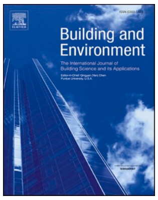
Building and Environment 228 (2023) 109899

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv



Building parameters that influence overheating of apartment buildings in a temperate climate in Southern Europe

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ARTICLE INFO

Keywords:
Apartment buildings
Monitoring
Built period
Indoor overheating hours
Adaptive threshold
Natural cooling

ABSTRACT

Overheating in dwellings is a global concern that is increasing due to global warming and more frequent and extreme heatwaves. This study assesses the relationship between different building parameters (built period, floor level, orientation, window area and solar shading) and compares indoor overheating hours during summer in twelve apartments monitored in Pamplona (North of Spain). They were selected as samples from different Spanish built periods related to different energy regulations, without mechanical cooling and with some kind of exterior solar shading. Overheating hours were calculated using the UNE-EN 16798 standard, which establishes a maximum acceptable operative temperature. This limit is adaptive and it is defined as the exponentially weighted running mean of the daily outdoor temperature. Multilevel mixed-effects linear and logistic regressions were used to analyse and compare overheating hours. Floor level, window area and solar shading were the parameters that showed a significant relationship with indoor overheating hours ($p < 0.01$). Orientation and built period did not reach a statistically significant value ($p > 0.01$). It is particularly noteworthy that the apartments built under the current Spanish Energy Regulations (after 2006) do not show a significant reduction in indoor overheating hours compared to those built without any energy regulations. This assessment reveals that current building energy regulations may not be enough to avoid overheating or ensure adaptation to warmer conditions. Therefore, this study contributes to establishing the main building parameters to improve in order to adapt Spanish apartment buildings to warming conditions in temperate climates.

1. Introduction and background

Indoor overheating in dwellings has become a major issue for public health concerns in Europe and all over the world [1,2]. A well-established relationship exists between high indoor temperatures and people's well-being and health [3,4], and even mortality at population level [5]. An event which illustrates this phenomenon is the exceptionally and extreme hot conditions in August 2003: during that heatwave, 50,000 excess deaths were registered across Europe [6]. The UK alone reported 2091 deaths throughout the country and 616 in London alone [7], and in Paris nearly 15,000 excess deaths were reported between August 1 and August 20 [8]. The elderly were the people with a greatest mortality risk during this catastrophic heatwave, especially those who were confined to bed (with a cardiovascular or neurological disease or mental disorder) or living alone (especially old women), those living in old buildings without insulation or in areas with high a heat island effect, and those with a bedroom located directly under the roof [9].

Overheating happens in a building either due to bad design, poor management and/or inadequate services [10] and, according to the literature, it might occur in different kind of dwellings, from those that are new and insulated [11–13] to those which are old and refurbished [14] or without refurbishment [15]. In Europe, measures used to achieve energy targets are mainly based on the reduction of energy demand and consumption and on ensuring adequate indoor environmental conditions in the heating period [16], as the highest energy consumption in the European Union and in Spain comes from heating needs [17].

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https://doi.org/10.1016/j.buildenv.2022.109899
Received 1 July 2022; Received in revised form 24 November 2022; Accepted 4 December 2022

ABREVIATIONS

IOH	Indoor overheating hours
IF	Intermediate floor
TF	Top floor
Lr	Living room
Br	Bedroom

However, regarding indoor overheating, they could be even counter-productive because highly insulated and airtight building envelopes have the potential to overheat if not designed properly [18] and, in particular, if energy efficiency measures are not combined with appropriate passive cooling strategies [19–21].

Global warming is exacerbating overheating risk in dwellings, and consequently, cooling energy demand is increasing globally [21]. Different research deals with these impacts considering current climate data (for instance, a study finds that 20% of UK homes experience indoor overheating under the current climate [22]) and future (projected) climate, as studies on the Mediterranean area included in the CIRCE project [23]. It should be noted that the largest warming trend in Southern Europe has occurred over the Iberian Peninsula [24] identified as one of the most prominent climate response hotspots around the world [25], where a considerable increase in the number of very hot days in future summers is predicted: up to around 20–24 days with the mean maximum of about 35 °C.

Besides, the probability of suffer mega-heatwaves will increase by a factor of 5–10 in the next 40 years in Europe [26]. Summer mega-heatwaves stand out from typical heatwaves due to their large spatial extension, intensity, and persistence. The most documented events of this type are the August 2003 event over western and central Europe and the July–August 2010 event in eastern Europe and Russia [27,28]. Based on the characteristics of these events, *Barriopedro* et al. defined mega-heatwaves as events which affect regionally (≥1,000,000 km2), with temperature anomalies of extraordinary amplitude (≥3 standard deviations) during more than 7 days [26]. Existing buildings, which will be in use during the next decades, have been designed for less severe climates than those expected in the future, and, based on existing predictions, they will have to face more extreme conditions, especially in summer. Therefore, it is important to assess overheating in order to know how to adapt these buildings to this harder climate with more extreme events (f.e:mega-heatwaves).

Therefore, it is urgent to bring the focus to assess indoor overheating in order to establish effective priorities in rehabilitations or in new constructions that might minimize this risk of suffering from overheating [29].

