Informes de la Construcción
Vol. 75, 572, e519
octubre-diciembre 2023
ISSN-L: 0020-0883
https://doi.org/10.3989/ic.6447

Indoor air quality in naturally ventilated dwellings in Spain

Calidad del aire interior en viviendas ventiladas de forma natural en España

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ABSTRACT

This article presents the results of the exploratory study on indoor air quality in existing dwellings with traditional ventilation systems based on natural ventilation. A preliminary study of the most representative typology of the Spanish housing stock has been conducted and, based on it, twelve dwellings located in Madrid have been monitored in different periods. Monitored indoor air quality has been compared to that required in the regulations in Spain, the *Código Técnico de la Edificación* (Technical Building Code). According to the results of the research, 50 % of the monitored dwellings do not comply with the CO_2-based air quality quantification offset in the regulations. Such non-compliance is primarily caused by high CO_2 concentrations in winter, especially in bedrooms. These high concentrations and their seasonality are attributed to the interference of the occupant's behaviour, influenced by weather conditions, that is affecting the efficiency of the existing natural ventilation systems.

Key words: Natural ventilation; ventilation system; IAQ; indoor air quality; CO_2; occupant behaviour; dwellings; IEQ; indoor temperature; CTE; Building Code; regulations.

RESUMEN

Este artículo presenta los resultados del estudio exploratorio sobre la calidad del aire interior en viviendas existentes con sistemas de ventilación tradicional basada en ventilación natural. Se ha realizado un estudio previo de la tipología de viviendas más representativa del parque inmobiliario español en base al cual se han monitorizado doce viviendas ubicadas en Madrid. La calidad del aire interior obtenida se ha comparado con la requerida reglamentariamente por el Código Técnico de la Edificación. Como resultado, el 50 % de las viviendas monitorizadas no cumplen con la cuantificación de calidad del aire en función del CO_2 de la reglamentación de aplicación. Dicho incumplimiento se produce fundamentalmente por las altas concentraciones de CO_2 alcanzadas en invierno, especialmente en los dormitorios. Estas altas concentraciones y su estacionalidad se atribuyen a las interferencias del comportamiento de los ocupantes, influenciado por la meteorología, en la eficacia de los sistemas de ventilación natural.

***Palabras clave**: ventilación natural; CAI; calidad del aire interior; CO_2; comportamiento de los ocupantes; viviendas; calidad del ambiente interior; temperatura interior; CTE; Código Técnico de la Edificación; regulación.*

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Cómo citar este artículo/*Citation:* Sonia García-Ortega, Pilar Linares-Alemparte (2023). Indoor air quality in naturally ventilated dwellings in Spain. *Informes de la Construcción,* 75(572): e519. https://doi.org/10.3989/ic.6447

Recibido/*Received*: 15/03/2023
Aceptado/*Accepted*: 11/09/2023
Publicado on-line/*Published on-line*: 26/10/2023

1. INTRODUCTION

Most dwellings of the current building stock in Spain are equipped with natural ventilation systems. These systems are based on the use of vertical ventilation shafts in wet rooms (e.g. bathrooms, toilets, kitchens) to exhaust stale air, and on the intake of fresh outdoor air to dry rooms through infiltration. In addition, occupants have operable windows to the outside to reinforce such ventilation in all dry rooms (e.g. living room, bedroom) and the kitchens, and sometimes also in the bathrooms or toilets, in which case the shaft is usually omitted.

In addition to this natural ventilation system, in contrast to other countries, the use of cooker hoods in kitchens is widespread in the housing stock in Spain, which often have an exhaust to the outside.

This type of natural ventilation of dwellings presents advantages such as being a simple equipment with generally low carbon footprint; low installation, operation and maintenance costs; and high adaptive thermal comfort (1, 2). It also presents some disadvantages, such as lack of control over the rate of ventilation and considerable challenge to predict ventilation under realistic conditions (including occupant interaction). The operation of ventilation shafts is based on the action of both wind and thermal buoyancy. Therefore, in periods when outdoor temperature is not significantly lower than indoor temperature and there is no wind, ventilation will not be feasible (3, 4). It could even be the case, in periods of thermal inversion in warm weather, that outdoor air enters the house through the shaft and is distributed from the wet rooms to the dry rooms.

In recent years, indoor air quality (IAQ) of dwellings with these systems may have decreased due to energy efficiency retrofitting that increases airtightness of buildings envelope reducing infiltrations as an intake for outdoor air. In fact, energy retrofit policies in recent years have generally prioritised increasing the airtightness of buildings envelopes, relegating to second place the possible impact on IAQ (5).

Since 2006, the *Código Técnico de la Edificación* (Spanish Technical Building Code, CTE) (6) sets the basic requirements for new and refurbished dwellings to ensure adequate IAQ. Regulatory compliance with entirely natural ventilation system as an approved solution is not allowed, but need to be hybrid or mechanical.

In terms of IAQ in existing dwellings in neighbouring countries, natural ventilation is generally considered to be insufficient (7, 8). No large-scale studies focused on the assessment of IAQ in naturally ventilated dwellings in Spain are available, but studies focused on aspects such as the influence of lockdown during the Covid pandemic (9), or the analysis of the frequency of window opening as a healthy habit (10).

CO_2 was chosen as the metric of IAQ because is easy to be measured with ready available sensors, is widely used as an indicator of IAQ in standards and regulations (11-13) and is correlated to other indoor air pollutants (14). However, it is not the purpose of this paper to determine the role of CO_2 as an indicator or metric of IAQ. The limitations of the assumption of CO_2 concentration as an indicator of IAQ are known. CO_2 generation is dependent on parameters such as age of occupants, weight, gender, activity, etc. (15) and its use can only be appropriate as an indicator of IAQ when there are no other specific dominant pollutants (16). Furthermore, it should not be forgotten that it is not a pollutant unless it is present in very large concentrations, and the broader literature is not consistent as to how CO_2 impacts on building occupants´ related issues as cognitive performance (17, 18). Recently, it has been used as a possible indicator to limit the spread of Covid-19 indoors (19, 20).

The main objective of this exploratory study is the evaluation of the IAQ of existing dwellings in Spain with predominantly natural ventilation systems and verification of its compliance with IAQ regulations. In order to conduct this evaluation, it has been necessary to determine the most common types of dwellings in the current building stock in terms of number of occupants, floor area and number of rooms. These factors are thought to be the most influential.

