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Energy consumption and indoor environmental quality evaluation of a cooperative housing nZEB in Mediterranean climate

Joana Ortiz [a,*], Juli Carrere [b,c], Jaume Salom [a], Ana M. Novoa [b,c]

[a] Thermal Energy and Building Performance Group, Catalonia Institute for Energy Research (IREC), Jardins de les Dones de Negre 1, 2a, 08930, Sant Adrià de Besòs, Spain
[b] Agència de Salut Pública de Barcelona, Pl. Lesseps 1, 08023, Barcelona, Spain
[c] Institut d'Investigació Biomèdica (IIB Sant Pau), C. Sant Quintí 77, 08041, Barcelona, Spain

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ABSTRACT

A cooperative housing is a more democratic and affordable alternative that could contribute to ecological sustainability in local context. The paper evaluates the cooperative housing La Borda (Barcelona) from two points of view: energy consumption at building and household level and indoor environmental quality of six representative households. The evaluation aims to investigate how this housing alternative may contribute to reduce the energy impact of the building providing comfortable conditions to the users. A post-occupancy evaluation has been performed where energy consumption, environmental data and user perception have been gathered to make a qualitative and quantitate analysis. The paper wants to investigate how thermal comfort can be characterized in depth, analysing only air temperature, relative humidity and outdoor conditions. Furthermore, it has been paid especial attention to the overheating analysis and the impact of the relative humidity in the thermal comfort satisfaction of the occupants. The paper demonstrates that La Borda is a model that contributes to reduce the energy impact of the building, which can be related to some of the characteristics of the cooperative housings: sharing goods and resources; community support; training initiatives; strong involvement during the design of the project; and sustainable design of the building. The thermal comfort evaluation combines different tools (adaptive comfort model, Givoni psychometric chart, Heat Index and surveys) to achieve a good understanding of the thermal behaviour of households and comfort perception, achieving satisfactory results; However, some discrepancies have been found between the different indicators and qualitative perception of the users.

1. Introduction

Accessing adequate housing is becoming increasingly difficult especially in urban populations. One of the main reason is associated to the commodification and financialisation of housing, which ties the development of residential space to the market rather than to social need [1]. Cooperative housing is an affordable housing alternative and can embody a more participatory, collective and decommodified housing. It has become into a significant alternative model in those countries that have promoted it through legal and public policy means, as well as through economic and financial measures to make it a truly affordable alternative. As a more democratic and affordable alternative to dominant housing provision, it is often announced as a model for 'housing commons' [2]. It is an important housing model that can achieve two additional goals: encourage residents to socialize, care and interact with each other; as well as caring, interacting, and modelling community within the neighbourhood [3]. Furthermore, the cooperative model is a potentially beneficial form of community living for health and well-being, as housing is an important determinant of health [4].

Cooperative housing and related alternative housing forms arrived in Spain only recently and is still an emerging phenomenon in the Barcelona area. The most favoured model is right-of-use housing cooperatives on land leased from the municipality [5]. The right-of-use cooperative model is already in use in Northern European countries such as Denmark, Norway and Sweden. The Danish model, also known as the Andel model [6], is based on the private initiative of non-profit co-operatives that develop and manage housing for their members. The cooperatives are constituted by partners who have the indefinite right to use one of the dwellings as long as they are members of the cooperative,

* Corresponding author.
E-mail address: jortiz@irec.cat (J. Ortiz).

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Nomenclature

CO_2	CO_2 concentration
DHW	Domestic hot water
E	Electricity consumption
HI	Heat Index
IEQ	Indoor Environmental Quality
N	North orientation household
nZEB	nearly Zero Energy Building
PMV	Predicted Mean Vote
POE	Post-Occupancy Evaluation
Q	Thermal consumption
S	South orientation household
T_i	Indoor air temperature
T_{max}	Daily maximum temperature
T_{min}	Daily minimum temperature
T_{op}	Operative temperature
$T_{o,rm}$	Weighted running mean of the daily mean outdoor air temperature
T_{rm}	Radiant mean temperature
v_a	Indoor air velocity

avoiding making profit from the dwellings. The right of use is generally acquired by paying an entry fee which is proportional to the area of the dwelling and will be returned when the tenant leaves the cooperative. It is kept by paying an affordable and adaptable monthly fee that is intended to cover the cost of the debt originated for the construction and subsequent maintenance costs [7]. The members of the cooperative participate in all the decision-making processes through an assembly, between other decision mechanisms. Different communal living settings are arranged between households. This system makes people jointly responsible for the development of the cooperative and the maintenance of the buildings.

In terms of sustainable urban development cooperative housing projects in the Barcelona area are through technical and social initiatives clearly contributing to ecological sustainability in the local context. Cooperative housing can provide community and solidarity in everyday life, in terms of social sustainability [5]. Cooperative housing is a social and political project aiming to organize everyday life in a less resource-intense way by means of pushing norms, questioning spatial and material standards and enacting low-impact everyday practices, with synergies between social and ecological sustainability [8].

One positive example in both perspectives, social and ecological sustainability, is the cooperative housing La Borda located in Barcelona (www.laborda.coop). In 2012 a group of neighbours of Can Batlló, a former industrial site located in the district of Sants-Montjuic, created the cooperative housing La Borda in order to collectively solve the problem of affordable housing. La Borda is based on the Andel model and has a high level of participation of the users of the building in all the phases of the project: design, construction, maintenance and operation. This level of involvement allows to design and adjust the building to the needs of the users. The work performed by Cabré and Andres [8] describes the cooperative housing model implemented in La Borda, including a detailed explanation about the strategies to develop and manage the building, the tenancy regime being used, the sustainable communal living model of the project, the features of the economic agents involved, the strategy to access land, and the affordability criteria.

The present paper performs a Post-Occupancy Evaluation (POE) of the cooperative housing La Borda (Barcelona) from two points of view: the energy consumption at building and household level and the Indoor Environmental Quality (IEQ) of six representative households of the building. The research aims to respond to the following objectives:

- to evaluate how the cooperative housing alternative may contribute to reduce the energy impact of the building and provide comfortable conditions to the users.
- to investigate how thermal comfort can be characterized in depth, analysing only air temperature, relative humidity and outdoor conditions, and
- to evaluate the overheating criteria and the impact of the relative humidity in the thermal comfort satisfaction of the occupants.

The paper is structured in the following sections: Literature review focused on POE and thermal comfort in residential buildings; Materials and Methods, where the climate, the building characteristics, the data used in the work and the key performance indicators are described; followed by Results section that presents the energy performance and the IEQ of La Borda; and concluding there are the Discussion and Conclusions sections where the main results are highlighted and compared with previous studies.

2. Literature review: Post-occupancy and thermal comfort evaluation in residential buildings

The reviewed literature involves latest studies on POE studies and thermal comfort assessment approaches, paying especial attention to those most suitable for an in-deep analysis in residential buildings.

POE is a method to analyse the operating performance of buildings and serves as a systematic process of evaluating buildings after they have been occupied. POE helps to identify the building's real performance, to diagnose operational problems, and finally to increase the performance of the building [9]. The most common methods implemented in POEs can be classified in subjective methods (survey, interviews) and objective methods (IEQ in-situ measurements, energy and water) [10]. There are several POE protocols, which consist in a systematic methodology where different methods are implemented. Most of the existing POE protocols are design for office buildings, and only few of them are for residential buildings [10], which are: Health Optimization Protocol for Energy-efficient buildings (Europe), Creative Energy Homes (UK) and Post-Occupancy Evaluation for Multi-Unit Residential Buildings (Canada). Those protocols implement different methods, but generally include a survey to the occupants and/or an energy, water and IEQ measurements. Unlike office building protocols, the IEQ monitoring is simpler and only covers the thermal comfort and the air quality evaluation, including experimental measurements of temperature, humidity and CO_2 concentration of one or several rooms of each apartment [11–14]. The measurements are complemented with surveys and/or interviews to the occupants. Depending on the objective of the study, the surveys are adapted to collect different kind of information, as for example: to assess how the occupants use their home [11,13]; to evaluate the efficiency of ventilation systems in relation to Indoor Air Quality, including environmental thermal sensation (temperature and relative humidity), CO_2 concentration (by the odour), noise, and data related to sick building syndrome [12]; to evaluate the maintenance level, damage or construction modification of the building [13]; or to assess the occupant satisfaction in terms of thermal comfort [14].

Through the POE is possible to evaluate the IEQ from qualitative and quantitative point of view. Herrera-Limones et al. [15] show that considering only measurable indices (quantitative) is clearly insufficient to evaluate the real conditions of habitability and comfort in residential buildings, being necessary to complement with surveys (qualitative). However, the quantitative analysis is limited to the available monitored data and, as the studies reviewed show, in some cases it only covers the main environmental parameters: temperature, humidity and CO_2 concentration. *Which are the most appropriate thermal comfort assessment approach for an in-deep analysis?* Forgiarini et al. [16] examines standards, indoor experiments in controlled environments (climate chamber) and semi-controlled environments, indoor field studies in different building types, productivity, human physiological models, outdoor and semi-outdoor field studies. In the last 10 years, different authors developed several new adaptive thermal comfort models and others worked to correct or adjust the Predicted Mean Vote (PMV) model for actual building types and different conditioning modes. Based on the review analysis done by Yao et al. [17], three representative thermal environment assessment approaches were classified as the heat balance approach, the adaptive regression-based approach and the adaptive heat balance approach. The heat balance approach considers environmental and physiological parameters but pays insufficient attention to human adaptation in practice, whereas the adaptive regression approach only regards outdoor temperature as its sole input, providing less evidence for indoor environmental design. The adaptive heat balance approach, aimed at bringing these two classic approaches together and filling the gap.

