1. Energy and Buildings
Volume 199, 15 September 2019, Pages 102-114

Thermal comfort and indoor air quality in low-income housing in Spain: the influence of airtightness and occupant behaviour.

Jesica Fernández-Agüera[1], Samuel Domínguez[1]*, Carmen Alonso[2], Fernando Martín-Consuegra[2]

[1]Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla, Spain. jfernandezaguera@us.es

[2]Instituto Eduardo Torroja de Ciencias de la Construccion, Consejo Superior de Investigaciones Científicas, Spain. c.alonso@ietcc.csic.es; martin-consuegra@ietcc.csic.es

*sdomin@us.es

Abstract

Thermal comfort and Indoor air quality (IAQ) in residential buildings with different degrees of airtightness was studied in two climates in Spain. Behaviour was compared in the areas occupied by day and by night. The IAQ of the buildings studied, erected before energy efficiency regulations were in place (1939-79) and lacking mechanical ventilation, was compared to their airtightness. The rationale for that approach was that under such circumstances air change depends on uncontrolled natural ventilation (=opening windows) and consequently on the outdoor temperature. Relative humidity was also taken into consideration, given the condensation that may be induced where ventilation is insufficient. In winter in both climates, the CO_2 levels were over 1200 ppm, with means on the order of 1900 ppm in Madrid and 1400 ppm in Seville and higher at night than during the day. Infiltration-mediated air changes/hour appeared to be insufficient to maintain the house under healthy conditions and the risk of surface condensation is higher in the most airtight dwellings.

Keywords: Thermal comfort; indoor air quality; residential buildings; airtightness; low-income housing

1. Introduction

In today's buildings thermal comfort is directly related to indoor air quality (IAQ), which in turn depends on envelope airtightness in buildings with no active ventilation systems. Those two parameters are more closely related in lower standard construction such as found in social housing in southern Europe, normally associated with lower income households. Unlike public buildings or higher income homes, such flats often lack suitable HVAC systems that might eliminate the dependence of IAQ on the envelope as a regulatory element.

Heat and water vapour, constantly exchanged across building envelopes due to infiltration (the air flow through enclosures) have a direct impact on occupants' thermal comfort and indoor air quality. Indoor temperature is a parameter widely studied in residential buildings, for its direct effect both on occupant comfort and on building energy demand and consumption. The implications of outdoor relative humidity have been suitably characterised and its direct impact on electric power consumption in cities has been identified[1]. In contrast, the effect of indoor relative humidity on domestic comfort and power consumption has been scantly explored.Comparing simulated temperature and humidity to simulated temperature only, Moon et al. [2] found that energy consumption was 4.4 % higher when the effect of humidity was included. The inference is that when that effect is excluded, building energy demand and consumption may be underestimated. In a similar vein, including indoor humidity as one of the variables in HVAC control strategy would enhance domestic energy efficiency. The use of enthalpy as an optimal indicator for achieving success on monitoring comfort for energy refurbishment has been proposed in previous studies [3], but not yet analized on occupied housing units under real conditions.

European authorities, Spain's among them, are planning substantial investment in the years to come to rehabilitate and improve energy habitability in the present building stock, geared primarily to meeting H2020 and subsequent objectives. Over 1.2 million multi-dwelling buildings built prior to 1981 are expected to receive such support in Spain alone [4] [5]. The primary aim is to raise the efficacy of the thermal insulation afforded by enclosures or to replace windows, although no mention is made of airtightness or indoor air quality (IAQ). In southern European countries with temperate climates such as Greece, Italy, Portugal and Spain, airtightness levels are not limited by law [6]. Spanish legislation only regulates window air permeability[7], [8].

The most common retrofits for such buildings include installing new windows with better thermal and acoustic insulation and airtightness and improving envelope sealings.Whilst such measures generally enhance the indoor thermal environment and reduce the energy needed for suitable control, they may also on occasion lower indoor air quality [9] and favour possible condensation-mediated pathologies.

This article is an outcome of the research conducted for REFAVIV, and the beginning of the research Habita-res, a new tool for evaluating vulnerable urban areas. Financed by the Spanish Government's R&D+I Plan, the project aims to foster energy self-sufficiency and healthy habitats.Its focus is the comprehensive rehabilitation of vulnerable quarters on the outskirts of large cities built after the Civil War through 1979 (before thermal regulations were introduced)[10]. The underlying conviction is that districts can be rehabilitated to near low energy standards while improving the resident population's environment, health and social situation.

This article analyses low-income multi-dwelling housing in Madrid, the capital city, and Seville, chosen as representative of construction typologies in southern Spain.The aim is to identify indoor parameter patterns in such housing, along with the relationship between envelope airtightness and occupant behavior. Temperature, humidity and CO_2 readings are discussed and compared in two different climates.

Background

In Spain as in the rest of Europe, housing construction was intense over the 40 years studied. The residential buildings dating from that period account for 42 % of today's total census of Spanish homes (source: Spanish National Statistics Institute) (Figure 1).

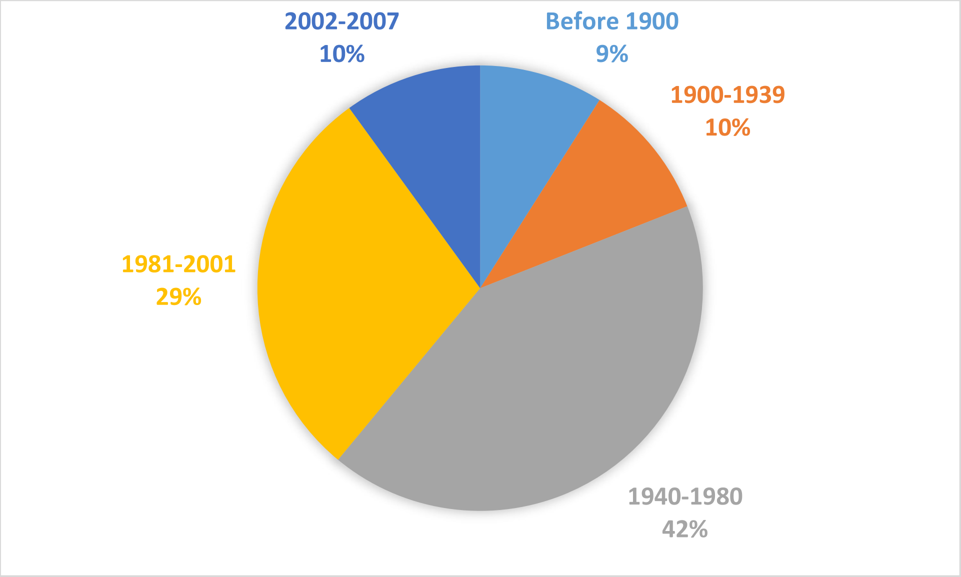

Figure 1. Housing stock in Spain by year of construction.

On the whole, those buildings' envelopes are characterised by fairly low energy performance. The façade and roof enclosures normally lack thermal insulation and a significant percentage of the façades consist in a single wythe of masonry with no air space. The windows generally have very simple joinery and non-insulating glazing, except where recently replaced [11] [12]. The flats in such buildings, close to half of the present stock, depend on natural ventilation (open windows) and the uncontrolled supply of outdoor air attributable to infiltration [13]–[15]. Controlled ventilation systems only made their appearance in these buildings when the European EPBD directives were transposed to Spanish law in 2007 with the adoption of its technical building code (CTE), a circumstance with parallels in other southern European countries [16].

Given the type and period of construction, envelopes tend to be scantly airtight [14]. The generally accepted parameter for determining indoor air quality in such spaces is CO_2 concentration[17], [18]. Carbon dioxide at concentrations higher in the indoor than in the outdoor air is not usually deemed to be a contaminant per se, but rather an indication of the presence of bioeffluents, a measure of occupant-induced contaminants and of the capacity of the indoor space to lower indoor concentrations via dilution and ventilation [19], [20]. Although as a rule the harmful effects of carbon dioxide on health are not associated with the concentrations normally found in buildings, concern has recently been voiced in that regard. Allen et al. [21] and Satish et al. [22] found CO_2 at concentrations routinely present in buildings to be directly related to cognitive processes.Agencies such as the National Collaborating Centre for Environmental Health in Canada, EPA in the USA and others are revising their recommendations on CO_2 levels in terms of exposure and the association with other indoor air contaminants. A need has likewise been felt for further study to acquire a fuller epidemiological overview.The general recommendation is to heighten official sensitivity to the effects of closed spaces on health, given the uncertainty surrounding the issue and the synergies between carbon dioxide and volatile organic compounds (VOCs).

Increasing building envelope airtightness in an attempt to lower heat loss and enhance energy efficiency may reduce air circulation, which would explain the often higher CO_2 levels in modern relative to older buildings. Since indoor air quality problems are usually solved by supplying outdoor air, in buildings dependent upon natural ventilation greater airtightness should be viewed as a higher risk of exposure to an unsuitable indoor atmosphere, particularly in light of recent concerns that envisage a heavier impact on occupant health.

Such considerations have prompted a significant number of pilot experiences in which efficient building construction has been geared not only to lowering consumption, but also to meeting demands to enhance IAQ. Although generally undertaken in cold climates [9], [23]–[26], a few studies in warm areas have also been published [27]–[29]. Such efforts tend to target new-builds, however, where integrating such requirements from the drawing board stage may be less complex.Fewer energy rehabilitation experiences have defined occupant health as one of the primary considerations, particularly in warm climates [30], [31]. In most cases the main tool for controlling the indoor atmosphere in residential buildings consists in mechanical ventilation associated with heat recovery systems, such as required under the *Passivhaus* standard. Such a solution is scantly plausible in many of the older and especially the lower income segments of the building stockin warm European climates, however.