This study contributes to a broader understanding of the existing situation of IAQ in dwellings in Spain, and may provide guidance for future actions in terms of regulation or subsidies for retrofitting.

2. METHODOLOGY

In order to assess the IAQ in existing dwellings and the potential for compliance with requirements included in national IAQ regulations, the following steps were conducted:

- study of existing housing stock and selection of representative dwellings;
- analysis of Spanish IAQ regulations;
- monitoring and characterisation of selected dwellings;
- occupant surveys on their perception of IAQ and ventilation habits; and
- analysis of the obtained results and its compliance with IAQ regulations.

2.1. Housing stock

In order to obtain a sample as representative as possible of the housing stock, considering it is an exploratory research, a preliminary study (see section 3.1) was carried out based on earlier work by the authors (21) and the latest available data from the population and housing survey of the *Instituto Nacional de Estadística* (National Statistics Institute, INE) (22). Existing housing stock was analysed in relation to number of occupants, usable floor area and number of rooms, as well as the relationships between these factors.

With the aim of obtaining results that reflect the most common situations, only primary dwellings were analysed, excluding secondary ones and touristic houses.

As an initial criteria it was set that all of them had to be: apartments in high-rise residential buildings, in consolidated urban environments located in the city of Madrid, with a specific climate: BSk (23).

2.2. Spanish regulation of IAQ

IAQ regulations for dwellings are established in *Sección Calidad del aire interior* (Section Indoor air quality DB HS 3) of the CTE (6).

The CTE is a performance-based regulation divided into two parts. In its first part (*Parte 1*) the basic requirements that buildings must meet are established. The IAQ basic requirement sets: *Buildings shall be provided with means to ensure that their enclosures can be adequately ventilated, removing pollutants […] providing a sufficient flow of outside air […].*

The second part, consisting of the so-called *Documentos Básicos* (Basic Documents, DB), characterises and quantifies the basic requirements and, among other verification methods, describes some approved solutions for the fulfilment of these basic requirements.

The DB HS 3 states, within the characterization and quantification of the basic requirement, that IAQ can be considered adequate in dwellings when all following conditions are provided:

- the annual average of CO_2 concentration in each room is lower than 900 ppm;
- the annual cumulative CO_2 concentration in each room above 1,600 ppm is lower than 500,000 ppm·h; and
- a minimum flow rate of 1.5 l/s per room is established.

Both CO_2 concentration thresholds have the aim to control human related pollutants, whereas the minimum flow intends to control no human related pollutants, even in non-occupancy periods.

As a means of complying with this basic requirement, the DB HS 3 provides a simplified verification method based on implementing constant minimum flow rates. Otherwise, simulations must be conducted to verify compliance of ventilation systems with basic requirement.

Additionally, the DB HS 3 establishes as an accepted solution the simultaneous arrangement of 3 ventilation subsystems in the dwelling:

- general ventilation system, in which the outside air enters through the dry rooms (bedrooms, living rooms) and leaves the dwelling through the wet rooms (bathrooms, kitchens). Such system is required to be mechanical or hybrid. The sizes of air inlets and air passage openings are established, as well as sections of ventilation conduits, and for air inlets, micro-ventilation of the window frames is allowed;
- complementary natural ventilation system, based on the provision of external operable windows or doors in kitchens, dining rooms, living rooms and bedrooms; and
- specific additional system in kitchens for pollutants and cooking vapours (such as an extractor hood).

Alternative solutions to those set out in the DB HS 3 can be used if it is justified that the achieved performance is at least equivalent to that obtained with the direct application of the accepted solutions. Accordingly, natural ventilation systems would be valid if they can meet the basic requirement at least as well as mechanical or hybrid systems. The latter is, however, rather complex to demonstrate.

2.3. Monitoring and characterization

75 measurements were carried out in 42 rooms belonging to 12 existing dwellings with ventilation systems based mainly on natural ventilation and airing. Dwellings were located in the urban area of Madrid (Spain). The monitoring was conducted in different periods, divided into winter and summer, between 6th December 2017 and 9th March 2020. The average duration of monitoring was 16 days, varying from 8 to 21 days.

Period between 10th June and 2nd October is considered to be summer, and between 19th October and 17th March winter, based on (24) where summer is considered between the last Sunday in March and the last Saturday in October, and winter the rest of the year.

The annual values have been calculated taking into account that the number of available data in winter and in summer varies. Therefore, the annual mean has been considered as the average between the summer mean value and the winter mean value. In the case of the annual cumulative CO_2 per room:

- the monitored results have been extrapolated to the rest of their season;
- the annual accumulated have been considered as the sum of the summer and winter cumulative;

In addition to this, when more than one monitored results has been obtained in the same season, the average value is considered; when only one monitored result has been obtained, it is extrapolated to the whole year.

All dwellings have been monitored in summer and winter, with the exception of dwelling 02 only in summer) and dwelling 12 (only in winter).

Indoor environment parameters

The following parameters were monitored and recorded at intervals of 5 minutes with various Rotronic CP-011 and Wöhler CDL 210:

- CO_2 concentration (ppm);
- relative humidity (%); and
- temperature (ºC).

The monitoring equipment was placed predominantly in bedrooms and living rooms. In some dwellings, kitchens and bathrooms were also monitored. Equipment data display screens were hidden so as not to influence the occupants.

Integrated radon measurements (Bq/m^3) were also carried out in potentially problematic rooms, but no significant concentrations were detected, so results have not been included.

During measurement, occupants were told to keep their activities as usual, including ventilation habits, turning on of cooker hoods and so on.

Collected data were subjected to an analysis process to eliminate possible measurement or error collection.

Outdoor environment parameters

The location of the dwellings in the urban environment can be seen in Figure 1. The Köppen-Geiger climate classification (23) of Madrid is BSk: Dry, Semi-Arid or steppe, Cold climate.

The Köppen-Geiger climate classification is a widely used worldwide system, developed in the 19th century, which classifies the world's climate into 3 categories identified by 3 letters:

- the first letter categorises the climate into A (Tropical) B (Dry) C (Temperate) D (Continental) E (Polar);
- the second letter assigned a seasonal precipitation subgroup; and
- the third letter indicates the level of heat.