There are different international standards to assess indoor overheating based on adaptive models:

1) The European UNE-EN 16798-1 [30] recommends ranges for indoor operative temperatures for buildings without mechanical cooling systems as function of the outdoor running mean temperature. This outdoor running mean temperature is defined as the exponentially weighted running mean of daily outdoor temperature. The maximum allowable operative temperature ("*upper limit*") is 3 °C above comfort temperature (for medium level of expectation buildings). Through this standard how many hours the maximum acceptable operative temperature is exceeded (Indoor Overheating Hours, IOH) could be assessed and compared but it does not set a fixed percentage of IOH above which a dwelling could be considered overheated.
2) The American ASHRAE 55 [31]: recommends ranges for indoor operative temperatures for building without mechanical cooling systems as function of prevailing mean outdoor temperature. This prevailing mean outdoor temperature is an exponentially weighted, running mean of a sequence of mean daily outdoor temperatures prior to the day in question. The maximum acceptable operative temperature ("*upper 80% acceptability limit*") is 2.5 °C above comfort temperature. It does not set a fixed percentage of IOH above which a dwelling could be considered overheated. It is very similar to UNE-EN 16798-1 but more restrictive.
3) The British CIBSE TM59 [10] considers two fixed criteria for assessing overheating risk in residential buildings: for living rooms, kitchens and bedrooms, the number of hours during which operative temperature is greater than maximum acceptable operative temperature during the period May to September included shall not be more than 3% of occupied hours (maximum acceptable operative temperature through the same methodology as UNE-EN 16798-1); for bedrooms only, to guarantee comfort during sleeping hours the operative temperature in the bedroom from 10 p.m. to 7 a.m. shall not exceed 26 °C for more than 1% of annual hours. Compliance is based on passing both criteria.

Besides, Annex 80 is developing a standard that quantifies overheating risk through the intensity and frequency of indoor overheating taking into account: different thermal comfort limits for different dwelling zones, the specific occupant's behaviour and the adaptation opportunity that occupants have in each identified zone [32].

In the Spanish Building Code (CTE) there is no specific regulation to ensure indoor overheating control, not even in the latest update of 2022 [16].

Several research studies working on these assessments have found that building overheating mainly depends on: (a) location in building (floor level) [33,34]; (b) façade orientation [35–37]; (c) area of transparent elements (windows) [29]; (d) ventilation [35] and (f) shading systems [35,38]. In general, these studies have found that apartments located on top floors of the buildings, facing south/west, with large window areas and without solar shading systems are the most overheated.

As is shown, large number of studies have investigated about overheating risk since it is an increasing problem. Studies based on energy simulation as modelling approaches have two main advantages: the ability to model a large number of building parameters with much lower cost and effort than monitoring studies, and also the ability to examine risks under a variety of possible scenarios. On the other hand, monitoring approaches have the advantage of making fewer assumptions since they have real users occupying the dwelling [39], and provide real information on limitations, barriers or improvements after implementation of measures [40].

In this context, this paper is focused on quantifying and comparing indoor overheating hours during summer in twelve case studies placed in Pamplona (North of Spain) and relate it with building parameters (leaving out of the study the parameters related to occupants' behaviour). Specific research aims are the following:

- To compare indoor overheating hours of different apartments according to their built period in relation to different energy saving regulations.
- To assess the influence of different building parameters in relation to indoor overheating.

The paper is organized as follows: after the Introduction, study methods are presented in Section 2 (2.1 contains a description of the climate where the case studies are placed, 2.2. Describes selected apartments and the studied regulatory period and 2.3 contains the description of data analysis). Results are shown in Section 3; results are discussed in Section 4 and finally conclusions are reached in Section 5.

2. Methods

2.1. Climate and monitoring period

Pamplona is a city in the north of Spain which has a Cfb climate (according to Koppen-Geiger classification), temperate without dry season, "oceanic" type. Following data from the 1980–2010 climate series of the Spanish State Meteorological Agency (AEMET) [41], August is the warmest month of summer (with a monthly mean of 21.4 °C and a monthly mean maximum of 28.3 °C).

The definition of heatwaves according to AEMET is an episode of at least three consecutive days where a minimum of 10% of the given weather stations register maximum temperatures over the 95% percentile of its 1971–2000 climate series during July and August [42].

The period studied in this paper comprises specifically the summer period: from 21/06/2021 to 21/09/2021 (93 days). As shown in Table 1 outdoor temperatures of the monitored period were very similar to those of the climate series 1980–2010 [43]. Therefore, it was not a warm summer for the location, but there was a heatwave that affected Pamplona between 12/08–14/08 which stood out for its extension (33 provinces through the Iberian Peninsula and Balearic Islands) and its intensity, according to AEMET report [44].

Seasonal summer (21/06–21/09) has been considered since it is the meteorological summer and the warmest period in Spain.

2.2. Selected dwellings

Twelve apartments of multifamily buildings were selected as samples of four built periods in Spain which are related to different energy regulations:

- 4 apartments (P01, P02, P03, P04) built prior to 1979 (*Pre CT-79 period*) when there were no energy regulations for buildings.
- 2 apartments (P05, P06) built between 1980 and 2006 (*CT-79 period*) with the first energy regulation in Spain NBE CT-79 [45] which appears after the 1970s energy crisis, as in other countries.
- 3 apartments (P07, P08, P09) built after 2006 (*CTE period*) with different updates of the Spanish Technical Building Code (CTE, according to its Spanish acronym) and following EPBD [16].
- 3 apartments (P10, P11, P12) built under CTE Code and with Passivhaus standard.

In general, dwellings were chosen "by pairs", aiming for two similar apartments in the same building but in different floor levels: one on an intermediate floor and another one on the top floor. Table 2 summarizes the selection criteria.

The envelopes' characteristics follow the energy regulation of each built period. The requirements are summarized in Table 3. As can be seen, the envelopes' performance is higher the more recent the built period.

For each of the monitored apartments, four architectural parameters that literature considers some of the most important in relation to overheating were analysed: floor level, orientation, window area and solar shading. Table 4 shows the characteristics for each parameter in each specific monitored room of the dwelling (living rooms, Lr; bedrooms, Br).

