Indoor environmental quality in social housing with elderly occupants in Spain: Measurement results and retrofit opportunities.

Abstract

Elderly people usually spend more than 80% of their daily lives in apartments that mostly belong to obsolete buildings with reduced spaces and inadequate indoor environmental quality, which may lead to tiredness and other adverse health symptoms. In an attempt to evaluate indoor environmental quality and identify the main influencing factors of social housing occupied by the elderly in the Mediterranean climate, this research develops a monitoring campaign covering different seasons to characterise temperature, relative humidity, and carbon dioxide concentrations, which are directly associated with the presence of potential air pollutants, in multi-family apartments that only depend on natural ventilation, representing the social housing patterns in Spain. The results contribute a detailed diagnosis of the indoor environmental quality under diverse scenarios, and highlight that elderly occupants frequently suffer from unhealthy carbon dioxide concentrations, above the 900-ppm recommended average value in indoor air guidelines, and from temperature values outside the established comfort range. The discussion shows the advantageous character of ventilation patterns during sleeping periods, with a 2,000-ppm reduction between certain scenarios. Additionally, retrofit opportunities are identified by diagnosing the influence of the building typology, occupation, climate conditions, air infiltration rates, and occupant behaviour, and holistic implications are provided to promote efficient urban regeneration. The conclusions indicate that ventilation habits and future energy renovation strategies should deal with the sick building syndrome by avoiding high airtightness of insulation solutions through moving towards healthier housing stock and should provide policy implications that promote efficient renovation proposals for ageing in place.

Keywords

Indoor air guideline values; Mediterranean climate; Elderly occupants; Renovation opportunities; Ventilation patterns.

1. Introduction

The World Health Organization (WHO) aims to adapt the existing housing stock to the new requirements and demands arising from the ageing of the global population [1]. This is especially relevant in Europe, where there is progressive growth in the number of elderly people. It is expected that 34% of the global population will be over 60 years old by 2050 [2]. Furthermore, the housing stock in European cities is also ageing, since over 40% of residential buildings in Europe were built prior to 1960, and more than 80% are over 20 years old [3].

The growth and expansion of cities throughout the 20th century generated housing typologies with small spaces that currently remain inhabited without complying with many basic requirements in terms of habitability, security, and comfort [4,5]. The United Nations [6] also warns of the global importance of urban regeneration in an efficient and sustainable way that would allow buildings to be adapted to the new demographic demands of the 21st century [7,8]. Urban, social, and health policies are promoting the "ageing at home" or “ageing in place” concept, which promotes a higher quality of life for the elderly in their usual residential environment through renovation proposals that would adapt and improve indoor and outdoor living conditions [9,10].

According to Almeida-Silva et al. [11], it is estimated that the elderly spend approximately 22 hours per day inside their homes, mainly in the bedroom and the living room, which highlights the importance of studying the thermal comfort and CO_2 environmental quality in these rooms, since they have been shown to directly affect residents’ well-being and health [12,13]. Heracleous and Michael [14] stated that efforts in energy retrofitting should also consider optimizing ventilation rates to avoid adverse health effects on residential built environments. In addition, Fan et al. [15] demonstrated the beneficial effects for health and comfort, especially for the elderly, of having adequate indoor temperatures, in a range of 22 ºC to 26 ºC, since they consequently improve the indoor environmental quality. Canha et al. [16] evaluated the indoor air quality in a bedroom through four different ventilation scenarios during the sleeping period, related to patterns of door and window use. The results showed significant variations in CO_2 levels that exceeded indoor air guideline values (IAGVs). Therefore, the elderly, who usually live in reduced spaces for long periods, can experience harmful concentrations of carbon dioxide, temperature, relative humidity, and other pollutants, which require appropriate ventilation patterns and efficient retrofitting actions [17,18].

Various studies have observed that high CO_2 concentration levels are directly associated with high concentrations of air pollutants in indoor environments [19,20]. The reference value of external CO_2 concentration ranges between 300 and 500 parts per million (ppm), although CO_2 levels are now constantly rising due to climate change [21]. In fact, certain urban areas of large cities have reached average values of over 500 ppm due to low air purification and the low presence of vegetation [22]. According to medical reports, CO_2 concentrations of any occupied indoor space with a good air exchange should not exceed the range 800 to 1,000 ppm [23,24]. In the case of exceeding this recommended limit, CO_2 concentrations between 1,000 and 2,000 ppm are considered as air of poor quality, and capable of causing certain health complaints and drowsiness. Strøm-Tejsen et al. [25] and Zhu et al. [26] showed that reaching high levels of CO_2 or high temperatures at sleeping time in the bedroom could affect not only sleeping quality and calmness but also the levels of concentration during the day. Levels between 2,000 and 5,000 ppm are considered to indicate stagnant and stale air that cause the appearance of headaches, loss of attention, and increasing heart rate [16]. Finally, for those extreme cases in which the levels are higher than 5,000 ppm, it is not recommended to remain for a long time since the consequences may worsen, and may even cause brain damage [27].

At a legislative level, several countries have, in recent years, specified certain limits of CO_2 indoor concentrations for non-residential buildings [28,29]. French regulation [30] limits the average to 1,000 ppm for occupation periods, and allows a maximum of 1,300 ppm. Portuguese legislation also limits CO_2 to a concentration of 984 ppm [31], with a margin of 10% in accordance with occupation levels, although this has been subsequently increased to an average of 1,250 ppm [32]. There is a strict regulation for non-residential buildings to obligatorily incorporate mechanical extractors to guarantee suitable levels of CO_2. Indoor levels in offices, schools, and hospitals are considered covered through mechanical ventilation [33,34]. Nevertheless, the real values move away in some cases from those suggested or stipulated in regulations. According to Persily and de Jonge [35], offices usually have an average concentration of 568 ppm above that of outdoors, although they can reach up to 2,000 ppm depending on the type of occupation, physical activity, and room; Stafford [36] stated that mean values in schools during classes exceed 1,000 ppm, and reach a maximum of 3,000 or 4,000 ppm in certain circumstances.

Regarding residential buildings, there are many countries with no strict regulations related to indoor CO_2 concentrations and in which mechanical ventilation is not mandatory [37,38]. In Spain, where this study is performed, minimum ventilation rates are required in new buildings through hybrid ventilation systems, which combine natural and mechanical systems. Maximum annual mean values of CO_2 concentrations have been established at 900 ppm, limiting maximum peaks values at 1600 ppm, by official regulations on ventilation for residential buildings [39] and indoor comfort levels in residential spaces have been set at between 22 ºC and 26 ºC for temperature and 55% for relative humidity [40].

However, the majority of existing buildings belonging to the housing stock, especially those built prior to 1980, have no mechanical devices and depend only on natural ventilation through apertures and windows, which can cause a major problem if air filtration rates are reduced with energy retrofitting measures and depend solely on occupant behaviour [41,42].