Raising envelope airtightness as a strategy to improve housing energy efficiency should be attendant upon maintaining a certain air change capacity that would suffice, even in the absence of voluntary user action, to guarantee the minimum required outdoor air supply.

2. Method

2.1. Sample studied

The sample of housing built in Madrid and Seville defined for this analysis, included flats highly representative of social housing (the prevalent category) dating from the period studied between 1939 and 1979. The procedure for identifying and classifying these units is described in [32]. The buildings studied were selected after a lengthy process designed to suitably represent the building stock. In the first phase, social housing developments were identified and characterised within the city limits in the period studied. Subsequent analysis led to grouping the developments into particularly representative types characterised by the features found in each sub-period. A second grouping (covering 83 developments and 46,476 units or 47 % of the population in Seville; and 73 developments and 57,478 units or 23 % of the population in Madrid) established the essential morpho-constructional features of these developments, identifying subject types by sub-period and building a matrix of typical characteristics also by sub-period, all of which is described in [32] and [12]. Figure 3 shows the location of the developments analysed in detail in Seville (46,476 dwellings) and Figure 2 the site of those in Madrid (57,478 dwellings). Six buildings, three in Madrid and three in Seville, were tested for airtightness and their environmental parameters were monitored for a full year.

The buildings chosen were premises with fully confined floor areas and volumes characterised by low form factors, a characteristic feature attributable to the need to optimise construction by minimising the economic and material resources deployed.These flats normally featured just one small window in the main rooms and had bathrooms with no ventilation or that vented into the kitchen. All the flats studied in Madrid were heated but none had mechanical ventilation. None was air-conditioned, as is the case in most of the area's housing. Whilst the homes in Seville were not heated, one had no air conditioning, another had individual room units and the third dwelling-wide facilities. None had mechanical ventilation.

In Madrid:

- Case M1. The development chosen for the airtightness tests is located in Manoteras, a city quarter on the northeast periphery of Madrid.Its 1204 flats were built in 1960. Representative of linear typology, its enclosures consist in 1-ft brick. The users were a middle-aged couple with one 16-year-old daughter.The flat exhibited normal upkeep, but had not been rehabilitated beyond the replacement of the original timber for aluminium joinery on its single glazed windows. Ventilated naturally by opening the windows, the flatwas fitted with an individual gas boiler for heating and DHW.
- Case M2. Here also, the development chosen for the airtightness tests is located in Manoteras. Its 80 flats were built in 1973.Representative of a linear typology,it is enclosed by a 0.5-ft brick+air space+partition wall system. The users were a young couple with two children, aged 8 and 10.The flat had undergone major retrofitting: new aluminium frame, double-glazed windows with thermal breaks, no thermal insulation on the façade enclosure and sealing around the gas vent in the kitchen. It was fitted with an individual gas boiler for heating and DHW.
- Case M3. The development chosen for the airtightness tests is located in Hispanoamérica, a city quarter on the northern area of the city. Its 164 flats were built in 1965. Representative of linear typology,it is enclosed by a 1-ft brick+air space+partition wall system. The users were a middle-aged couple with one teenage son. The flat's original openings had been replaced with new aluminium frame, double glazed windows. The building was fitted with central heating.

In Seville:

- Case S1. The development chosen for the airtightness tests is located in Bami, a city quarter. Its 554 flats were built in 1963.Representative of H-shaped apartment blocks, it is enclosed with 1-ft brick walls. The users chosen were three young students. The flat had been kept up routinely, but not rehabilitated.It had no HVAC.
- Case S2. The development chosen for the airtightness tests is located in San Pablo, a city quarter. Its 270 flats were built in 1965.Representative of linear typology, it is enclosed by a 0.5-ft brick+air space+partition wall system. The users were a childless couple. The flat had undergone basic upkeep, but no rehabilitation.It was fitted with two split AC units, one to cool the bedroom and the other to cool and heat the living room.
- Case S3. The development chosen for the airtightness tests is located in Diez Mandamientos, a city quarter.Its 300 flats were built in 1964. Representative of H-shaped apartment blocks, it is enclosed by a 0.5-ft brick+air space+partition wall system. The users were a young couple with two school-age children. Basic upkeep had been supplemented with replacement of the original openings with aluminium frame, double glazed windows. Heating and cooling were supplied by a flat-wide system as well as electric radiators (one per room), which were the users' option of choice for heating.

Figure 2. Developments located in Madrid and case studies (source: [12]).

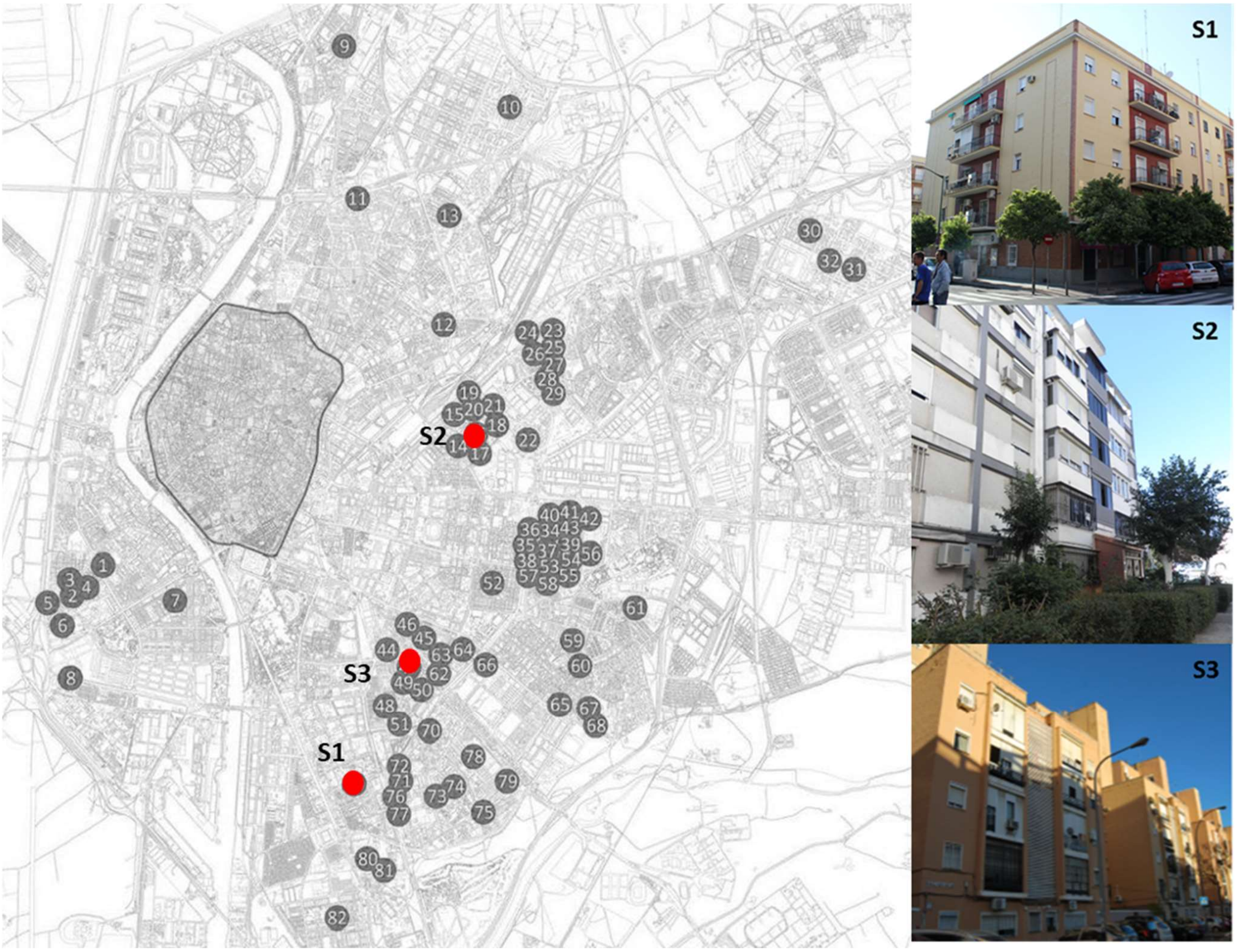

Figure 3. Developments located in Seville and case studies.

2.2. Experimental design

2.2.1. Physical measurements

An environmental data gathering campaign was designed to continuously monitorthe flats chosen for analysis, which had been characterised previously for morphology, construction, floor area and composition. Two measuring stations were used, one in the main bedroom and other in the livingroom, to record air temperature, relative humidity and CO_2 concentration at 10- min intervals for a full a year (August 2014 to July 2015). A Wöhler CDL 210 datalogger recorded the air temperature and relative humidity with an accuracy of 0.5 °C and 3 %, respectively, and measured CO_2 over a range of 0–9000 ppm, with an accuracy of 50 ppm ±5 %. Outdoor humidity, temperature and wind velocity were furnished by Spain's weather agency (AEMET).

As indoor CO_2 concentration, temperature and RH are never the same throughout a room[33], the sensor was positioned to detect a mean value, i.e., in the area where occupants would be breathing. That is, between 1 m and 1.5 meters high on the living room, and on the bedside table on bedrooms.