Table 1
Summary of the monitoring period and the climate series 1980–2010 temperatures, based on AEMET data [44].

	TM	TMax	TMin
CLIMATE SERIES 1980–2010 (June, July, August and September)	19.8 °C	26.5 °C	13.1 °C
STUDY PERIOD (21/06/2021 to 21/09/2021)	19.9 °C	26.3 °C	14.8 °C
HEATWAVE (12–14/08/2021)	25.9 °C	38.1 °C	17.9 °C

Mean of mean temperatures (TM); Mean of maximum temperatures (TMax); Mean of minimum temperatures (TMin).

Table 2
Monitored apartments grouped according to the built period and floor level.

COD	FLOOR LEVEL[a]	BUILDING	BUILT PERIOD
P01	IF	B1	Pre CT-79
P02	TF		
P03	IF	B2	
P04	TF	B3	
P05	IF	B4	CT-79
P06	TF		
P07	IF	B5	CTE
P08	TF		
P09	TF	B6	
P10	IF	B7	PASSIVHAUS
P11	TF		
P12	TF	B8	

[a] IF: Intermediate floor (IF); Top floor (TF).

Table 3
Typical envelopes' parameters and requirements according to each built period.

BUILT PERIOD/ ENERGY REGULATION	Umax façade W/m2K	Umax roof W/m2K	Umax windows W/m2K	Infiltrations (50Pa)
Pre CT-79 period/No energy regulation	1.68[a]	2.9[a]	5.7[a]	7[b]
CT-79 period/NBE CT-79	1.2	0.9	3.5	7[b]
CTE period/CTE 2006	0.66	0.38	2.7	5[b]
Passivhaus/ Passivhaus standard	0.30	0.30	1.05	0.6

[a] These estimated values of the Pre CT-79 buildings are based on numerous projects and previous analysis (from the same built period) carried out by this research group in other studies.

[b] *Infiltration rates were not regulated in the Spanish CTE until the 2019 update. These estimated values are based on* [46].

Dwellings of the *Pre CT-79 period* (P01-P02-P03-P04) and the *CT-79 period* (P05-P06) are naturally ventilated; dwellings of the *CTE period* (P07-P08-P09) have a hybrid ventilation system (with vents in windows and vertical ducts to the roof: these ducts extract the air by the effect of pressure difference and, when this difference does not occur naturally, a motor is activated to enhance it); dwellings with *Passivhaus standard* (P10-P11-P12) have mechanical heat recovery ventilation (HRV) with free-cooling option.

A questionnaire per dwelling was sent to each monitored dwelling after the installation of the data loggers, at the beginning of the monitoring period. Its objective was to find out typical occupants' behaviour and the way they manage their apartment during the monitoring period (summer). Table 5 shows some specific questions related to the patterns of use (see *legend*) and summarizes the occupant's answers.

Despite having different types of ventilation (even in those dwellings with mechanical ventilation systems), the user's ventilation behaviour in summer is similar in most dwellings according to questionnaires of use: the occupants open the windows during the night and early in the morning (if outdoor temperatures are cool), and close them when outdoor temperatures start raising, a deeply rooted habit in temperate Mediterranean climates [47]. Regarding the use of solar shading, the pattern of use is also similar: almost all occupants use them all day long or/and when there is direct solar radiation on windows to avoid it.

Since the dwellings show a similar pattern and due to the difficulty of controlling every day occupants' behaviour, it was assumed that the behaviour of the occupants was the same, thus being a controlled

Table 4
Studied parameters of monitored rooms in the selected apartments.

COD	ROOM[a]	FLOOR LEVEL[b]	FAÇADE ORIENTATION[c]	WINDOW AREA[d]	SOLAR SHADING[e]
P01	Lr	IF	W	1–2 m^2	EB + A
	Br	IF	E	≤1 m^2	EB
P02	Lr	TF	W	1–2 m^2	EB
	Br	TF	E	≤1 m^2	EB
P03	Lr	IF	SE	2–4 m^2	EB
	Br	IF	NW	1–2 m^2	EB
P04	Lr	TF	E-W	≥4 m^2	EB
	Br	TF	N	≥4 m^2	EB
P05	Lr	IF	W	1–2 m^2	EB + FS
	Br	IF	W	≤1 m^2	EB
P06	Lr	TF	E	≥4 m^2	EB
	Br	TF	E	2–4 m^2	EB
P07	Lr	IF	SW	≥4 m^2	EB + FS
	Br	IF	NE	1–2 m^2	EB + FS
P08	Lr	TF	SE	≥4 m^2	EB + FS
	Br	TF	NE	1–2 m^2	EB + FS
P09	Lr	TF	NW	≥4 m^2	EB + FS
	Br	TF	SW	1–2 m^2	EB + FS
P10	Lr	IF	NW	≥4 m^2	EB + FS
	Br	IF	NE	1–2 m^2	EB
P11	Lr	TF	SW	≥4 m^2	EB
	Br	TF	NE	1–2 m^2	EB
P12	Lr	TF	SE	≥4 m^2	EB + FS
	Br	TF	NW	1–2 m^2	EB

[a] Living room (Lr); Bedroom (Br).

[b] Intermediate floor (IF); Top floor (TF).

[c] North (N); South (S); West (W); East (E); Northwest (NW); Northeast (NE); Southwest (SW); Southeast (SE).

[d] Exterior blinds (EB); Awning (A); Eaves and similar fixed elements (FS).

Table 5
Typical occupant daily usage pattern based on questionnaires to each dweller.

