively, of 27.5 % and 11.4 %.

1.3. Research gap and objectives of this study

Even though some research have suggested the idea of adaptive energy consumption models [35], none of them have specifically focused on predicting energy consumption from comfort-based adaptive energy consumption models. Additionally, although older people spend 80 % of their time indoors, their health and comfort are significantly influenced by indoor thermal environment, none of the studies found in the literature evaluated the impact of implementing adaptive thermal comfort models on energy consumption in nursing homes.

Against this background, this study is aiming at assessing the impact on energy consumption of the implementation of validated adaptive thermal comfort models in nursing homes by using real energy consumption data during the cooling season, in different climatic conditions, Mediterranean and Continental climates. This research will contribute to improving energy efficiency of nursing homes by reducing their energy consumption while guaranteeing the thermal comfort of the residents, as a vulnerable group. The results can be useful in the energy management of buildings and should be considered by facility managers of nursing homes.

The paper is organized as follows. Following this introduction, the methodology is detailed in the second section. The third section explain the case studies. The development of energy consumption models for the cooling season are presented in the fourth section. The results of integrate adaptive thermal comfort models into the energy consumption models and its energy implications are described in the fifth section. Finally, the conclusions are given in the sixth section.

2. Methodology

This study is based on the developed adaptive thermal comfort models for older adults in both climates, the Mediterranean climate by Forcada et al. [20] and the Continental Mediterranean climate by Baquero and Forcada [18]. Based on these models, the methodology to analyse the energy implications of using adaptive comfort models during the cooling season is devised in four phases:

- Phase 1. Collection and processing of electricity consumption. indoor and outdoor environmental data. Indoor conditions include air temperature, radiant temperature, relative humidity, and air speed. Outdoor conditions include temperature and relative humidity. This phase includes the energy consumption and environmental data collection for the eight case studies, and subsequent data processing. Then, the cooling period is determined.
- Phase 2. Development of energy consumption models for the cooling season. This step encompasses the analysis of regression models under different parameters for each case study.
- Phase 3. Integration of the adaptive thermal comfort models into the energy consumption models. In this phase, the comfort temperature obtained in the validated adaptive thermal comfort models is integrated into the energy consumption models.
- Phase 4. Analysis of energy implications. Finally, the energy consequences of the adoption of the thermal comfort model are evaluated in terms of potential energy savings.

2.1. Collection and processing of electricity consumption data

In order to assess the energy implications of implementing adaptive comfort models based on real data, one year's electricity consumption data is gathered from smart meter systems installed in the studied nursing homes.The standardization across the HVAC energy consumption of the case studies is obtained by retrieving the total energy consumption of the buildings and using the same method for filtering the different consumptions. To obtain accurate, complete, and consistent values, energy consumption data is cleaned, pre-processed, and filtered to remove inaccurate readings and fill in blank numbers. Data processing involves analysing similar consumption data from the building, considering the time slot and average values of reliable data from similar days, to avoid an overrepresentation of the treated values. For those buildings with energy production through photovoltaic solar cells, self-consumption is added to the electricity consumption data.

After the energy data debugging process and solar self-consumption inclusion, the cooling period is obtained from energy consumption patterns that show higher demand from the daytime electricity consumption (CED). The main process entails comparing the electricity consumption from one day and the following day and observing the results with larger differences. If the observed date coincides with the start or end of the typical cooling season, the date is selected to set the cooling period.

To isolate the daytime electricity consumption due to cooling (CEDc) the average electricity consumption during the interval of time without cooling (CEDnoc) is subtracted from the average electricity consumption demand of the air-conditioned period (see Fig. 1).

2.2. Development of energy consumption models for the cooling season

To develop an energy consumption model for the cooling season the influencing variables are determined. The selected variables of study primarily depend on the environmental meteorological and indoor characteristics, as stated by Kassas [39] and Ibarra et al. [40]:

- Running mean temperature, T_{rm}: The outdoor temperature functions as a crucial variable in determining the optimal level of cooling intensity required to mitigate the thermal loads that arise from the temperature differential between the outdoor and indoor environments. Running mean temperature is selected because it gives information of the thermal inertia which leads into significant differences in the thermal comfort of the occupants, partially conditioning the consumption of the building.

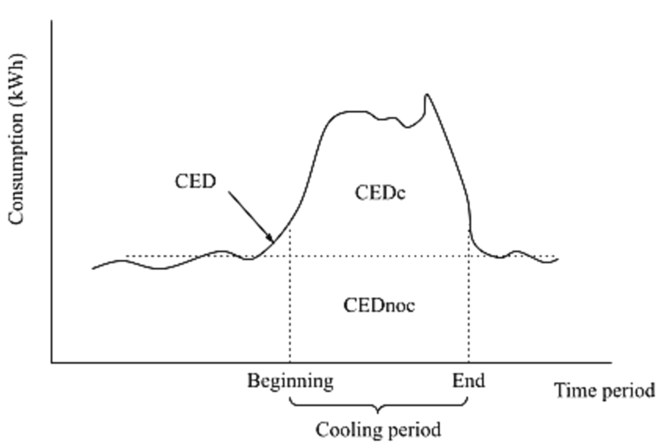

Fig. 1. Electricity consumption pattern for buildings. * CED: Daily electrical consumption, CEDc: Daily electrical consumption due to cooling, CEDnoc: Daily electrical consumption excluding cooling.

T_{rm} is the 7-day weighted running mean of outdoor temperature which is calculated using the formula (ISO 7726) [41]:

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

where T_{ed-1} is the daily mean outdoor temperature for the previous day and T_{ed-2} is the daily mean outdoor temperature for the day before that, and so on.

- Operative temperature, T_{op}: The indoor temperature of a building is also determinant when assessing the thermal loads between indoor and outdoor conditions to determine the quantity of cooling required. Likewise, operative temperature is also important when evaluating the thermal comfort of the occupants.

The operative temperature (T_{op}) is calculated as a combination of the mean radiant temperature (Tr) and air temperature (Ta) effects by this formula:

$$T_{op} = (T_a + T_r)/2 \quad (2)$$

- Indoor and outdoor relative humidity, RH & RH_{out}: Relative humidity alter the human perception of heat and thus they are a parameter of control when evaluating the thermal comfort and HVAC consumption of a building.
- Indoor air speed, v_a: The indoor air velocity serves as a control variable to determine if the HVAC system is switched on or off.

After analysing the linear, quadratic, exponential, and logarithmic regression models, the most accurate one was obtained with the linear regression. The linear system is mathematically defined as follows:

$$Y = \beta_0 + \beta_1\chi_1 + \beta_2\chi_2 + \beta_3\chi_3 + \beta_4\chi_4 + \beta_5\chi_5 \quad (3)$$

The description of this multivariate linear model encompasses different generic parameters, which are further detailed in Table 1.