Cheung et al. [18] use the ASHRAE Global Thermal Comfort Database II [19] to evaluate the prediction accuracy of the PMV model. The validation concludes that the thermal sensation is incorrectly predicted two out of three times, and the accuracy of PMV was similarly low for air-conditioned, naturally ventilated and mixed-mode buildings. Similarly, Parkinson et al. [20] evaluate ASHRAE 55 adaptive comfort model using ASHRAE Global Thermal Comfort database II. Results validated the standard's current adaptive comfort model for naturally ventilated buildings, while suggesting several potential nudges relating to the adaptive comfort standards, adaptive comfort theory, and building operational strategies. They present evidence that adaptive comfort processes are relevant to the occupants of all buildings, including those that are air conditioned, as the thermal environmental exposures driving adaptation occur indoors where we spend most of our time. This suggests significant opportunity to transition air conditioning practice into the adaptive framework by programming synoptic- and seasonal-scale setpoint nudging into building automation systems.

De Dear et al. [21] review the adaptive thermal comfort research, including adaptive comfort theory, adaptive comfort practice (standards), contextual effects on adaptive comfort (building typologies), shifting boundaries of the comfort zone and the dynamics of comfort expectations. The adaptive comfort theory fits better in the residential context than in the office context because of a higher degree of adaptive opportunities afforded by one's own home (environmental and clothing features). In addition, people in their homes are more tolerant of greater indoor temperature variations than those in office settings [21]. Furthermore, there are a number of other factors that influence the sensation of thermal comfort, like cultural and behavioural aspects, age, gender, space layout, possibility of control over the environment, user's thermal history and individual preferences [16].

Focused on the adaptive comfort approach, the main indicator to be calculated is the operative temperature, which depends on the air temperature, the mean radiant temperature and the air velocity. However, as the literature review has concluded, the POE implemented in residential building does not include a detailed monitoring campaign and only air temperature is recorded. *Are the monitored data enough to perform the thermal comfort evaluation?* The work done by Li et al. [22] evaluate existing long-term thermal indices found in standards and their correlation with the thermal satisfaction of building occupants, using data from office buildings in Australia. One of the findings concludes that air temperature is sufficient as an input parameter for calculating long-term indices when operative temperature has not been measured. Furthermore, Vellei et al. [23] demonstrate the influence of the relative humidity on the adaptive thermal comfort in naturally ventilated buildings over 8 different climates, deriving a new adaptive model that includes the impact of relative humidity. *However, are the long-thermal indices appropriate to evaluate the overheating risk of residential buildings?* Dartevelle et al. [24] result in a critical review of the capacity of several criteria used for the evaluation of overheating risks in free-running residential buildings to predict the satisfaction of occupants with their summer thermal comfort, concluding that larger studies are needed to re-evaluate the boundaries and/or the tolerable frequencies of the adaptive criteria within the residential context.

3. Materials and Methods

3.1. Climate characteristics

The cooperative housing La Borda is located in the district of Sants-Montjuic, Barcelona (Fig. 1). Barcelona is a city of the north-west coast of the Mediterranean Sea. According to Köppen-Geiger climate classification, the climate type for Barcelona is Csa, typical Mediterranean climate [25]. The Barcelona's climate is characterized by hot and dry summers, and temperate winters. Fig. 2 summarizes the weather conditions in Barcelona during the studied period of this work (01/11/2019 - 31/10/2020) obtained from the Zona Universitària weather station [26,27]. The monthly average temperature in winter is around 12 °C, and is around 25 °C in summertime. The relative humidity is in average around 70% during the whole year, having a relevant role in the thermal comfort perception. The daily global solar irradiation varies from 2 to 3 kWh/m^2 in winter to 6–7 kWh/m^2 in summer.

3.2. Building description

The cooperative housing La Borda is a nearly Zero Energy Building (nZEB) constructed on 2018. The design of the building includes 28 apartments around a central courtyard, designed to be the centre of the social interaction. The courtyard is a closed atrium designed with dynamic openings that allows to be automatically adjusted depending on the season (Fig. 3): the atrium is closed during winter to avoid energy losses and act as a greenhouse, and is partially opened in summer to increase natural ventilation. The atrium acts as a thermal comfort regulator. Additionally, the building has installed solar protections devices in the atrium and south facades to avoid solar radiation during summer and increase natural lighting and the solar gains in winter. The apartments are distributed over six floors and most of them are situated on the south façade in order to get the maximum solar radiation. The insulation of the envelope (Table 1) and the thermal mass are higher than the code requirements when designed (Spanish Building Code 2017), and in some cases, even higher than the current regulation (Spanish Building Code 2019 [28]). The structure and the envelope materials are made of timber in order to reduce the embodied energy, compared to a conventional Spanish building. Additionally, industrialized elements are used to optimize the construction solutions, such as the one implemented in the north façade: industrialized corrugated sheet materials in the opaque façade and polycarbonate in the translucent ones. On the south façade, continuous terraces are built with roller shutters and large glass openings. The façade of the courtyard is made with cross-laminated timber and vertical openings. The average area of the households is 58 m^2 and there are around 600 m^2 of common areas.

The building has a centralized system to cover the heating and domestic hot water (DHW) needs of the households. The system consists of two biomass boilers of 48 kW each one. The system has two water tanks, one that distributes the hot water to the households (2,500 L) and a smaller one that accumulates water for the common kitchen (300 L). Each household has a substation heat exchanger that includes a heat meter to count the total amount of energy used for each household. There is not cooling system in the building.

The building has a building management system that allows to monitor the behaviour of the building, collecting energy consumption from the whole building disaggregated by households (thermal energy and electricity), water consumption of each household, indoor temperature of all households, detailed indoor environmental variables from 6 households, and weather data. This information is accessible by all the users of the building through a web page with the aim of optimizing the general consumption and increase the energy awareness of occupants.

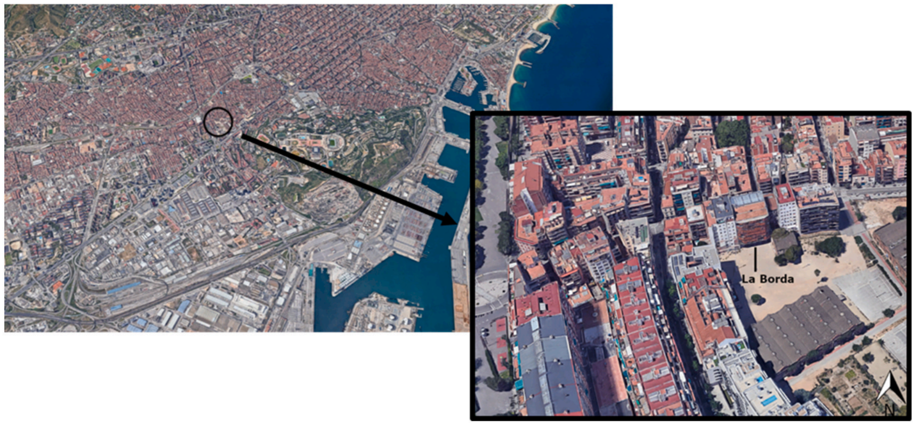

Fig. 1. Cooperative housing La Borda (Barcelona).

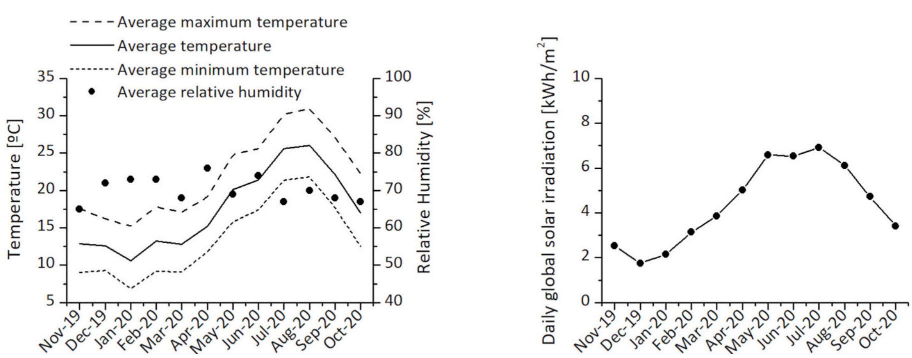

Fig. 2. Monthly weather data from the weather station Zona Universitària, Barcelona [26,27]: temperature, relative humidity and daily global solar irradiation.

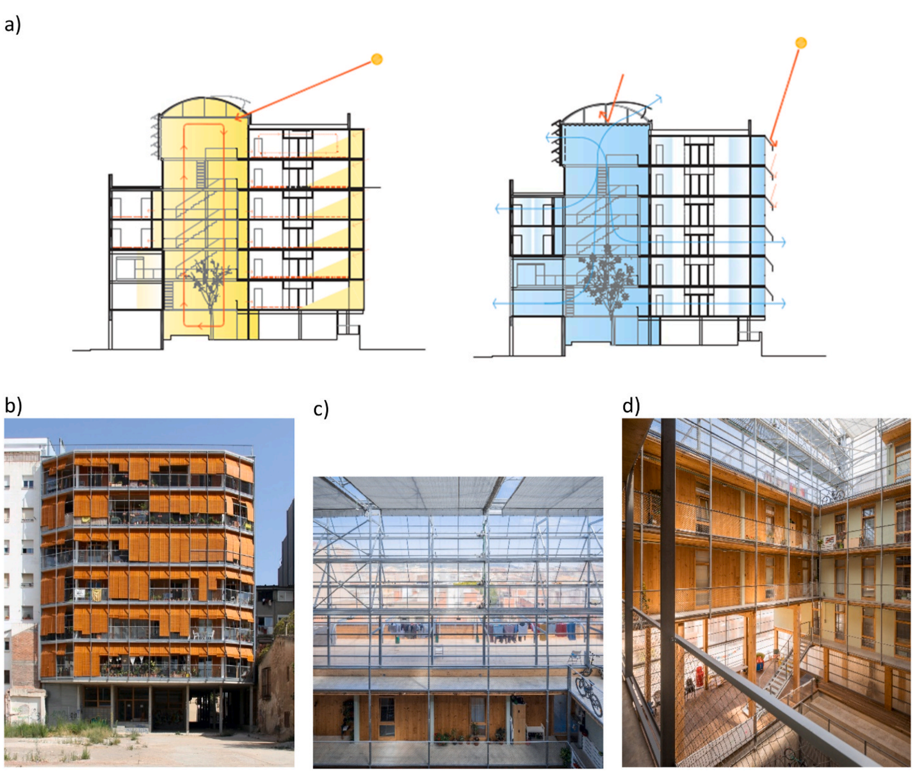

Fig. 3. Bioclimatic design of La Borda. a) Passive strategies for summer and winter seasons (Source: Lacol). b) Solar protections of the south façade (Source: Lacol). c) Solar protections of the atrium (Source: Lluc Miralles). d) Central courtyard and its social function (Source: Lluc Miralles).