COD	Day ventilation[a]/Night ventilation[b]	Solar shading use[c]
P01	Y-M/Y	Y
P02	Y-M/Y	Y-W
P03	Y-M/Y	Y-M
P04	Y/Y	Y-W
P05	Y-M/N	Y
P06	Y-M/Y	Y-W
P07	Y-M and Y-A/Y	Y-A
P08	Y-M and Y-A/Y	Y-A
P09	Y-M/N	Y
P10	Y-M/N	N
P11	N/Y	Y-W
P12	Y-M/Y	N

Legend based on specific questions of general use.

[a] During the day, do you ventilate your apartment in summer?Yes, in the morning if the outdoor temperatures are cool (Y-M); Yes, in the afternoon if outdoor temperatures are cool (Y-A); Yes, but regardless temperatures (Y); No, never (N).

[b] During the night, do you ventilate your apartment in summer?Yes, all night (Y); No, never (N).

[c] Do you use solar shading in summer?No, never (N); Yes, all day (Y); Yes, in the morning (Y-M); Yes, in the afternoon (Y-A); Yes, but only when there is solar radiation on windows (Y-W).

variable.

None of the apartments has air conditioning, the norm in this location due to climate conditions, although its installation is increasing in the residential stock due to the warming temperatures.

Occupied hours for living rooms (day) and bedrooms (night) were not differentiated. Authors have considered a continuous occupation of all the rooms (24 h) but leaving out of the study the days in which the dwelling was not occupied (f.e: users' holidays). It has been decided to carry out the study in this way since the dwellings are increasingly used in a more flexible way, especially the "small" apartments (like de apartment monitored) where the different spaces can be used during 100% of the hours: teleworking in bedrooms, children studying, living rooms used as bedrooms because they are the cooler spaces during summer … In this way, it is considered that the most unfavourable situation has been analysed for all spaces.

2.3. *Measurements and analysis of monitored data*

Monitoring data was collected with MICADesk dattalogers (temperature accuracy of ±0.5 °C). Dataloggers measured indoor air temperatures in 10-min intervals during all monitoring study with data available on line. These data loggers measure other parameters as relative humidity or CO_2 concentration, although that data was not used in this specific study. Besides, occupants of dwellings were surveyed regarding the adaptive measures they took during hot days (e.g. opening windows, solar shading use).

For the purpose of this study measured indoor air temperatures were considered as indoor operative temperatures. This approach is used where mean radiant temperature is not available as in this case study, and is also used and justified in other studies [33,48,49]. It is an approximation that works well when differences between air and mean radiant temperatures are limited [34], but taking into account that this approach may underestimate the effect of mean radiant temperature on indoor heat stress [49]. The air movement speed was not monitored because the necessary means were not available and because the air speed inside the apartments was very low.

First, 10-min indoor temperature data were analysed descriptively in order to have a general picture of the dwelling's temperatures during summer.

Second, percentage of indoor overheating hours (%IOH) was calculated as specified in UNE-EN 16798-1 [30], which is a European standard applied in Spain.

UNE-EN 16798-1 recommended ranges of indoor operative temperatures for buildings without mechanical cooling systems in relation to outdoor running mean temperature.

This outdoor running mean temperature is defined as the exponentially weighted running mean of daily outdoor temperature:

$$T_{RM} = (1\text{-}0.8)\ (T_{ed\text{-}1} + 0.8\ T_{ed\text{-}2} + 0.8_2 T_{ed\text{-}3}...) \tag{1}$$

$T_{ed\text{-}i}$= daily mean outdoor air temperature for the i-th previous day; It has been calculated for the previous 7 days

For naturally ventilated buildings in free-running mode, the equation that relates comfort temperature (T_C) to the exponentially weighted running mean of daily mean outdoor temperature (T_{RM}) is:

$$Tc\ (Category\ II) = 0.33\ T_{RM}\ (°C) + 18.8\ (°C) \tag{2}$$

The maximum acceptable operative temperature (T_{MAX}), also called "upper limit", was calculated for Category II which refers to medium level of expectation buildings (Category IEQ_{II}). This maximum acceptable operative temperature (T_{MAX}) considered for the analysis was the one defined for the following equation (3°C above Tc):

$$T_{MAX}\ (Category\ II) = 0.33\ T_{RM}\ (°C) + 21.8\ (°C) \tag{3}$$

Through this limits and methodology, the calculations were performed with hourly operative indoor temperatures for each room. First, the hours during which each room was above the upper limit (during the monitored period) were added up (number of IOH). Secondly, these hours were related to the rooms' occupancy hours (which represent the total hours for the period) resulting in the %IOH presented. When the number of IOH is equal to the number of occupied hours, the result will refer to 100% IOH, i.e. the hourly temperatures of the dwelling are above the limit in all hours of the monitored period.

This standard does not establish the limit of indoor overheating hours (IOH) that should not be exceeded in a dwelling, so IOH were used as a comparison between dwellings.

To cope with the potential existence of correlation between dwellings' building parameters (i.e most dwellings with windows over 4 m^2 are on the top floor), we conducted multivariate statistical analyses, an adequate method to obtain a result for each analysed building parameter independent of (or adjust for) all the other parameters [50]. When we analysed the percentage of indoor overheating hours (%IOH) during a monitoring period, since it is a continuous variable, we used multilevel mixed effects linear regression models to also take into account intra-cluster correlation. As a result, we obtained beta coefficients (and their 95% confidence interval) for each category of each parameter considering Pre CT-79 built period, top floor, N, NE and NW orientation, window area less than 2 m^2, and solar shading with exterior blinds only, as references categories. These coefficients represent the average difference between each of the other categories for each parameter and the reference category considering potential correlations between parameters. Additionally, we analysed the existence of any IOH as a dichotomous variable (yes/no) using multilevel mixed effects logistic regression. As a result, we obtained adjusted Odds Ratios independent of potential correlations. These Odds Ratio mean how many times the existence of any indoor overheating hour is more likely (above 1 more likely, below 1 less likely) between each category of each parameter in comparison with the same categories of reference cited above. The analyses were performed with the STATA statistical package version 16 (College Station, TX, USA; Stata Corp LLC). All p values are two-tailed and the statistical significance was set at 0.01 in order to be more conservative.