As a result, the regression model is a function that depends on the aforementioned variables (see Equation (4).

$$CEDr = f(T_{rm}, T_{op}, RH, RH_{out}, v_a) \quad (4)$$

Real-world data is used to define a linear model for each building. However, to facilitate the implementation of the model for the buildings' management and control, a reduced model only incorporating indoor and outdoor temperatures [37] is also developed. While this simplified model may result in a lower coefficient of determination and reduced accuracy compared to a more complex model, it provides greater simplicity and applicability, making it a robust alternative to study HVAC consumption patterns in the studied buildings.

Given that every regression inherently incorporates an associated error, it becomes paramount to discern the underlying characteristics of the regressors. This understanding is pivotal in establishing a suitable

Table 1
Summary of variables considered for the multivariate linear regression model.

Parameter	Variable	Unit	Description
Y	$CEDc$	kWh	Electric consumption due to cooling
χ_1	T_{rm}	°C	Running mean temperature
χ_2	T_{op}	°C	Indoor operative temperature
χ_3	RH	%	Indoor humidity
χ_4	RH_{out}	%	Outdoor humidity
χ_5	v_a	m/s	Indoor air speed
β_1	–	°C	Outdoor temperature constant
β_2	–	°C	Indoor temperature constant
β_3	–	%	Outdoor humidity constant
β_4	–	%	Indoor humidity constant
β_5	–	m/s	Air speed constant

confidence interval, thereby bolstering the clarity and robustness of the results yielded by the modelling techniques.

Thus, the first analysis encompasses the determination of the residuals of the models, which are obtained through the following formulation:

$$r = \overline{X} - X \tag{5}$$

With r representing the residual, $\overline{X}$ being the predicted estimate from the model, and X representing the real value.

Building upon this formulation, negative residuals suggest that the regressor underestimates real consumption values, while positive residuals indicate higher model-predicted consumption estimates than expected.

Subsequently, an assessment of the residuals is essential to determine the most appropriate approach for assessing model accuracy and establishing a confidence interval. Typically, model residuals present normal distributions, enabling the calculation of a confidence interval under the assumption of normality. The resulting confidence interval is presented below:

$$CI = \overline{x} \pm z\frac{\sigma_d}{\sqrt{n}} \tag{6}$$

Being $\overline{x}$ the sample mean, σ_d the standard deviation, n the sample size, and z representing the point on the standard normal density curve such that the probability of observing a value greater than z is equal to probability p is known as the upper p critical value of the standard normal distribution. For a 95 % confidence interval, z = 1.96.

These intervals serve to enhance the understanding of the model and contribute to assessing the likelihood of error for specific values. In regressors where the residuals do not conform to a reasonably normal distribution, alternative approaches must be considered.

2.3. Integration of adaptive thermal comfort models into the energy consumption models

Adaptive comfort theory considers that the comfort temperature for occupants relates to the mean outdoor temperature, building types and climatic regions. Although EN 16798:2019 [12] includes adaptive thermal comfort models for adults in office buildings, the thermal sensation and adaptation of older people in nursing homes is different [42]. The age affects regulating the body temperature and thus the thermal comfort perception. Forcada et al. [20] and Barquero et al. [18] developed adaptive thermal comfort models for nursing homes in a Mediterranean and Continental-Mediterranean climates, respectively.

These validated adaptive thermal comfort models are implemented into the adaptive consumption models in order to analyse their energy implications. The adaptive thermal comfort models provide data on the ideal operative temperature for a neutral thermal sensation, regardless of energy consumption. Then, the impact of applying these models on cooling consumption levels is investigated, determining if it leads to an increase or decrease in energy usage.

2.4. Analysis of energy implications

The energy implications of implementing adaptive thermal comfort models are analysed by processing real-world data. Modelled results are compared on a daily basis, allowing for a comprehensive evaluation of their performance over time. Differences between the elaborated models (i.e., complete and reduced) are also be studied. Fig. 2 illustrates the overall methodology scheme. Reduced models follow an identical methodology scheme but only considering T_{rm} and T_c as inputs between Phase 2 and Phase 3.

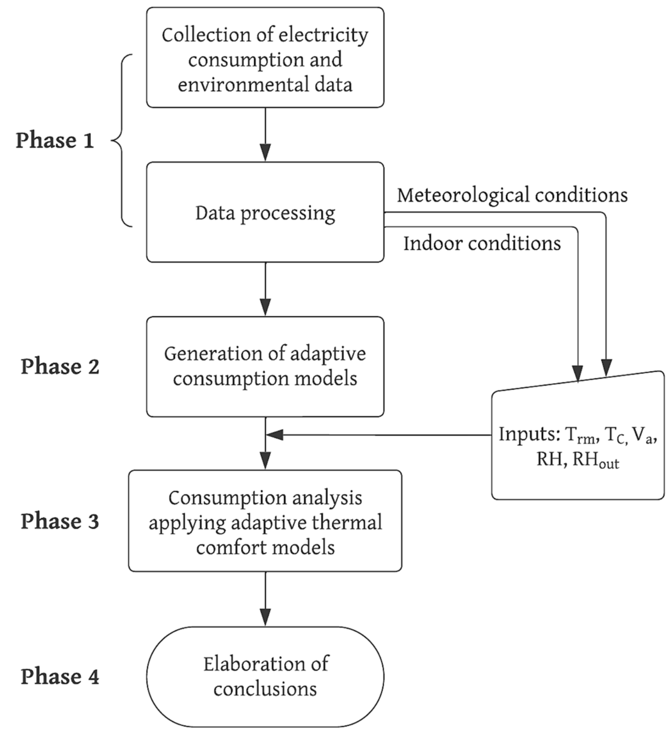

Fig. 2. Flowchart of overall methodology scheme. * T_{rm}: Running mean temperature, T_c: Comfort temperature, v_a: Air speed, RH: Indoor relative humidity, RH_{out}: Outdoor relative humidity.

3. Case studies

This paper uses eight Spanish nursing homes as case studies in two different climate zones, Mediterranean climate and Continental-Mediterranean climate, with two different HVAC systems, direct expansion systems and variable refrigerant volume.

A nursing home is a place of residence with 24-hour health care and assistance offered by professionals to people who can no longer stay in their own home environment due to increasing need for assistance with activities of daily living, complex health care needs and vulnerability [43]. Rooms might be occupied individually or by pairs while common areas such as living rooms, dining rooms, gyms and occupational therapy rooms are occupied by a group of residents. Nursing homes have medical professionals of staff, including doctors and nurses who can monitor their health condition and respond to medical emergencies. Caregivers assist residents with daily living activities such as group social activities, rehabilitation activities, etc.

3.1. Case studies description

From the eight Spanish nursing homes, four correspond to a Mediterranean climate (Csa-m), located in the Community of Valencia and Catalonia, and four correspond to a Continental-Mediterranean climate (Csa-c), located in the Community of Madrid. For the studied nursing homes, the age of the residents was in average 84 years and around 70 % were female and 30 % male. The main HVAC system of these nursing homes is an all-water system with fan-coils, while two of the nursing homes are cooled by a Variable Refrigerant Volume (VRV) systems. The main characteristics of the nursing homes including the location, the year of construction, the number of floors and the cooling area and the HVAC system, are summarized in Table 2. Fig. 3 shows the location of the nursing homes.