Indoor air quality can usually be assessed, often with CO_2 concentration as an IAQ indicator [34], [35]. The standards in place establish air quality as low, medium or high depending on the difference in indoor and outdoor CO_2 concentration. Studies have been conducted on the effect of temperature and air quality (assessed as CO_2 concentration) on sleep in flats located in warm humid climates in the absence and presence of mechanical ventilation. A similar study undertaken in cold climates, specifically in Denmark, concluded that objectively measured sleep quality and the perceived freshness of bedroom air improved significantly when the CO_2 level was lower, as did next-day reported sleepiness and subjects' ability to concentrate and their performance on a test of logical thinking [36].

2.2.2. Airtightness

Blower door testing was conducted to method A in Spanish and European standard UNE EN 13829:2002 and specific protocols [37] to determine the actual airtightness of the envelope. The buildings were not tested as a whole. Rather each flat, conceived as a volume confined inside a building with scantly any exchange with the adjacent premises, was tested individually. This method has been shown to deliver the greatest amount of information with the lowest percentage of error due to differences in the façade on a given building. The effect of infiltration from adjacent premises could be ruled out, for in such typologies it normally accounts for under 5 % of the total [14].

3. Results

3.1. Outdoor conditions

Seville has a Mediterranean climate, with warm summers and temperate winters, whilst Madrid's is more continental, with colder winters and somewhat cooler summers. More generally, the warm season may be said to prevail in the former and the cold in the latter. Those features must be borne in mind when characterising user behaviour and the facilities with which the flats are fitted. The urban heat island effect identified in both cases was more intense in Madrid [38] [39] than in Seville [40].

The mean monthly air temperature and relative humidity values in Seville and Madrid are given in Figure 4.

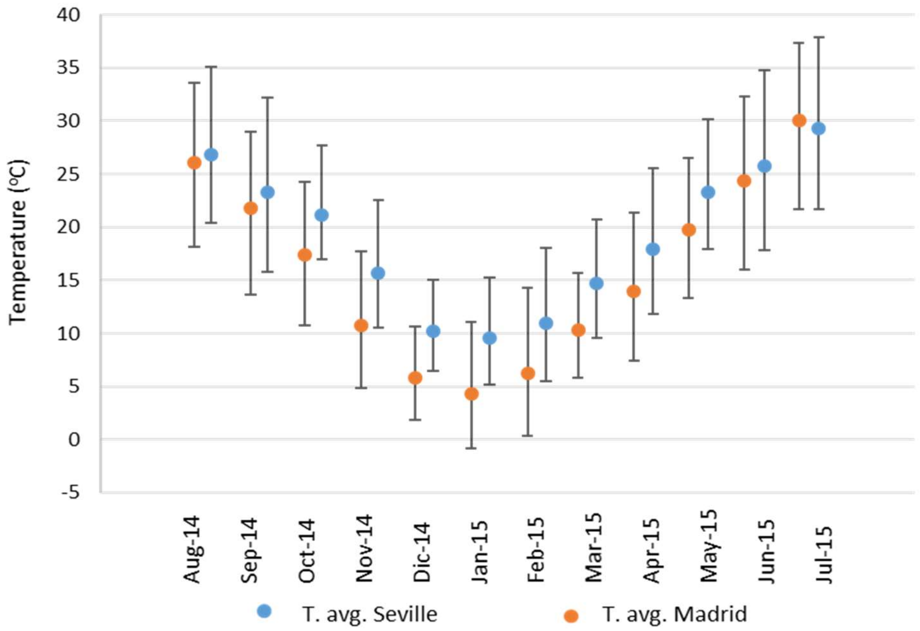

Figure 4. Mean monthly air temperature values in Seville and Madrid during the period measured.

Heating (HDD) and cooling (CDD) degree days (Figure 5) were used to assess seasonal thermal severity and determine possible overall climate-related demand for air conditioning. The cut-off values were 16 °C for HDD and 25 °C for CDD, to be the temperatures that best reflect the construction types and use patterns at issue.

Whilst Madrid's heating demand was nearly double Seville's, the differences in cooling demand were less significant and even greater in Madrid in certain months. In that period, in addition to vacation-related vacancies, flat use changes, with occupants spending more time outdoors and keeping windows open during most of the day. In the period studied, the flats in Madrid were exposed to much more accentuated wintertime demand, present in 8 months of the 12 studied, than Seville, where the needs were less intense and their duration shorter. The need for cooling was substantially lower than for heating in both cities and extended over fewer months, with a prevalence of warm weather in Seville.

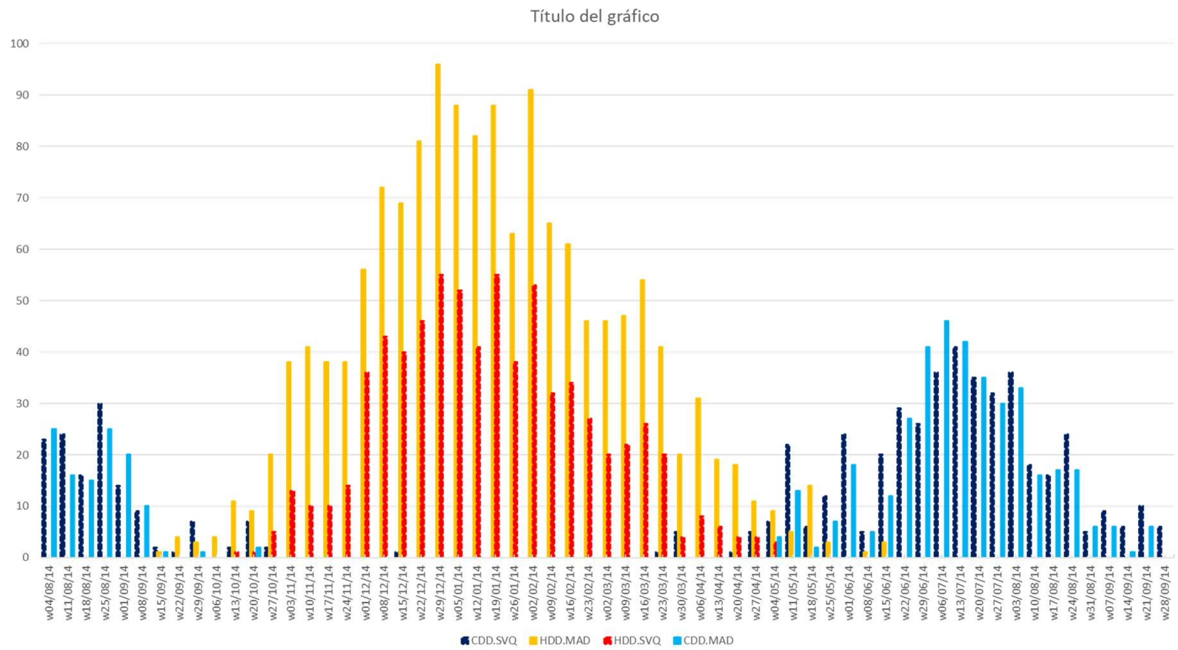

Figure 5. Heating (HDD) and cooling (CDD) degree days in Seville and Madrid

3.2. Indoor conditions

The mean values and standard deviations for each season and dwelling studied are given in Table 1. Daytime (living room) was defined to run from 8:00 to 23:00 and consequently night time from 23.00 to 8:00. All the bedrooms were occupied by two people except in case study S1, where it had a single occupant.

In winter, the mean bedroom temperature in Madrid was 16.7 °C (ranging from 14 °C to 18.5 °C). Unlike the other two flats, M3 lay within the thermal comfort zone most of the time. In Seville, the mean bedroom temperature was 15.4 °C (ranging from 13 °C to 17.5 °C). The mean indoor temperatures were lower than in Madrid despite the more temperate values in Seville (4 °C to 5°C higher on average) due to the less intense use of heating. Similar values were recorded in the living rooms, although they were around 0.5 °C higher in Madrid as a result of daytime heating.

In summer, the mean bedroom temperature in Madrid was 28.2 °C (ranging from 26.5 °C to 30 °C), whilst the living room temperature was around 0.5 °C higher. In Seville, the mean bedroom summertime temperature was 27.6 °C (ranging from 25.5 °C to 30.5 °C), whilst the living room temperature was likewise around 0.5 °C higher. In summer the mean indoor temperatures were slightly higher in Seville than in Madrid because the mean outdoor temperature was higher in the former city. The living room temperatures were only around 0.5 °C higher in both cities, despite their occupancy at the time of day when outdoor temperatures were highest and the absence of the passive natural ventilation found in some bedrooms overnight in the summer.

In spring and autumn, indoor temperatures were closer to the thermal comfort zones: around 20 °C to 22 °C in Madrid and 22°C to 24°C in Seville.

In Madrid relative humidity values were widely scattered in winter, with a mean of 66 % in the living room (ranging from 50 % to 80 %) and 70 % in the bedroom (55 % to 84 %). In Seville, mean relative humidity was similar in the bedroom and living room and in all three flats, at around 65 % (varying from 55 % to 78 %). Those values were higher than the 40 % to 50 % defined as comfortable by Spanish legislation and in some cases very near the 80 % RH that induces mould in housing.

In Madrid M3 was fairly exceptional, for as the flat was heated all day, the mean relative humidity dipped to around 37 %, much lower than in the other two cases where the temperature tended to lie outside the comfort zone. That value likewise fell below the comfort range, albeit only barely.