Table 1
Envelope characteristics of La Borda.

Envelope	Thermal transmittance [W/m^{2}K]		
	Building Code 2017	Building Code 2019	La Borda
Roof	0.50	0.40	0.17
Façade - north	0.50	0.49	0.23
Façade - south	0.50	0.49	0.29
Ground floor	0.75	0.70	0.31
Windows - north	3.10	2.10	1.44
Windows - south	3.10	2.10	2.67

3.3. *Monitoring data & surveys*

Monitoring data are collected at household level from the building management system. The analysed period covers a complete year from 01/11/2019 to 31/10/2020. The energy analysis has been done for the whole building in terms of thermal energy and electricity consumption. The indoor environmental analysis is focused on 6 households, where temperature, relative humidity and CO_2 concentration are monitored. Characteristics of monitoring instruments are detailed in Table 2. The 6 monitored households are distributed among the building in different floors (one in each floor, from 1 to 6) and different locations of the floor (north orientation, N type, and south orientation, S type), as Fig. 4 shows. Furthermore, a survey has been done to almost all adults of those households to know their comfort perception and their energy habits (use of the heating system, solar protection devices and natural ventilation). Table 3 gives details of the occupants of each apartment and the number of surveys done. The survey was distributed by email and was completed by occupants themselves just after the analysed period.

3.4. *Key performance indicators for energy and IEQ evaluation*

In terms of energy consumption, two main indicators have been analysed: the thermal energy and the electricity consumption. The evaluation has been done at two levels: household and building.

Thermal consumption (Q, kWh) represents the thermal energy used for each household to cover the heating and DHW needs. This energy is monitored by the substation heat exchanger and represents the energy demand covered in each household. This thermal energy does not include the losses of the distribution system (from the boiler to the households), neither the performance of the boiler. Analysing the thermal demand in warmer months is possible to estimate the fraction used for DHW and heating.

Electricity consumption (E, kWh) represents the electricity consumption of each household, which includes the appliances, electric kitchen and lighting consumption. It is important to take in consideration that there are some common facilities in the building, as the laundry room and an additional common kitchen (each apartment has also its own kitchen), which consumption are not included at household level, but are included in the building level analysis.

A deeper analysis has been done in terms of IEQ, paying especial attention on how to characterize the overheating during summer periods.

Table 2
Monitoring instruments characteristics.

Instrument	Characteristics	
Carlo Gavazzi SHSUCOTH	Temperature	±0.5 °C
	Relative Humidity	±3% (30 … 70%), otherwise ±5%
	CO_2 concentration	±50 ppm + 2% of measured value
LEAKO	Heat meter (heating and DHW)	
CERM1	Single-phase remote control meter (electricity household)	

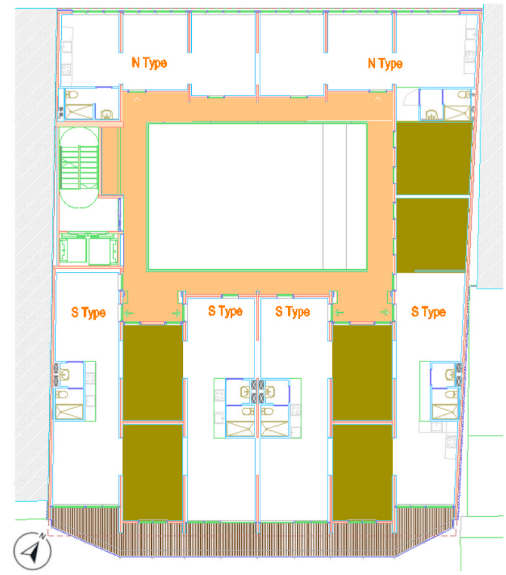

Fig. 4. Standard floor distribution of La Borda (Original source: Lacol). Green area: common spaces for private use. Orange area: common spaces. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Occupancy description and number of surveys of each monitored household.

Household	Occupants	Number of surveys
1S	1 adult	1
2S	2 adults	2
3N	1 adult	1
4N	1 adult & 2 children	1
5S	2 adult & 3 children	1
6S	2 adults	2

Daily minimum and maximum temperature (T_{min} and T_{max}, °C) is the minimum and maximum temperature of a day. The minimum temperature can represent the minimum temperature reached during night hours, and the maximum temperature, the maximum reached during the day hours. Analysing these variables, a general overview about the temperature range in the apartments can be obtained, as well as, the number of days or the number of consecutive days with temperatures below/above certain value. The temperature thresholds analysed are described in Table 4.

Operative temperature (T_{op}, °C) is a thermal comfort index for

Table 4
Minimum and maximum temperature thresholds.

Temperature	Description	Reference
<18 °C	It is the minimum temperature where there is no demonstrable risk to the health of healthy sedentary people.	[29]
>20 °C	*Tropical night threshold*. It is considered when the minim temperature at night is above 20 °C.	–
>25 °C	*Equatorial night or torrid night threshold*. The higher frequency of minimum temperatures exceeding 20 °C in the last decades has led to the use of higher thresholds to emphasize the importance of these very warm nights.	[30]
>26 °C	Following the *Guide A: environmental design*, it stablishes that the exposure to temperatures higher that 26 °C should be less than 5% of the occupied time.	[31]
>28 °C	Following the *Guide A: environmental design*, it stablishes that the exposure to temperatures higher that 28 °C should be less than 1% of the occupied time.	[31]

adaptive comfort method [32], that relates acceptable temperature ranges to weather conditions. The adaptive comfort method is applied in occupant-controlled naturally conditioned spaces.

$$T_{op} = A \cdot T_i + B \cdot T_{rm} \quad (1)$$

Where, T_i is the indoor air temperature, T_{rm} is the radiant mean temperature, and A and B are parameters that depends on the indoor air velocity (v_a) (if $v_a < 0.2$ m/s, then $A = B = 0.5$; if $0.2 < v_a < 0.6$ m/s, then $A = 0.6$ and $B = 0.4$, if $v_a > 0.6$ m/s, then $A = 0.7$ and $B = 0.3$, which method for obtaining the operative temperature is described in ASHARE 55 [33]). Indoor air temperature is the only parameter measured in the households, to simplify the monitoring and do not disturb households' occupants, therefore the following assumption has been done: $T_{rm} = T_i$, and consequently $T_{op} = T_i$. Table 5 details the operative comfort ranges depending on the IEQ category, being IEQ_{II} for a new residential building. The equations are valid for a weighted running mean of the daily mean outdoor air temperature ($T_{o,rm}$) between 10 and 30 °C, taking the T_{op} ($T_{o,rm} = 10$ °C) when the $T_{o,rm} < 10$ °C and T_{op} ($T_{o,rm} = 30$ °C) when the $T_{o,rm} > 30$ °C.

Heat Index (HI, °C) is a measure of how hot it really feels when relative humidity is factored in with the actual air temperature [34]. High humidity combined with hot temperatures reduce the body's ability to cool itself increasing the risk of heat exhaustion, heat stroke, and other heat related health problems. The Heat Index, also referred to as apparent temperature, is an estimate of the temperature that would similarly affect the body at normal humidity (about 20%). The equation for obtaining the Heat Index are described in Ref. [35] and Table 6 describes the Heat Index categories.

Givoni bioclimatic chart is a representation of a psychometric chart that facilitate the analysis of indoor climatic characteristics of a building, temperature and humidity, from the viewpoint of human comfort. The chart defines the "comfort zone" and represents the range of climatic conditions within which the majority of persons would not feel thermal discomfort [36].

CO_2 concentration (CO_2, ppm) is used as a tracer of human occupancy and allows to determine if the household has appropriate ventilation rates to guarantee acceptable indoor air quality. The comfort ranges are introduced in Table 5 and corresponds to the CO_2 concentration above outdoors conditions. The outdoor CO_2 concentration used in the present work is 400 ppm.

4. Results

4.1. Energy performance of La Borda

The energy performance of La Borda is analysed through the thermal and the electricity consumption of the households, which are represented in Fig. 5. The graphs represent the consumption of the monitored households and the average consumption of all the households of La Borda.

The thermal consumption, Fig. 5-left, represents the heating and DHW needs of each household, disaggregated in heating and DHW. The DHW consumption has been estimated based on the thermal energy consumed during intermediate months where the use of the heating system is very limited or null (April, May and October), and extrapolated to the rest of the cold months of the year (summer months are not considered to estimate the DHW average consumption because the households presents low consumptions due to vacation periods and/or the warmer temperature of the tap water). The heating is calculated as a difference between the total thermal consumption and the estimated DHW. The thermal consumptions show two different patterns related to the orientation of the households: the heating consumption of the southern apartments is very low (below 100 kWh/yr); on the contrary, the ones located in the north façade have a consumption around 800 kWh/yr. The results are in line with the survey responses, where the north-oriented households (3N and 4N) switch on the heating system in autumn until the end of winter; however, the south apartments use the heating system only when is very cold outside. The estimated DHW needs of each apartment are related to the number of occupants and their behaviour, being in general, higher for those with higher number of occupants. The average thermal consumption of all the households of La Borda is around 830 kWh/yr (11.6 kWh/m^2·yr), including heating and DHW needs.

