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Indoor environmental assessment: Comparing ventilation scenarios in pre- and post-retrofitted dwellings through test cells

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ABSTRACT

In the next few years, outdoor temperature is expected to increase significantly as a result of climate change, a noticeable phenomenon, especially in the Mediterranean. In this future scenario, ventilation is a low-cost and useful strategy for tackling indoor overheating, mainly in energy-poor housing buildings. This research assesses the influence of different ventilation systems, air rates and schedules on the thermal comfort and indoor air quality of a residential retrofitted space when compared to an un-retrofitted environment, through test cell measurements. To do so, the methodology combines on-site monitoring with numerical models, simultaneously analysing both spaces under the same climate conditions. Results obtained show barely perceptible differences between the implementation of a mechanical ventilation system and a natural one, when it comes to thermal comfort in spaces with low thermal inertia, highlighting the clear advantage of energy and economic savings of the passive system.

1. Introduction

Nowadays, global warming is a widely recognized public issue, with the reduction of energy consumption of the building sector as one of the main concerns to be tackled [1]. According to the Eurostat Static Explained database, final energy consumption by end-users in the European residential sector accounted for 26.0% of the total energy consumed in 2018 [2], with the subsequent environmental problems due to pollutant emissions into the atmosphere. In recent years, environmental quality and thermal comfort requirements for indoor spaces have been revised and updated through legislation and international standards [3,4]. These modifications have noticeably impacted the energy consumption of buildings. Energy efficiency and indoor comfort improvement, which also results in an adequate ventilation level that guarantees minimum conditions for indoor environmental quality (IEQ), is one of the greatest challenges to the building sector [5], especially when retrofitting existing residential buildings.

Several studies show that guaranteeing an adequate IEQ has highly positive repercussions on occupants' health, wellbeing and mood [6,7]. Among the principal IEQ indices, thermal comfort (air temperature and relative humidity) and indoor air quality (IAQ) are normally assessed in residential buildings, analysing different air pollutants, such as particle matter ($PM_{2.5}$, PM_{10}), carbon dioxide (CO_2), volatile organic compounds (VOCs) and formaldehyde (CH_2O) [8].

However, these indices are frequently assessed independently: from a thermal comfort perspective, linked to its impact on energy consumption and, in terms of IAQ, considering only its influence on people's health. Escandón et al. [9] analyse the thermal comfort and energy performance of three residential buildings in a Mediterranean area during hot summer periods, reporting an unsuitable use of natural night ventilation and solar protection passive strategies on the part of occupants. Daniel et al. [10] conduct a thermal comfort study in 4500 dwellings, taking into account energy usage. These authors use extensive comfort surveys, identifying low thermal satisfaction among occupants, as well as a reluctance to carry out retrofit actions on their homes. Medrano-Gómez et al. [11] assess different retrofitted actions to improve thermal comfort in two residential buildings in a hot and semi-humid climate, aiming to reduce electric consumption and economic investment. Ting Kwok et al. [12] use DesignBuilder simulations to analyse thermal comfort and energy performance of typical public rental housing under near-extreme summer conditions. Montalbán Pozas et al. [13] study several bioclimatic strategies to reduce energy consumption in different dwellings, through a hygrothermal comfort assessment.

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Other studies have extensively evaluated the importance of reducing the risk of poor IAQ in residential buildings: Miller et al. [14] monitor carbon monoxide (CO), carbon dioxide (CO_2) and $PM_{2.5}$ levels during a 24-h period in 100 dwellings, considering occupants' use profile. Nonetheless, despite the poor IAQ results obtained, these authors do not clarify possible strategies to improve indoor air conditions in these spaces. Colton et al. [15] compare the indoor air quality of conventional multifamily houses and green buildings, by monitoring nitrogen dioxide (NO_2), CH_2O, $PM_{2.5}$, nicotine and CO_2 levels. Porras-Salazar et al. [16] analyse thermal comfort levels and indoor air quality in 41 dwellings in central-southern Chile, using on-site measurements and surveys to analyse indoor temperatures and CO_2 concentrations. Canha et al. [17] record CO_2, air temperature, relative humidity, VOCs, $PM_{2.5}$, PM_{10} and CH_2O levels in 10 dwellings. These authors highlight how all case studies considered fully meet the mandatory requirements for CO and PM_{10}, although indoor temperatures and CO_2 conditions only meet maximum values in 50% of cases.