All-Water HVAC systems and Variable Refrigerant Volume (VRV) systems are both used for heating and cooling in buildings, but they

Table 2
Main characteristics of the sample of nursing home buildings.

Case study	Climate	Location	Year of construction	Number of floors	Cooling area (m^2)	HVAC system
M1	Mediterranean climate	Bétera	2000	5	2506	All-water
M2	Mediterranean climate	Barcelona	N/A	5	4832	All-water
M3	Mediterranean climate	Barcelona	N/A	7	1855	All-water
M4	Mediterranean climate	Tarragona	1960	11	7857	VRV
CM1	Continental Mediterranean climate	El Viso	2005	6	5869	All-water
CM2	Continental Mediterranean climate	Alameda	2010	6	5285	VRV
CM3	Continental Mediterranean climate	La Moraleja	2003	5	5152	All-water
CM4	Continental Mediterranean climate	Las Rozas	1988	4	5284	All-water

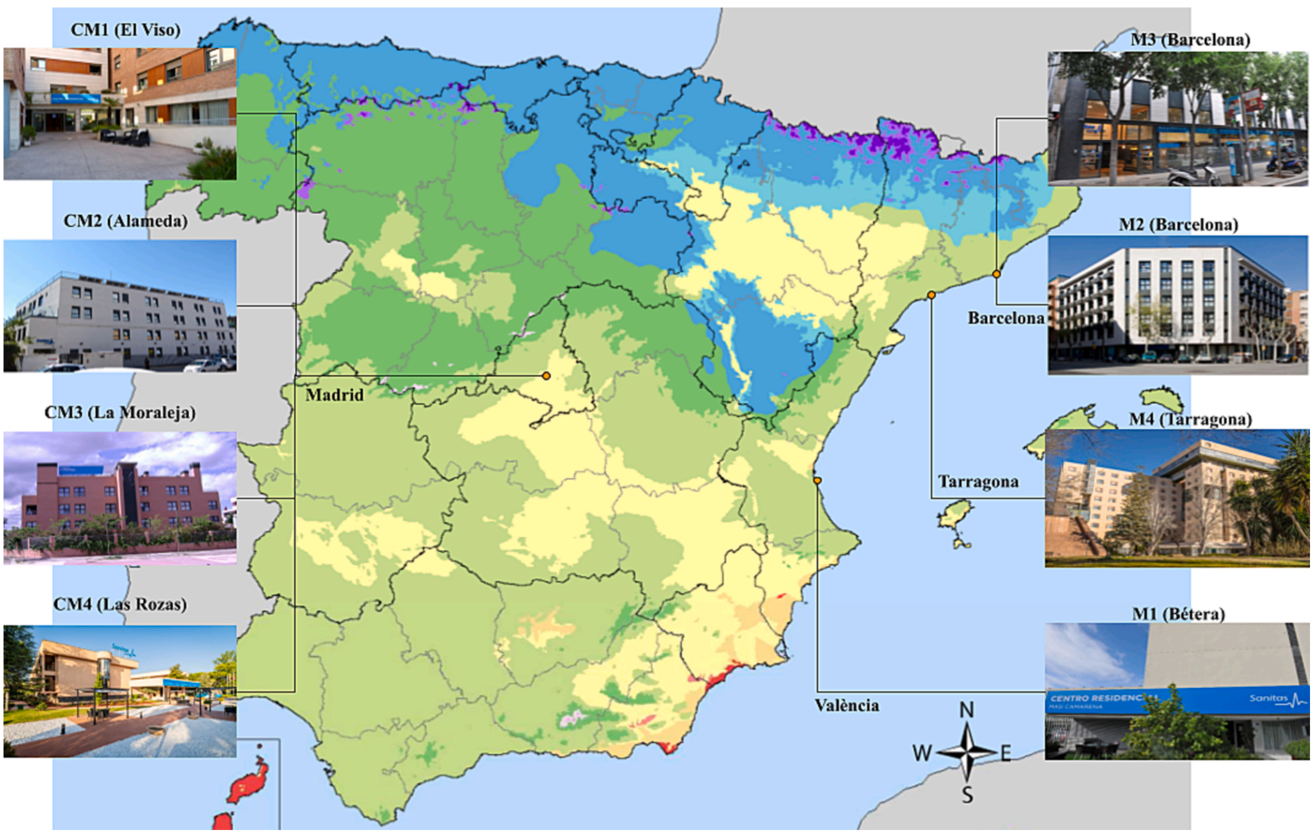

Fig. 3. Geographical distribution of the nursing homes in Spain, according to Köppen climate classification. Adapted from AEMET [46].

operate on different principles. All-Water systems use water as the heat transfer medium for both heating and cooling. In general, they incorporate a boiler to heat the water and a chiller to cool it. Then, the most common energy source for heating is gas and for cooling is electricity. On the other hand, VRV systems use refrigerant as the heat transfer medium. A single outdoor condensing unit is connected to multiple indoor units. Electricity source is used both for heating and cooling and thus, have energy fluctuations along the different seasons.".

3.2. Case studies climatology description

As previously mentioned, thermal comfort is largely influenced by the climate and the characteristics of the occupants, with older adults perceiving temperature differently from younger adults, or even children. Therefore, each demographic requires a tailored thermal comfort model that is better suited for their specific needs, rather than relying on general models that may be too broad and imprecise. Likewise, the case studies outlined above specifically focus on nursing homes, located in the Mediterranean and Continental-Mediterranean climates. Although these climates are both found in the Iberian Peninsula, they present significant differences that are worth mentioning.

The Mediterranean climate corresponds to the section of the eastern peninsular coastline, is characterised by temperate climate with dry and hot summers [44] and has an average annual temperature of 16 °C although they are highly variable throughout the year. In summer, average temperatures ranges from 18 °C to 28 °C, and in winter ranges from and 4 °C to 15 °C. The average humidity remains quite stable throughout the year, between 64 % and 70 % [45].

The Continental-Mediterranean climate is mainly found in the interior of the peninsula, has an average yearly temperature of 14.1 °C. During the summertime, the average temperature ranges from 25 °C to 32.8 °C and the relative humidity is low, around 37 %. Whereas in wintertime, temperature range from 2 °C to 11 °C and the humidity is moderate-high, reaching maximums of 71 % [46,47].