3. Results

First, a descriptive analysis of indoor temperatures during the monitored period is developed. Fig. 1 presents indoor temperatures summary and Fig. 2 presents indoor temperatures comparatively according to each studied parameter.

Regarding the built period, there are no clear differences between the four periods. The mean temperatures are between 23.9 °C (Pre CT-79) and 24.6 °C (Passivhaus) and there is no clear tendency of improvement in the maximum or minimum temperatures when the built period is more energy demanding.

Comparing the other parameters, the most noticeable differences regarding indoor temperatures are:

- Floor level: the difference between maximum temperatures in IF and TF is 1.1 °C ($TMax_{IF} = 27.7$ °C; $TMax_{TF} = 28.9$ °C).
- Façade orientation: there is an increase of 1.58 °C in maximum temperatures in the apartments with a S/SW/W orientation in comparison to those facing N/NE/NW or E/SE ($TMax_{S/SW/W} = 29.7$ °C; $TMax_{N/NE/NW\text{-}E/SE} = 28.1$ °C).
- Window size: a temperature increase trend is observed as window size increases. The group with windows with an area higher than 4 m^2 presents the highest temperatures with differences - in comparison to the other two groups - of 0.7 °C in maximum temperature, 0.6 °C in mean temperature and 0.7 °C in minimum temperatures.
- Solar shading: indoor temperatures are reduced as more solar shading is added on the outside of the window. This temperature reduction is especially noticeable in minimum temperatures where the difference in comparison to the other groups is 0.8 °C.

Table 6 shows %IOH considering the UNE-EN 16798-1 adaptive threshold. Descriptively and following temperature analysis, the main difference seen is the important difference between apartments located in IF (with a median of 0.05%IOH) and those in top floors (with a median of 8.28%IOH).

It is worth mentioning the highest overheating hours were detected in the living room of dwelling P11 (62.76% IOH), since it presents not

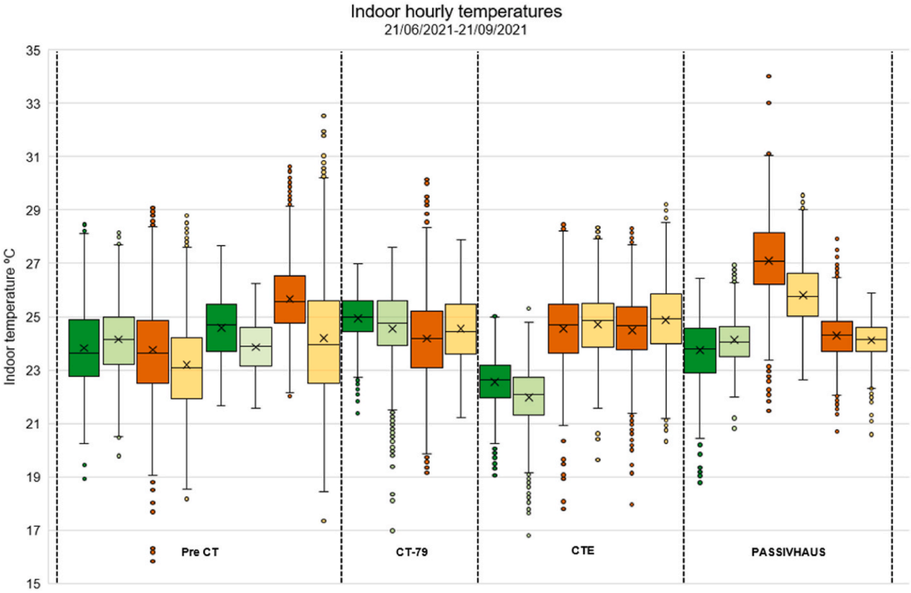

Fig. 1. Indoor hourly temperatures in **apartments** during monitoring period (green: intermediate floors; orange: top floors/dark colour: living rooms; light colours: bedrooms). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