The electricity consumption of each household (Fig. 5-right) includes the lighting, appliances and electric kitchen consumption, except washing machines because there exits the centralized laundry room. However, the average consumption of La Borda is calculated considering the households' electricity consumption and the electricity consumption of the common areas of the building. As happens with the DHW, the electricity consumption is related to the number of occupants, being in general the more occupied households the ones that have a higher electricity consumption. In average, a household in La Borda has an electricity consumption around 1,000 kWh/yr (15.1 kWh/m^2·yr).

Fig. 6 represents the daily thermal and electricity consumption of each household during the whole analysed year. This representation allows having a general overview of the main patterns of the households, in terms of heating consumption, occupancy of the households and impact of the COVID-19 lockdown period (from March to May 2020). Regarding the daily thermal consumption, as has been observed previously, there is a clear difference between the north and south oriented households, where the firsts ones (3N and 4N) shows a more intense

Table 6
Likelihood of heat disorders with prolonged exposure [35].

Heat Index Category	Effects description	HI [°C]
Caution	Fatigue is possible with prolonged exposure and activity. Continuing activity could result in heat cramps.	26–32
Extreme	Heat cramps and heat exhaustion are possible. Continuing activity could result in heat stroke.	32–41
Danger	Heat cramps and heat exhaustion are likely; heat stroke is probable with continued activity.	41–54
Extreme danger	Heat stroke is imminent.	>54

Table 5
Comfort range for the different comfort indexes: Operative temperature and CO_2 concentration [32].

Comfort range	Level of expectation	T_{op} [°C]	CO_2 [b] [ppm]
IEQ_I	High. Occupants with special needs (children, elderly, persons with disabilities, etc.).	$T_{op} = 0.33 \cdot T_{o,rm} + 18.8 + 2$ [a] $T_{op} = 0.33 \cdot T_{o,rm} + 18.8 - 3$	550
IEQ_{II}	Medium. Standard level.	$T_{op} = 0.33 \cdot T_{o,rm} + 18.8 + 3$ $T_{op} = 0.33 \cdot T_{o,rm} + 18.8 - 4$	800
IEQ_{III}	Moderate. It will not provide any health risk but may decrease comfort.	$T_{op} = 0.33 \cdot T_{o,rm} + 18.8 + 4$ $T_{op} = 0.33 \cdot T_{o,rm} + 18.8 - 5$	1,350
IEQ_{IV}	Low. Acceptable only for very short periods of time throughout the year.	–	>1,350

[b] $T_{o,rm}$ is the weighted running mean of the daily mean outdoor air temperature.
[a] Corresponding CO_2 concentration above outdoors.

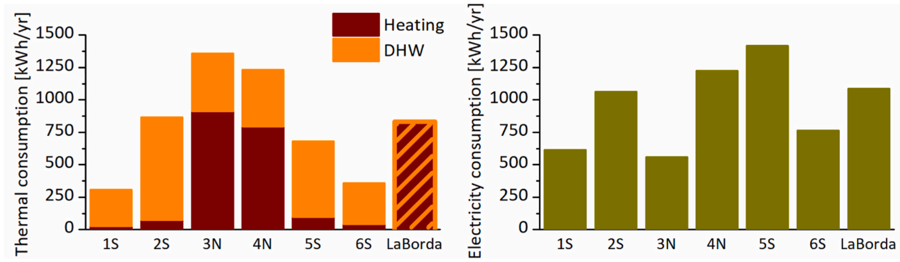

Fig. 5. Annual thermal consumption (left) and electricity consumption (right) of each monitored household and the average consumption of La Borda.

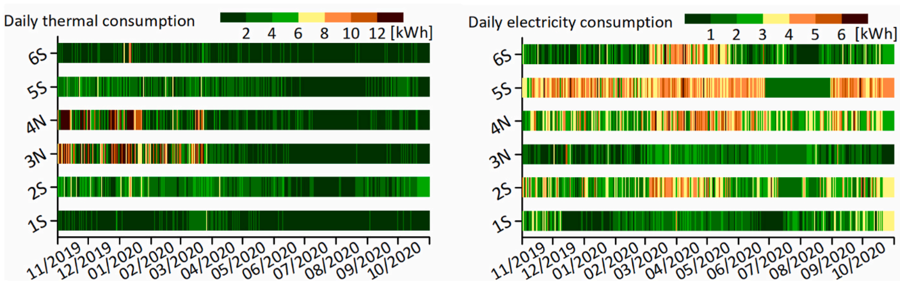

Fig. 6. Daily thermal consumption (left) and electricity consumption (right) of each monitored household.

consumption during the colder months. On the contrary, households 1S and 6S has a consumption below 4 kWh/day during all the year, what is coherent with the low annual thermal consumption of the households. Additionally, it is important to mention the lower consumption of all the households during the warmer months (below 2 kWh/day).

In terms of electricity consumption, two main patterns can be distinguished: the increased consumption in all the households during the lockdown period, and the very low consumption during the vacation periods (identified as long periods with constant consumption lower than 2 kWh/day). The identification of the long periods of unoccupied households has been estimated and used for the indoor environmental comfort evaluation, which allows a more accurate evaluation (the comfort should be analysed only when there are occupants in the households).

4.2. IEQ evaluation

Fig. 7 summarizes the IEQ perception of the inhabitants of the 6 monitored households. The perception is provided in terms of general comfort, thermal comfort in winter and summer, and visual comfort (general, daylighting and glare). The graphs show the individual response of each occupant (grey dot) and the average of all responses (purple dot). Looking at the average perception, all the values are between 1 and 2, being 1 the best valuation. The only category that provides worse perception is the thermal comfort in summer, resulting in an average of 3.6. Looking at the individual responses, there is a large dispersion in the answers, from 1 to 7, what clearly shows different thermal behaviour of the households. This is reflected also in Fig. 8, where the summer thermal comfort perception varies from "*slightly warm*" to "*hot*". To better understand what is happening, the monitored data are analysed in detail. Finally, the visual comfort perception presents some dissatisfied answers, but there is a majority trend of satisfaction amount users.

Fig. 9 represents the daily minimum and maximum indoor temperatures of each monitored household, together with the outdoor temperature obtained from a weather station installed in the roof of La Borda. Following the trends observed in the thermal energy consumption, there is a clear difference between the households of different orientation: the ones oriented to the north registered lower daily minimum and maximum temperatures in winter months (temperatures between 15 and 20 °C). Most of the daily minimum temperatures of household 1S are also in the range of 15–20 °C, however, the maximum temperatures are mostly in the upper range of temperatures (20-25 °C), as happens in the other southern apartment. In summer, the difference

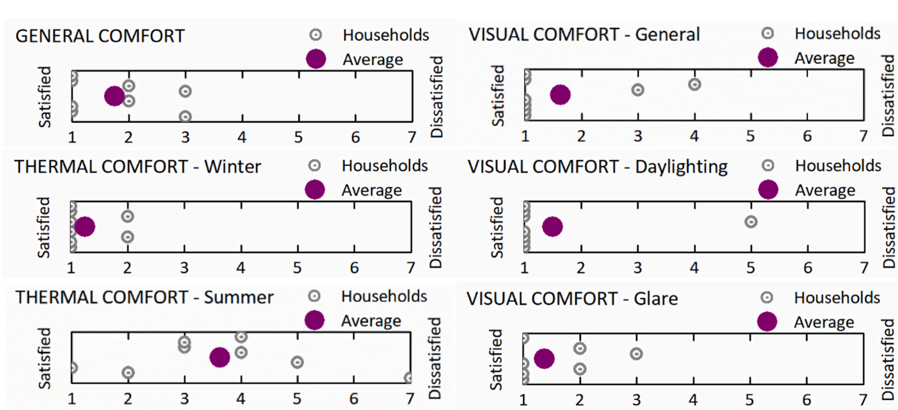

Fig. 7. Indoor environmental quality perception of the inhabitants' households in La Borda (6 monitored households).

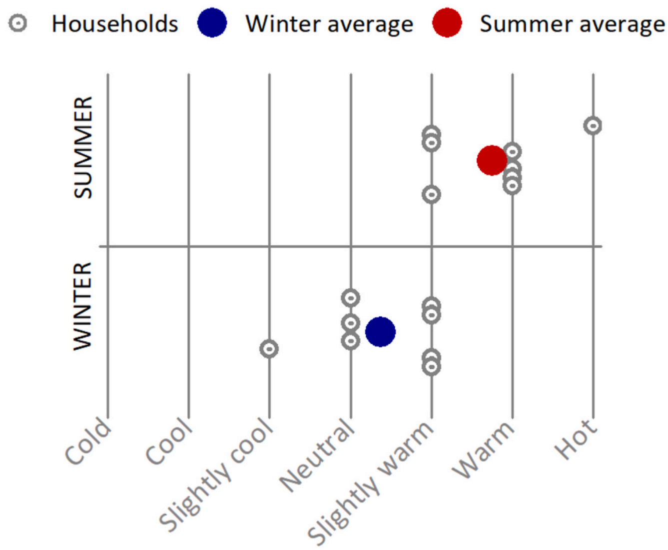

Fig. 8. Thermal comfort perception in winter and summer.

between households is not so evident; nevertheless, the maximum temperatures of the households show a clear relation with the outdoor temperatures due to the absence of cooling system. The daily minimum temperatures in summer are around 25-30 °C, achieving values higher than 30 °C during some days. In relation to the daily maximum temperatures, the frequency of temperatures above 30 °C increases in all households. It is important to mention that in Fig. 9 the estimated unoccupied periods have not been discarded, fact that could overestimate the discomfort periods due to low or high temperatures.