3.3. Case studies data treatment

3.3.1. Data acquisition

The data acquisition was carried out over the course of one year, from December 1st, 2018, to November 30th, 2019, for the nursing homes located in the Mediterranean region. Similarly, for the nursing homes situated in the Continental Mediterranean region, the campaign was conducted from February 1st, 2021, to February 28th, 2022. The dataset comprises 35,040 quarter-hour consumption measurements for each nursing home, resulting in a total of 280,320 data-set values before processing. Indoor consumption monitoring and acquisition was performed through *Supervisory Control And Data Acquisition* (SCADA) systems for each nursing home. The system is composed by three levels; the measurement systems that are located within the first level; the *Programmable Logic Controller* (PLR) which is at a second level and served to control and acquire the required data; the third level acts as a supervising and management tool of the PLR system.

The outdoor environmental data collection was obtained from AEMET [48]. Daily outdoor temperature and relative humidity from nearby meteorological stations was collected. The dataset comprises 365 measurements for each nursing home, resulting in a total of 2,920 data-set environmental values.

The primary differentiating factor between the two datasets concerns the granularity in the collection of environmental data, which is conducted on a daily basis. Consequently, the adaptive consumption models developed through this study are designed to be applied daily, aligning with the frequency of the environmental data collection.

Indoor environmental data collection was conducted in the common areas of the nursing homes (living room, therapy room, dining room and gym-physiotherapy room).

Field measurements included globe temperature, dry air temperature, relative indoor humidity, and air speed were collected during the indoor environmental data collection. These data were acquired on-site during randomly selected days (three days per nursing home and season). The chosen timeframe for data collection spanned from 10 a.m. to 6p.m., aligning with the period of peak occupancy of these rooms. After 10 min of equipment stabilization, measurements were recorded every 15 s for periods between 15 and 60 min. During the data acquisition process, a total of 1,890 indoor environmental averaged data values were specifically obtained during the cooling season. Equipment specifications are detailed in Table 3.

3.3.2. Data processing

Data processing includes eliminating erroneous data together with dismissing night-time values, so data from 6:00 a.m to 10:00p.m is retrieved (both times inclusive). A representation of the debugged results is illustrated in Fig. 4. It is noteworthy that the figure presented depicts the two primary HVAC systems utilized in nursing homes, namely all-water system, and variable refrigerant volume (VRV) systems. Due to the similarity of the results obtained across the different nursing homes, it is unnecessary to include all the debugged results, as they exhibit the same overall trends and patterns as those illustrated in the figure.

The variation in consumption between all-water and VRV systems arises from the utilization of different energy sources. VRV systems use electrical energy for both heating and cooling, while all-water nursing homes rely on gas for heating during the winter season. All-water nursing homes have an alike consumption behaviour. No significant differences regarding energy consumption overall tendency are found between Mediterranean and Continental Mediterranean climates.

Table 3
Equipment specifications for indoor environmental measurement.

Probe	Measured variable	Range	Accuracy
TP3276.2	Radiant temperature (T_r)	−10 °C to 100 °C	±0.2 °C
HP3201.2	Air temperature (T_a)	−10 °C to 80 °C	±0.5 °C
HP3201.2	Relative humidity *(RH)*	5 % to 98 %	±3 %
AP3203.2	Air speed (v_a)	0.05 m/s to 5 m/s	±0.05 m/s

From the analysis of the consumption pattern of the selected buildings, the cooling period of each nursing home is obtained (see Table 4).

It can be observed that subtle differences arise when comparing Mediterranean cases to Continental-Mediterranean ones. In general, Continental-Mediterranean nursing homes tend to start the cooling season several weeks before the Mediterranean climate. A similar behaviour is also found when studying the ending of the cooling period.

4. Development of energy consumption models for the cooling season

The development of adaptive consumption models is performed through *IBM SPSS Statistics* (29.0.0.0 version) [49].

The coefficients of determination from the linear regression models show a strong correlation between the meteorological and indoor conditions with the cooling electricity consumption of the nursing homes. Tables 5 and 6 summarise the obtained adaptive regression models, whether extended or reduced, respectively.

The analysis of the consumption models of the nursing homes cooled by VRV systems revealed inconsistencies. With respect to the extended models, there is an overemphasis on humidities influence, which renders the resulting consumption estimates inapplicable to data values beyond the dataset, thereby lacking accuracy. Conversely, the reduced models present a low coefficient of determination, making the results unreliable. This phenomenon can be attributed to two potential theories: i) The consumption patterns in VRV systems are non-linear and cannot be accurately determined using linear regression techniques, or ii) There is insufficient data available, leading to inadequate representativeness. Therefore, the nursing homes cooled by VRV were excluded from the analysis.

All extended consumption models for the nursing homes cooled by all water systems present a high coefficient of determination with a mean of 0.76, while the reduced regression models yield a mean coefficient of determination of 0.69. The high R^2 of the two models allow concluding that they are both reliable to predict the HVAC consumption during the cooling period. These results align with the findings of López-Perez et al. [37], who also developed simplified models that did not incorporate air velocity or relative humidity as parameters in their simulation of air conditioning in educational buildings. Although outdoor relative humidity influences HVAC energy consumption in some climates with very high RH_{out} where dehumidifiers are needed, for the Mediterranean and Continental Mediterranean climates this effect is disregarded [37]. Results also reveal that the utilization of reduced models for these climates is appropriate.

On the other hand, and to further validating the models, Fig. 5 illustrates the insights gained from plotting histograms of the residuals, which helps to determine behaviour of the regressors under different predictive scenarios.

The histograms for all models show a tendency toward a somewhat normal distribution, with central values more prevalent than higher residual values. Hence, normality can be assumed for calculating the 95 % confidence interval. So, Table 7 summarises the obtained results within all models.

As observed, all regressors present a negative average of residuals, indicating a tendency for the models to slightly overestimate cooling consumption, possibly attributable to nonlinearities in consumption estimations. Consequently, the results from these regressors may lean towards conservative estimates. Nevertheless, as a precautionary measure to avoid unrealistic savings in cooling consumption, the models are treated in this study as if they did not tend to overestimate it.