In BSk climate, winters are cold or very cold, and summers can be mild or hot, with rather low levels of rain. It tends to be located in temperate latitudes and far from the sea, such as in inland North America, the interior of the Ebro valley, the interior of Iran and the steppes of central Asia (23) (see Figure 1, a and b).

Meteorological data were obtained mainly from stations 3195 and 3194U of the Spanish Meteorological Agency (25) (AEMET) (see Figure 1, c) and from station 28079102 of the Integrated Air Quality System of Madrid City Council, extracting the following parameters:

- air temperature (°C), hourly and average per day;
- relative humidity (%), hourly and average per day;
- wind speed: average per day and gust (m/s); and
- atmospheric pressure (Pa).

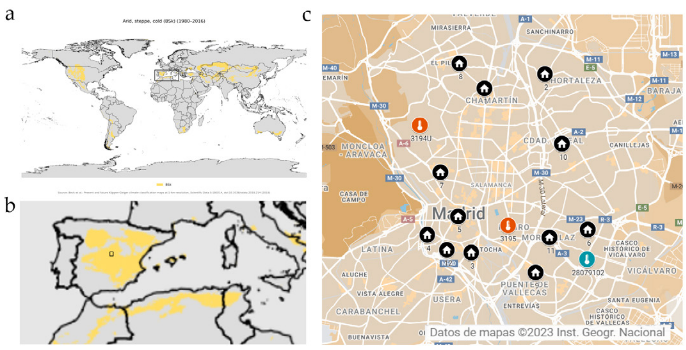

Figure 1. a, b – Köppen - Geiger climate map for BSk (23). c - Location of the monitored dwellings (dots in black) and meteorological stations (dots in red: Spanish Meteorological Agency, dot in blue: Madrid City Council).

Ventilation systems parameters

Ventilation systems of dwellings are based on natural ventilation, with the following observations:

- dwellings 01, 02, 04, 05, 08, 11: vertical ventilation shafts in bathrooms and kitchen, with operable windows in all dry rooms and kitchen;
- dwellings 03, 09: operable windows in all dry rooms and bathrooms;
- dwellings 06, 07: vertical ventilation shafts in bathrooms and kitchen, with operable windows in all dry rooms and kitchen, and a small extractor fan with an on-off switch (06) or connected to light switch (07);
- dwelling 10: vertical ventilation shaft in one bathroom with a small extractor fan connected to light switch; and operable windows in all dry rooms, kitchen and in the other bathroom; and
- no specific air inlets on the façades.

The correct operation of passive stacks was checked with a funnel vane anemometer model PCE-VA 20.

Occupant parameters

Table 1 shows the number of occupants in each dwelling. In addition to this, two types of occupant's surveys have been carried out: general surveys on their perception of IAQ and their occupancy habits; and in some cases, detailed surveys on specific actions carried out within recent periods of time.

3. RESULTS AND DISCUSION

3.1. Characterization of the housing stock

According to INE, the most common range of **usable floor area** of dwellings is between 76 and 90 m². Small differences have been observed between different size municipalities according to number of inhabitants: large cities (over 500,000 inhabitants) present higher percentage of dwellings smaller than 76 m² and the difference between the 46-60 and 61-75 m² range and the 76-90 m² range decreases.

Figure 2 shows a graphical representation of the percentage of dwellings as a function of usable floor area, plotted in 15 m² intervals. 74 % of the dwellings size is between 46 and 105 m², and 92% between 30 and 150 m².

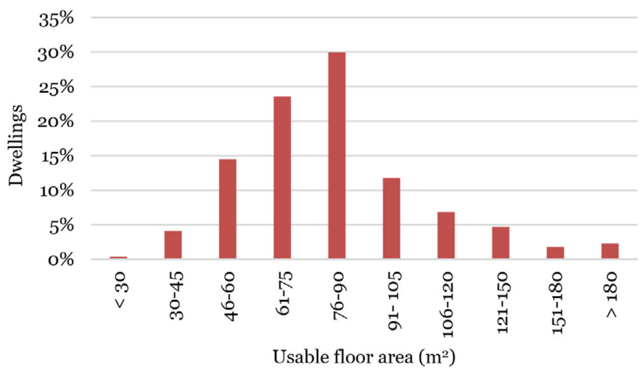

Figure 2. Percentage of dwellings in Spain by usable floor area. Source of data: INE (22).

The most common **number of rooms** (excluding bathrooms and rooms smaller than 4 m²) is 5, considered as 3 bedrooms, kitchen and dining living room plus toilets/bathrooms. In relation to the second and third most common number of rooms, differences can be observed according to the size of the municipality: in small municipalities (less than 100,000 inhabitants), 4-bedroom dwellings are followed by 2-bedroom dwellings; while in medium-sized or large mu-

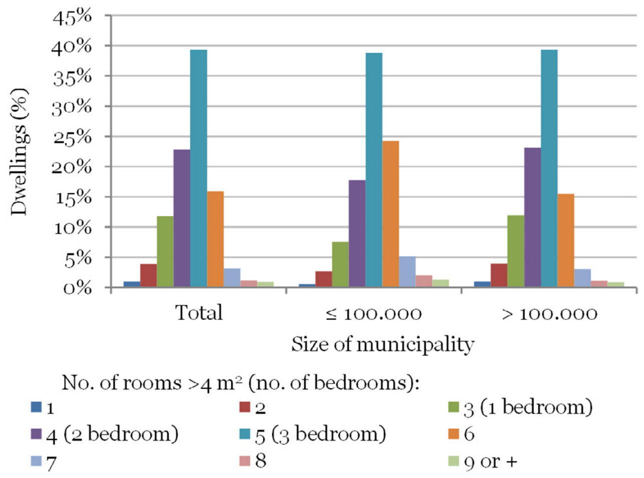

Figure 3. Percentage of Spanish dwellings by number of rooms, total and broken down by size of municipality. The most common number of bedrooms for each number of rooms on the x-axis is indicated in brackets. Source of data: INE (22).

nicipalities (more than 100,000 inhabitants) is the other way round. (See Figure 3).

98 % of the dwellings have from 1 to 7 rooms (from studio flats to flats with e.g. dining living room, kitchen, bathrooms and 5 extra rooms which could be bedrooms, separate dining rooms, offices, etc.).