Fig. 10 and the following ones take in consideration the estimated occupancy and the unoccupied periods are removed from the sample data of each household. Fig. 10 shows the number of days that each household has a daily minimum or maximum temperature above a certain value and Fig. 11 counts how often these events occur on consecutive days and during how many consecutive days. Households 3N, 4N and 1S are the ones with more time with daily minimum temperatures below 20 °C (representing a 45-30% of estimated occupied days) which can be associated to minimum night-time temperature. Going in detail, these households present daily minimum temperatures below 18 °C during 2, 3 and more than 5 consecutive days, with a frequency of once or twice over the year. The low frequency of these events could be related to not identified unoccupied periods based on the occupant answers. In relation to the highest daily minimum temperatures, the households 4N and 3N are the ones that spend more time with temperatures above 26 °C, representing around a 15% of estimated occupied days; and 5–7% of estimated occupied days with temperatures above 28 °C. The south oriented apartments present similar patterns, with a percentage around 10% with daily minimum temperatures higher than 26 °C and 2% higher than 28 °C. The relatively high percentages obtained with daily minimum temperatures above 26 °C, together with the high frequency of events with more than one consecutive days with this minimum temperature suggest that is a recurrent situation and some measure should be taken to improve the thermal comfort during the hottest days. The frequency of events with minimum temperatures over 28 °C is lower, however due to the uncertainties on the unoccupied periods it is difficult to confirm the relevance of these values.

Looking at the daily maximum temperatures (which can be associated to maximum daytime temperatures), south oriented households have temperatures above 20 °C during more than 95% of estimated occupied days, in comparison to the 80% of the north-oriented households. However, there is not a clear pattern related to the highest daily maximum temperatures, where all the households spend around 25% of the estimated occupied days with temperature over 26 °C, and around 5–15% over 28 °C. It is important to mention that the daily maximum temperature achieved in the households is around 30 °C, with low frequencies (less than 5% in the worst case). Analysing the daily maximum temperatures, it can be confirmed that additional strategies for cooling are needed in these households. Finally, as has been observed in Fig. 9, the indoor maximum temperatures is correlated with the highest outdoor daily maximum temperatures, which is not the case for the daily minimum temperatures.

The adaptive comfort model is evaluated in order to analysed how these maximum and minimum temperatures are affecting the thermal perception of the users. Fig. 12 represents the indoor operative temperature related to the weighted running mean of the outdoor

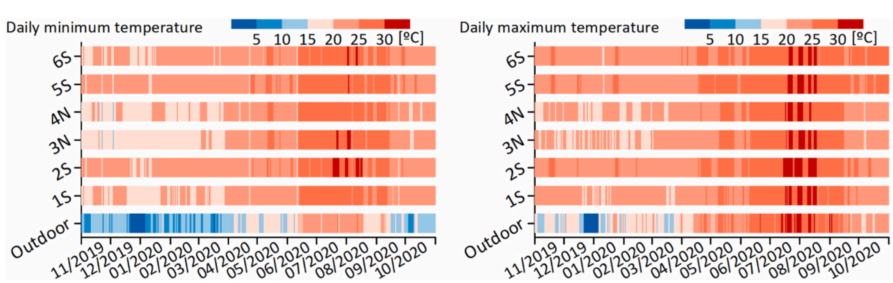

Fig. 9. Daily minimum and maximum temperature of the 6 monitored households of La Borda and its weather station (outdoor).

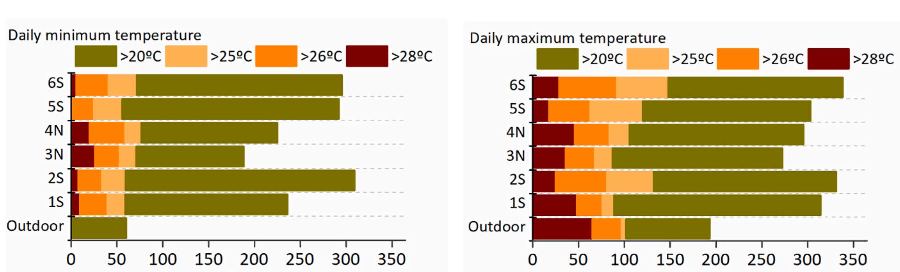

Fig. 10. Number of days that each household has a daily minimum (left) and maximum (right) temperature above 20, 25, 26 and 28 °C, taking in consideration the estimated occupancy. The daily outdoor temperature is also included.

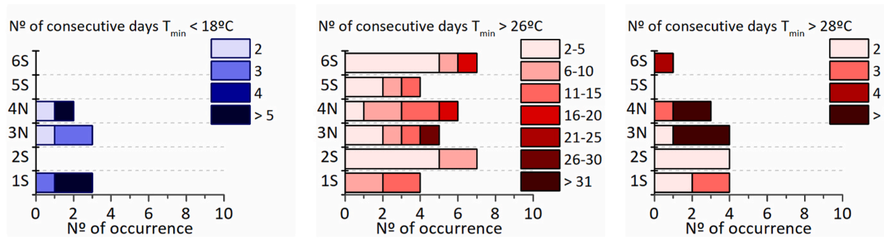

Fig. 11. Number of occurrences that each household has a minimum temperature (T_{min}) above or below certain value (<18 °C, >26 °C and 28 °C) for several consecutive days (colour scale), taking in consideration the estimated occupancy

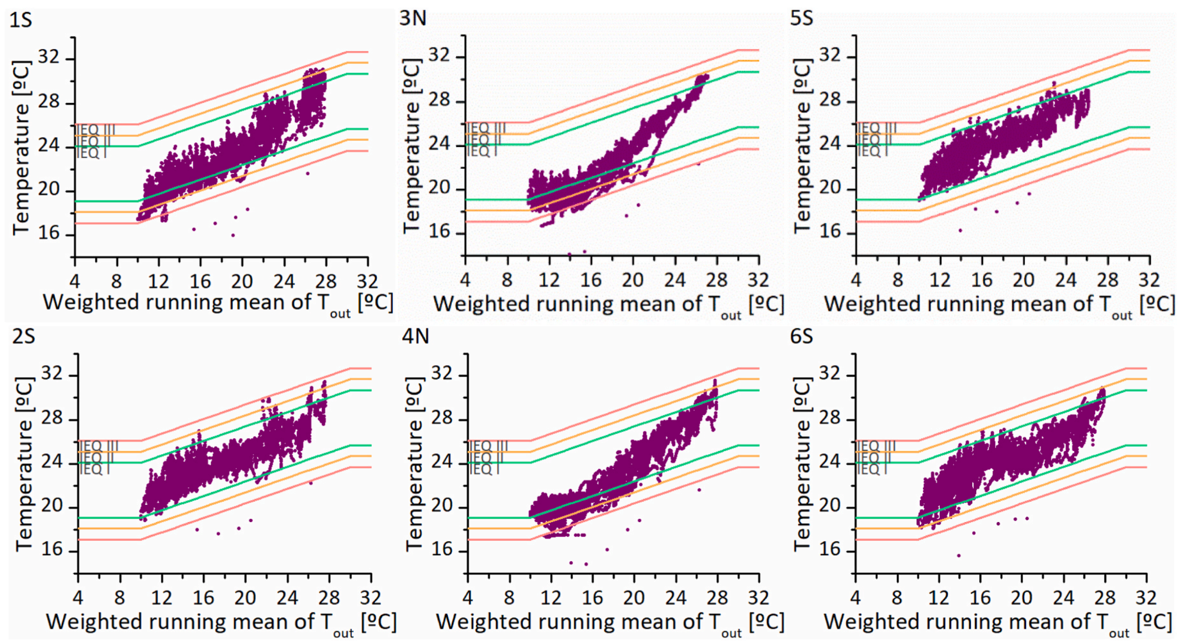

Fig. 12. Indoor operative temperature as a function of weighted running mean of outdoor temperature for each monitored household of La Borda, taking in consideration the estimated occupancy.

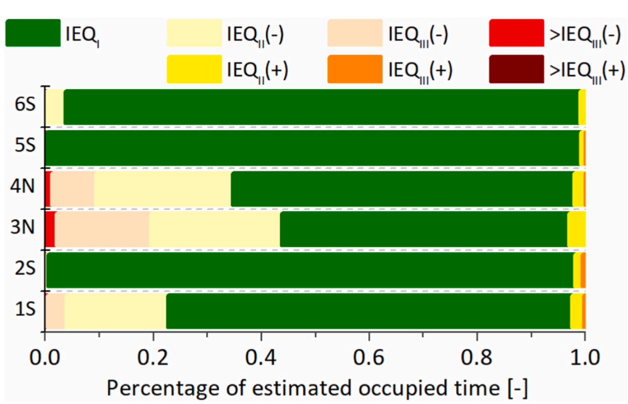

Fig. 13. Percentage of time that indoor operative temperature is in each adaptive comfort category (IEQ), for each monitored households of La Borda. (+) represents the upper temperature range and (−) the lower temperature range. The estimated occupancy is taken in consideration.

temperature for each monitored household of La Borda and, Fig. 13 shows the percentage of time in each adaptive comfort category (IEQ_I, IEQ_{II} and IEQ_{III}). In line with the previous analysis, two main behaviours can be distinguished: south and north-oriented apartments. The shape of the point cloud is different in both group of households. The slope of the point cloud of the southern ones is, in general, parallel to the adaptive comfort ranges, meaning that the passive strategies to provide comfortable conditions in winter and summer are efficient, providing comfortable condition to the users. However, the point cloud of northern ones shows two different slopes: almost 0 for weighted running mean of outdoor temperatures below 16 °C and a higher slope than the comfort range for temperatures above 16 °C. The first slope, horizontal trend, is related to the use of the heating system, meaning that the behaviour of the indoor temperature is not linked to the outdoor temperature variations, because there is an active system that is providing the comfortable conditions, instead of passive strategies. In relation to the higher slope segment, one explanation could be that the passive strategies designed for cooling provide comfortable conditions (most of the measure are inside the comfort range) however, they are not so efficient as in the southern households, because all the data are in the upper band of the comfort range presenting less temperature amplitude. Some possible causes could be that the north-oriented households have the main façade on a narrow street with relative high level of traffic, and there are facing away of the sea breeze, which helps reduce the temperature at night.