All of these previous studies show the importance of considering indoor air quality in the residential built environment. However, there is a lack of specific studies that diagnose the social housing situation from the second half of the 20th century, which is generally occupied by elderly people. Thus, the innovation of this study arises on the assessment of indoor air environmental quality of living spaces occupied by the elderly in the Mediterranean climate, with the purpose of identifying needs, influential factors, and retrofit opportunities in order to promote sustainable and healthier urban regeneration of housing stock.

This research develops indoor air measurements in three residential apartments that belong to different reference multi-family buildings, built more than forty years ago. Temperature, relative humidity, and CO_2 levels in living rooms and main bedrooms are characterised during two entirely different seasons, winter and spring, in an effort to verify the climatic impact on the indoor environmental performance throughout the year. Occupation rates and ventilation patterns of the occupants are also registered.

This study provides a detailed diagnosis of the indoor environmental quality before the implementation of housing renovation proposals, and a diagnosis of its impact on health and well-being that exceeds certain limits. The results are assessed with respect to IAGVs as defined in various reports and regulations, and lead to a discussion regarding the influence of the building typology, occupation, building envelope, climate conditions, and ventilation patterns, thereby identifying opportunities for improvement and providing holistic renovation implications to prevent airtightness and unhealthy spaces.

The manuscript is structured as follows. First, the selected case studies are defined, including their characterisation and data collection procedures, and then the monitoring campaign is explained. Second, the results are provided and assessed, and are organised in terms of data on living rooms and main bedrooms as well as on both seasons. Finally, average, minimum, and maximum values are discussed, and the hourly evolution is displayed in order to identify general and specific conclusions from the various cases and seasons. These provide practical perspectives and environmental implications for the improvement of the quality of life of this vulnerable population and promote efficient urban regeneration.

2. Materials and methods

A general outline of the characterisation and measurement developed in this research is shown in Figure 1. The framework focuses on multi-family buildings in the Mediterranean climate belonging to the existing social housing stock, mostly built before 1980 that contain reduced spaces and require renovation actions. The research is focused on studying the impact on elderly people, and the influence of ventilation patterns and long periods of occupation on indoor environmental quality.

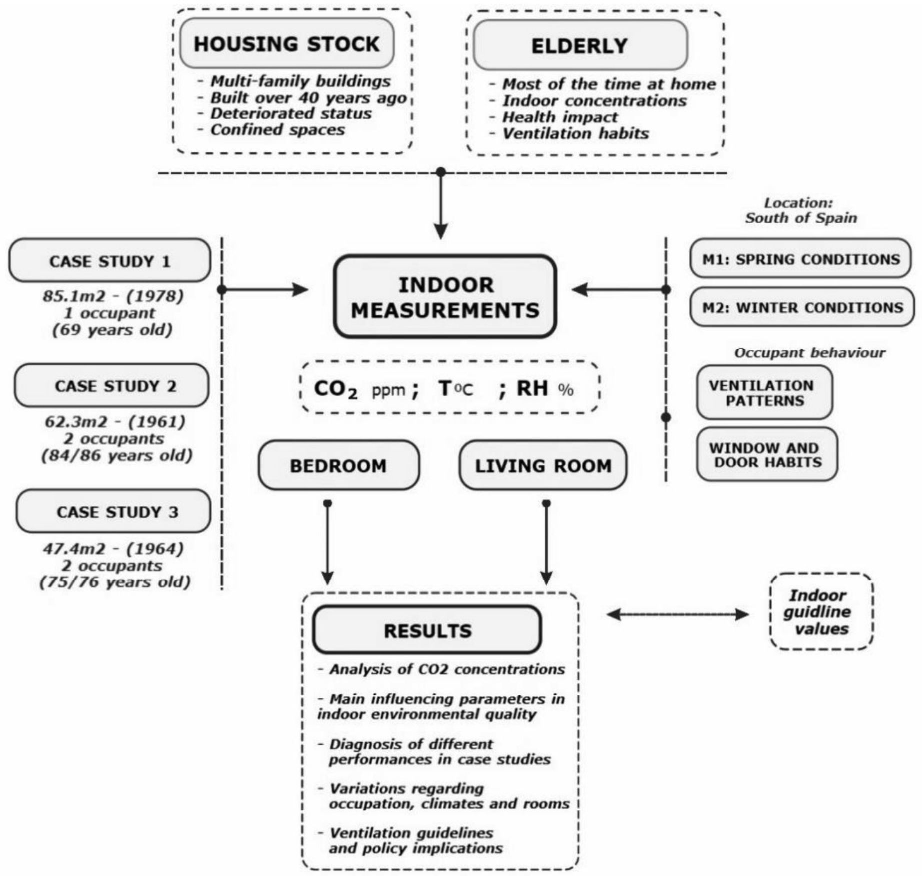

Figure 1. General outline of the research

2.1. Characterisation of case studies

Three reference multi-family apartments located in Southern Spain were selected as case studies in the Mediterranean climate. The apartments present reference design patterns for social housing built between 1960 and 1980, with a total surface between 45 and 85m^2 and reduced dimensions in their main rooms.

Figure 2 illustrates the distribution layout of the three apartments, which are also characterised in Table 1, with identification of the number, gender, and age of the occupants in the bedroom (BR) and living room (LR) for each case study.

All cases present a regular distribution, with approximately the same area per room. Case 1 presents the largest surface area, with four bedrooms, and Cases 2 and 3 are smaller and have three and two bedrooms respectively. The main uses are represented in different colours, the selected bedroom and living room for the measurement are marked with a dashed line, and the exact location where the measuring equipment was placed is indicated by an isolated red dot. The height of the measuring point was fixed at 1.20m.