In summer, Madrid's slightly dryer climate was mirrored in a lower relative humidity throughout the dwelling (mean 36 %, varying from 35 % to 56 %) than in Seville (mean 48 %, varying from 35 % to 75 %). Those values compared to the summertime comfort range of 45 % to 60 % laid down in Spanish legislation.

In spring and autumn, the mean relative humidity recorded in the bedroom and living room was very similar in the two cities, at around 55 % (ranging from 45 % to 73 %) in Madrid and 54 % (43 % to 73 %) in Seville. In both cases the values lay within the comfort range 95 % of the time.

In all seasons and flats, the mean relative humidity was higher in the bedroom than in the living room, which is consistent with the continued use of space where people are the primary source of humidity.

Table 1.Case studies: temperature, relative humidity and CO_2 concentration by season and area.

		Living room (day)				Bedroom (night)			
		W	Sp	Su	A	W	Sp	Su	A
M1	Mean temperature (°C)	17.2	19.3	29.3	22.0	16.3	17.9	28.6	18.3
	StD (°C)	1.6	2.3	1.5	3.0	2.4	1.1	1.4	2.3
	Mean humidity (%)	56.9	50.2	33.0	54.6	61.9	57.0	35.8	67.4
	StD (%)	5.1	8.5	4.6	9.6	7.3	5.9	4.7	9.1
	Mean CO_2 concentration (ppm)	1425	859	454	862	1461	1139	466	1137
	StD (ppm)	582	430	153	483	582	540	161	591
M2	Mean temperature (°C)	17.6	19.9	26.7	21.2	17.1	19.9	27.7	20.5
	StD (°C)	0.8	2.1	1.1	3.1	1.3	2.6	1.2	3.3
	Mean humidity (%)	75.9	60.1	38.3	61.0	77.9	58.4	36.6	63.2
	StD (%)	4.3	13.3	5.4	14.3	6.8	14.3	4.7	15.3
	Mean CO_2 concentration (ppm)	2076	1157	439	1186	2848	1125	445	1602
	StD (ppm)	706	976	176	1113	1132	1130	212	1382
M3	Mean temperature (°C)	23.7	22.9	27	23.5	22.4	22.2	25.7	23.0
	StD (°C)	1.1	1.9	1.7	1.9	1.0	2.3	1.8	1.5
	Mean humidity (%)	36.8	38.4	33.7	39.4	40.3	42.0	29.0	41.0
	StD (%)	3.0	8.5	7.0	7.5	2.8	8.3	12.3	2.4
	Mean CO_2 concentration (ppm)	1034	804	446		1031	848	487	
	StD (ppm)	291	376	93		290	381	90	
Overall mean, Madrid	Mean temperature (°C)	17.4	19.6	28.0	21.6	16.7	18.9	28.2	19.4
	Mean humidity (%)	66.4	55.2	35.7	57.8	69.9	57.7	36.2	65.3
	Mean CO_2 concentration (ppm)	1750	1008	446	1024	2327	1132	455	1369
S1	Mean temperature (°C)	16.6	23.2	26.8	20.7	15.4	21.1	27.2	19.7
	StD (°C)	0.8	3.1	1.4	3.1	1.1	3.1	1.5	3.3
	Mean humidity (%)	64.9	53.6	49.8	67.0	59.3	58.4	50.8	64.7
	StD (%)	8.1	10.1	7.9	9.3	4.6	7.3	3.9	6.1
	Mean CO_2 concentration (ppm)	721	538	483	586	452	445	438	460
	StD (ppm)	285	175	86	212	88	232	35	187
S2	Mean temperature (°C)	15.1	22.3	29.4	23.2	14.5	22.3	27.1	22.9
	StD (°C)	1.2	3.4	1.8	3.0	1.5	3.3	1.6	3.3
	Mean humidity (%)	65.4	53.1	44.5	59.9	72.3	55.8	50.1	62.3
	StD (%)	6.7	10.6	9.1	9.1	6.3	10.2	8.2	9.1
	Mean CO_2 concentration (ppm)	733	521	444	523	1182.3	774.1	596	604
	StD (ppm)	503	298	77	324	1461	1325	576	848
S3	Mean temperature (°C)	17.0	25.5	27.8	25.5	16.4	24.2	28.5	24.7
	StD (°C)	1.2	1.8	1.9	1.0	1.1	4.0	2.0	1.7
	Mean humidity (%)	65.0	51.9	47.8	60.1	67.6	55.8	46.2	61.0
	StD (%)	6.1	7.4	6.8	4.2	5.5	11.5	7.3	7.6
	Mean CO_2 concentration (ppm)	102	680	462	691	1059	753	465	690
	StD (ppm)	523	352	197	266	523	463	197	352
Overall mean, Seville	Mean temperature (°C)	16.2	23.7	28.0	23.1	15.4	22.5	27.6	22.4
	Mean humidity (%)	65.1	52.8	47.4	62.3	66.0	57.0	49.0	62.7
	Mean CO_2 concentration (ppm)	825	580	463	600	1434	657	500	585

As mean CO_2 concentration differed between bedrooms and living rooms, they were analysed separately here, stressing the night-time area, continuously occupied for approximately 8 hours. The bedroom CO_2 concentrations given in Table 2 for each case study are graphed in Figures 6 (winter) and Figure 8 (summer). In Madrid in winter the mean night-time CO_2 concentration was 2327 ppm, ranging from 1300 ppm to 3000 ppm with peaks of around 4000 ppm. Here also M3 stood out for its better infiltration-mediated ventilation. In Seville, bedroom CO_2 concentration averaged 1434 ppm, varying from 1000 ppm to 3000 ppm with peaks of around 5000 ppm.In all cases users routinely ventilated bedrooms early the next day, when CO_2 concentrations declined steeply in a very short time (Figure 6).

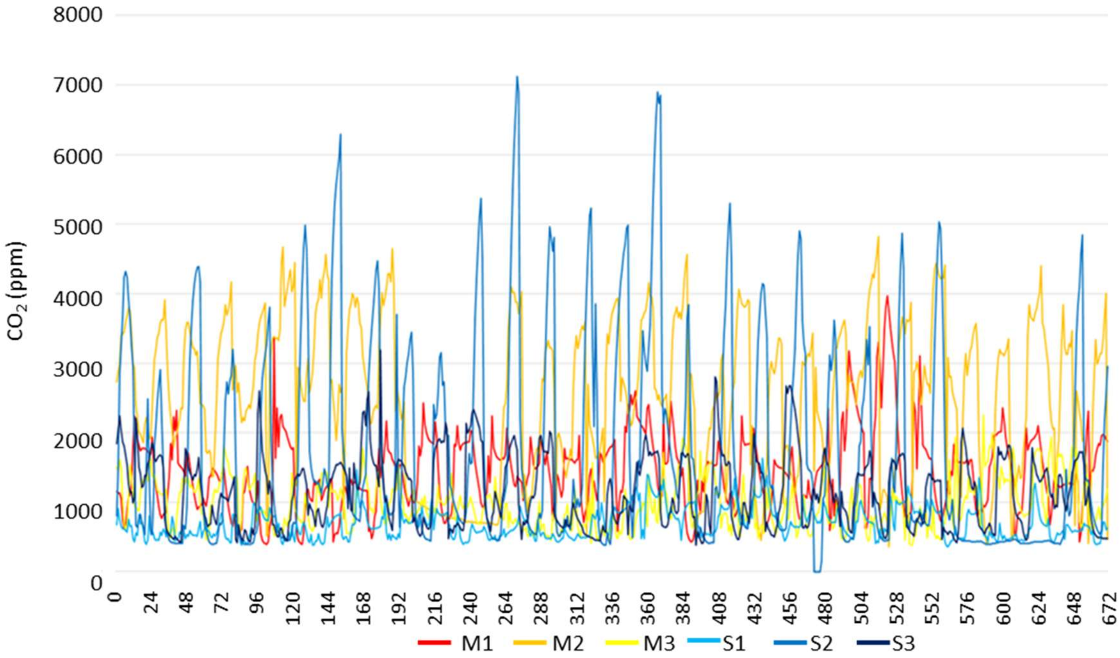

Figure 6. Hourly fluctuation in CO_2 in bedrooms in winter for all the case studies

In winter CO_2 concentration was below 600 ppm 22 % of the time in all the case studies. Levels were lowest in case study S1. In all the others, they were in the unhealthy range from 20 % to 40 % of the time (Figure 7).

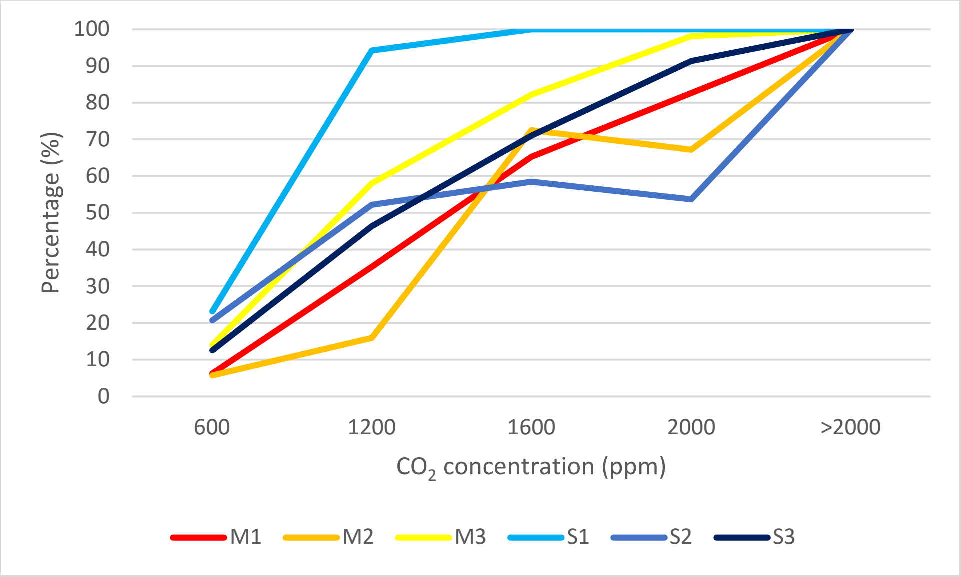

Figure 7. CO_2 concentration: percentage of hours below a given value in winter

In Madrid in summer the mean night-time CO_2 concentration was 466 ppm, ranging from 370 ppm to 620 ppm with peaks of around 2000 ppm. In Seville in summer the mean night-time CO_2 concentration was 500 ppm, ranging from 375 ppm to 1000 ppm with peaks of around 2000 ppm.