The number of rooms is related to the usable floor area of the dwelling, with 5-room dwellings (usually 3 bedrooms) and 76 to 90 m² (see Figure 4) standing out in percentage above all others.

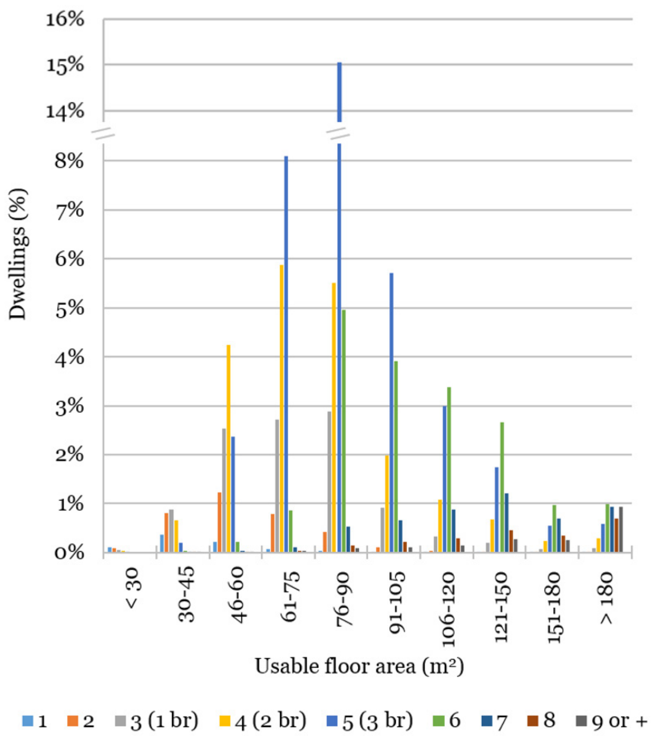

Figure 4. Percentage of Spanish dwellings by usable floor area and number of rooms. The most common number of bedrooms for each number of rooms on the x-axis is indicated in brackets. Source of data: INE (22).

The most common **number of occupants** is 2, followed by 1, 3 and 4 depending on the size of the dwelling and the number of rooms, with an average occupancy of 2.58.

When studying the number of occupants in relation to the number of rooms in the dwelling (see Figure 5), it is observed that the number of occupants does not increase linearly with the number of rooms and the number of occupants is usually contained at 4, regardless of the number of rooms in the dwelling.

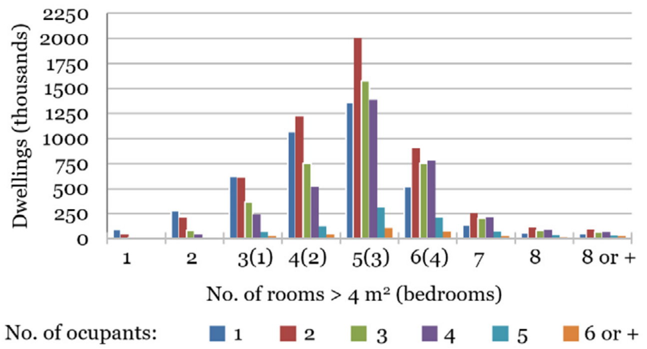

Figure 5. Spanish dwellings by number of rooms and number of occupants. The most common number of bedrooms for each number of rooms on the x-axis is indicated in brackets. Source of data: INE (22).

The number of occupants is less affected by the usable floor area than would be expected since the usable floor area per inhabitant decreases as the number of inhabitants increases: 85.2 m² for one inhabitant, 47.2 m² for two, 32.9 m² for three and 26.1 m² for four. The distribution of the number of occupants by dwelling floor can be seen in Figure 6.

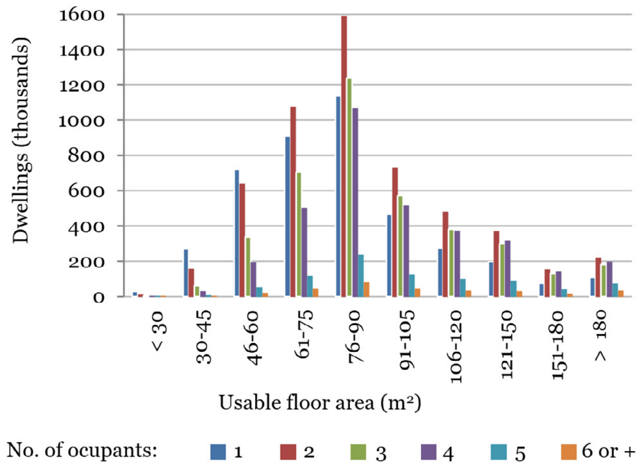

Figure 6. Spanish dwellings by usable floor area and number of occupants. Source of data: INE (22).

Dwellings occupied by 1 to 4 occupants account for 93.48% of the total. A rather low relevance has been observed between the number of occupants, the usable floor area and the number of rooms in a dwelling, but it is not sufficient to determine the number of occupants with certainty.

As a summary of the characterisation of the real estate stock, it can be established that:

- 93% of the dwellings are occupied by 1 to 4 occupants,
- the average occupancy is 2.58;

- 74% of the dwellings size is between 46 and 105 m², and 92% between 30 and 150 m²; and
- the most common dwelling is that with 3 bedrooms (5 rooms) (39%), followed by 2 bedrooms (4 rooms) (23%) and 4 bedrooms (6 rooms) (16%); 98% of the dwellings have up to 7 rooms.

Considering the modal values, a typical dwelling in Spain would have a floor area of 83 m², 3 bedrooms and 2 occupants.

According to those results, dwellings were selected fitting the following criteria:

- 1 to 4 occupants;
- from 30 to 150 m² usable floor; and
- up to 7 rooms (e.g. living room, dining room, kitchen, three bedrooms and office room).

12 dwellings were selected (see Table 1), and 42 rooms were monitored. Dwellings 01 to 11 have the kitchen separated from the dining room, and dwelling 12 is a studio.

Table 1. Monitored rooms.