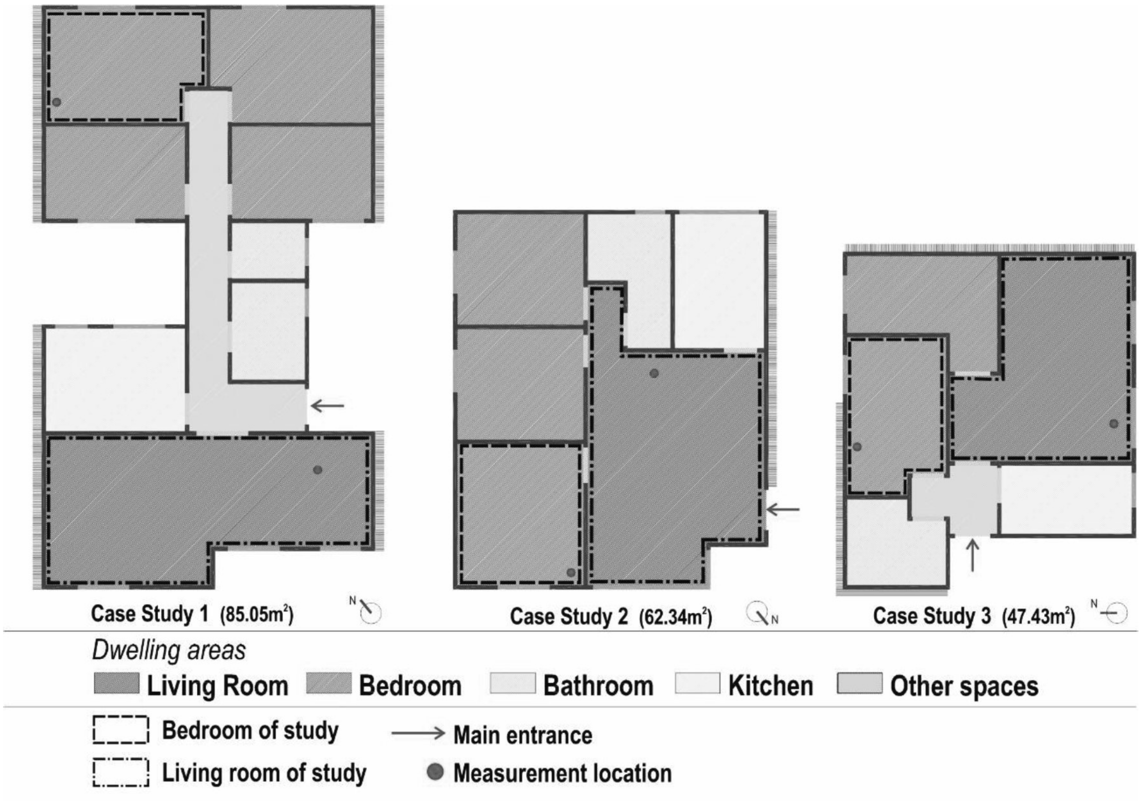

Figure 2. Floor distribution and measuring information of the three case studies

Table 1. Characterisation of dwellings and occupants of each case study

Case Study	**Apartment**								**Occupants**			
	Year	Floor	N. of bedr.	Total area (*m²*)	Area of study (*m²*)		Volume of study (*m³*)		Number		Gender	Age
					BR	*LR*	*BR*	*LR*	*BR*	*LR*		
CS-1	1978	1st	4	85.1	10.1	24.3	25.8	62.1	1	1	Female	68
CS-2	1961	Ground	3	62.3	10.4	23.5	24.3	55.2	2	2	Male Female	85 83
CS-3	1964	3rd (upper)	2	47.4	8.7	18.0	21.2	44.0	2	2	Male Female	75 74

All these selected cases represent reference social housing apartments with reduced dimensions that generate confined residential environments in their daily use. In fact, the main bedrooms are commonly of less than ten square metres, and in the case of the living rooms, the surface barely exceeds twenty square metres. The height of these apartments is also low, lying in a range of between 2.35 and 2.55 metres. Furthermore, these apartments are located on the ground or first floor, except CS-3, which is located on the top floor, under the roof of the building. Regarding the occupants, all residents are over 65 years old, composed of one widow (CS-1) and two married couples (CS-2/3), with 68 years old as the minimum age and 85 years old as the maximum.

Table 2 characterises the composition and the thermal performance of the façade and windows in the three cases, and also the local heating and sanitary hot water (DWH) systems for these apartments. Each case study is accompanied by a transmittance value (U) and permeability (P) for the windows. Table 3 also defines the number, size, opening, and area of windows in the selected rooms of study and the general ventilation system in each case study, and specifically describes the ventilation in kitchens and bathrooms.

Table 2. Thermal characterisation of case studies

Case Study	Façade		Windows			Heating	SHW
	Main composition	U (W/m²·K)	Type	U (W/m²·K)	P_{window} (m³/h·m²)	General System	System (*Location*)
CS-1	Solid brick (12cm) + air chamber (4cm) + ceramic partition (7cm)	2.45	Single-glazed - wood	4.10	≥80	No[1]	Gas boiler (Kitchen)
CS-2	Solid brick (24cm)	3.65	Single-glazed - metallic	5.70	≥80	No[1]	Gas boiler (Kitchen)
CS-3	Solid brick (12cm) + air chamber (3cm) + ceramic partition (5cm)	2.82	Double-glazed - aluminium	3.40	≤50	No[1]	Electric boiler (Bathroom)

[1] Temporary use of local heating system based on electric radiators (Joule effect)

Table 3. Characterisation of windows and ventilation systems of case studies

Case Study	Windows										Ventilation
	Living room					Bedroom					
	N.	Sizes (*m x m*)	Open.	Area (*total m²*)	Ratio (*wind/room*)	N.	Sizes (*m x m*)	Open.	Area (*total m²*)	Ratio (*wind/room*)	Type (*General system/Kitchen/Bathroom*)
CS-1	3:	1.20x1.00	Hinged	3.60	0.15	1:	1.30x1.15	Hinged	1.50	0.15	Infiltration and natural openings[1] K: Window and extractor hood[2] B: Window openings
CS-2	2:	1.20x1.20	Sliding	2.88	0.12	1:	0.90x1.20	Sliding	1.08	0.10	Infiltration and natural openings[1] K: Window and extractor hood[2] B: Window openings
CS-3	2:	1.20x1.00	Hinged	2.40	0.13	1:	0.90x1.20	Sliding	1.08	0.12	Infiltration and natural openings[1] K: Window and extractor hood[2] B: Local extractor fan[3]

[1] Dwellings without mechanical ventilation systems. Ventilation is only produced due to infiltration and window openings.
[2] Extractor hood whose use is temporary and limited to the times of day when occupants are cooking.
[3] Local extractor fan in bathroom whose use is temporary. Its operation is active when the bathroom light is turned on.

The thermal envelope has no specific insulating materials and, in certain cases, the windows present single glazing and very high levels of air permeability. These transmittance values are far above the minimum required in current thermal regulations for residential buildings [40]. CS-3 has replaced the windows in recent years, and therefore its transmittance and permeability values are lower, which causes a higher airtightness inside the room. Regarding heating and domestic hot water production, Table 2 defines the use in the three cases of local heating systems based on electric radiators, which generates no additional CO_2 production, and in Case 1 and 2 there are gas boilers for domestic hot water located in the kitchen, which could generate a small additional amount of CO_2 in the apartment.

Furthermore, it should be noted in Table 3 that none of these apartments have mechanical ventilation systems, and hence airflows are only obtained through infiltration and window openings. In fact, there is a reduced ratio in the area of windows with respect to the floor area of the room, of approximately 10 and 15%, with some sliding windows which reduce the opening surface for the airflow renovation. As for the interior doors, they are not sealed around the perimeter in any of the cases, not even at the bottom face. Therefore, in cold or hot periods, where windows are completely closed, ventilation air flow is characterised only by infiltration leakage, whose value can be defined by an air change rate (ACH) of between 5.6 per hour and 9.4 per hour (n50), according to previous studies of the building stock built in the 1960s, 1970s, and 1980s in southern Europe, as reported by Escandón et al. [43] and Lizana et al. [44].