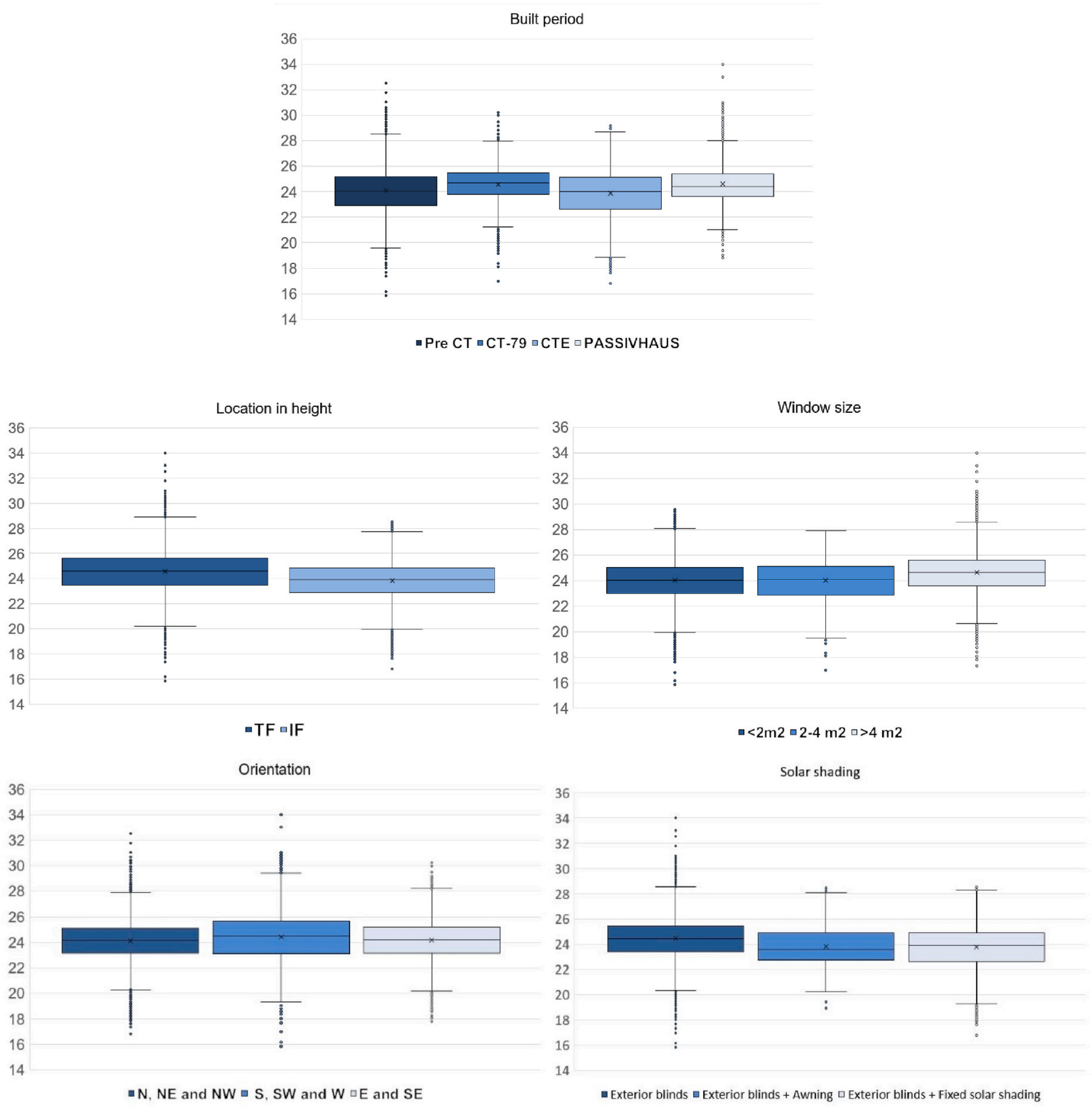

Fig. 2. Comparative analysis of indoor temperatures grouped per studied parameter.

only the position in height but also the other most detrimental building parameters (they will be explained below) in relation to IOH (southwest orientation, window size larger than 4 m^2 and only exterior blinds).

A multilevel mixed-effects linear regression was developed to relate the dependent variable (Percentage of Indoor Overheating Hours, % IOH) and the five independent variables analysed (built period, floor level, orientation, window area and solar shading), and results are shown in Table 7. Table 8 shows the Odds Ratios for IOH according to these five different building parameters. For the relation of each independent variable with IOH in both methods, the rest of the variables analysed have been considered, adjusted/equalized (i.e the obtained results are independent of the potential correlation between parameters). Among these five independent variables that were studied, floor level, window' area and solar shading had a statistically significant relationship with overheating.

Regarding the relation between IOH and **built period** according to energy standards, significant results were found only in relation to the dwellings built in the CT-79 period (1979–2006), which present 2.5% less IOH than in the reference period ($p = 0.001$) (Table 7). Later periods do not show a significant reduction ($p = 0.527$; $p = 0.295$) in IOH compared to those built without energy regulation (before 1979).

Considering the relation between IOH and **floor level** (studying differences between apartments located in the intermediate floor and the upper floor), intermediate floors have 1.5% less of IOH than those located on top floors. However, it was not a significant relation ($p = 0.038$) (Table 7). The dichotomic logistic regression showed significant results: apartments on intermediate floors have a 97% less relative probability of experience IOH compared to those on top floors (Odds Ratio (OR) = 0.03; 95% CI: 0.01–0.15) ($p < 0.001$) (Table 8).

Main **orientation** of facades showed the highest IOH in south and southwest orientations, but differences did not reach a statistically significant value ($p = 0.128$; $p = 0.495$) (Tables 7 and 8).

Table 6
Percentage of Indoor Overheating Hours (%IOH) above UNE-EN 16798-1 adaptive threshold for IEQII category during monitoring period.

COD	ROOM	FLOOR LEVEL	BUILT PERIOD	%IOH
P01	Lr	IF	Pre CT-79	0.32%
	Br	IF	Pre CT-79	0.00%
P02	Lr	TF	Pre CT-79	**3.61%**
	Br	TF	Pre CT-79	1.48%
P03	Lr	IF	Pre CT-79	0.00%
	Br	IF	Pre CT-79	0.00%
P04	Lr	TF	Pre CT-79	**11.17%**
	Br	TF	Pre CT-79	**11.03%**
P05	Lr	IF	CT-79	0.00%
	Br	IF	CT-79	0.14%
P06	Lr	TF	CT-79	**4.23%**
	Br	TF	CT-79	1.88%
P07	Lr	IF	CTE	0.00%
	Br	IF	CTE	0.00%
P08	Lr	TF	CTE	1.91%
	Br	TF	CTE	1.17%
P09	Lr	TF	CTE	0.34%
	Br	TF	CTE	**3.60%**
P10	Lr	IF	PASSIVAHUS	0.00%
	Br	IF	PASSIVAHUS	0.00%
P11	Lr	TF	PASSIVAHUS	**62.76%**
	Br	TF	PASSIVAHUS	**12.50%**
P12	Lr	TF	PASSIVAHUS	0.16%
	Br	TF	PASSIVAHUS	0.00%

Table 7
Adjusted[a] percentage of Indoor Overheating Hours (%IOH) according to different building parameters.