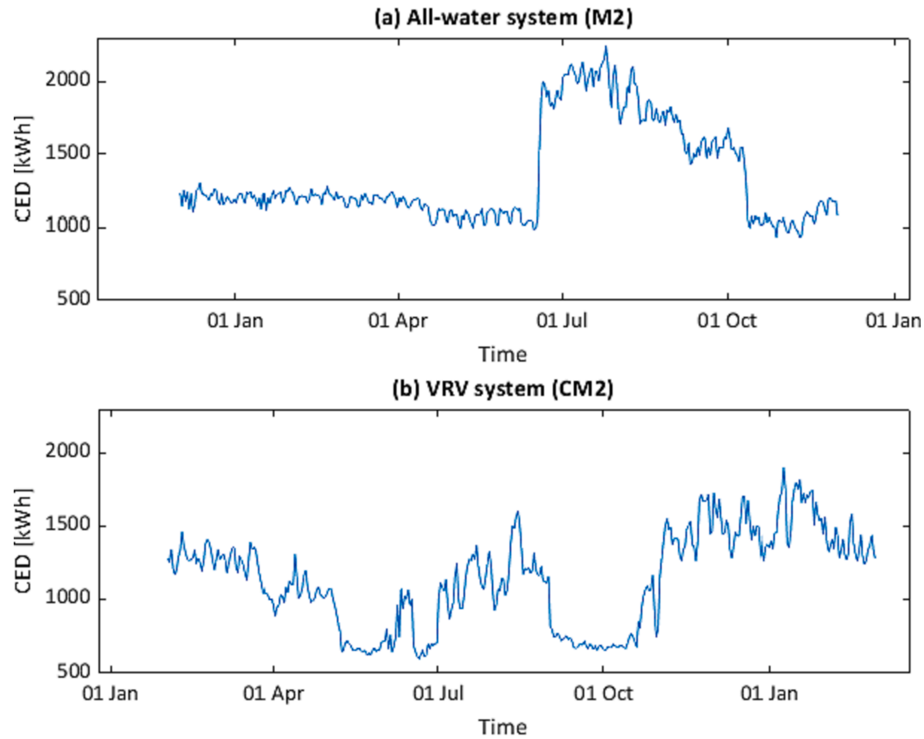

Fig. 4. Sample of daily electrical consumption data once debugged and processed.

Table 4
Cooling periods of the analysed case studies.

Case study	Period of cooling	Number of days
M1	From June 19th to October 9th	112
M2	From June 17th to October 11th	116
M3	From June 29th to September 8th	71
M4	From June 27th to September 1st	66
CM1	From May 30th to September 13th	106
CM2	From June 30th to August 31st	61
CM3	From June 4th to September 20th	108
CM4	From June 6th to September 7th	93

Table 5
Extended adaptive consumption models for each nursing home considering indoor (v_a, T_{op}, RH) and outdoor (T_{rm}, RH_{out}) variables.

Case study	Regression model	R^2
M1	$CEDc = 464 + 1535.7v_a + 15.8RH + 5.5RH_{out} - 88.3T_{op} + 28.9T_{rm}$	0.80
M2	$CEDc = 997.1 + 587.6v_a - 14.2RH + 4.9RH_{out} - 93.1T_{op} + 96.4T_{rm}$	0.78
M3	$CEDc = 196.6 + 293.3v_a + 3.2RH - 5.6RH_{out} - 33.6T_{op} + 50.1T_{rm}$	0.72
M4	$CEDc = -2094.7 + 961.4v_a - 20.7RH + 61.2RH_{out} - 97.4T_{op} + 102T_{rm}$	0.78
CM1	$CEDc = -453.7 + 867.3v_a + 10.7RH - 6.5RH_{out} + 8.5T_{op} + 17.6T_{rm}$	0.70
CM2	$CEDc = 2792.9 + 2633.7v_a - 32.4RH - 6RH_{out} - 46.2T_{op} + 39.1T_{rm}$	0.83
CM3	$CEDc = -1158.8 + 2609.1v_a + 13.4RH - 5.7RH_{out} + 26.8T_{op} + 13.1T_{rm}$	0.77
CM4	$CEDc = 785.2 + 1323v_a - 1.4RH - 5.4RH_{out} - 63.2T_{op} + 72.9T_{rm}$	0.80

Table 6
Reduced adaptive consumption models for each nursing home considering indoor (T_{op}) and outdoor (T_{rm}) variables (only-temperature regression models).

Case study	Regression model	R^2
M1	$CEDc = 1930.9 - 123.7T_{op} + 59.8T_{rm}$	0.65
M2	$CEDc = 872.7 - 82.5T_{op} + 73T_{rm}$	0.72
M3	$CEDc = 95.5 - 37.3T_{op} + 48.9T_{rm}$	0.68
M4	$CEDc = -1380.1 - 84.7T_{op} + 163.3T_{rm}$	0.46
CM1	$CEDc = -220 - 10.9T_{op} + 37.2T_{rm}$	0.65
CM2	$CEDc = -1824.1 + 34.9T_{op} + 52.7T_{rm}$	0.59
CM3	$CEDc = -1026.3 + 27.4T_{op} + 30.6T_{rm}$	0.66
CM4	$CEDc = 337.9 - 70.8T_{op} + 81.8T_{rm}$	0.77

5. Integration of adaptive thermal comfort models into the energy consumption models

The analysed case studies utilize the adaptive thermal comfort models specifically developed for older populations in Mediterranean and Continental Mediterranean climates [18,20].

The adaptive thermal comfort models are the following:

- For the Mediterranean climate [20]:

$$T_c = 0.16 \cdot T_{rm} + 20.4 \quad (7)$$

- For the Continental Mediterranean climate [18]:

$$T_c = 0.16 \cdot T_{rm} + 20.8 \quad (8)$$

Where T_c accounts for the comfort temperature, and T_{rm} is the running mean temperature.

ASHRAE 55 comfort models focus on office buildings ($T_c = 0.31 \cdot T_{rm} + 17.8$), which tend to be occupied by adults aged less than 65 years old. A nursing home is a 24-hour care and assistance residence for