Monitored dwelling code	Usable floor area (m²)	No. of occupants	No. of rooms (exc. < 4 m² and bathrooms)	Monitored rooms[1]	Year of construction (or refurbishment)
01	66	2	4	1, 2, 7	1986 (2014)
02	106	4	5	1, 2, 3, 6	2000
03	50	2	4	1, 2	1956 (2000)
04	96	4	5	1, 2, 3, 8	1960 (2016)
05	150	2	4	1, 2, 6, 8	1987
06	113	4	5	1, 2, 4, 6	1991
07	133	2	7	1, 2, 3	1970
08	52	2	3	1, 2 , 6, 7	1963
09	60	1	3	1, 2, 7	1956
10	113	2	6	1, 2, 6, 7, 7	1982
11	67	4	3	1, 2, 3, 6, 7	1960
12	30	1	1	1/2/6	2011

1: Living/dining room; 2: Master bedroom, 3: 2nd Bedroom; 4: 3rd Bedroom; 5: 4th Bedroom; 6: Kitchen; 7: Bathroom; 8: Other room, e.g. a home office or study.

3.2. IAQ evaluation

There are different methods of assessing the IAQ in dwellings. One of the most widespread is through CO_2 concentration, which is also the basis for the applicable Spanish regulations.

As previously exposed, the DB HS 3 states that IAQ can be considered adequate in dwellings when, in each room, the annual average of CO_2 concentration is lower than 900 ppm and the annual cumulative CO_2 concentration above 1,600 ppm is lower than 500,000 ppm·h, plus a minimum flow rate of 1.5 l/s per room.

In order to analyse the IAQ with the DB HS 3 CO_2 parameters, the average CO_2 concentrations of the monitored rooms were calculated from the experimental measurements and are shown in Figure 7.

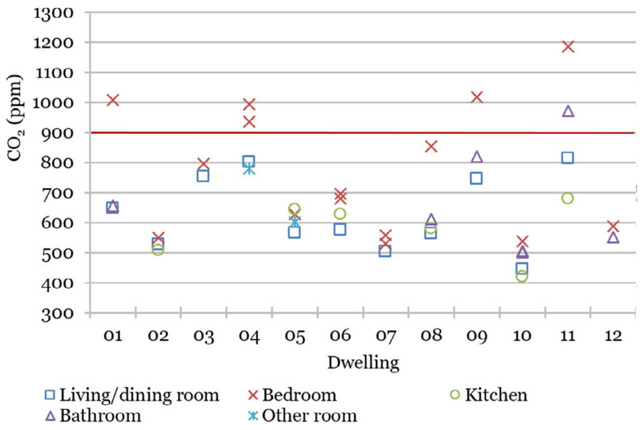

Figure 7. Annual average CO2 concentrations per room.

From the 12 monitored dwellings, 4 (dwellings 01, 04, 09 and 11) do not comply with DB HS 3 as the average CO_2 in some of the bedrooms exceeds 900 ppm. These four dwellings are joined by dwellings 03 and 08 for exceeding the annual cumulative above 1,600 ppm of 500,000 ppm/h as shown in Figure 8.

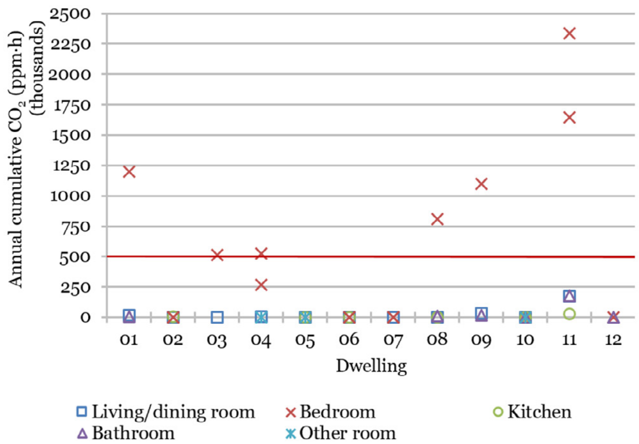

Figure 8. Annual cumulative CO2 above 1,600 ppm per room. Scale 0 – 2,500,000 ppm·h.

The results show that 6 out of 12 dwellings do not comply with the CO_2 performance stipulated in DB HS 3. A 50% non-compliance rate proves the unfeasibility of guaranteeing an adequate IAQ in existing dwellings with the use of the current natural ventilation systems.

In addition to the CO_2 concentration performance, to be in accordance with the characterisation and quantification criteria of DB HS 3, the ventilation system should provide a minimum constant flow rate of 1.5 l/s per room, even during non-occupancy periods. This requirement has not been analysed in the monitored dwellings as it is complex and irrelevant given the high degree of non-compliance with the CO_2 performance.

Figure 8 also shows that the average CO_2 concentrations of each room in the same dwelling vary greatly. This is why the average concentration of a dwelling should not be considered as a good indicator of its IAQ but each room should be assessed separately.

However, the average value of CO_2 concentration in each room is not the only interesting indicator. Based on the surveys of occupants' habits and the analysis of the pollutant graphs, two periods of high occupancy have been identified: in the living room from 19:00 to 00:00; and in the bedrooms from 00:00 to 08:00. The CO_2 average concentration for this periods separated by season are shown in Figure 9.

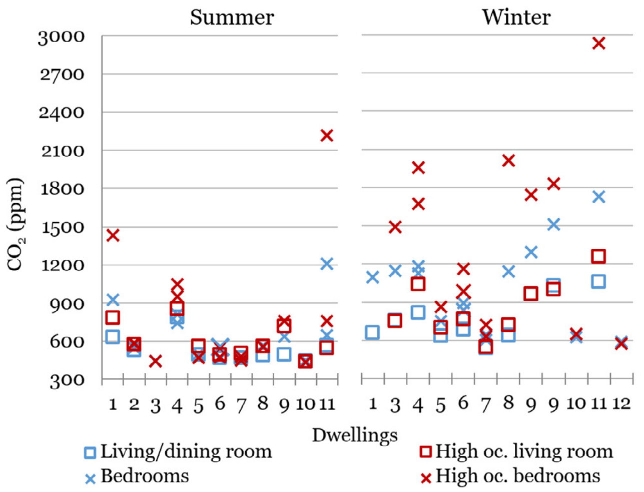

Figure 9. Average CO2 concentrations (in blue) and averages during periods of high occupancy (in red).

In summer, for the most part, there are no major differences between the overall average values and those during these periods of high occupancy, but in winter, the differences are remarkable, especially in the bedrooms, where the highest concentrations were found, as mentioned above.