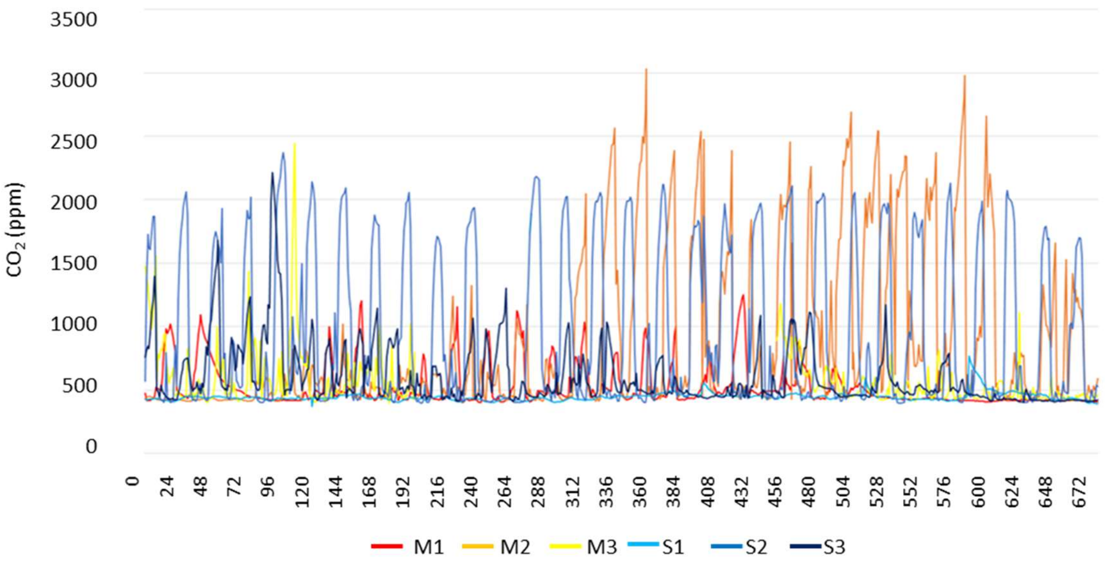

Figure 8. Hourly fluctuation in CO_2 in bedrooms in summer for all the case studies

In summer CO_2 concentration was below 600 ppm 42 % to 93 % of the time, depending on the case study. Dwellings M2 and S2 exhibited higher CO_2 concentration than the other case studies and values of over 2000 ppm 11 % and 29 % of the time, respectively (Figure 9). Ventilation routines in S2 and the extreme airtightness value recorded for M2 explained those findings.

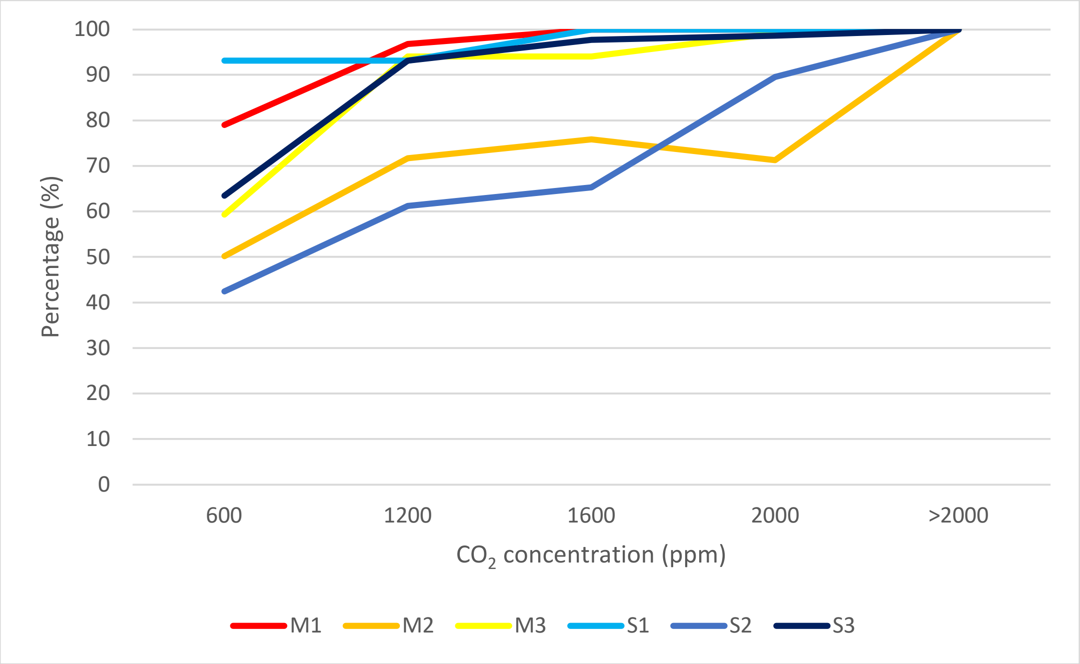

Figure 9. Percentage of hours that CO_2 concentration is low a threshold in summer

1.1. Occupant behaviour

The hours of occupancy in bedrooms and living rooms and the number of occupants in each, along with reported ventilation times, are shown in Figure 10 for winter and Figure 11 for summer. The graphs also plot CO_2 concentration by time of day for a randomly chosen typical day in winter and summer to determine whether users' replies to the surveys were consistent with the occupancy data recorded.

The hours of occupancy and number of occupants reported varied widely. Bedrooms were used by two people at night in all except case study S1 (flat with students tenants), where the master bedroom had only one occupant. In all the case studies, intensity of occupancy and CO_2 concentration were observed to be related in summer and winter.

In winter in Seville and Madrid both, dwellings were ventilated for 10 min to 30 min in the morning (Figure 10). In contrast, in summer windows remained open all night, except in S2, where ventilation was not continuous (Figure 11). CO_2 concentration was consequently very low in all six cases and depended on room use, which varied more in summer than in winter.

In M1 usage was consistent with the data recorded, with CO_2 levels rising in the living room during the day and the bedroom at night. Low concentration was related to high permeability. In contrast, the high airtightness in M2 was attendant upon likewise high CO_2 levels that could not be lowered with natural ventilation or infiltration. CO_2 concentration was lowest in M3, in line with the general data for winter (Table 1).

In S1 the number of occupants tended to be small, for the users were not usually present at the same time. This dwelling also had the lowest airtightness in Seville as well as the lowest CO_2 concentration. S2, the least permeable dwelling in the sample, exhibited the highest CO_2

concentration, while S3, with the largest number of occupants in the Seville subsample, had intermediate CO_2 values.

The bedroom-living room differences in temperature, relative humidity and CO_2 concentration rose when the doors separating them were closed. That may explain the differences in CO_2 concentration between living and bedroom in M2, S2 and S3.