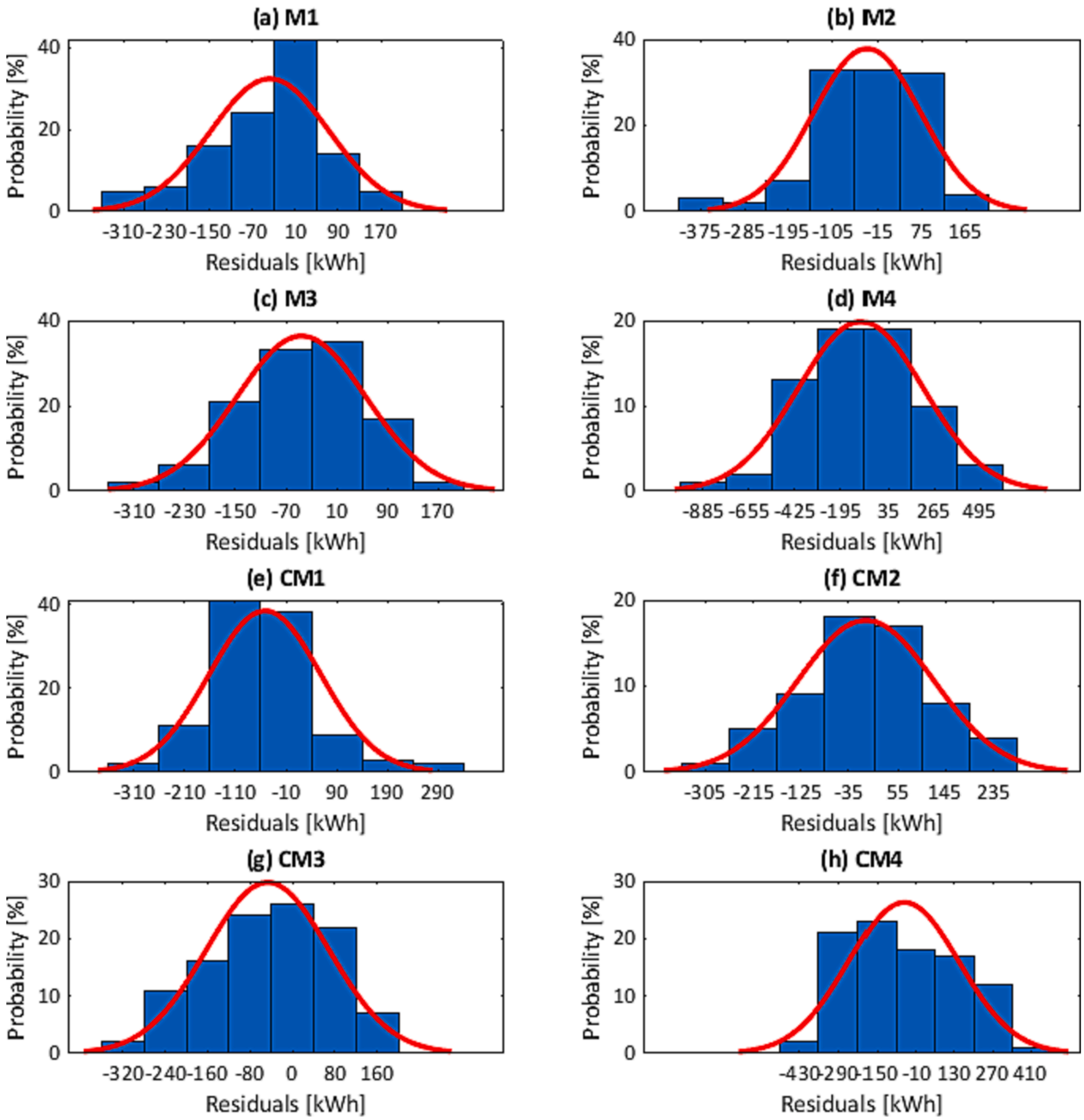

Fig. 5. Histograms of residuals for different regressors with fitted normal distribution curves.

Table 7
Summary of regressors performance and confidence intervals.

Regressor	R^2	Average of residuals [kWh]	Standard deviation [kWh]	95 % confidence interval [kWh]
M1	0.65	−37.1	110.3	[-57.7, −16.4]
M2	0.72	−35.9	108.3	[-55.9, −15.8]
M3	0.68	−45.8	101.8	[-64.5, −27.0]
M4	0.46	−98.4	309.9	[-174.0, −22.9]
CM1	0.65	−51.4	110.0	[-72.6, −30.2]
CM2	0.59	−4.1	126.3	[-36.1, 28.0]
CM3	0.66	−46.7	115.7	[-68.7, −24.6]
CM4	0.77	−52.9	199.6	[-93.7, −11.8]

people who cannot stay alone and need daily living assistance and complex health care needs. Therefore, in comparison to occupants in offices, the thermal sensation and adaptation of older people in nursing homes is different. Although ASHRAE 55 narrows the comfort temperatures for spaces occupied by weak and sensitive people with special requirement, such as the elderly, several field studies found that elderly are less sensitive to outdoor conditions and comfort temperature remains fairly constant along the different seasons [18,20].

Fig. 6 depicts the running mean temperature for each climate and the corresponding comfort temperature obtained from the adaptive thermal comfort models. It shall be noted that only one sample of each climate is depicted because no significant differences are found in-between the Mediterranean nursing homes themselves nor the Continental-Mediterranean ones.

As expected, an increase in the running mean temperature indicates a rise of the comfort temperature. The higher the running mean temperature, the higher the operative temperature, residents can withstand more extreme indoor temperatures as outdoor environments get hotter. This phenomenon arises from the gradient of indoor and outdoor temperatures and the building envelope performance. Comfort temperatures range from 22 °C to 26 °C for running mean temperatures of 5 °C and 33 °C, respectively. More extreme temperatures, both during cooling and heating periods, are found in the continental climate.

To evaluate the energy savings of implementing adaptive comfort models, the comfort temperature from the adaptive thermal comfort

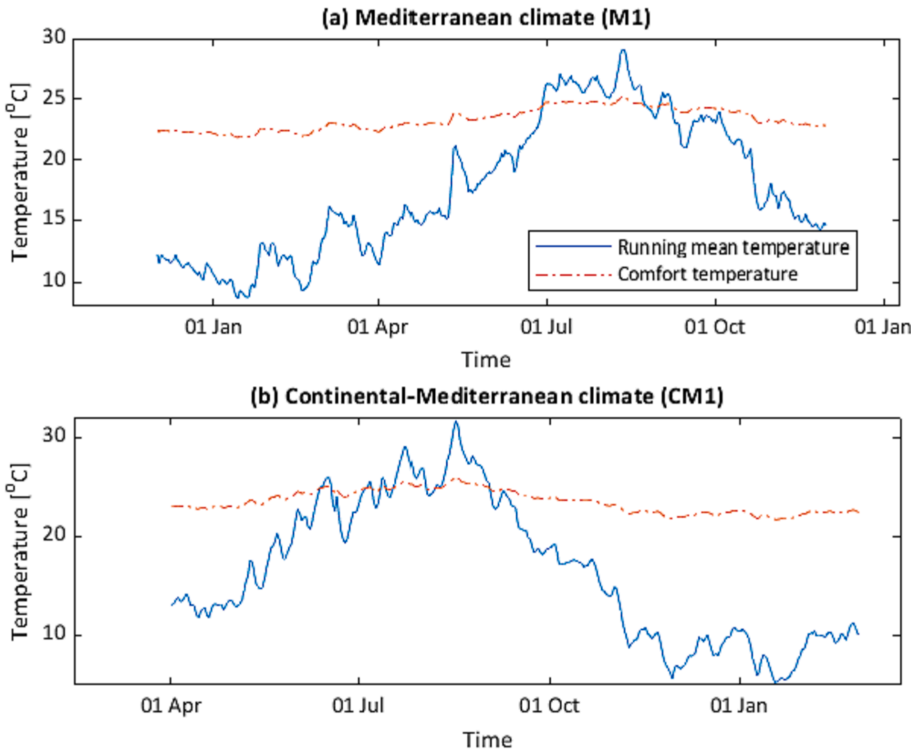

Fig. 6. Sample of running mean temperature and comfort temperature along the analysed period.

models is set to be the operative temperature within the energy consumption models. Considering and implementing the expressions to calculate the operative temperature of the nursing homes is imperative to obtain the theoretical cooling consumption while maintaining the thermal comfort.

Fig. 7 presents the real daily cooling consumption for each nursing home and the predicted consumption when implementing adaptive comfort temperatures, both using the extended and the reduced consumption models.