Indoor environment conditions play a major role in occupants' comfort due to the longer periods currently spent indoors and limited access to outdoor spaces as a result of the COVID-19 lockdown [18]. Even though ventilation in dwellings becomes a fundamental necessity in the current conditions, inadequate ventilation habits can lead to negative consequences for occupants' thermal comfort. For IEQ improvement, the use of passive approaches, such as natural or mechanical ventilation, is an environmental strategy with a significant energy-saving and efficiency target [19] and, moreover, it is crucial to mitigating indoor overheating derived from climate change. Likewise, passive approaches become a widely used tool for retrofitting energy poor households [20], given the limited resources of the occupants.

The scientific community has analysed the influence of mechanical and hybrid ventilation in residential buildings, as well as passive ventilation through natural means. McGill et al. [21] assess indoor CO_2 concentrations in eight dwellings, comparing the use of mechanical ventilation and natural ventilation systems. Among their conclusions, they report IAQ problems in all cases, especially due to occupant use. Park and Kim [22] evaluate occupants' habits in relation to ventilation measurements in 139 apartments with mechanical ventilation systems, analysing monitoring and survey data. These authors prove that the operation of the mechanical ventilation system significantly affects the perceived acceptability of the indoor air. Turner and Walker [23] compare the use of natural, mechanical and hybrid ventilation systems in order to optimise IAQ in residential buildings. This shows that natural and hybrid systems provide equivalent indoor air quality results to the mechanical ventilation systems.

Taking into account the literature review on indoor environmental assessment, two major gaps still require further analysis. Firstly, it is necessary to jointly assess indoor thermal adaptive comfort and air quality, since these variables have been commonly addressed independently and under users' influence. Secondly, the assessment of adaptive comfort conditions under the EN 16798–1:2019 [24] adaptive model, which has recently replaced EN 15251:2007 [25], generally analysed in similar studies conducted so far [26]. For all this, the following research hypothesis is considered: What is the influence of ventilation on indoor thermal comfort and air quality conditions in a social housing space under the Mediterranean climate?

The aim of this paper is to provide a comparative analysis on how different ventilation scenarios in both pre- and post-retrofitted social housing spaces may impact on thermal comfort and indoor air quality, analysing several ventilation systems, air rates and schedules normally used in social residential buildings in southern Spain (Mediterranean climate). With especial attention to the Mediterranean area, the comparison of the influence of different ventilation protocols in social housing spaces is done considering passive strategies, since there is a generalized lack of Heating, Ventilation and Air Conditioning Systems (HVAC) in social housing sector. This research evaluates the efficiency of minimum ventilation rates, as required by current legislation, to guarantee indoor CO_2 concentrations below maximum recommended values, analysing the influence of different ventilation measures (only natural or mechanical and natural + mechanical ventilation) on indoor comfort conditions. This is done through the use of test cells, controlled environments equipped with an important monitoring system which allow several ambient variables with high-detail resolution to be registered, avoiding users' influence and the uncertainties which may derived from this. This research ought to provide a useful guide to establish the most adequate ventilation habits and measures for thermal comfort and indoor air quality in the Mediterranean social dwellings.