2.2. Monitoring campaign

This study has been performed over two separate measurement periods, one during spring conditions, carried out in March and April, and another during winter conditions, carried out in December and January, in order to compare the effectiveness of natural ventilation and the influence of occupant behaviour on the indoor environmental quality in a warm season and in a cold season of the year. The measurement was carried out by simultaneously using two sets of equipment for each apartment, one for the living room and the other for the main bedroom. It was organized sequentially between the three case studies, thereby establishing a fixed time for each apartment of at least 48 continuous hours during weekdays, taking into account that the users' occupancy in their apartments exceeded 80% of the daily time, in order to monitor the standard daily operation for each 24 hours [45]. Permission for the measurement was previously obtained from the occupants, and the purpose and phases of this study were explained. The occupants were also asked to carry out their normal daily lives in their homes and not to make any unusual variations during those days of measurement.

Table 4 characterises the equipment that was used in the measurement of the living room and of the main bedroom of each apartment, both of the same model. The data collection was taken at two-minute intervals during the 48 hours of measurement during weekdays (Monday to Friday) in each case study.

Table 4. Characterisation of the measuring equipment

Equipment	Measuring interval	Duration	Variables	Limit range	Accuracy
Delta OHM HD 21ABE17	2 minutes	2 days – 48h (continuous monitoring)	CO_2 Carbon Dioxide (ppm) Temperature (ºC) Relative humidity (%)	0…5,000 ppm -20…+60 ºC 0…100 % RH	±50ppm ±0.2 ºC ±2% RH

The outdoor CO_2 levels, temperature, and relative humidity during the measurement were taken as those given in the records of the city obtained from the State Agency of Meteorology [46]. The average, maximum, and minimum temperature values were obtained for each season, as were the average outside CO_2 values and relative humidity.

Once the measurement was completed, the occupants of each case study answered a short questionnaire regarding the use of windows and doors and way of living during the measurement. This information was useful in the identification of the various ventilation patterns during the day and night, by defining scenarios related to the conditions of closing (CD) or opening (OD) doors in bedrooms and living rooms and by specifying how often they tended to open the windows for ventilation. Ventilation patterns regarding opening windows were much less frequent in winter than under spring conditions.

Finally, these answers also included information regarding the hours when the apartment was unoccupied. This information was useful in confirming that the occupants were mostly in their apartments during the two days of measurement, following the previously explained habit of spending approximately 80% of the day inside their homes.

3. Results

The results of the indoor measurements carried out in the three apartments are summarised in Tables 4 and 5, for the spring and winter seasons respectively. The values are structured in terms of the living room and main bedroom. The principal data regarding the outdoor conditions during the measurement days for each case study is also displayed [46].

Each table characterises the indoor conditions during the measurement, and offers information about the operating scenario in terms of open (O) or closed (C) windows (W) and doors (D) in the main bedroom and the living room. Regarding the indoor CO_2 concentrations and temperature, each table presents the mean values (Mean), the standard deviations (SD), the minimum values (Min.), and the maximum values (Max.). Finally, regarding relative humidity, the mean, minimum, and maximum values are also defined.

Table 5. Summary table of the results obtained under spring conditions

Case Study	Indoor Conditions	CO_2 (ppm)				Temperature (ºC)				Relative Humidity (%)		
		Mean [1]	SD [1]	Min.	Max.	Mean	SD	Min.	Max.	Mean	Min.	Max.
OUTDOORS												
CS-1	-	389	-	-	-	12.6	-	7.4	17.2	36.0	-	-
CS-2	-	387	-	-	-	11.8	-	7.2	15.4	38.9	-	-
CS-3	-	395	-	-	-	17.3	-	13.2	24.9	44.7	-	-
LIVING ROOM												
CS-1	CW-OD	600	133	401	1102	18.7	0.3	15.4	19.9	49.8	42.1	54.5
CS-2	CW-OD	659	170	389	1097	13.4	0.5	12.4	14.0	61.8	48.6	72.0
CS-3	CW-CD	649	161	410	1092	22.2	0.7	21.5	23.6	58.8	50.5	64.3
BEDROOM												
CS-1	CW-OD	747	164	408	1115	17.2	0.2	15.7	17.6	58.4	52.4	61.9
CS-2	CW-OD	665	194	400	1148	14.9	0.4	14.1	15.6	56.1	44.3	68.4
CS-3	CW-CD	1687	1438	456	4623	22.2	0.5	21.4	22.9	67.1	53.1	82.8

[1] Mean and SD values obtained for the entire measurement period.

Table 6. Summary table of the results obtained under winter conditions

Case Study	Indoor Conditions	CO_2 (ppm)				Temperature (ºC)				Relative Humidity (%)		
		Mean [1]	SD [1]	Min.	Max.	Mean	SD	Min.	Max.	Mean	Min.	Max.
OUTDOORS												
CS-1	-	381	-	-	-	10.6	-	4.1	14.4	54.5	-	-
CS-2	-	386	-	-	-	9.3	-	1.7	14.8	56.3	-	-
CS-3	-	391	-	-	-	10.4	-	2.1	16.6	61.6	-	-
LIVING ROOM												

CS-1	CW-OD	829	219	475	1273	15.8	0.4	14.2	16.9	54.5	43.1	58.5
CS-2	CW-OD	925	244	455	1982	14.5	0.5	13.7	15.5	60.1	51.6	64.9
CS-3	CW-OD	1230	185	828	1758	17.7	0.9	16.2	19.4	65.7	55.8	71.8
BEDROOM												
CS-1	CW-OD	864	178	383	1391	14.5	0.2	11.7	14.7	59.4	48.3	64.3
CS-2	CW-OD	953	269	437	1728	14.3	0.6	13.0	15.1	61.5	50.4	66.6
CS-3	CW-OD	1384	447	481	2551	17.0	0.7	15.3	17.7	68.5	57.2	75.4

[1] Mean and SD values obtained for the entire measurement period.

The graphical display of these results, obtained for the living room or main bedroom during two different seasons, are shown in subsections 3.1. and 3.2. The data presented in the following subsections generates a detailed discussion of each use of the dwelling in Section 4. The CO_2 and temperature values are represented through time evolution and the relative humidity is equally considered in the discussion of the results.

3.1. Living room

Figures 3, 4, and 5 present the results obtained in the living room for the measurements taken during the spring. Figure 3 shows the average, minimum, and maximum CO_2 values for each case study, while Figures 4 and 5 show the time evolution of the CO_2 levels and temperature within the 48 hours of measurement. In the case of the living room, the CO_2 values remain below 2,000 ppm in every case, and hence the display range has been adjusted to lie between 0 and 2,000 ppm and, in the case of temperature, a range between 10 and 25°C is established.