Analysing Fig. 13, the south-oriented households are in IEQ_{II} or better more than 95% of the estimated occupied time, and the northern ones around 80–90%. In the north-oriented households, the main reason of discomfort is related to low temperatures; however, the user perception does not express discomfort due to low temperatures. There is no significant discomfort due to high temperatures according to the adaptive comfort model; however, the main discomfort expressed by the users is related to higher temperatures.

The adaptive comfort analysis is complemented with the Givoni bioclimatic chart and the Heat Index (Fig. 14) in order to understand the discrepancy between the adaptive comfort results and the user perception. The area of the Givoni psychometric chart is divided in different zones, which are described in Table 7. In addition, the indoor data of the Givoni psychometric diagram is classified by Heat Index categories: Normal (green dots), Caution (orange dots) and Extreme (red dots). The Heat Index is a parameter that relates the temperature to the humidity of the air and provides an estimation about how hot it really feels. Analysing the Heat Index, in general, there is a good correlation between the comfort zone and the Heat Index categories: the comfort zone includes mostly green dots (Normal Heat Index), and Caution and Extreme categories are outside the comfort zone. Finally, the estimated non-occupancy periods are identified with grey dots.

Looking at the colder temperatures, the south-oriented households registered all the indoor data in the comfort zone, except very few monitored data of household 1S. The north-oriented apartments show a similar situation than household 1S, most of the indoor data is inside the comfort zone, with some few dots in the heating area. The evaluation of the cold period is in line with the previous analysis. Regarding the warmer temperatures, most of the data are outside the comfort zone; however, the data are inside the 1 m/s comfort zone, meaning that the users would be in comfortable conditions if there is an effective natural ventilation with an air velocity of 1 m/s. It seems that the discomfort of the users could be related to a reduced natural ventilation (<1 m/s) that is not able to counteract the effect of the high humidity and temperature (Heat Index values of Caution and Extreme categories). This pattern is observed in all the households, with the difference of the non-occupied periods: there are households that are unoccupied during the hottest periods, which results in better comfort perceptions (a clear example is

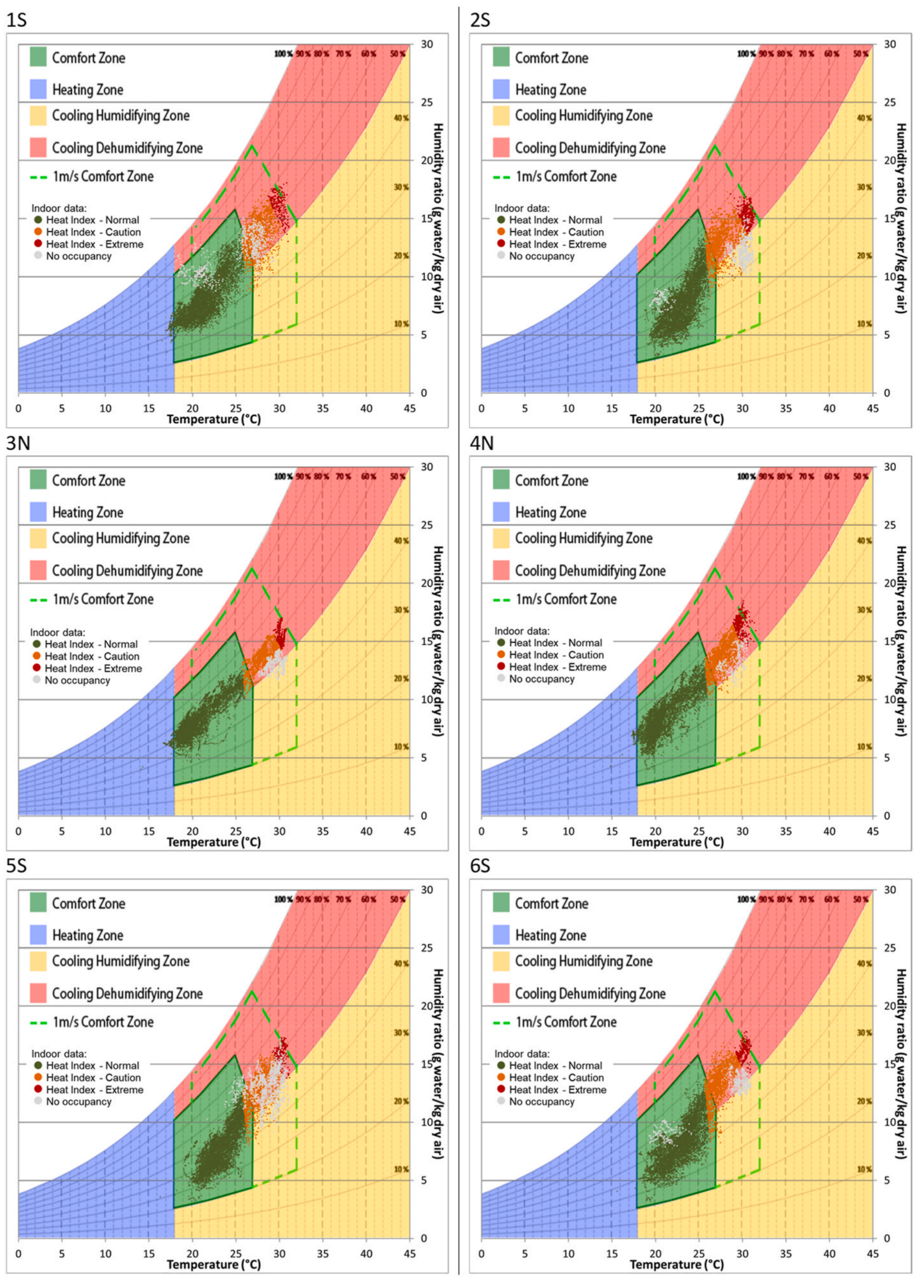

Fig. 14. Givoni psychometric chart for each monitored households in La Borda. Indoor data is classified by Heat Index categories: Normal (green dots), Caution (orange dots) and Extreme (red dots). Indoor data related to periods without occupancy are highlighted with grey dots. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 7
Description of the zones highlighted in the Givoni psychometric chart.

Zone	Description	Area colour
Comfort	Temperature and humidity conditions that provide comfort to the users	Green
1 m/s Comfort	Temperature and humidity conditions that provide comfort to the users if the air velocity is 1 m/s (effective natural ventilation)	Light green dashed line
Heating	Discomfort conditions that can be improved with the use of heating strategies	Blue
Cooling Humidifying	Discomfort conditions that can be improved with the use of cooling and humidifying strategies	Yellow
Cooling Dehumidifying	Discomfort conditions that can be improved with the use of cooling and dehumidifying strategies (excess of temperature and humidity)	Red

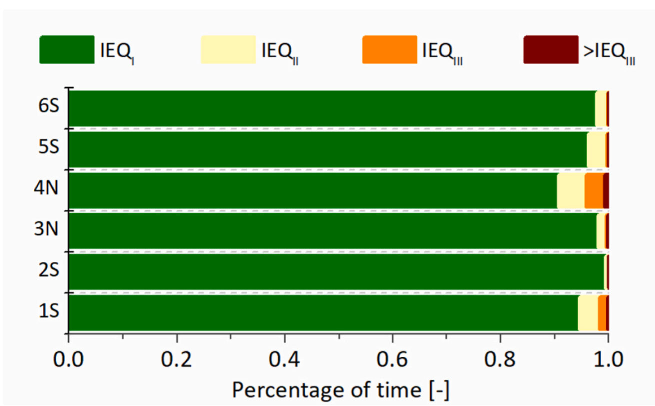

Fig. 15. Percentage of time that CO_2 concentration is in each air quality category (IEQ), for each monitored households of La Borda.

household 5S).

To complete the IEQ analysis, the air quality has been evaluated through the CO_2 concentration. Fig. 15 shows the percentage of time that the indoor CO_2 concentration is in each air quality category, defined in Table 5. The monitored data of all households shows that more than 90% of the time the CO_2 concentration is in IEQ_I, reflecting very good levels of indoor air quality. The apartment 4N expressed difficulties in practice natural ventilation due to outdoor pollution and noise, which can be reflected in higher values of CO_2 concentration, around 10% of the time in category IEQ_{II} or worst.

5. Discussion

The energy performance of La Borda has been analysed in term of heating and DHW demand (11.6 kWh/m^2·yr), and electricity consumption (15.1 kWh/m^2·yr). In both cases, the annual consumptions are substantially lower than the average consumption of a household in Spain. The average thermal energy demand for heating is around 7.1 kWh/m^2·yr, which is lower than a label A of the energy certificate (7.7 kWh/m^2·yr), thanks to the high quality construction design. In addition, the average thermal heating demand of the monitored households of La Borda is almost the half of the average heating demand of 29 nZEBs in Spain analysed in the framework of the European project ZEBRA2020 (zebra-monitoring.enerdata.net) which heating demand is around 13.3 kWh/m^{2}yr.

However, if the heating demand is analysed household by household, the figures change significantly. The south-oriented apartments have much lower heating demand, below to 2.2 kWh/m^{2}yr, being higher the difference with the other exiting nZEBs. Nevertheless, the north-oriented apartments substantially increase their heating demand, up to 20.0 kWh/m^{2}yr, which is higher than the other nZEBs and represents a C label in the energy certificate. An important difference is observed between the south and north oriented apartments, which could be greater if additional insulation and better window performance on the north façade were not included during the design process, assuming the additional cost between all the cooperative. The analysis of the minimum and maximum temperatures reflects a rational use of the heating system, so that the increased energy consumption of the north-oriented households is needed to provide comfortable conditions to the users. As one of the pillars of the cooperative housing is to guarantee the affordability to the inhabitants, La Borda has established a mechanism to distribute the thermal energy costs among the users taking in consideration the difference in heating loads due to the location of the apartment (north or south façade).