2. Methods

This paper analyses the influence of different ventilation protocols on several indoor ambient and air quality variables, mainly using on-site monitoring techniques through test cells. A statistical descriptive analysis has been conducted using the Matlab R2017a matrix tool [27] and Microsoft Excel 2016 software [28] to evaluate indoor operative temperatures and relative humidity values, as well as CO_2 concentrations. To this end, the cells have been monitored during several representative periods, testing different ventilation techniques commonly used in the residential buildings of the Mediterranean area.

The influence on thermal and ambient indoor comfort has been assessed based on the statistical results obtained. The use of test cells has made it possible to simultaneously compare the results obtained in two indoor spaces with the same geometric characteristics and different vertical envelope construction solutions, considering two scenarios - a thermally retrofitted space and an un-retrofitted space - in order to determine how these facades may impact indoor ambient conditions.

2.1. *Considerations for indoor air quality assessment*

In order to guarantee adequate indoor IAQ conditions, indoor carbon dioxide concentrations in the test cells have been analysed, considering the reference maximum values recommended by different standards as baseline. Due to technical limitations, no information could be gathered on other air pollutants.

In Spain, where this research is conducted, the Technical Building Code CTE DB-HS3 [29] establishes minimum ventilation rates for housing buildings to maintain maximum annual mean values of CO_2 concentrations below 900 ppm, also limiting maximum peak values to 1600 ppm. The European Technical Report CEN CR 1752 [30] establishes a limit value of indoor CO_2 concentrations due to human metabolism, depending on the building category: for existing buildings (C category), with a Predicted Percentage of Dissatisfied (PPD) below 15% and a ventilation rate of 4 l/(s person), recommended indoor CO_2 levels should be below 1190 ppm over outdoor CO_2 concentrations. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 62.1:2013 [31] recommends a steady-state CO_2 concentration in indoor spaces no greater than 700 ppm above outdoor air levels. According to a medical and health report conducted in 51 countries, indoor spaces must guarantee an adequate air exchange within the 800–1000 ppm range [32]. Finally, considering an ambient indoor building category type II (IEQ_{II}), relating to a medium expectation level (PPD <10%), EN 16798–1:2019 [24] recommends indoor CO_2 maximum values of 800 ppm over outdoor CO_2 levels. In this research, the maximum values recommended in this last standard are used as baseline for IAQ assessment, as this is the current legislation and the limit considered is an average value when compared to the other standards mentioned.

2.2. *Considerations for thermal comfort assessment*

For the analysis and results discussion on thermal comfort, the indoor operative temperature in the case study has been established following the procedure included in ISO 7726:2002 [33]; operative temperature is calculated as an average value of indoor air temperature and radiant indoor temperature.

For the thermal comfort assessment, in recent decades the scientific community has proposed different statistical models, many of which are included in international standards. This paper considers two of these statistical models. The first, developed in ISO 7730:2005 [34], is a steady-state model which considers Fanger's thermal model [35] as base reference and a Predicted Mean Vote (PMV). Different factors should be considered when calculating thermal comfort in this model: metabolic rate activities, thermal resistance of clothing, relative humidity, air velocity and average radiant and air temperatures. The average relative humidity taken into account in the case study is 50%, with a Predicted Percentage of Dissatisfied (PPD) lower than 15%, a metabolic rate of 1.2 met and a thermal resistance of 0.5 clo for outdoor temperature conditions similar to severe summer; and 1.0 clo for outdoor temperature conditions similar to winter, mid-season and light summer. In other words, the comfort bands established are 22.8–26.8 °C and 18.5–24.5 °C, respectively.