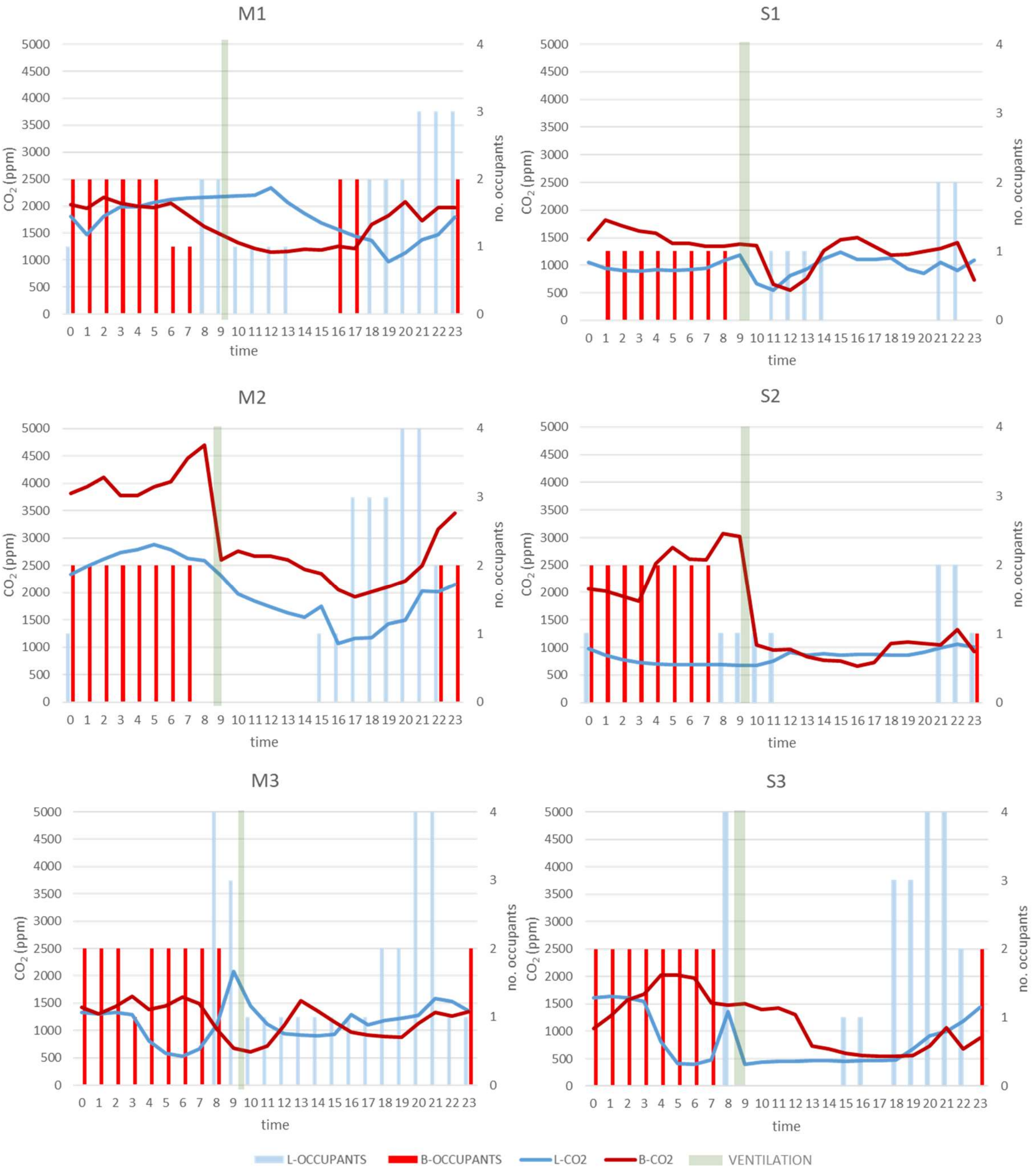

Figure 10. Hourly CO_2 concentration and number of occupants in bedrooms and living room on a typical winter day for all the case studies (L= living room, B= bedroom).

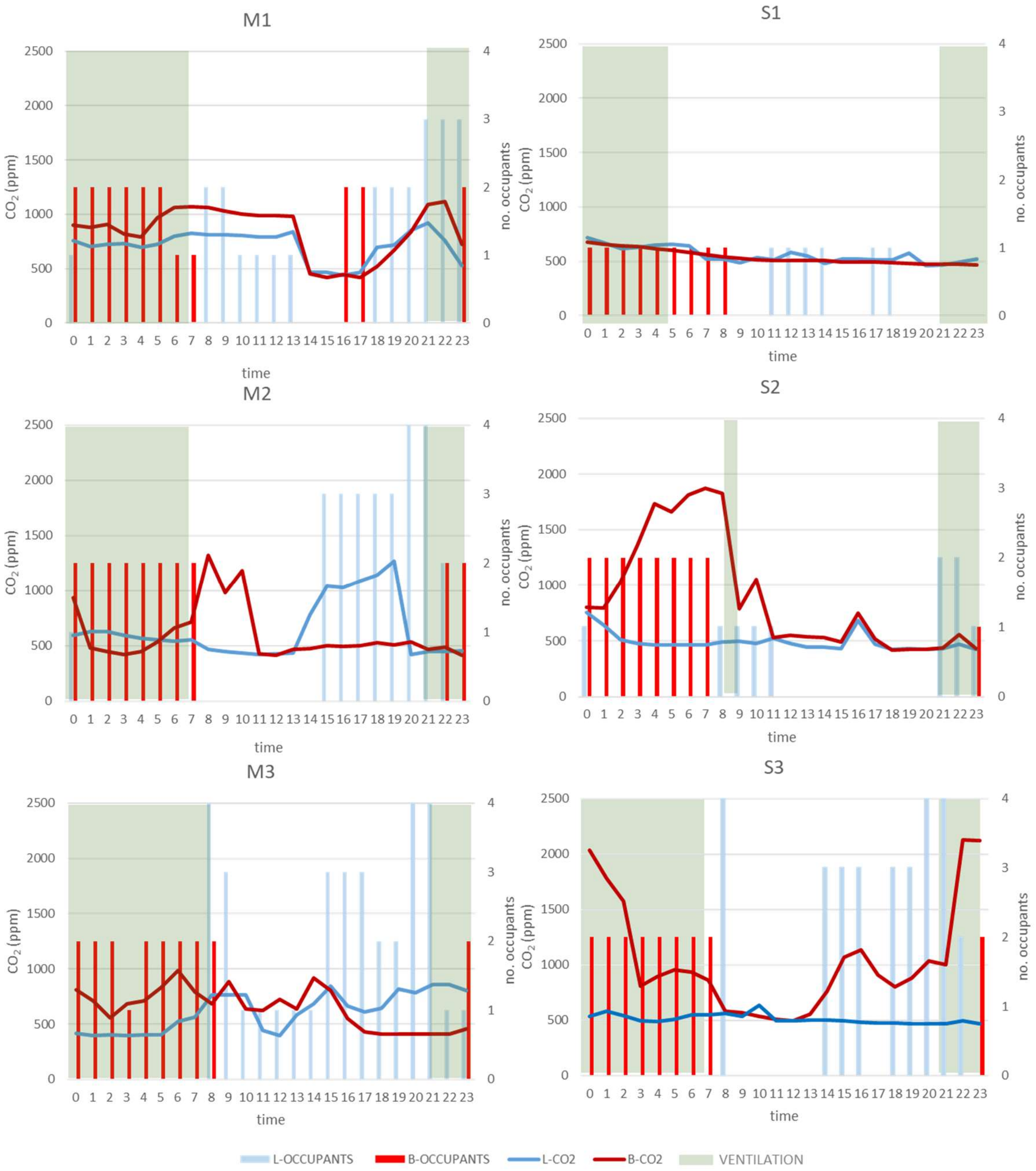

Figure 11. Hourly CO_2 concentration and number of occupants in bedrooms and living room on a typical summer day for all the case studies (L= living room, B= bedroom).

1.2. Calidad del aire

According to a guide on efficient air change in housing published by the regional government of Madrid[41], CO_2 concentrations of 1000 ppm to 1200 ppm are indicative of sufficient indoor air quality to prevent adverse effects on health. Those values are also a good benchmark for other parameters, such as volatile organic compounds (VOCs), which evolve in parallel and affect odour perception. Low IAQlevels were observed in winter in Madrid and Seville and in autumn in Madrid.In the other seasons optimal levels of indoor air quality were reached with natural ventilation alone (Figure 12).

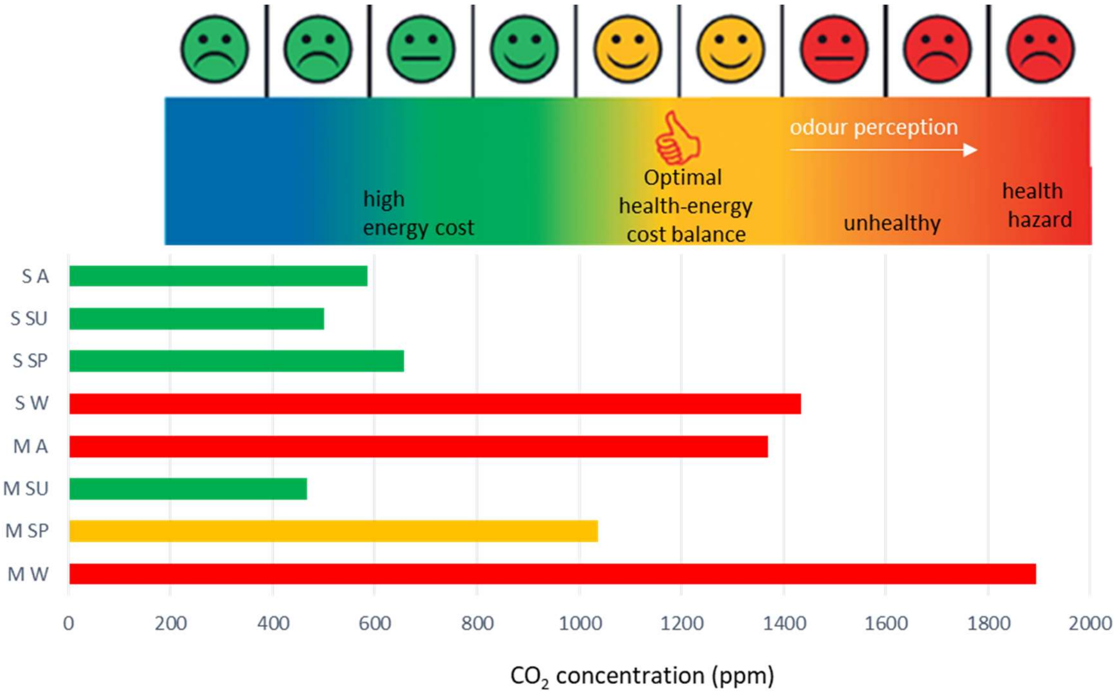

Figure 12. Balance between energy consumption for ventilation and indoor air quality (legend: S: Seville; M: Madrid; A: autumn; SU: summer; SP: spring; W: winter).