Related to the electricity consumption of La Borda, the annual average is considerable lower than the Spanish average electricity consumption, 1000 kWh/yr and 2500 kWh/yr, respectively. Several aspects contribute to the reduction of the energy consumption. Sharing the communal spaces, as the common kitchen, helps to use the spaces and consequently the energy more efficiently. The review done by Daly [37] found that sharing goods and resources is a common practice across communities, and their relative environmental benefits are one of the advantages of cooperative housings. The community support and training initiatives increase the knowledge of the inhabitants, resulting in an efficient use of the building and its energy systems. A strong involvement of residents during the design and further lifespan of the project can influence the energy consumption not only by behaviour, but also by the choice of technology and sources. Processes of collective learning and adapted behaviour influence the real performance of the building and technology [38].

Regarding to the IEQ, the building is able to provide comfortable condition to the inhabitants from a general point of view. The perception of the users and the comfort indexes show satisfactory levels of acceptance, however, some differences are observed between seasons and between the north and south oriented households.

In winter, the passive strategies together with the heating system are able to guarantee comfort in both household orientations, despite of the huge difference on the heating use that has described previously. The user perception of all monitored apartments is satisfactory. Nevertheless, the temperatures and the comfort indexes present lower temperatures in north-oriented households and consequently there are some levels of thermal discomfort (around 10–20% of estimated occupied time outside IEQ_{II} of the adaptive comfort model due to cold temperatures). Despite this low level of discomfort, the temperature is usually above 18 °C, minimum temperature where there is no demonstrable risk to the health for healthy sedentary people. Additionally, occupants do no report discomfort due to low temperatures when surveyed.

In summer, the measures to regulate the indoor thermal comfort are passive strategies (natural ventilation and solar shading devices) and according to the survey responses of inhabitants there are some discomfort perception ("Warm", as average valuation). Nevertheless, the operative temperature considering adaptive comfort theory provide positive results, suggesting comfortable condition during almost all the time. After analyse the different comfort indicators, Heat Index and Givoni psychometric chart, the results suggest that the natural ventilation is not efficient enough to provide appropriate air velocity to feel comfortable, and is not able to prevent the effect of temperature and high humidity values. It is important to remark that Heat Index does not reflect the effect of the air velocity. Additionally, comparing north and south oriented households, the natural ventilation seems to be even less effective in the northern ones: the maximum temperatures are similar, however, the minimum temperatures are higher, representing a lower thermal amplitude during the day. During the design phase of the building, the installation of cooling devices was discarded by the cooperative for economic reasons; Now, in the operational phase, the cooperative proposes the installation of fans to improve the thermal comfort in summer.

After analysing the thermal comfort in summer and evidencing the discrepancy between the comfort indexes and the thermal perception of the users, some questions arise about how to estimate the overheating. *Is it possible to establish an overheating threshold based on a constant temperature? Should this threshold be the same for all climates?* In this paper, the overheating thresholds used are based on the “Guide A: Environmental Design” [31] that established a maximum exposure time to temperatures above 26 °C and 28 °C. Are these temperatures appropriate in Mediterranean climate as Barcelona, where the mean outdoor temperature in summer is around 25 °C (July and August 2007–2016, Barcelona [39]), while in United Kingdom is around 15 °C (July and August 1981–2010, United Kingdom [40])? In the area of meteorology, a heatwave is an extended period of hot weather relative to the expected conditions of the area at that time of year. A heatwave threshold is met when at least three consecutive days with daily maximum temperatures meeting or exceeding the heatwave temperature threshold. This threshold is adapted to each geographical zone and according to the climatologic data. This definition could may lead to the need to establish different overheating thresholds depending on the climate of the region. This “variable” overheating threshold can easily remind us to the adaptive comfort model, which is providing a variable comfort range depending on the outdoor conditions. The maximum accepted temperature in the adaptive comfort model is 31.7 °C for category IEQ_{II}, and 32.7 °C for IEQ_{III}, which correspond to a weighted running mean of outdoor temperature of 30 °C. Ozarisoy and Altan [41] conducted field study over 288 flats where the weather is subtropical (Csa) and partly semi-arid (Bsh). The occupants' thermal sensation vote indicated that the ‘neutral’ temperature was 28.5 °C, and the upper limit of the comfort range in warm indoor air temperature conditions was 31.5 °C, suggesting that in hot and dry climates in which thermally uncomfortable indoor environments occur, occupants appear to tolerate a warmer condition than at other high and medium altitudes. Laouadi et al. [42] defined and characterized the overheating events in a similar way to the concept of outdoor heat waves. They used the transient standard effective temperature metric to define and discern overheating events, which take in consideration environmental variables (i.e., temperature, mean radiant temperature, relative humidity, air velocity) and occupant variables (i.e., hourly activity levels and clothing insulation). They proposed an overheating threshold selected to ensure the health of building occupants during extreme overheating events, distinguishing two collectives: healthy adults and healthy older people. For healthy adult people, Laouadi establishes a threshold of 30 °C for non-acclimatized and 31.2 °C for acclimatized persons. Persons not recently exposed to hot environments may initially find them very stressful (non--acclimatized) but after a few days there will be a significant increase in tolerance (acclimatized) [43]. In that sense, it seems that the use of the upper limit of the adaptive comfort model for IEQ_{II} is a good approach to define the overheating threshold, having a good compromise between the simplicity of the calculation and the hypothesis behind the method.

Nevertheless, looking at the results of the adaptive comfort model and the user perception there are some discrepancies that could be related to the difficulty of measuring some variables, as the air velocity or the mean radiant temperature. The measurement of both variables have some specific characteristics that make difficult to include them in the monitoring campaigns: 1) expensive sensors that does not allow to make “massive” measurement campaigns; 2) the air velocity sensor and the black globe temperature sensor (for measuring the mean radiant temperature) can be quite big causing some inconvenience to the occupants 3) the measurement of both variables are very linked to the position of the sensors and the measure can change drastically if the position change, or what is the same, if the position of the occupants is different, the measure could not represent the actual exposure of the occupant. This difficulty in measuring additional variables to the air temperature leads us to the question: *Is it reliable to assess the overheating risk by analysing only the air temperature?* Rahif et al. [44] made a comprehensive review on time-integrated overheating evaluation methods, suggesting the need to evaluate the overheating including additional comfort parameters (humidity, air velocity, mean radiant temperature, between others). Then, it clearly seems that considering more environmental parameters it could improve the estimation of the overheating; however, a balance must be struck between the representativeness of the measurements (number of monitored households), the details of the monitoring (number of monitored variables) and avoid inconvenience to the users.

6. Conclusions

The present paper analysed the energy consumption and the IEQ of a cooperative housing nZEB in Mediterranean climate, La Borda. In terms of energy consumption, the results show that the thermal demand for covering the heating and DHW needs, and the electricity consumption are lower than nZEBs in Spain. This reduction of consumption can be related to some of the characteristics of the cooperative housings: sharing goods and resources; community support; training initiatives; strong involvement during the design of the project; and sustainable design of the building. Some difference has been observed between the heating consumption of the north and the south-oriented households, being much higher for the north-oriented households (20.0 kWh/m^2yr and 2.2 kWh/m^2yr, respectively). La Borda has established a mechanism to distribute the thermal energy costs among the users taking in consideration the energy differences due to the location of the apartment, as one of the pillars of the cooperative is to guarantee the affordability of the inhabitants.

The evaluation of the IEQ shows that the building is able to provide comfortable condition to the inhabitants from a general point of view. The perception of the users and the comfort indexes show satisfactory levels of acceptance; however, some differences are observed between seasons and between the north and south oriented households. The north-oriented apartments present lower temperatures in winter; however, their perceptions are satisfactory. In summer, there are less difference between façades; nevertheless, there is a discrepancy between the user perception and the comfort indexes: the inhabitants have some discomfort perceptions, but the adaptive comfort model results in comfort conditions during almost all the time. Further research is needed to investigate this discrepancy between user perception and the adaptive comfort model, complementing the data analysis with the ASHRAE Global Thermal Comfort database II.

After analysing together the adaptive comfort model, the Givoni psychometric chart and the Heat Index, the results suggest that the natural ventilation is not efficient enough to provide appropriate air velocity to feel comfortable, and is not able to prevent the effect of high temperature and humidity conditions. Despite only having temperature and relative humidity to evaluate the overheating, the use of different comfort models and indexes, and the feedback from users have made it possible to identify the possible reasons for the thermal discomfort in summer. Nevertheless, further research is needed to improve the overheating estimation and to define the appropriate threshold, considering additional variables, but at the same time without increasing the complexity of the monitoring campaign.

Concluding, the paper demonstrates that the cooperative housing, in particular La Borda, is a model that could contribute to reduce the energy impact of the building, guaranteeing appropriate indoor environmental conditions to the users.

CRediT authorship contribution statement

Joana Ortiz: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Juli Carrere:** Writing – review & editing, Data curation. **Jaume Salom:** Writing – review &

editing, Supervision, Methodology. **Ana M. Novoa:** Writing – review & editing, Supervision, Conceptualization.

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 authors do not have permission to share data.