This analysis highlights the difference between the average concentration of a room and the average concentration reached during the time it is occupied, which, as in the case of bedrooms, can be very high.

Figure 10 shows the average of CO_2 concentrations in winter periods. If these periods were considered for the IAQ assessment according to the average CO_2 threshold set in DB HS 3, the number of dwellings with inadequate IAQ would increase to 8, with problems generally occurring in the bedrooms and, in lesser amounts, in the living rooms.

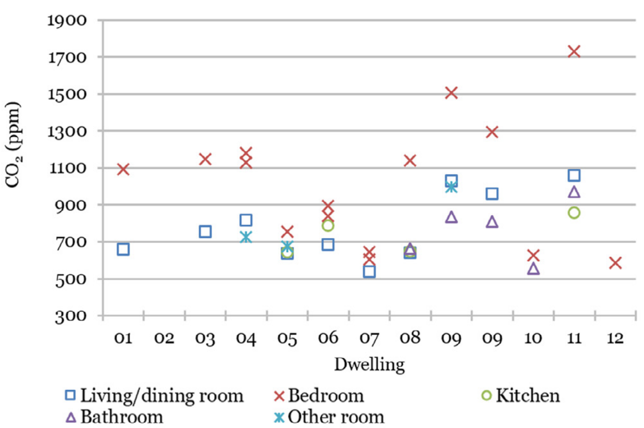

Figure 10. Average CO2 values per room in winter period.

In winter, the rooms with the worst IAQ are the bedrooms, mainly due to the greater compartmentalisation carried out by the occupants, such as closing the bedroom door. This way pollutants are concentrated in a smaller volume. In addition to this, in winter, occupants do not increase ventilation by opening doors or windows to the outside as they do in summer.

It is probably due to this high variability of ventilation depending on the occupants´ habits that we encounter particularly severe cases of average and cumulative CO_2 concentrations.

3.3. Other findings

Ventilation shafts

83% of the dwellings analysed (01, 02, 04, 05, 06, 07, 08, 10, 11 and 12) present a natural ventilation system based on exhaust shafts. Hence, the difference between indoor and outdoor temperature was expected to be one of the most relevant driving variables to influence the efficiency of ventilation and therefore, on the expected IAQ. In fact, thermal buoyancy due to the observed difference between average indoor temperature in wet rooms and outdoor temperatures (see Figure 11), could lead us to believe that a higher ventilation level would have been expected in winter rather than in summer.

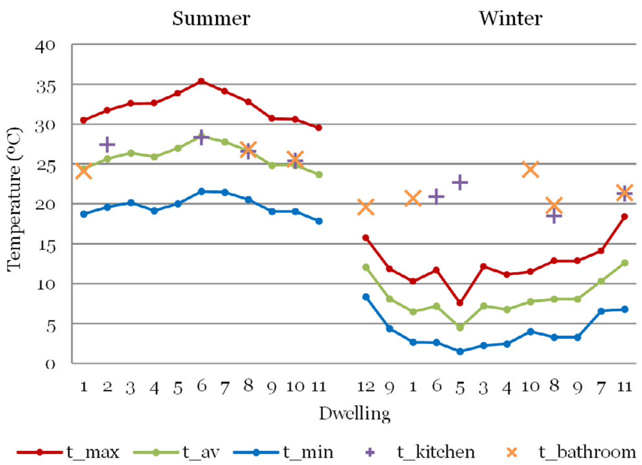

Figure 11. Averages of outdoor temperatures recorded during the measurement periods for each dwelling[1] at station 3194U - AEMET: t_max: daily maximum, t_mean: daily mean, t_min: daily minimum, and average temperatures in the kitchens and bathrooms of the dwellings.

However, monitored results of CO_2 concentration for each room reflect quite the opposite (see Figure 12): in winter, average CO_2 concentration levels are higher than in summer. The correct operation of the shafts was checked with a bell-shaped anemometer, so it was assumed that other variables might interfere with the measured efficiencies.

1 In Figure 11 the dwellings are ordered by month of measurement: from June to October in the summer graph and from October to March in the winter graph, independently of the year in which the measurements were taken, in order to better appreciate the evolution during the meteorological periods.

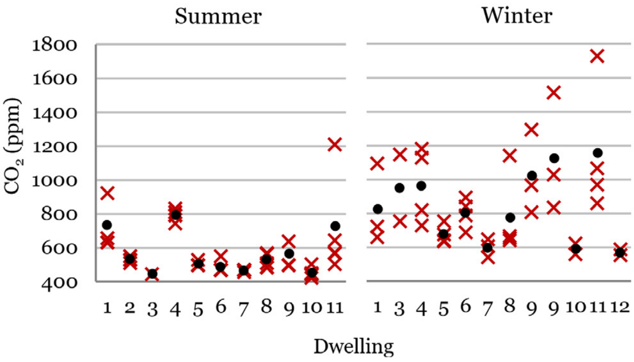

Figure 12. Average CO2 concentration in summer and in winter. Red cross: in each room. Black dot: in each dwelling.

Occupancy in the regulation

When the number of occupants is studied in relation to the number of rooms in the dwelling, it is observed that except for dwellings with 3 or fewer rooms, the distribution pattern is very similar. There is no clear relationship between the number of occupants and the number of rooms in a dwelling, so assumptions that establish occupancy as a linear function of the number of bedrooms have to be questioned.

The DB HS 3 in force from 2006 until June 2017 established an overall occupancy for dwellings depending on the number and type of bedroom: 2 persons per each double bedroom and 1 person per each single bedroom. It has been observed that this limitless estimation of the number of occupants based on the number of bedrooms was not adequate as it produced over-occupancies that did not correspond to reality. In June 2017, DB HS 3 was reviewed. The overall occupancy was reduced in a way that is consistent with the analyses carried out in this paper being more representative of reality: overall occupancy is estimated as 2 in the main bedroom and 1 in the rest of the bedrooms, up to a maximum overall number of occupants of 4, regardless of whether there are more bedrooms, whether the bedrooms can be considered double due to their size, or the ultimate purpose of their usage.

Differences between summer and winter

Significant differences were observed between the mean CO_2 concentrations of the different rooms in winter and summer. The box plot in Figure 13 shows that the summer Q_3 does not overlap with the winter Q_1.