Discussion

Despite Madrid having colder winters than Seville (fig 4), higher indoor temperatures are registered (Table 1). Even though the low quality of construction of social housing on the period of the study has been reported in both cities, a higher amount of façades with air chambers are found in Madrid [12] than in Seville [11]. Also, better appliances for heating are used in Madrid. Eventhough social housing during the period 40-80 rarely included this service, the implementation of heating systems in Madrid has been increasing, particulary based on natural gas [42]. In Seville, electricity is the main source of energy for heating, which causes higher energy costs and the reduction of these services by the inhabitants of social housing, especially on vulnerable households. Poor thermal quality of residential buildings and inadequate facilities are more determinant in comfort than external temperatures, as described in some studies that point to the paradox that the areas of Europe with milder winters, where average winter temperatures are not lower than 5ºC, exhibit greater variations of seasonal mortality caused by discomfort [43]. This distribution is repeated also in the case of Spain, where it can be concluded that there are higher levels of energy poverty in the southern than in the northern regions [44].

During the summer, higher outdoor temperatures are reported in Sevilla than in Madrid, but lower indoor temperatures are monitored in the former. This could reveal a more intensive use of cooling facilities in Seville.

Figure 13 and Table 2 show the airtightness values found with the blower door test, along with the CO$_2$ concentration, temperature and relative humidity readings by case study.

An indirect correlation was observed between n_{50} and CO_2 concentration: the higher the n_{50} values (the more permeable the envelope), the lower was indoor CO_2 concentration. In living rooms, the highest correlation was found in winter (0.56), when windows were kept closed for more hours, especially in the middle of the day when those spaces were occupied.

In bedrooms the indirect correlation was somewhat looser in winter and autumn. In contrast, in summer n_{50} and CO_2 concentration were directly related, for higher permeability prompted more leakage that contributed to ventilation and the inflow of air at lower temperatures. Occupants consequently felt less need to open windows than those living in flats with less permeable envelopes. As night time bedroom window opening routines were reported to be very variable in the spring, no correlation was observed.

The table listing the correlation between n_{50} and temperature shows that the living rooms in the flats where leakage was most intense had the highest indoor temperatures in summer. Nonetheless, in bedrooms, where the indirect correlation was much laxer, the most permeable flats had lower temperatures as a result of the beneficial effect of the ingress of outdoor air at lower temperatures than those prevailing inside.

The correlations observed between n_{50} and relative humidity also showed that the humidity generated by occupants was dissipated more effectively in flats with more permeable envelopes.

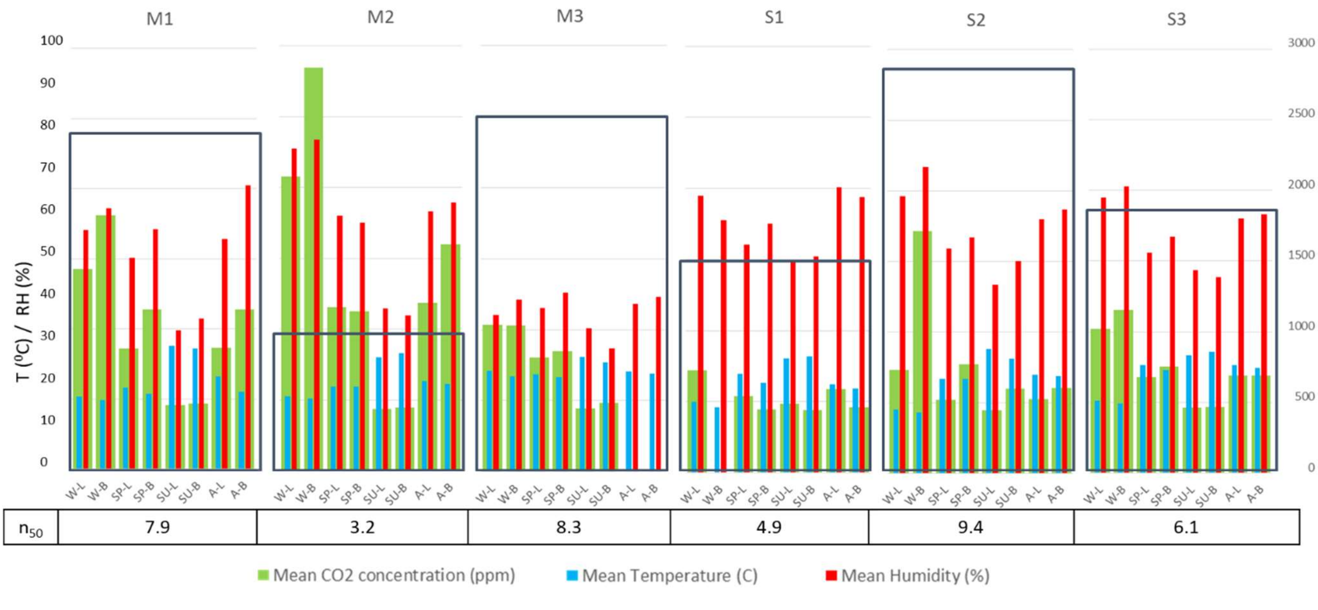

Figure 13. Airtightness (n_{50}), temperature, humidity and CO_2 concentration by case study. (legend: S: Seville; M: Madrid; A: autumn; SU: summer; SP: spring, W: winter, L: living room, B: bedroom).

Table 2. Correlation between n_{50} and temperature (T), relative humidity (H) and CO_2 concentration by season and area.

		T	H	CO_2
Living room	Winter	0.133	-0.606	-0.562
	Summer	0.728	-0.265	-0.235
Bedroom	Winter	0.116	-0.397	-0.454
	Summer	-0.290	-0.058	0.760

2. Conclusions

Mean winter CO_2 concentration in bedrooms was 1895 ppm in Madrid and 1434 ppm in Seville, with night-time peaks of 4000 ppm in the former and 5000 ppm in the latter.

In Seville, CO_2 concentrations in spring, summer and autumn were very similar to the outdoor values, given the practice of opening windows to lower the temperature to more comfortable levels during the hours with less solar radiation.In Madrid, indoor CO_2 concentration was similar to outdoor levels in the summer only, whilst lower values were related to the thermal comfort zone.

Measured in terms of carbon dioxide concentration, indoor air quality was found to be wanting, in light of the high values recorded, especially in cold seasons. Occupants were keenly aware of the need to open windows to ventilate their flats, especially early in the morning in light of the lack of mechanical ventilation systems.For that reason also, in winter, during the rest of the day flats were only ventilated by infiltration across the building envelope.The observed outcome was poor quality and often unhealthy indoor air, not only due to the high levels of carbon dioxide, but also to the risk of condensation.

Co-dependence was established between airtightness and a low air change rate associated with high indoor CO_2 concentrations, particularly in colder areas, although with wide scatter due to the variability in window opening routines and natural ventilation intervals. That relationship was much looser in warmer climates, where no clear dependence could be identified due to the significant differences in dwelling performance stemming from individual ventilation routines. Nonetheless, the amount of air inflows attributable to the uncontrollable infiltration stemming from poor quality enclosures, is insufficient to maintain the house under healthy conditions.

Occupants of dwellings dating from 1940 to 1980 were observed to ventilate by opening windows, often to the detriment of energy efficiency. In cooler areas such as Madrid the practice of replacing the original windows with more airtight elements was observed to induce condensation, such as in case study M2, found in the BD tests to be more airtight than any others in the sample.

Improving indoor air quality in Madrid and Seville would call for improved ventilation practice (except in the summer months) or the installation of mechanical air renewal systems. In Seville, more effective heating would be needed to raise winter indoor temperatures to meet comfort standards.

Acknowledgements

This study was funded by the Spanish Ministry of Economy and Competitiveness under project BIA 2012-39020-C02-01-REFAVIV and BIA2017-83231-C2-1-R. The outdoor data were furnished by Spain's National Meteorology Agency.

References

[1] L. Hernández *et al.*, "A Study of the Relationship between Weather Variables and Electric Power Demand inside a Smart Grid/Smart World Framework," *Sensors*, vol. 12, no. 9, pp. 11571–11591, Aug. 2012.

[2] H. J. Moon, S. H. Ryu, and J. T. Kim, "The effect of moisture transportation on energy efficiency and IAQ in residential buildings," *Energy Build.*, vol. 75, pp. 439–446, Jun. 2014.

[3] F. Martín-Consuegra, C. Alonso, B. Frutos, and M. Olaya, "User utility as the financial justification for low energy refurbishment.," in *10th ENERGY FORUM: ADVANCED BUILDING SKINS.*, 2015.

[4] "Orden de 19 de octubre de 2015, por la que se modifica la Orden de 28 de abril de 2015, por la que se aprueban las bases reguladoras para la concesión, en régimen de concurrencia competitiva, de subvenciones destinadas al fomento de la rehabilitación edificatoria en la Comunidad Autónoma de Andalucía, y se efectúa su convocatoria para el ejercicio 2015." [Online]. Available: https://www.juntadeandalucia.es/boja/2015/208/1. [Accessed: 03-Feb-2019].

[5] E. de Santiago, "La estrategia para la rehabilitación energética en el sector de la edificación residencial en España: metodología y principales resultados.," *Ciudad Territ. Estud. Territ*, pp. 773–788, 2014.