To reinforce the suitability of the reduced consumption models, the predicted data for the cases studies using both models were obtained. The average difference of the two models was found to be $1.8\% \pm 6.3\%$. Given the simplicity of the reduced model which only requires indoor and outdoor temperatures, the reduced model will be used to analyse the energy implications in the case studies.

Analysing the tendencies, as the outdoor temperature rises, the cooling demands are noticeably higher and, therefore the electricity consumption also increases. Conversely, the indoor temperature has an inverse effect on electrical consumption, since an increase in the operative temperature in summer causes a reduction electrical consumption, aligning with Baquero et al. [18] and Forcada et al. [20] findings.

6. Analysis and discussion of energy implications

The mean monthly energy savings regarding cooling consumption is obtained from the relationship between mean predicted consumption under a comfort temperature (incorporating the adaptive thermal comfort models) and mean real energy consumption in which a fixed set point temperature is defined. Monthly expected energy savings expressed in percentages are summarized in Table 8 and depicted in Fig. 8. "The analysis of electricity consumption of each nursing home highlighted non-linear consumption patterns with significant fluctuations for VRV systems. Therefore, linear regression analysis cannot be used and VRV systems were excluded from this analysis.

Energy savings when implementing adaptive thermal comfort models range from 6.9 % to 16.7 %, with an average monthly energy saving of 9.9 % of the total energy devoted to These differences are attributed to the age of the HVAC systems, thermal performance of the building envelope, and differences between the building management systems, among others. The higher the outdoor temperature, the more savings are observed. Given the direct impact of climate change on increasing outdoor temperatures [50], it is anticipated that greater savings will be achieved over time.

The over cooling of the majority of the nursing homes (22–24 °C) when fixed set point temperatures are used is one of the main reasons of the high energy consumption of nursing homes. When implementing adaptive comfort models for older people the comfort temperatures increase to a range of 24 °C − 26 °C in summer resulting to high energy savings.

There is a lack of comparable studies on the use of adaptive thermal comfort models as there are no studies on nursing homes, and studies on other typologies of buildings do not use real data but simulations, with the exception of Barbadilla-Martin et al. [35].

For educational buildings in a tropical climate, López-Perez et al. [37] through simulation obtained cooling energy savings ranging from 43.7 % to 15.1 % when using AI-based models, and energy savings between 15.6 % and 3.2 % using linear models. It must be taken into consideration that these percentages of savings in energy consumption correspond to simulated values for a tropical climate, where temperatures are higher than those of the Mediterranean climate, and therefore the potential for energy savings is higher.

In office buildings in a Mediterranean climate, Sanchez-García et al. [38] reached a reduction in energy consumption in cooling between 59.5 % and 36.7 % when applying the adaptive comfort model by

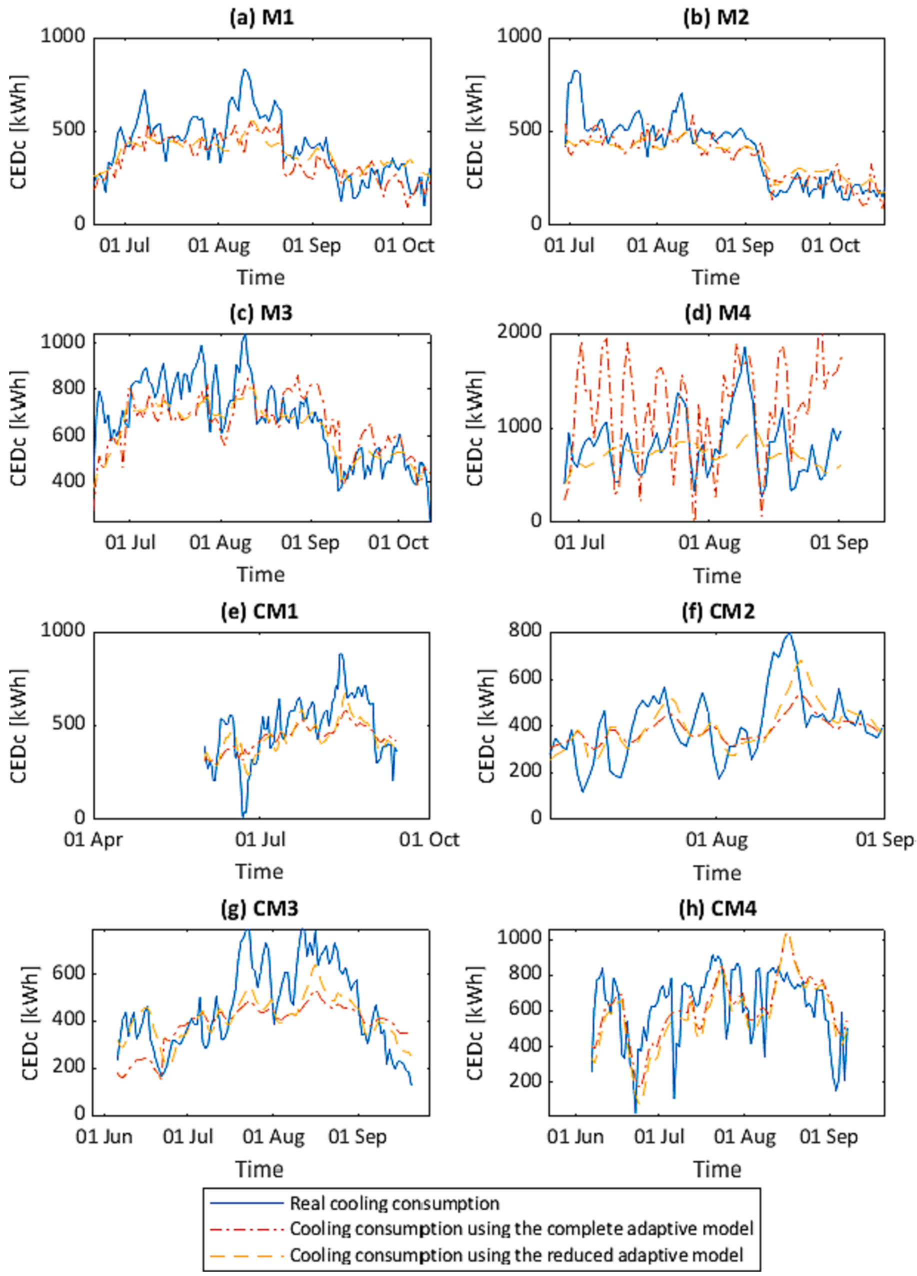

Fig. 7. Adaptive consumption models to assess daily consumption due to cooling.

Table 8
Mean real and predicted monthly consumption and expected savings regarding cooling energy consumption when implementing adaptive thermal comfort models.

Nursing home	Mean real energy consumption [kWh/month]	Mean predicted energy consumption [kWh/month]	Monthly expected energy savings [%]
M1	12842.4	11537.0	10.2
M2	19482.2	18130.9	6.9
M3	11519.8	10683.3	7.3
CM1	15818.3	13179.4	16.7
CM3	13465.4	12003.5	8.9
CM4	19318.5	17490.1	9.5

simulation, while Barbadilla-Martin et al. [35] reached energy savings during the cooling season of 27.5 % by comparing the predicted baseline with measured energy consumption. Table 9 offers a summary and comparison of the energy savings found by different studies using adaptive modelling techniques.