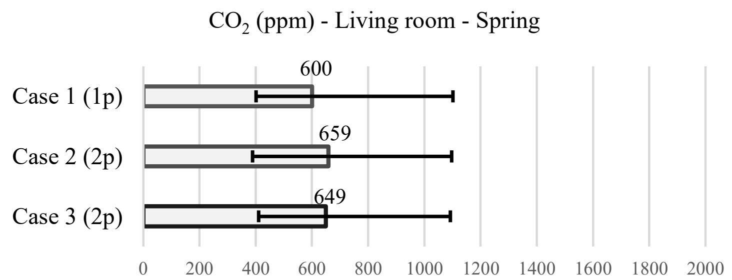

Figure 3. Display of average, minimum, and maximum CO_2 values under spring conditions

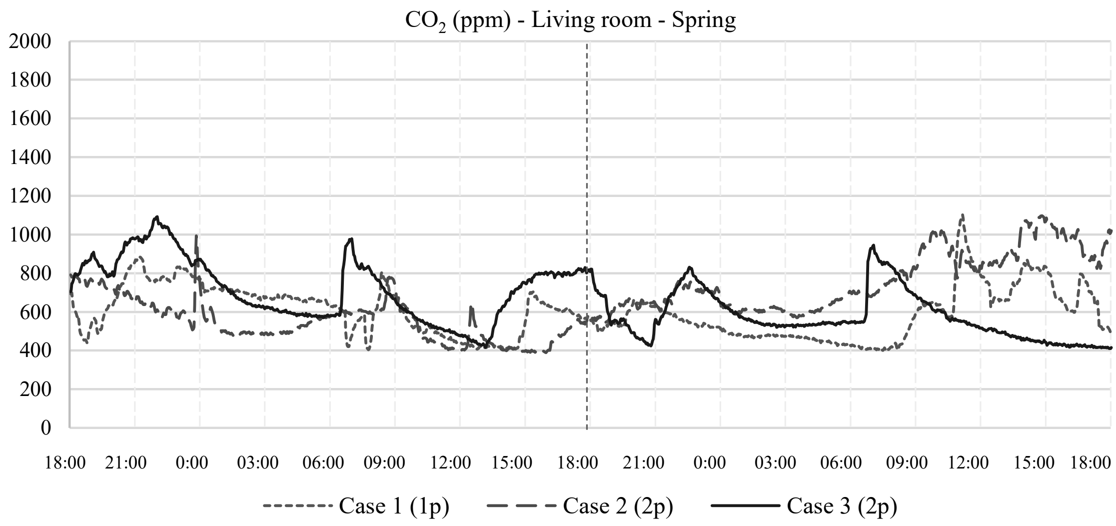

Figure 4. Hourly evolution of CO_2 levels under spring conditions

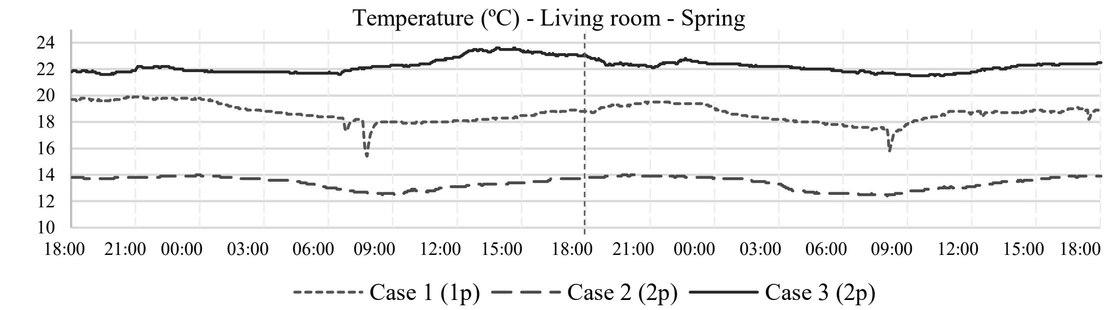

Figure 5. Hourly evolution of temperature under spring conditions

Following the same structure, Figures 6, 7, and 8 present the results obtained in the living room during the winter season, in December and January. The display range is the same for the previous CO_2 levels as well as for the temperature range.

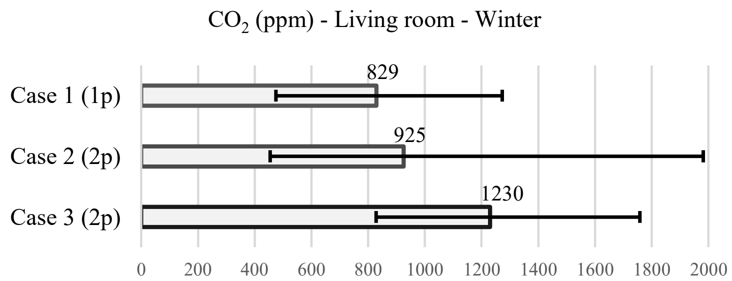

Figure 6. Display of average, minimum, and maximum CO_2 values under winter conditions