Parameters	Beta Coefficients.	[95% Conf. Interval]	p value
Built period			
Pre CT-79	0 (Ref.)		
CT-79	−2.5	(-3.9 to −1.07)	0.001
CTE	+1.0	(-2.2 to +4.2)	0.527
CTE + Passivhaus	+3.1	(-2.7 to +8.8)	0.295
Floor level			
Top floor	0 (Ref.)		
Intermediate floor	−1.5	(-2.9 to −0.9)	0.038
Orientation			
N, NE and NW	0 (Ref.)		
S, SW and W	+1.9	(-0.6 to +4.4)	0.128
E and SE	−0.6	(-2.5 to +1.2)	0.495
Window area			
≤2 m^2	0 (Ref.)		
2–4 m^2	+1.0	(-0.4 to +2.4)	0.148
>4 m^2	+5.2	(+3.0 to +7.4)	<0.001
Solar shading			
Exterior blinds	0 (Ref.)		
Exterior blinds + Awning	−1.9	(-3.4 to −0.5)	0.011
Exterior blinds + Eaves (o similar fixed elements)	−5.1	(-8.8 to −1.3)	0.008

[a] Results are adjusted for all the variables in the table using a multilevel mixed effects linear regression.

Table 8
Adjusted[a] Odds Ratios for any overheating hour according to different building parameters.

Parameters	Odds Ratios	[95% Conf. Interval]	p value
Built period			
Pre CT-79	1 (Ref.)		
CT-79	0.64	(0.17–2.31)	0.502
CTE	0.85	(0.27–2.66)	0.775
CTE + Passivhaus	0.56	(0.17–1.80)	0.328
Floor level			
Top floor	1 (Ref.)		
Intermediate floor	0.03	(0.01–0.15)	<0.001
Orientation			
N, NE and NW	1 (Ref.)		
S, SW and W	1.66	(0.77–3.58)	0.198
E and SE	0.56	(0.20–1.56)	0.265
Window area			
≤2 m^2	1 (Ref.)		
2–4 m^2	1.29	(0.25–6.55)	0.758
>4 m^2	2.96	(1.39–6.28)	0.005
Solar shading			
Exterior blinds	1 (Ref.)		
Exterior blinds + Awning	3.75	(0.44–32.04)	0.227
Exterior blinds + Eaves (o similar fixed elements)	0.17	(0.04–0.86)	0.032

[a] Results are adjusted for all the variables in the table using a multilevel mixed effects logistic regression.

Rooms of dwellings with a **window area** larger than 4 m^2 had higher IOH than those with smaller areas, with an estimate of 5.2% ($p = 0.008$) (Table 7). Dichotomic logistic regression showed that they were almost 3 times more likely to experience IOH (OR = 2.96; 95% CI: 1.39–6.28) than those with a window area smaller than 2 m^2 (Table 8).

In relation to **solar shading**, the best performance and statistically significant was obtained with the combination of exterior roller blinds and eaves or similar elements, which reduced IOH by 5.05% compared to solar shading with only exterior roller blinds, ($p = 0.008$) (Table 7). In addition, a dichotomic logistic regression model found that rooms which have windows with eaves (o similar fixed elements) are 83% less likely to be affected by IOH compared to those with only exterior roller blinds (OR = 0.17; 95% CI: 0.04–0.86) (Table 8) but the relation was not statistically significant.

4. Discussion

This research assesses IOH in twelve apartments of different built periods and its relation with different building parameters. The authors wanted to contribute to the knowledge quantifying this overheating in a comparative way based on monitoring real case studies, with data from the monitoring campaign of summer 2021 in a Spanish temperate climate.

Five building parameters were assessed: built period in relation to energy regulation, floor level, orientation, window area and solar shading. Since the dwellings show similar patterns of use and due to the difficulty of controlling every day occupants' behaviour, it was estimated based on questionnaires, therefore considering patterns of use a controlled variable.

Results regarding IOH and **built period** show that only dwellings built in the CT-79 period (1979–2006) have 2.5% less IOH than those in the reference period (prior CT-79) independently of other building parameters. There is, however, no significant improvement in later built periods: new apartments built under current energy regulations do not present a significant lower IOH than others in current summer conditions. This result is in line with other research which has found that "new" dwellings (built or refurbished with a high energy efficiency standard) have a proved thermal comfort improvement and an energy consumption reduction in the winter period (heating season), but do not have the expected improvement in the reduction of IOH [35]. What is more, some studies have found significant results of higher overheating risk in refurbished or new dwellings. As some examples, *Mavrogiani* et al. found that insulation on floor and wall internal insulation increased daytime living-room temperatures up to 0.46 °C [36] and the Department of Health and the Health Protection Agency from the UK found that new apartments could be approximately 1 °C warmer than older ones [29].

Regarding the **dwelling position** in the residential building (floor level) results show that intermediate floors have 1.5% less of IOH than apartments located in top floors, adjusting for other building parameters. These results are aligned with other studies: one study in Australia showed that top floors are warmer than ground floors for more than 50% of summer hours [13]; another based on CIBSE assessment demonstrated that top floor apartments failed all the criteria while intermediate ones passed [33]; a third one, analysing mean temperatures found that apartments in top floors have a temperature 1.2 °C higher than in other floors [51].