The second model used for thermal comfort assessment is the adaptive approach included in EN 16798–1:2019 [24]. The adaptive model, with widespread application, is used in free-running buildings with low metabolic rate and where occupants can freely control window operation and clothing modifications. The parameters considered in the calculations are a metabolic rate of 1.0–1.3 met and a thermal resistance of 0.5 clo in summer and 1.0 clo in winter. The adaptive comfort temperature (T_{co}) (Equation (1)) is directly related to the running mean dry bulb outdoor temperature ($T_{ext,ref}$) (Equation (2)). Depending on the building category, three acceptability ranges can be established: category I for a PPD <6% (high level of expectations) and with a temperature interval of +2 °C and −3 °C; category II for PPD <10% (normal level of expectation) and with a temperature interval of +3 °C and −4 °C; and category III for PPD <15% (moderate level of expectation) and with a temperature interval of +4 °C and −5 °C. In this case study, building category II has been considered.

$$T_{co} = 0.33 \times T_{ext,ref} + 18.8 \tag{1}$$

$$T_{ext,ref} = (T_{ext,ref1} + 0.8\ T_{ext,ref2} + 0.6\ T_{ext,ref3} + 0.5\ T_{ext,ref4} + 0.4\ T_{ext,ref5} + 0.3\ T_{ext,ref6} + 0.2\ T_{ext,ref7})/3.8 \tag{2}$$

where:

$T_{ext,ref}$: running mean dry bulb outdoor temperature for today
$T_{ext,ref1}$ to $T_{ext,ref7}$: daily mean dry bulb outdoor temperature for the previous 1–7 days

In general, upper and lower limits of average outdoor running temperatures are met in the adaptive model implemented. Specifically, average outdoor running temperatures must be between 10 °C and 30 °C.

Another variable analysed to assess thermal comfort is relative humidity. According to EN 16798–1:2019 [24], relative humidity values recommended in spaces with human occupancy depend on the building category: between 30 and 50% for category type I (PPD <6%), 25–60% for category II (PPD <10%) and 20–70%, for category III (PPD <15%).

On the other hand, ASHRAE 62.1:2013 [31] limits relative humidity content in occupied spaces to a maximum value of 65%. Likewise, the Spanish Technical Building Code CTE DB-HE [36] establishes a 55% limit value of relative humidity for indoor thermal comfort in residential buildings.

For this research, a relative humidity comfort band of 25–60% has been considered, according to building category type II of EN 16798–1:2019 [24].

3. Case study

3.1. Description of case study

For this research, on-site measurements recorded were obtained through test cells (Fig. 1), monitoring equipment managed by the University of Seville and located in an open space of the Mediterranean region of southern Spain (37° 23′ N, 5° 58' W).

The test cells (Fig. 2) are two independent modules raised from the ground by a ventilated air chamber measuring 90 cm. Each module includes two test cells, one facing south and another facing north, separated by a service room where management, monitoring and systems are located. Each cell, 2.40 m wide, 3.20 m deep and 2.70 m high, reproduces a typical living space of a social housing building of southern Spain. Each of these spaces is totally autonomous and allows the simultaneous evaluation of different construction solutions of vertical envelopes, under the same climatic conditions. Both south and north-facing personalized facades are 2.60 m wide and 2.96 m high. The southern cells have a sliding window with metal frame and no thermal bridge, with a glazing surface accounting for around 16.2% of the total surface of the personalized façade.

Table 1 shows a brief description of the thermal envelope of the test cells, including the definition of the retrofitted south and north facades (retrofitted wall in cell 1 and cell 2) and un-retrofitted facades (un-retrofitted wall in cell 3 and cell 4). León et al. [37] and Calama-González et al. [38] provide a more extensive and detailed description of the cells and their constructive and structural characterisation, among other

Fig. 1. Experimental test cells: (**a**) South cells; (**b**) service room.