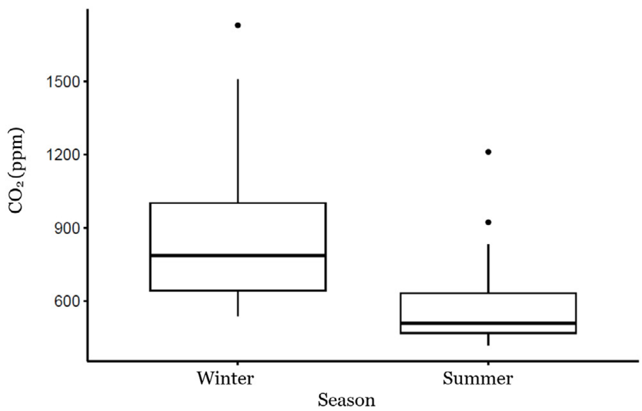

Figure 13. Box-plot for winter and summer CO_2 concentration.

These large differences observed lead to the conclusion that annual CO_2 average, in the case of natural ventilation, would not be adequate to stablish the IAQ. Instead, both periods, winter and summer, should be analysed independently to avoid that the better air quality observed in the summer period could compensate the worse concentrations in the winter periods.

Year of construction

A possible correlation has been found between the year of construction and CO_2 concentration: modern buildings have lower CO_2 concentrations. Figure 14 shows the concentration in the bedrooms (the type of room with the highest values) in winter and the year of construction.

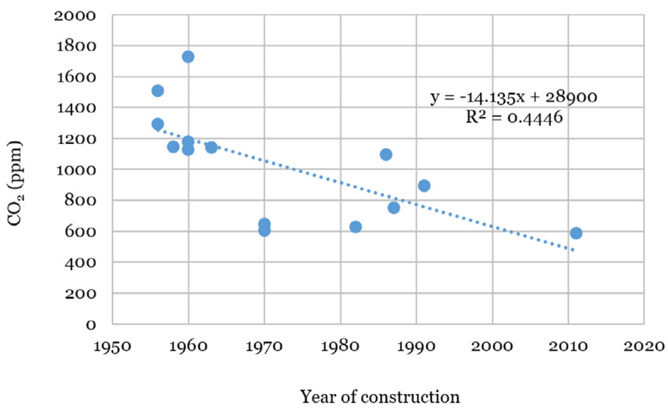

Figure 14. Average winter CO2 concentrations in bedrooms and year of construction (bedrooms of dwellings 04 and 07 have been monitored twice in winter).

The coefficient of determination of the linear fit is low, R2 = 0.44, so further studies would be necessary to elucidate whether this correlation really exists and under what conditions.

It could be thought that the relationship between year of construction and CO_2 concentration should be the opposite, assuming that the newer the building the more airtight, but the opposite relationship is observed. It is difficult to explain this fact with the collected data, but it could be possible to be due to a better efficiency of the ventilation systems of the newer buildings. In the experimental results of infiltrations tests by construction period of other authors (26), no significant differences in the values of infiltration are observed.

4. CONCLUSIONS

The analysis of the results obtained indicates that at least 50% of the monitored dwellings with predominantly natural ventilation would not be offering adequate IAQ according to the criteria based on CO_2 concentrations of the Spanish Building Code (CTE). IAQ is particularly problematic in bedrooms, where ventilation systems generally do not work properly in winter.

This poor air quality in winter can be attributed to the behaviour of the occupants. In winter, occupants take measures that compromise air quality, such as closing windows and interior doors, which concentrates pollutants in smaller spaces and hinders indoor air circulation; while in summer, on the contrary, they tend to keep doors and windows open.

The occupants seem not to be able to perceive the events of low IAQ, as there is no connection between the air quality subjectively declared in the surveys and the real situations. This discrepancy between occupants perception and monitored results were also observed by (9). They do not have the necessary fundamental knowledge neither to recognise how their ventilation system works nor how to use it correctly, as (7) points out. They often block ventilation openings and hinder infiltration, especially in cold weather, when they open their windows less often.

According to the results obtained, the IAQ requirement in CTE based on annual average values of CO_2 concentration does not seem to be the most suitable for determining air quality in natural ventilated dwellings because of the higher values detected during winter. Checking only winter CO_2 average, or both summer and winter CO_2 average, would be more appropriate from a health protection point of view for existing dwellings based mainly on natural ventilation located in the BSk (semi-arid) climate. Even further, in view of the results obtained experimentally, assessment of each room separately for average and cumulative CO_2 would be more appropriate.

Some relationship between the number of occupants, the usable floor area and the number of rooms in a dwelling can be observed, but it is not sufficiently univocal to determine the number of occupants on the basis of any of these parameters.

This exploratory study has limitations due to the nature of the sample. In future research, it is planned to increase the size of the sample in order to make the results more robust and to broaden the geographical area of application.

5. ACKNOWLEDGEMENTS

We would like to express our gratitude to the dwellings occupants who have allowed the monitoring of their homes in order to carry out these studies.

REFERENCES

(1) B. Chenari, J. Dias Carrilho, and M. Gameiro da Silva (2016). Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: A review, *Renewable and Sustainable Energy Reviews*, 59, 1426–1447, https://doi.org/10.1016/j.rser.2016.01.074.

(2) S. Emmerich, W. Dols, and J. Axley (2001). Natural Ventilation Review and Plan for Design and Analysis Tools, *National Inst. Stand. Technol.* https://www.researchgate.net/publication/239538858_Natural_Ventilation_Review_and_Plan_for_Design_and_Analysis_Tools

(3) D. Etheridge (2015). A perspective on fifty years of natural ventilation research, *Building and Environment*, 91, 51-60, https://doi.org/10.1016/j.buildenv.2015.02.033.

(4) Y. Li and A. Delsante (2001). Natural ventilation induced by combined wind and thermal forces, *Building and Environment*, 36(1), 59-71, https://doi.org/10.1016/S0360-1323(99)00070-0.

(5) M. Domínguez-Pérez, J. Leal-Maldonado, and M. Barañano-Cid (2021). Vivienda, transformaciones urbanas y desigualdad socioespacial en las grandes ciudades españolas, *Ciudad y Territorio Estudios Territoriales*, 53(Monográfico 2021), 5-12, https://doi.org/10.37230/CyTET.2021.M21.00.