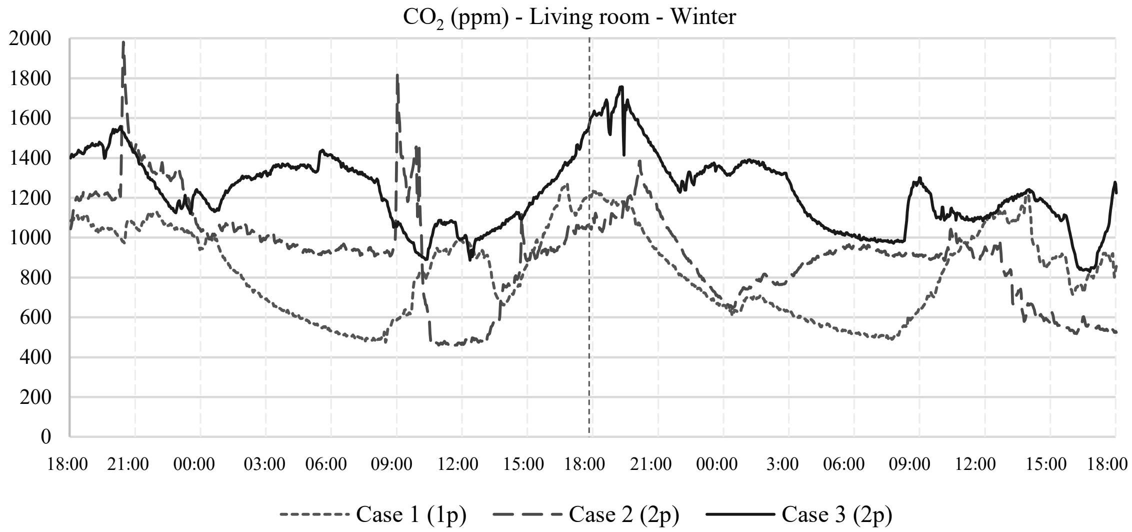

Figure 7. Hourly evolution of CO_2 levels under winter conditions

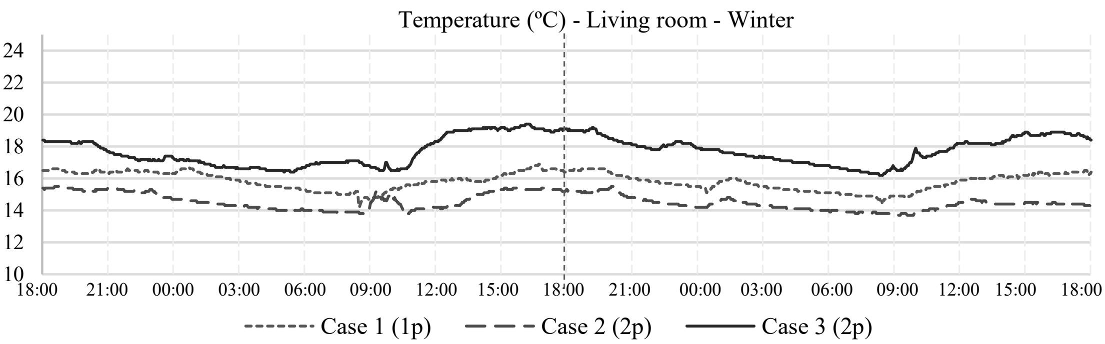

Figure 8. Hourly evolution of temperature under winter conditions

Although these results are discussed in further detail in Section 4, the main variation arises from the large increase in CO_2 levels within the winter period. Both the average and maximum values are much higher and there are major elevations in the CO_2 levels in the hourly evolution, which reach up to 2,000 ppm. In fact, the hourly evolution in spring presents generally more stable levels at around 1,000 ppm. Furthermore, the indoor temperature drops an average of about 5 ºC or 6 ºC in the winter season with respect to spring, with average indoor temperatures of around 15 ºC, which implies a high degree of discomfort with respect to the comfort temperature range and leads the occupants to ventilate less during winter, thereby increasing the indoor CO_2 concentrations. Lastly, since there is no general heating system in these social dwellings, and only electric local heating devices are available in the living room, there are temperature fluctuations of 3 ºC or 4 ºC in the living room between day and night.

3.2. Bedroom

In this subsection, the results obtained in the bedroom measurements during spring and winter are shown in Figures 9 to 14. These figures represent the same sequence as that defined in subsection 3.1. for the living room. However, due to the high CO_2 concentrations reached in the bedroom in certain cases, the display range of CO_2 has been adjusted to represent concentrations between 0 and 5,000 ppm, which allows visualization of the jumps and variations in these results.

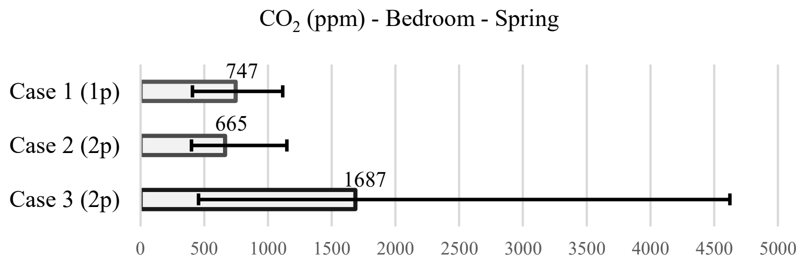

Figure 9. Display of average, minimum, and maximum CO_2 values under spring conditions

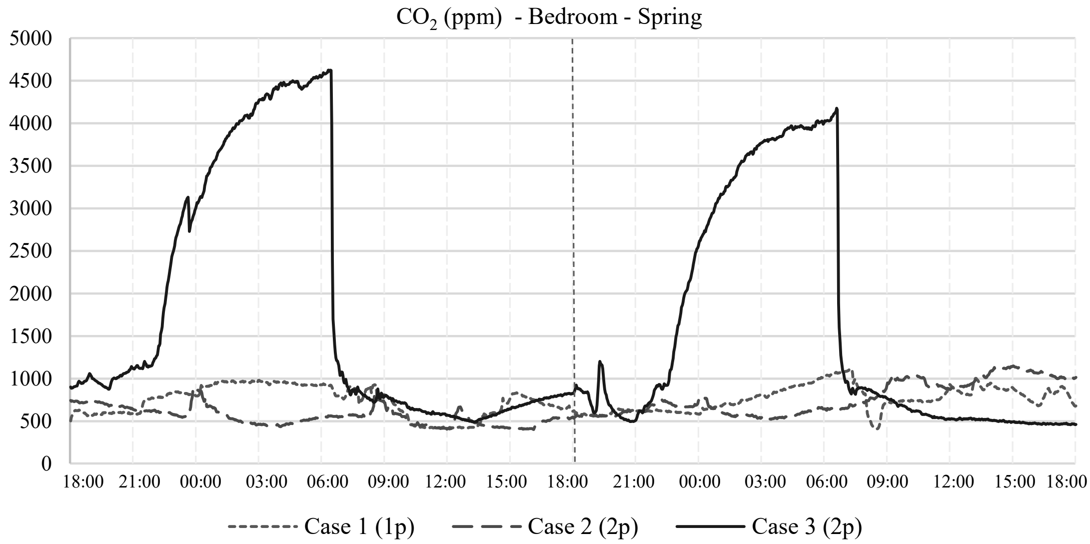

Figure 10. Hourly evolution of CO_2 levels under spring conditions

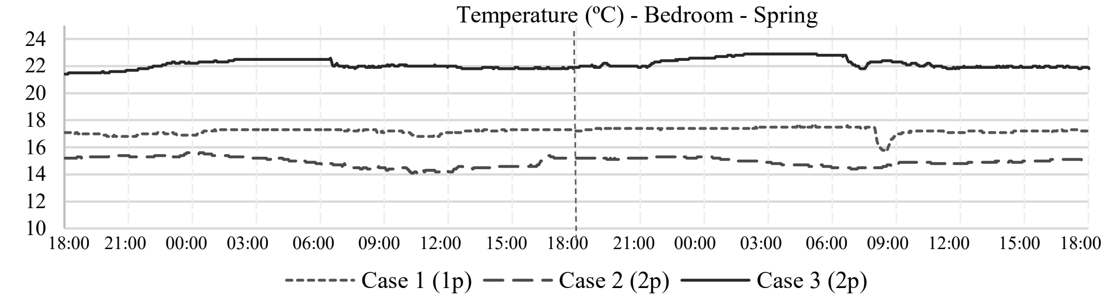

Figure 11. Hourly evolution of temperature under spring conditions

Likewise, Figures 12, 13, and 14 show the measurement carried out in the bedroom during the winter, in which the display range of the results has remained similar to that of the immediately preceding figures.