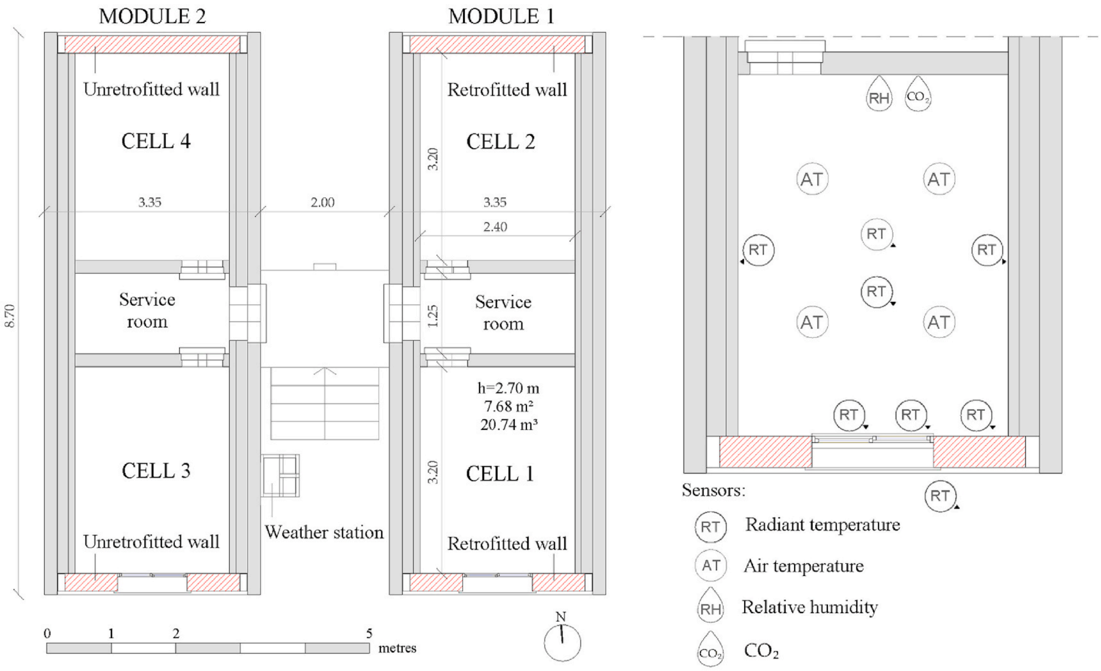

Fig. 2. Floor plan of the Test Cells with the location of the sensors of the monitoring system.

Table 1
Thermal envelope definition and U values.

Envelope	Description (outside to inside layers)	U (W/ m^{2}K)
Un-retrofitted wall	Exterior mortar rendering + 11.5 cm perforated brick wall + interior rendering + 5 cm air chamber + 4 cm simple brick partition wall + gypsum plaster.	1.43
Retrofitted wall	Exterior rendering + EPS 50 mm thermal insulation + Un-retrofitted wall	0.47
Other walls	200 mm sandwich panel + MW 80 + 80 thermal insulation +100 mm sandwich panel	0.05
Floors		0.05
Roofs		0.05
Partition wall	100 mm sandwich panel	0.17
Opening	4.8.4 double-glazing with metal frame	3.30

Table 2
Main technical characteristics of the sensors installed.

Sensor	#	Location	Unit	Range	Accuracy
Thermocouple	8	Indoor: in each Test Cell	°C	−250, +350	±1 ± 0.75%
Thermometer	4		°C	−40, +80	±0.15 ± 0.1%
Hygrometer	1		%	0–100	±3%(0,70%) ±5%(71,100%)
CO$_2$ detector	1		ppm	0–2000	±2.0%
Thermometer	1	Outdoor: in Weather Station	°C	−40, +80	±0.15 ± 0.1%
Hygrometer	1		%	0–100	±3%(0,70%) ±5%(71,100%)
CO$_2$ detector	1		ppm	0–2000	±2.0%
Anemometer	1		m/s	0–50	±0.5
Vane	1		°	0–360	±2.5

aspects. For this research, southern cells 1 (retrofitted) and 3 (un-retrofitted) have been analysed since they are the only ones with a window, so the comparison between natural and mechanical ventilation is possible, as well as between spaces with higher and lower thermal inertia. Neither of these cells is occupied (no users have been considered) and no HVAC systems have been used.