In relation to **dwellings' façade orientation** this study showed a higher IOH in south and southwest orientations but differences with other orientations did not reach statistical significance. It should be noted that all monitored apartments had at least roller blinds as solar shading and all dwellers reported using them every day. There are other monitoring studies with south-facing rooms (i.e., rooms with at least one window facade facing south, between 90 and 270°) that did not find statistically significant different mean temperatures than north-facing rooms [51]. Other studies, especially those which are simulation based, illustrate a significant difference between IOH in different orientations [52], with results around 1.5%–2% more IOH in south-facing rooms than in north-facing ones [53]. This percentage, although it might seem low, can be the difference in meeting or not overheating standards such as CIBSE.

Results showed a strong relationship between **window area** and IOH, in accordance with existing literature that considers it a key factor. Large and poorly shaded windows can contribute to the building overheating problem [29]. It is important to consider that new architecture design tends to increase the glazing ratio in dwellings. This is beneficial for daylight, but it is a building parameter that has a direct impact on overheating if it is not properly designed [52].

In general, **solar shading** appears in the literature as a factor with great influence over overheating [54]. In other monitoring research, which compares dwellings with internal, external, and no shading on their windows, it was found that rooms with external shading met all the criteria within CIBSE TM52, rooms with internal shading only passed two of the three criterions and rooms with no shading failed all of them [55]. Results showed in this paper are in line with these conclusions. Nevertheless, although external solar shading has been shown to be more effective than internal shading, it is not a widespread practice in latitudes north of the Mediterranean region, such as northern France or the United Kingdom.

The major limitation of this study is the size of the sample. However, this study has a selection of dwellings with different and relevant building characteristics. At this point, it is important to highlight the challenge of post-occupancy studies on dwellings that tackle real users and the effort required in the follow-up data measurement in spite of having online data available. Because of that, future research should continue to analyse indoor overheating through monitoring data obtained during the summer, especially in heatwave events, in spite of the recognized monitoring barriers [52].

The installation and use of air conditioning might be a solution to face the increasingly severe summers. However, it is widely accepted that it cannot be the only approach, since it supposes the increase of energy consumption and greenhouse gas emissions (which precisely trigger the warming conditions) it does not protect vulnerable people who cannot afford high energy expenses (people in energy poverty), and peak loads and fails in energy supply may also happen [2,56].

Consequently, further research should promote passive design optimization and energy efficiency in residential buildings, considering in their design the most influential parameters studied in order to prevent indoor overheating and their consequences on wellbeing and health of the population.

5. Conclusions

Indoor overheating risk in residential buildings has become an issue that is being analysed by several researchers and concerns many public administrations around the world as global warming is increasing.

This paper presents results on indoor overheating hours (IOH) in twelve apartments located in Pamplona, a city in the north of Spain with temperate climate. It is based on monitoring data (from 21/06/2021 to 21/09/2021), following the UNE-EN 16798-1 adaptive approach and using multilevel mixed-effects linear and logistic regressions.

This paper is focused on quantifying and comparing IOH during summer in these twelve case studies. The research aims are to compare IOH of different apartments built in different periods and under different energy saving regulations and to assess the influence of different building parameters in relation to indoor overheating. Five building parameters were analysed: built period, floor level, orientation, window area and solar shading.

In relation to the analysed building parameters, floor level, window area and solar shading were the parameters that showed significant relationship with IOH ($p < 0.01$): apartments located on intermediate floors had 1.5% less IOH than those on top floors and have a 97% less relative probability of experience IOH compared to top floors (OR = 0.03; 95% CI: 0.01–0.15); spaces with a window area larger than 4 m^2 had 5.2% more overheating hours and they were almost 3 times more likely to be affected from it (OR = 2.96; 95% CI: 1.39–6.28) than those with a window area smaller than 2 m^2; exterior fixed elements (added in addition to the exterior blinds) reduced IOH by 5.1% and made the dwellings 83% less likely to experience IOH compared to those with only exterior roller blinds (OR = 0.17; IC 95%: 0.04–0.86).

Orientation and built period did not reach a statistically significant value ($p > 0.01$). However, this has also led to some conclusions: regarding the built period, the differences in overheating hours between the newest period (after 2006) and the reference one (1979, prior to any energy regulation) was not significant ($p = 0.527$). The orientation parameter did not reach a significant relationship with overheating hours ($p = 0.128$; $p = 0.495$). However, although it is not statistically significant, it could be said that dwellings in South and Southwest orientations present 1.9% more IOH than the ones with North orientation, as was expected. It should be noted that all windows had some kind of exterior shading.

This study could contribute to the necessary development of regulations related to overheating in buildings. These results could contribute to establish which may be the main building parameters to improve in order to adapt the residential building stock to warming conditions in temperate climates.

CRediT authorship contribution statement

Ainhoa Arriazu-Ramos: Writing – original draft, Software, Methodology, Investigation. **Maira Bes-Rastrollo:** Writing – review & editing, Visualization, Methodology. **Ana Sánchez-Ostiz Gutiérrez:** Writing – review & editing. **Aurora Monge-Barrio:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Universidad de Navarra reports financial support was provided by Spain Ministry of Science and Innovation.

Data availability

The data that has been used is confidential.

Acknowledgements

This paper is part of the Research Project CLIMAREADY "Adaptation Assessment of Spanish residential buildings" (2020–2023), funded by Convocatoria I + D + I "Retos de Colaboración" del Programa Estatal de

Investigación, Desarrollo e Innovacion Orientada a los Retos de la Sociedad. Plan Estatal de Investigación Científica y de Innovación". Reference: PID2019-109008RB-C21. The authors would like to give special thanks to all the occupants that allowed the monitoring of their apartments.

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