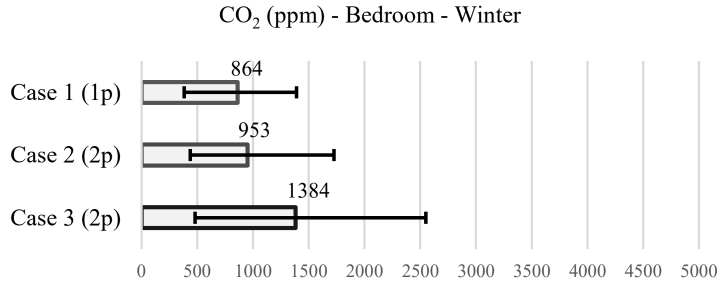

Figure 12. Display of average, minimum, and maximum CO_2 values under winter conditions

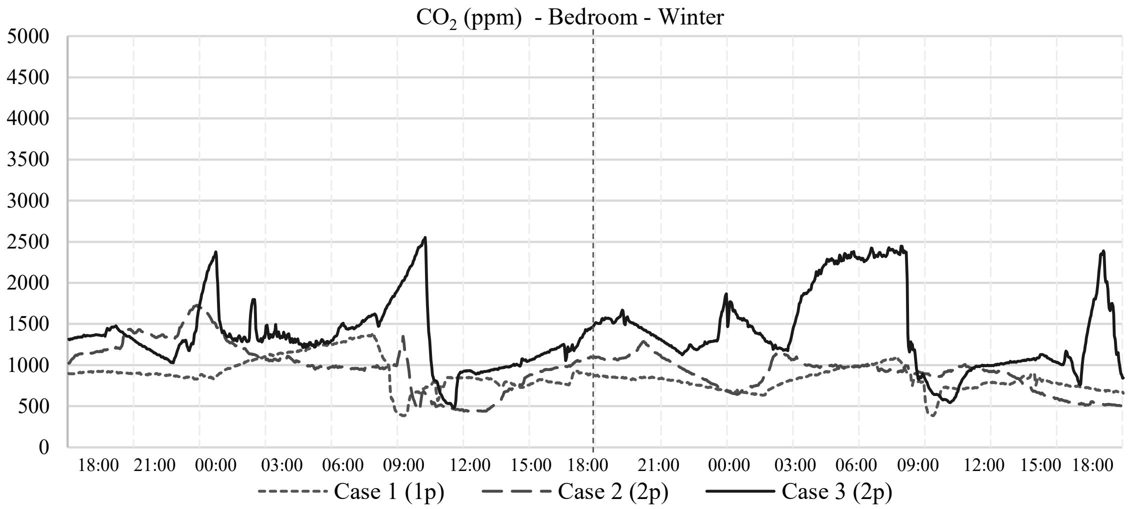

Figure 13. Hourly evolution of CO_2 levels under winter conditions

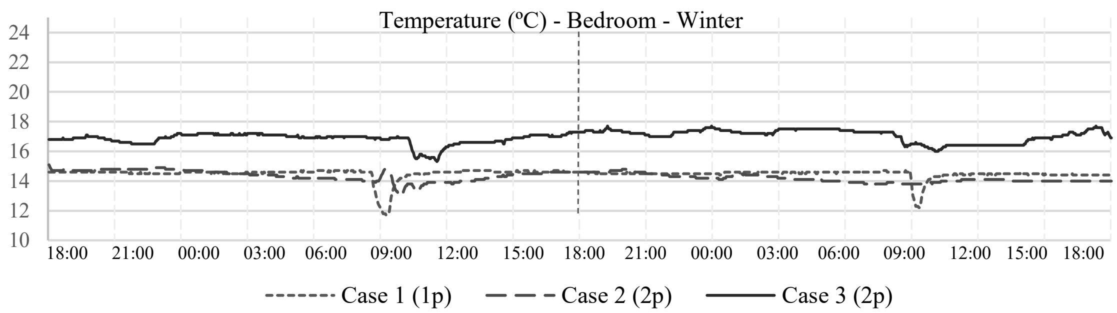

Figure 14. Hourly evolution of temperature under winter conditions

In the case of the bedroom, highly unfavourable CO_2 levels are reached for certain cases, such as Case 3, where a level of 4,500 ppm was exceeded in the spring measurement, and subsequently a notable reduction in CO_2 concentration, of about 2,000 ppm, was measured in winter once the occupants changed the operating scenario of the bedroom by sleeping with the bedroom door left half-open. In fact, Case 2 also presents a more favourable value mainly because they also slept with their bedroom door left ajar. Regarding temperature, there are peaks of temperatures that fall in the early hours of the morning, when the occupants wake up and usually open the windows. However, during the rest of the day, the temperatures remain approximately constant due to the inertia of the thermal envelope, but fail to reach the minimum required temperature values, and remain at around 6 ºC to 8 ºC below the comfort range for these occupants, which underlines the inadequacy of the thermal performance and heating systems in cold periods of the year. Moreover, the variations between winter and spring are similar to those obtained in the living room, whereby there is discomfort due to the indoor temperatures during the winter months, and comfort parameters are approached in spring with warmer indoor temperatures.

4. Discussion

This section aims to assess the results presented in Section 3 and to identify the fundamental variables that have caused a difference in the performances in the indoor environmental quality in Mediterranean apartments where elderly people live. First, the results are discussed independently for each Case Study, and then those factors that have exerted a major influence on the final performance are interrelated.

Case 1 is characterised by having a single occupant in the apartment with the largest surface area. Even so, it is observed that both the living room and main bedroom have average CO_2 values of over 900 ppm, especially during the winter, with maximum values that exceed 1,200 ppm for many hours, mainly during the night in the bedroom and at certain peak times of the day in the living room. This apartment does not reach alarming CO_2 levels, but it could be said that the air change rate is insufficient even for just one occupant. Regarding the temperature, the apartment presents an average of approximately 15 ºC during the winter and 18 ºC during the spring, without using any permanent heating system, and therefore the thermal range is insufficient to maintain comfort conditions indoors, especially for the elderly. In terms of relative humidity, intermediate values between 40% and 60% are presented in both measurements, with the highest percentages measured in the bedroom during the night, mainly due to the latent breathing of the occupants.

Case 2 presents acceptable CO_2 levels during the spring season, with average values of around 700 ppm, both in the living room and bedroom, but which nevertheless increased considerably during the winter, and reached average values close to 1,000 ppm in the living room and bedroom and maximum levels close to 2,000 ppm, which are unhealthy for the elderly. Regarding these maximum values, it is observed again in the hourly evolution that that the ventilation patterns are insufficient, especially in winter conditions, where voluntary natural ventilation is avoided since it would entail the entry of colder air and a consequent drop in indoor temperature. In fact, this apartment registered the coldest indoor temperatures, with an average of between 13 ºC and 14 ºC in winter in the bedroom and living room, which are highly unfavourable for indoor thermal conditions, and around 16 ºC during the spring, which can show that unfavourable temperatures incite occupants to ventilate insufficiently in these seasons. Finally, the relative humidity values remain constant between 50% and 60%, and are generally higher than the levels obtained in Case 1.