[6] Sara Kunkel, Alesandra Arcipowska, Eleni Kontonasiou, and Francesco Mariottini, "Indoor air quality, thermal comfort and daylight. Analysis of residential buildings regulations in eight EU member states." [Online]. Available: https://www.researchgate.net/publication/274695177_Indoor_air_quality_thermal_comfort_and_daylight_Analysis_of_residential_buildings_regulations_in_eight_EU_member_states. [Accessed: 03-Feb-2019].

[7] Ministerio de Vivienda, *Real Decreto 314/2006, de 17 de marzo, por el que se aprueba el Código Técnico de la Edificación.* Ministerio de Vivienda. Gobierno de España: BOE-A-2006-5515, 2006.

[8] Ministerio de la Presidencia. Gobierno de España, "Real Decreto 235/2013, de 5 de abril, por el que se aprueba el procedimiento básico para la certificación de la eficiencia energética de los edificios. Boletín Ofical del Estado," Madrid (Spain), 2013.

[9] M. Derbez *et al.*, "Indoor air quality and comfort in seven newly built, energy-efficient houses in France," *Build. Environ.*, vol. 72, pp. 173–187, Feb. 2014.

[10] P. del Gobierno, *Real Decreto 2429/1979, de 6 de julio, por el que se aprueba la norma básica de edificación NBE-CT-79, sobre condiciones térmicas en los edificios. Boletín Oficial del Estado.* 1979.

[11] S. Domínguez-Amarillo, J. J. Sendra, and I. Oteiza San José, *La envolvente térmica de la*

vivienda social: el caso de Sevilla, 1939 a 1979 Title, 1st ed. Madrid (Spain): Editorial Consejo Superior de Investigaciones Científicas, 2016.

[12] C. Alonso, F. Martin-Consuegra, and J. Monjo, *La envolvente energética de la vivienda social: el caso de Madrid en el periodo 1939-1979*, Monografía. 2018.

[13] J. Fernández-Agüera, S. Domínguez-Amarillo, J. J. Sendra, R. Suárez, and I. Oteiza, “Social housing airtightness in Southern Europe,” *Energy Build.*, vol. 183, pp. 377–391, Jan. 2019.

[14] J. Fernández-Agüera, S. Domínguez-Amarillo, J. J. Sendra, and R. Suárez, “An approach to modelling envelope airtightness in multi-family social housing in Mediterranean Europe based on the situation in Spain,” *Energy Build.*, vol. 128, pp. 236–253, 2016.

[15] M. Jesús, Feijó-Muñoz; Irene, Poza-Casado; Roberto Alonso, González-Lezcano; Cristina, Pardal; Víctor, Echarri; Rafael, Assiego L.; Jesica, Fernández-Agüera; María Jesús, Dios-Viéitez; Víctor José, del C.-D.; Manuel, Montesdeoca C.; Miguel Ángel, Padilla-Mar, “Methodology for the Study of the Envelope Airtightness of Residential Buildings in Spain: A Case Study,” *Energies*, vol. 4, no. 704, 2018.

[16] D. Pennestrì, “The energy and Enviromental requalification of post-war housing: problematics and innovative solutions for the building envelope. Central Europe Towards Sustanaible Buildings 2013: Sustanaible refurbishment of existing building stock,” in *Central Europe Towards Sustainable Buildings 2013: Sustainable refurbishment of existing building stock*, 2013, pp. 1–7.

[17] ASHRAE, *ASHRAE Handbook 2013 Fundamentals*, vol. 53, no. 9. 2013.

[18] CEN EN Standrad 15251, *Indoor environment input parameters for design and assessment of energy performance of buildings*. 2007.

[19] J. M. Daisey, W. J. Angell, and M. G. Apte, “Indoor air quality, ventilation and health symptoms in schools: An analysis of existing information,” *Indoor Air*. 2003.

[20] M. Maroni, “[Indoor air quality and occupational health, past and present].,” *G. Ital. Med. Lav. Ergon.*, vol. 26, no. 4, pp. 353–363, 2004.

[21] J. G. Allen, P. MacNaughton, U. Satish, S. Santanam, J. Vallarino, and J. D. Spengler, “Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments,” *Environ. Health Perspect.*, vol. 124, no. 6, pp. 805–812, Jun. 2016.

[22] U. Satish *et al.*, “Is CO2 an indoor pollutant? Direct effects of low-to-moderate CO2 concentrations on human decision-making performance.,” *Environ. Health Perspect.*, vol. 120, no. 12, pp. 1671–7, Dec. 2012.

[23] S. Langer, G. Bekö, E. Bloom, A. Widheden, and L. Ekberg, “Indoor air quality in passive and conventional new houses in Sweden,” *Build. Environ.*, vol. 93, pp. 92–100, Nov. 2015.

[24] E. M. Wells *et al.*, “Indoor air quality and occupant comfort in homes with deep versus conventional energy efficiency renovations,” *Build. Environ.*, vol. 93, pp. 331–338, Nov. 2015.

[25] M. Derbez *et al.*, “A 3-year follow-up of indoor air quality and comfort in two energy-efficient houses,” *Build. Environ.*, vol. 82, pp. 288–299, Dec. 2014.

[26] G. McGill, M. Qin, and L. Oyedele, “A Case Study Investigation of Indoor Air Quality in UK Passivhaus Dwellings,” *Energy Procedia*, vol. 62, pp. 190–199, Jan. 2014.

[27] A. Figueiredo, J. Figueira, R. Vicente, and R. Maio, “Thermal comfort and energy performance: Sensitivity analysis to apply the Passive House concept to the Portuguese climate,” *Build. Environ.*, vol. 103, pp. 276–288, Jul. 2016.

[28] R. Suárez and J. Fernández-Agüera, “Passive energy strategies in the retrofitting of the residential sector: A practical case study in dry hot climate,” *Build. Simul.*, 2015.

[29] M. Á. C. Laborda, I. A. García, J. F. A. Escudero, and J. J. Sendra, “Towards finding the optimal location of a ventilation inlet in a roof monitor skylight, using visual and thermal performance criteria, for dwellings in a Mediterranean climate,” *J. Build. Perform. Simul.*, 2015.

[30] A. Curado, V. Peixoto De Freitas, and N. M. M. Ramos, “Variability assessment of thermal comfort in a retrofitted social housing neighborhood based on ‘in situ’ measurements,” *Energy Procedia*, vol. 78, pp. 2790–2795, 2015.

[31] R. Suárez and J. Fernández-Agüera, “Retrofitting of Energy Habitability in Social Housing: A Case Study in a Mediterranean Climate,” *Buildings*, 2011.

[32] S. Domínguez-Amarillo, J. J. Sendra, J. Fernández-Agüera, and R. Escandón, *La construcción de la vivienda social en Sevilla y su catalogación 1939-1979*. Sevilla, 2017.

[33] O. A. Seppänen, W. J. Fisk, and M. J. Mendell, “Association of ventilation rates and CO2 concentrations with health and other responses in commercial and institutional buildings.,” *Indoor Air*, vol. 9, no. 4, pp. 226–52, Dec. 1999.

[34] Y. Al horr, M. Mohammed Arif, A. Katafygiotou, A. K. Mazroei, and E. Elsarrag, “Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature,” *Int. J. Sustain. Built Environ.*, 2016.

[35] M. Kotol, C. Rode, G. Clausen, and T. R. Nielsen, “Indoor environment in bedrooms in 79 Greenlandic households.,” *Build. Environmen*, vol. 81, pp. 29–36, 2014.

[36] P. Strøm-Tejsen, D. Zukowska, P. Wargocki, and D. P. Wyon, “The effects of bedroom air quality on sleep and next-day performance,” *Indoor Air*, 2015.

[37] J. Fernández-Agüera, J. J. Sendra, and S. Domínguez-Amarillo, “Protocols for measuring the airtightness of multi-dwelling units in Southern Europe,” in *Procedia Engineering*, 2011, vol. 21, pp. 98–105.

[38] F. J. S. de la Flor, S. Á. Domínguez, J. L. M. Félix, and R. G. Falcón, “Climatic zoning and its application to Spanish building energy performance regulations,” *Energy Build.*, vol. 40, no. 10, pp. 1984–1990, 2008.

[39] S.-G. C. Sánchez, M. Núñez Peiró, and F. J. Neila González, “Urban Heat Island and Vulnerable Population. The Case of Madrid,” *Sustain. Dev. Renov. Archit. Urban. Eng. Springer Int. Publ. Cham, pp. 3–13. https//doi.org/10.1007/978-3-319-51442-0_1*, 2017.

[40] B. A, J. A. De la Morena Carretero, C. Adame, M. Carrillo, J. J. Corzo, and G. F. Cáceres,

“Estudio de la isla de calor urbana en el área metropolitana de Sevilla,” in *Congreso Nacional de Medio Ambiente*, 2010.

[41] “Guía de renovación de aire eficiente en el sector residencial - PDF.” [Online]. Available: https://docplayer.es/4235121-Guia-de-renovacion-de-aire-eficiente-en-el-sector-residencial.html. [Accessed: 03-Feb-2019].

[42] F. Martín-Consuegra, A. Hernández-Aja, I. Oteiza, and C. Alonso, *Distribución de la pobreza energética en la ciudad de Madrid (España)*. Rev. EURE - Rev. Estud. Urbano Reg, 2019.

[43] J. . Healy, *Housing, Fuel Poverty and Health : A Pan-European Analysis.* 2017.

[44] O. Aristondo and E. Onaindia, “Counting energy poverty in Spain between 2004 and 2015,” *Energy Policy*, vol. 113, pp. 420–429, 2018.