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References

[1] C. Baiges, M. Ferreri, L. Vidal, Public-cooperative Housing Policies: an International Comparative Perspective, 2019.
[2] M. Ferreri, L. Vidal, Public-cooperative policy mechanisms for housing commons, Int. J. Hous. Policy (Mar. 2021) 1–19, https://doi.org/10.1080/19491247.2021.1877888.
[3] D. Fromm, Seeding community: collaborative housing as a strategy for social and neighbourhood repair, Built. Environ. 38 (3) (2012) 364–394 [Online]. Available: http://www.jstor.org.recursos.biblioteca.upc.edu/stable/23290269.
[4] J. Carrere, et al., The effects of cohousing model on people's health and wellbeing: a scoping review, Publ. Health Rev. 41 (1) (2020) 22, https://doi.org/10.1186/s40985-020-00138-1.
[5] H. Gutzon Larsen, Barcelona: housing crisis and urban activism, in: P. Hagbert, H. Gutzon Larsen, H. Thörn, C. Wasshed (Eds.), Contemporary Co-housing in Europe. Towards Sustainable Cities?, Routledge, Taylor & Francis Group, 2020, pp. 74–93.
[6] R. Turmo, Andel: El Model Escandinau D'accés a L'habitatge, 2004 [Online]. Available: https://fundaciobofill.cat/uploads/docs/y/m/l/6/b/0/6/c/4/378.pdf.
[7] H. Thörn, H. Gutzon Larsen, P. Hagbert, C. Wasshede, Constraints and possibilities for co-housing to address contemporary urban and ecological crises: a conclusion, in: P. Hagbert, H. Gutzon Larsen, H. Thörn, C. Wasshede (Eds.), Contemporary Co-housing in Europe. Towards Sustainable Cities, Routledge, Taylor & Francis Group, 2020, pp. 202–213.
[8] E. Cabré, A. Andrés, La Borda: a case study on the implementation of cooperative housing in Catalonia, Int. J. Hous. Policy 18 (3) (Jul. 2018) 412–432, https://doi.org/10.1080/19491247.2017.1331591.
[9] Y. Geng, W. Ji, Z. Wang, B. Lin, Y. Zhu, A review of operating performance in green buildings: energy use, indoor environmental quality and occupant satisfaction, Energy Build. 183 (Jan. 2019) 500–514, https://doi.org/10.1016/J.ENBUILD.2018.11.017.
[10] P. Li, T.M. Froese, G. Brager, Post-occupancy evaluation: state-of-the-art analysis and state-of-the-practice review, Build. Environ. 133 (Apr. 2018) 187–202, https://doi.org/10.1016/J.BUILDENV.2018.02.024.
[11] S. Pretlove, S. Kade, Post occupancy evaluation of social housing designed and built to Code for Sustainable Homes levels 3, 4 and 5, Energy Build. 110 (Jan. 2016) 120–134, https://doi.org/10.1016/J.ENBUILD.2015.10.014.
[12] M.F. Silva, S. Maas, H.A. de Souza, A.P. Gomes, Post-occupancy evaluation of residential buildings in Luxembourg with centralized and decentralized ventilation systems, focusing on indoor air quality (IAQ). Assessment by questionnaires and physical measurements, Energy Build. 148 (Aug. 2017) 119–127, https://doi.org/10.1016/J.ENBUILD.2017.04.049.
[13] A. Gonzalez-Caceres, A. Bobadilla, J. Karlshøj, Implementing post-occupancy evaluation in social housing complemented with BIM: a case study in Chile, Build. Environ. 158 (Jul. 2019) 260–280, https://doi.org/10.1016/J.BUILDENV.2019.05.019.
[14] S. Colclough, et al., Post occupancy evaluation of 12 retrofit nZEB dwellings: the impact of occupants and high in-use interior temperatures on the predictive accuracy of the nZEB energy standard, Energy Build. 254 (Jan. 2022), 111563, https://doi.org/10.1016/J.ENBUILD.2021.111563.
[15] R. Herrera-Limones, A. Millán-Jiménez, Á. López-Escamilla, M. Torres-García, Health and habitability in the solar Decathlon University competitions: statistical quantification and real influence on comfort conditions, Int. J. Environ. Res. Publ. Health 17 (16) (2020), https://doi.org/10.3390/ijerph17165926.
[16] R.F. Rupp, N.G. Vásquez, R. Lamberts, A review of human thermal comfort in the built environment, Energy Build. 105 (Oct. 2015) 178–205, https://doi.org/10.1016/J.ENBUILD.2015.07.047.
[17] R. Yao, et al., Evolution and performance analysis of adaptive thermal comfort models – a comprehensive literature review, Build. Environ. 217 (Jun. 2022), 109020, https://doi.org/10.1016/J.BUILDENV.2022.109020.
[18] T. Cheung, S. Schiavon, T. Parkinson, P. Li, G. Brager, Analysis of the accuracy on PMV – PPD model using the ASHRAE global thermal comfort database II, Build. Environ. 153 (Apr. 2019) 205–217, https://doi.org/10.1016/J.BUILDENV.2019.01.055.
[19] V. Földváry Ličina, et al., Development of the ASHRAE global thermal comfort database II, Build. Environ. 142 (Sep. 2018) 502–512, https://doi.org/10.1016/J.BUILDENV.2018.06.022.
[20] T. Parkinson, R. de Dear, G. Brager, Nudging the adaptive thermal comfort model, Energy Build. 206 (Jan. 2020), 109559, https://doi.org/10.1016/J.ENBUILD.2019.109559.
[21] R. de Dear, J. Xiong, J. Kim, B. Cao, A review of adaptive thermal comfort research since 1998, Energy Build. 214 (May 2020), 109893, https://doi.org/10.1016/J.ENBUILD.2020.109893.
[22] P. Li, et al., Improved long-term thermal comfort indices for continuous monitoring, Energy Build. 224 (Oct. 2020), 110270, https://doi.org/10.1016/J.ENBUILD.2020.110270.
[23] M. Vellei, M. Herrera, D. Fosas, S. Natarajan, The influence of relative humidity on adaptive thermal comfort, Build. Environ. 124 (Nov. 2017) 171–185, https://doi.org/10.1016/J.BUILDENV.2017.08.005.
[24] O. Dartevelle, G. van Moeseke, E. Mlecnik, S. Altomonte, Long-term evaluation of residential summer thermal comfort: measured vs. perceived thermal conditions in nZEB houses in Wallonia, Build. Environ. 190 (Mar. 2021), 107531, https://doi.org/10.1016/J.BUILDENV.2020.107531.
[25] M. Kottek, J. Grieser, C. Beck, B. Rudolf, F. Rubel, World Map of the Köppen-Geiger climate classification updated, Meteorol. Z. 15 (3) (Jul. 2006) 259–263, https://doi.org/10.1127/0941-2948/2006/0130.
[26] Servei Meteorologic de Catalunya - Meteocat, Taules de Dades de la Xarxa d'Estacions Meteorològiques, 2019.
[27] Servei Meteorologic de Catalunya - Meteocat, Taules de Dades de la Xarxa d'Estacions Meteorològiques, 2020.
[28] Ministerio de Fomento, Código Técnico de la Edificacion, 2019, pp. 1–129.
[29] World Health Organization - Europe, Environmental Burden of Disease Associated with Inadequate Housing, 2011.
[30] O. C. J, R. Serrano-Notivoli, J. Miró, O. Meseguer-Ruiz, Tropical nights on the Spanish Mediterranean coast, 1950-2014, Clim. Res. 78 (3) (2019) 225–236 [Online]. Available: https://www.int-res.com/abstracts/cr/v78/n3/p225-236/.
[31] Chartered Institution of Buildings Services Engineers (CIBSE), Guide A: Environmental Design, London, 2006.
[32] UNE, EN 16798-1:2019 Energy Performance of Buildings - Ventilation for Buildings - Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acous, 2019.
[33] ASHRAE 55, *ANSI/ASHRAE Standard 55-2017, Thermal Environmental Conditions for Human Occupancy*, American Society of Heating Refrigerating and Air-Conditioning Engineers Inc., Atlanta, 2017.
[34] R.G. Steadman, The assessment of sultriness. Part I: a temperature-humidity index based on human physiology and clothing science, J. Appl. Meteorol. Climatol. 18 (7) (1979) 861–873, https://doi.org/10.1175/1520-0450(1979)018<0861:TAOSPI>2.0.CO;2.
[35] NOAA - National Weather Service, National centers for environmental prediction, and weather prediction center, Heat Index (2020). https://www.wpc.ncep.noaa.gov/html/heatindex.shtml.
[36] M. Milne, B. Givoni, Architectural design based on climate, in: D. Watson (Ed.), Energy Conservation through Building Design, McGraw-Hill. Inc., New York, NY, 1979, pp. 96–113.
[37] M. Daly, Quantifying the environmental impact of ecovillages and co-housing communities: a systematic literature review, Local Environ. 22 (Jul. 2017) 1–20, https://doi.org/10.1080/13549839.2017.1348342.
[38] L. Tummers, Learning from Co-housing Initiatives: between Passivhaus Engineers and Active Inhabitants, 2017.
[39] Servei Meteorologic de Catalunya - Meteocat, Normals Climàtiques, Barcelona - El Raval, 2017 [Online]. Available: https://static-m.meteo.cat/wordpressweb/wp-content/uploads/2018/01/26082003/BR-Barcelona-el-Raval1.pdf.
[40] M. Kendon, M. McCarthy, S. Jevrejeva, A. Matthews, T. Sparks, J. Garforth, State of the UK climate 2020, Int. J. Climatol. 41 (S2) (Jul. 2021) 1–76, https://doi.org/10.1002/joc.7285.
[41] B. Ozarisoy, H. Altan, Regression forecasting of 'neutral' adaptive thermal comfort: a field study investigation in the south-eastern Mediterranean climate of Cyprus, Build. Environ. 202 (Sep. 2021), 108013, https://doi.org/10.1016/J.BUILDENV.2021.108013.

[42] A. Laouadi, M. Bartko, M.A. Lacasse, A new methodology of evaluation of overheating in buildings, Energy Build. 226 (Nov. 2020), 110360, https://doi.org/10.1016/J.ENBUILD.2020.110360.
[43] K. Parsons, in: Human Thermal Environments: the Effects of Hot, Moderate, and Cold Environments on Human Health, Comfort and Performance, second ed., CRC Press, 2002.
[44] R. Rahif, D. Amaripadath, S. Attia, Review on time-integrated overheating evaluation methods for residential buildings in temperate climates of Europe, Energy Build. 252 (Dec. 2021), 111463, https://doi.org/10.1016/J.ENBUILD.2021.111463.