Lastly, Case 3 is the most notable of the three cases, and has enabled a higher number of variables to be identified that are interrelated in the performance of the results. Case 3 presents particularly extreme CO_2 values in the bedroom, especially during spring but also in winter, with 1,600 ppm as the average value and a peak of 4,500 ppm was obtained in the spring period, which can exert a direct effect on the high air-pollutant concentration and on the health of the occupants. During the spring measurement, the occupants informed the authors that they had slept with the door and the window closed in their bedroom, which involves two occupants in a much reduced space without mechanical ventilation, thereby increasing the possibility of reaching extremely high CO_2 concentrations, as shown in Figure 10. In addition, during the winter measurement, the occupants reported that they had slept with the door half-open, hence in the winter measurement the peak was reduced to a maximum value of 2,500 ppm during the night, which implies a reduction of 2,000 ppm only with the variation of the regime of use of the door, although this value is also unfavourable and unhealthy for the occupants. Further to the influence on the situation of the door, another possible influencing factor is that of the windows being recently replaced and the permeability values being reduced, and hence in the case of there being a more airtight envelope, the air change values are lower. In the case of the living room, normal values were obtained during the spring measurement, similar to those of the other cases. The values were much higher during winter, however, with an average of 1,200 ppm in the living room, which fails to comply with the established recommended values. It is also worthy of note that the occupants of Case 3 claimed that they slept better and felt more rested since they slept with the door half-open instead of closed. Regarding the temperature obtained in Case 3, this is the case with the highest temperatures of the three cases, mainly because the measurement was carried out during the days in which the outdoor temperature was higher. Average values of 22 ºC have been obtained in the spring and 18 ºC in the winter measurement; these are pleasant indoor temperatures which were perhaps influenced by sunny days and the fact that the apartment is located on the top floor of the building. Finally, the relative humidity has been more unstable than in previous cases, due to the high concentrations of CO_2 and damp when two occupants are in smaller enclosed spaces. This relative humidity could facilitate internal condensation and could consequently prompt the appearance of fungi and possible health problems.

In addition to the particular analysis of each case, it has been observed in all cases that, at certain times of the day, the occupants reach CO_2 concentrations that are much higher than the advisable values, as was previously identified by Strøm-Tejsen et al. [25] and Zhu et al. [26]. The data obtained in the three case studies show that the elderly spend many hours of the day with undesirable CO_2 levels, way above healthy limits. This study also highlights the influence of natural ventilation patterns and the importance of occupant behaviour in the indoor performance of each apartment. It has been demonstrated that sleeping with the door closed can cause higher concentrations of CO_2, thereby reaching extreme levels, and therefore a consequence of this study is the influence of the door conditions to balance the CO_2 levels with the remaining rooms. Alternatively, this balance could be achieved by installing doors that incorporate a ventilation grid, since these would increase permeability and prevent high concentrations of CO_2. This statement also justifies the need to implement different natural ventilation habits and to introduce mechanical systems that guarantee acceptable indoor conditions.

The results have also provided evidence on the connection between high CO_2 concentrations and winter periods, due to the reduced willingness of the occupants to introduce natural ventilation because of the low temperatures. However, it is observed that once natural ventilation through the windows is introduced, CO_2 levels fall to the same CO_2 levels of the outdoor conditions, and hence natural ventilation can be effective and the problem is mainly the insufficient frequency of ventilation carried out by the occupants in their daily operation.

These results are also related to the constructive composition of the building's thermal envelope. The selected apartments, which belong to social housing stock built more than 40 years ago, present poor thermal performance without the addition of specific insulating materials. The windows also present high permeability values, which can be beneficial, in terms of natural air change rates, in periods with an absence of adequate ventilation patterns by the occupants, but this flies in the face of energy renovation policies, which promote the provision of airtight spaces. In fact, in those dwellings where single-glazed windows have been replaced with double-glazed windows, CO_2 levels have increased, since there is no mechanical ventilation system that accompanies natural ventilation.

Finally, these results have shown that the bedroom usually has higher CO_2 concentrations mainly because it is a smaller space, where the occupants spend many hours at night. On the other hand, the living room, being a larger space and better connected to the remaining rooms, contains concentrations of a more balanced and uniform nature.

5. Conclusions

This paper measures and assesses CO_2 levels, temperature, and relative humidity in three representative apartments occupied by the elderly in southern Europe. Its contribution involves the characterisation of indoor environmental quality and its relationship with indoor space typology, occupation, operating scenarios, constructive composition of the building envelope, and ventilation patterns. This characterisation has further enriched the understanding of the results and has supported the identification of unfavourable habits and the promotion of sustainable renovation strategies to prevent airtightness and unhealthy indoor spaces.

The results highlight that elderly people live for long periods of the day with CO_2 levels above the recommended limit of 900 ppm. These results have revealed that indoor CO_2 concentrations can reach unhealthy levels, and that this is mainly because the ventilation in the majority of the apartments that belong to the social housing stock depends exclusively on infiltration and ventilation rates through window openings, which can vary throughout the year, and depend heavily on the ventilation habits of the users. Furthermore, indoor temperature values have also been registered far outside the established ranges for thermal comfort, which in turn greatly limits any desire to open windows to generate natural ventilation in cold seasons. Regarding relative humidity, the airtightness obtained in the apartments and the lack of adequate ventilation lead to significant increases in the relative humidity which facilitates the appearance of damp in indoor spaces and decreases indoor air quality.

Level of occupancy, use of doors and windows, ventilation patterns, climate conditions, and room typologies have shown their influence and impact with regard to measured values. The highest CO_2 concentrations have been located mainly in the bedroom during sleeping periods, and can affect rest, concentration, and the well-being of the tenants. The maximum values have frequently exceeded 2,000 ppm, with peak periods over 4,500 ppm, which are classified as very harmful to health in any space. These results have also shown the influence of the opening or closing of a door in a room during sleeping periods, by identifying the direct impact on the accumulated concentrations and highlighting the advantageous character of leaving a door fully open or half-open, whose scenarios show CO_2 concentration values with a reduction of 2,000 ppm.

The results have demonstrated the need to introduce practical guidelines and advice for those members of the elderly population who solely depend on natural ventilation in order to improve the air change rate in their apartments. Other possible solutions can involve balancing the CO_2 concentrations inside the apartment through the introduction of grilles in doors and interior partitions, thereby preventing the aforementioned maximum peaks in such small spaces. However, these findings also justify the need to reconsider ventilation requirements for the social housing stock and to promote renovation plans focused on improving ventilation systems and incorporating elements that complement natural ventilation in the built environment. Additionally, future energy retrofitting actions based on highly insulated buildings must also consider that high airtightness of certain energy-reduction solutions introduces additional needs and challenges for healthy indoor air quality.

The implications of this study should have an impact on health, environmental, social, and urban policies in terms of introducing a better definition of ventilation requirements and regulations to ensure adequate indoor parameters, thereby preventing health disorders and improving the quality of life of the elderly. One consequence of this implication could be based on defining air renewal flows in the built environment that could be guaranteed through aerators in the windows or via electro-mechanical systems, further to voluntary natural ventilation. If these minimum flows are not guaranteed, then current regulations regarding thermal comfort and energy saving require new windows to be fitted, which supposes an even greater controversy between sealing against air filtration and generating higher concentrations of CO_2.

Future research will be addressed towards an in-depth study into the concentrations of indoor air pollutants and their impact on the health of the elderly.

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