3.2. *Monitoring system*

The monitoring system installed meets the requirements established by UNE-EN ISO 7726:2002 [33] and consists of a star network with several sensors recording data at 5-min intervals. The information recorded is stored in several data loggers for a limited period of time. Every 30 min, this information is uploaded to a FPT using the University of Seville's RedIris network. The stored data is subsequently compiled by local computing equipment, creating several .txt files. These files are combined in a single .csv file to be processed using Microsoft Excel 2016 [28] worksheets and statistical software such as Matlab R2017a [27] for analysis. This monitoring system allows the measurement of different ambient conditions and indoor air quality parameters in each cell (air and surface temperature, relative humidity and CO$_2$), as well as the control of outdoor ambient variables (air temperature, relative humidity, CO$_2$, wind speed and direction). Four air temperature sensors (thermometers) have been hanged form the false ceiling and placed as a matrix in the centre of the cell (at 1.5 m height). Eight surface temperature sensors (thermocouples) have been placed in the cells: 6 on the walls at 1.5 m height and at 0.7 m, 1.5 m and 1.8 m height in the main facade; 1 on the roof and, finally, 1 in the floor (see Fig. 2). The operative temperature in the cells has been calculated according to the method established in ISO 7726:2002 [33], through the average of indoor air temperatures, obtained from the thermometers, and radiant interior temperatures, calculated from the surface temperatures of the space, obtained from the thermocouples and weighted according to the form factors. The indoor CO$_2$ detector and relative humidity sensor have been placed at 0.5 m. A local weather station located in the roof of the experimental west module (module 2) registers several outdoor parameters. The main technical characteristics of the sensors included in the weather station are indicated in Table 2.

3.3. *Ventilation protocols*

In order to assess the influence of ventilation on indoor comfort, several ventilation protocols have been analysed to determine how they may impact the indoor ambient variables (temperature, relative humidity and indoor air quality) monitored in the cells. These protocols have been defined taking into account common ventilation periods used

Table 3
Characteristics of the ventilation protocols analysed.

Ventilation type	Duration	Period analysed*[1]	Period minimum T_{out} (°C)	Period maximum T_{out} (°C)	Period average T_{out} (°C)
No Ventilation	-	4 days	4.1	21.5	11.3
Natural	8:30-9:30 (1h)	4 days (14–17/03)	3.5	23.3	12.2
	13:00-14:00 (1h)	4 days (28/02–03/03)	8.4	22.2	14.6
	8:30-8:30 (24h)	1 day (28–29/05)	13.4	29.8	20.8
Mechanical	8:30-9:30 (1h)	6 days (18–23/03)	6.6	25.4	14.2
	13:00-14:00 (1h)	6 days (04–09/03)	9.8	22.0	14.9
Natural and Mechanical	13:00-14:00 (1h)	4 days (05–08/06)	14.1	30.9	21.4
	13:00-17:00 (4h)	4 days (14–17/05)	7.5	31.3	19.5
	21:00-8:30 (night)*[2]	4 days (11–14/06)	16.2	36.6	24.9

*[1]: during the periods, heating and cooling systems are OFF, so free-running conditions are analysed.
*[2]: night ventilation corresponds to the 11-h ventilation period.