(6) Ministerio de Vivienda (2022). Documento Básico HS Salubridad. Sección HS 3: Calidad del aire interior, in *Código Técnico de la Edificación*, 2017th ed. Gobierno de España, 2006. Accessed: Mar. 01, 2023. [Online]. Retrieved from https://www.codigotecnico.org/pdf/Documentos/HS/DBHS.pdf.

(7) C. Dimitroulopoulou (2012). Ventilation in European dwellings: A review, *Building and Environment*, 47, 109–125, https://doi.org/10.1016/j.buildenv.2011.07.016.

(8) G. McGill, L. O. Oyedele, and K. McAllister (2015). Case study investigation of indoor air quality in mechanically ventilated and naturally ventilated UK social housing, *International Journal of Sustainable Built Environment*, 4(1), 58–77, https://doi.org/10.1016/j.ijsbe.2015.03.002.

(9) F. de Frutos *et al.* (2021). Indoor Environmental Quality and Consumption Patterns before and during the COVID-19 Lockdown in Twelve Social Dwellings in Madrid, Spain, *Sustainability*, 13(14), 7700, https://doi.org/10.3390/su13147700.

(10) M. Á. Navas-Martín and T. Cuerdo-Vilches (2023). Natural ventilation as a healthy habit during the first wave of the COVID-19 pandemic: An analysis of the frequency of window opening in Spanish homes, *Journal of Building Engineering*, 65, 105649, https://doi.org/10.1016/j.jobe.2022.105649.

(11) A. Persily (2015). Challenges in developing ventilation and indoor air quality standards: The story of ASHRAE Standard 62, *Building and Environment*, 91, 61–69, https://doi.org/10.1016/j.buildenv.2015.02.026.

(12) G. Guyot, I. Walker, M. Sherman, P. Linares, S. Garcia-Ortega, and S. Caillou (2019). VIP 39: A review of performance-based approaches to residential smart ventilation. Accessed: Feb. 27, 2023. [Online]. Retrieved from https://www.aivc.org/resource/vip-39-review-performance-based-approaches-residential-smart-ventilation.

(13) G. Guyot, I. S. Walker, and M. H. Sherman (2019). Performance based approaches in standards and regulations for smart ventilation in residential buildings: a summary review, *International Journal of Ventilation*, 8(2), 96–112, https://doi.org/10.1080/14733315.2018.1435025.

(14) M. Sandberg (1981). What is ventilation efficiency?, *Building and Environment*, 16(2), 123-135, https://doi.org/10.1016/0360-1323(81)90028-7.

(15) A. Persily and L. de Jonge (2017). Carbon dioxide generation rates for building occupants, *Indoor Air*, 27(5), 868–879, https://doi.org/10.1111/ina.12383.

(16) W. F. de Gids and P. Wouters (2010). VIP 33: CO2 as indicator for the indoor air quality - General principles, Accessed: Feb. 27, 2023. [Online]. Retrieved from https://www.aivc.org/resource/vip-33-co2-indicator-indoor-air-quality-general-principles.

(17) A. Persily (2022). Carbon Dioxide in Ventilation and IAQ Evaluation, in *AIVC Technical Note 70 40 years to build tight and ventilate right: From infiltration to smart ventilation*, in AIVC Technical Note, no. 70. INIVE EEIG, pp. 55–58.

[Online]. Retrieved from https://www.aivc.org/resource/tn-70-40-years-build-tight-and-ventilate-right-infiltration-smart-ventilation.

(18) X. Zhang, A. Mishra, and P. Wargocki (2022). Effects from Exposures to Human Bioeffluents and Carbon Dioxide, in *Handbook of Indoor Air Quality*, Y. Zhang, P. K. Hopke, and C. Mandin, Eds., Singapore: Springer, pp. 1–12. https://doi.org/10.1007/978-981-10-5155-5_63-1.

(19) B. Li and W. Cai (2022). A novel CO_2-based demand-controlled ventilation strategy to limit the spread of COVID-19 in the indoor environment, *Building and Environment*, 219, 109232, https://doi.org/10.1016/j.buildenv.2022.109232.

(20) X. Lyu, Z. Luo, L. Shao, H. Awbi, and S. Lo Piano (2023). Safe CO2 threshold limits for indoor long-range airborne transmission control of COVID-19, *Building and Environment*, 234, 109967, https://doi.org/10.1016/j.buildenv.2022.109967.

(21) S. Garcia-Ortega and P. Linares-Alemparte (2017). Pollutant exposure of the occupants of dwellings that complies with the Spanish indoor air quality regulations, Accessed: Feb. 27, 2023. [Online]. Retrieved from https://www.aivc.org/resource/pollutant-exposure-occupants-dwellings-complies-spanish-indoor-air-quality-regulations.

(22) INE (2013). Censos de Población y Viviendas 2011. Accessed: Dec. 12, 2016. [Online]. Retrieved from http://www.ine.es/censos2011_datos/cen11_datos_inicio.htm.

(23) H. E. Beck, N. E. Zimmermann, T. R. McVicar, N. Vergopolan, A. Berg, and E. F. Wood (2018). Present and future Köppen-Geiger climate classification maps at 1-km resolution, *Sci Data*, 5, 180214, https://doi.org/10.1038/sdata.2018.214.

(24) AICIA (2009). Condiciones de aceptación de procedimientos alternativos a LIDER y CALENER | IDAE. IDAE, Ministerio de Vivienda, Goberment of Spain. Accessed: Mar. 08, 2023. [Online]. Retrieved from https://www.idae.es/publicaciones/condiciones-de-aceptacion-de-procedimientos-alternativos-lider-y-calener

(25) Agencia Estatal de Meteorología, Agencia Estatal de Meteorología - AEMET. Gobierno de España. https://www.aemet.es/es/portada (accessed Aug. 14, 2023).

(26) J. Feijó-Muñoz, A. Meiss, I. Poza-Casado, and M.-Á. Padilla-Marcos (2018). *Permeabilidad al aire de los edificios residenciales en España. Estudio y caracterización de sus infiltraciones*. Accessed: Jul. 29, 2023. [Online]. Retrieved from https://www.researchgate.net/publication/331346742_Permeabilidad_al_aire_de_los_edificios_residenciales_en_Espana_Estudio_y_caracterizacion_de_sus_infiltraciones.