From the previous studies it can be observed that energy savings obtained by simulation tend to be higher values than in the studies that use real-world data. On the other hand, in comparison to the results of Barbadilla-Martin et al. [35], who also used real data, it is highlighted that the type of use of the building associated with the comfort conditions of its users have an impact on the potential for savings in energy consumption. Nursing homes are buildings that operate constantly every day of the week and have more demanding thermal comfort conditions than office buildings. These constraints have an impact on the energy saving potential, so that in office buildings the energy saving potential is greater than in nursing homes.

The analysis by climate reveals that when considering the climates separately, the application of adaptive thermal comfort models results in energy savings of 8.1 % for the Mediterranean climate and 11.7 % for the Continental-Mediterranean climate. The greater savings observed in the

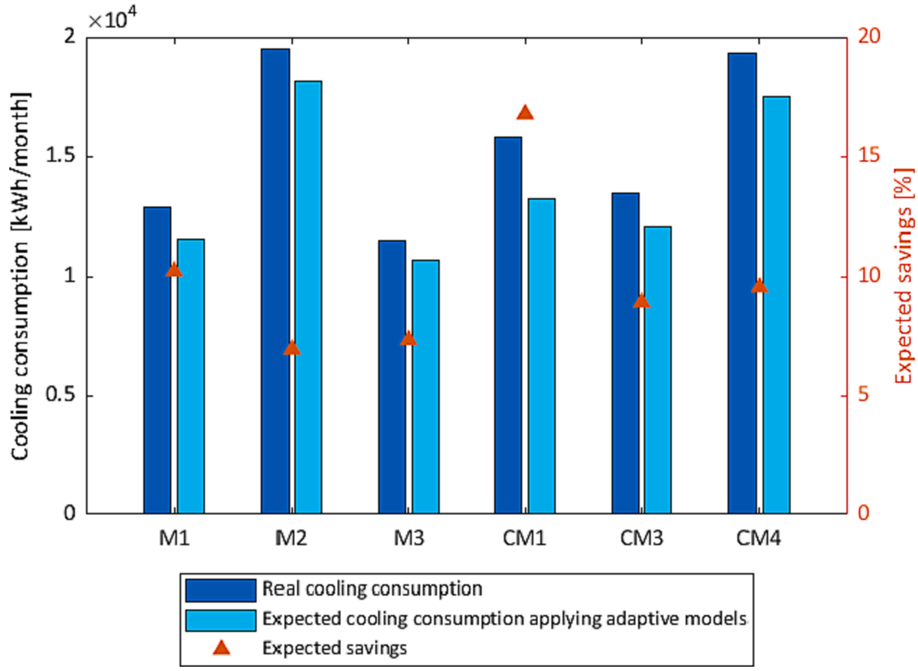

Fig. 8. Mean real (fixed setpoint temperatures) and predicted (adaptive comfort temperatures) monthly consumption and expected savings regarding cooling energy consumption.

Table 9
Expected energy savings applying adaptive modelling techniques in different studies and scenarios, and comparison with the present field study.

Reference	Energy savings [%]	Difference [%]
Field study	9.9	-
López-Perez et al. [37]	3.2 to 15.6	−6.7 to 5.7
Sanchez-García et al. [38]	36.7 to 59.5	26.8 to 49.6
Barbadilla-Martin et al. [35]	27.5	17.6

Continental-Mediterranean climate can be attributed to its slightly, although noticeable, higher temperatures compared to the first region. However, it is important to note that other factors, such as variations in humidity levels and local building characteristics, may also contribute to these differences in energy savings.

7. Conclusions and future steps

7.1. Conclusions

In this study, the energy implications of implementing adaptive thermal comfort models in nursing homes during the cooling season in Mediterranean and Continental-Mediterranean climates were assessed. The research aims to address the pressing concerns of high energy costs, climate change, thermal comfort, and population aging. The analysis was conducted using real-world data collected from eight nursing homes, providing valuable insights into the practical application of adaptive strategies in these buildings. The methodology involved developing adaptive energy consumption models through multivariate linear regressions, considering both outdoor and indoor parameters. Subsequently, validated adaptive comfort models were integrated into the consumption models, and finally energy implications were assessed. The following results were observed:

- Results demonstrated reliability of both (extended and reduced) energy consumption models with a mean coefficient of determination of 0.76 and 0.69 respectively. The analysis of the case studies allowed concluding that the use of the reduced models is feasible while only a 1.8 % difference in the cooling consumption estimates was found between both models. The effectiveness of both models has been demonstrated in real-world scenarios, highlighting the significance of utilizing real data over simulated environments.
- The results confirmed that the implementation of adaptive thermal comfort models during the cooling period leads to energy savings in nursing homes for Mediterranean and Continental-Mediterranean climates. The average energy savings for the analysed case studies was 9.9 %.Findings indicated that cooling consumption is dependent on climate characteristics. Higher savings were observed in the Continental-Mediterranean climate (11.7 %) compared to the Mediterranean climate (8.1 %). These savings are mainly attributed to slightly higher temperatures. However, other factors such as humidity levels and local building characteristics may also play a role.
- This study demonstrated that the cooling consumption for nursing homes depends mainly on outdoor conditions. The highest the outdoor temperatures, the potential for obtaining greater savings increase. Considering the direct influence of climate change on escalating outdoor temperatures, it is expected that progressively larger savings will be attained over time.

7.2. Limitations and future research

The developed models in this study are tailored specifically to the nursing homes involved in the field study, thus their applicability remains limited to these particular typologies of buildings. Consequently, each model is designed to address the specific characteristics of a single building, highlighting a constraint in their general applicability. Furthermore, although factors like building size and orientation are implicitly considered in the collected consumption data, the absence of data on outdoor variables such as wind speed, solar radiation, and precipitation hinders the inclusion of these factors in the analysis. Consequently, adapting these models to encompass all nursing homes becomes unfeasible due to limitations in data availability. All regressors presented a tendency to overestimate cooling consumption in their estimates. Consequently, the results of this analysis may reflect a conservative approach, potentially yielding slightly higher savings potential.

Future steps in this research involve exploring the application of nonlinear models, such as neural networks, to enhance the accuracy and predictive capabilities of adaptive consumption models. Additionally, expanding the dataset to include a larger number of case studies would further strengthen the reliability and generalizability of the results. Furthermore, the development of a generic model incorporating additional variables, such as nursing home cooling area and other relevant factors, would enable the widespread implementation of adaptive models in various nursing home settings. These advancements would contribute to optimizing energy efficiency and thermal comfort for older populations, promoting sustainable practices in nursing home facilities.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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