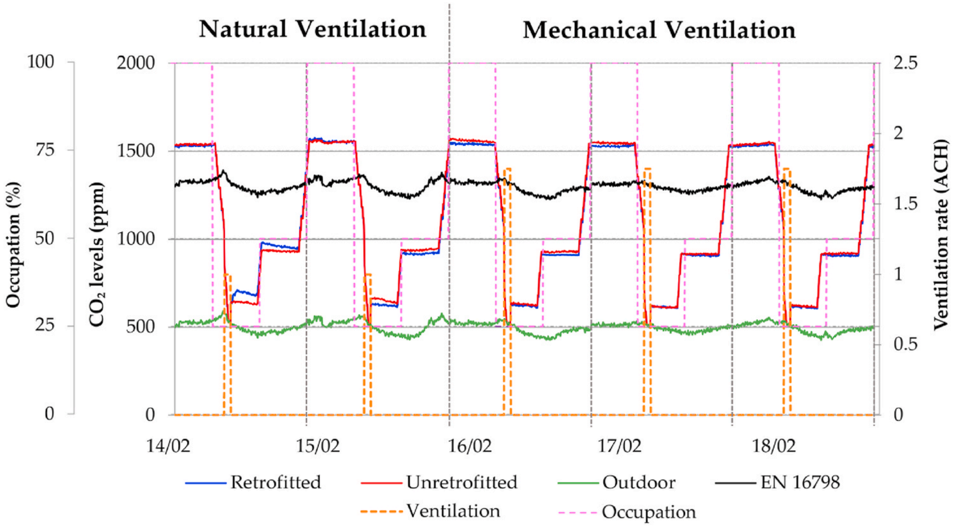

Fig. 3. CO_2 levels during the natural and mechanical ventilation protocols.

in social housing buildings and their main characteristics are shown in Table 3. These protocols have also been established to comparatively assess different ventilation schedules in the cells (morning, evening, night), length of the ventilation periods (1-h, 4-h, 11-h and 24-h), and types of ventilation (natural, mechanical and combined). The periods analysed refer to mid-season data, as their values are representative of annual average results.

Natural ventilation occurs through the window described in subsection 3.1, located in the south-facing cells. Thus, there is single-sided natural ventilation (no cross-side ventilation), which is the most common in social housing buildings in southern Spain [39]. Natural ventilation rate has been approximated using the Warren and Parkins wind driven flows method [40] (Equation (3)), for single sided-windows, since wind speed data is monitored in the local weather station.

$$Q_v = 0.025\ A\ x\ U_{ref} \tag{3}$$

where:

$Q_{v:}$ volume flow rate (m^3/s).
A: area of the opening (m^2).
U_{ref}: is the reference wind speed (m/s).

During natural ventilation protocols, wind speed levels normally vary from 0.1 to 0.5 m/s on the surface of the window. Taking into account the window ventilation aperture (half of the window area), natural ventilation rate was considered to be 1 ACH, which was the most unfavourably value obtained from the calculations.

For the mechanical ventilation, a mechanical extractor has been installed over the access door to the cells. This device allows a fixed ventilation rate of 1.75 ACH (Air Changes per Hour), which is the minimum ventilation rate required by the Spanish Technical Building Code CTE DB-HS3 [29] for a bedroom. This extractor and the air admission duct located on one side of the cells (as can be seen in the floor plans of subsection 3.1) allow the outdoor air to enter into the cells (with no additional thermal treatment). Finally, both mechanisms are simultaneously and complementarily used during the combined ventilation protocols (natural + mechanical).

Due to the intensive characteristics of natural ventilation, the number of days analysed is lower than those for the mechanical ventilation.

3.4. Box model for indoor air CO_2 pollution

As explained previously, the test cells are unoccupied, so monitored CO_2 levels do not consider carbon dioxide emission due to human metabolism. The box model has been implemented in order to resolve this issue and consider human presence in the cells. This model considers the building as a single, well-mixed box, with sources and sinks for air pollutants, which can be characterized from different emission rates [41]. The box model establishes that the increase rate of air pollutants inside the building is due to three factors: (1) the pollutant rate entering the indoor space from the outdoor environment due to infiltration; (2) the pollutant rate leaving the building by exfiltration; and (3) the decay rate of the pollutant itself (Equation (4)).

$$C_{(t)} \;=\; \left[\frac{\left(\frac{S}{V}\right) + C_a \cdot I}{I + K}\right] \cdot \left[1 - e^{-(I+K)t}\right] \;+\; C_{(0)} \cdot e^{-(I+K)t} \tag{4}$$

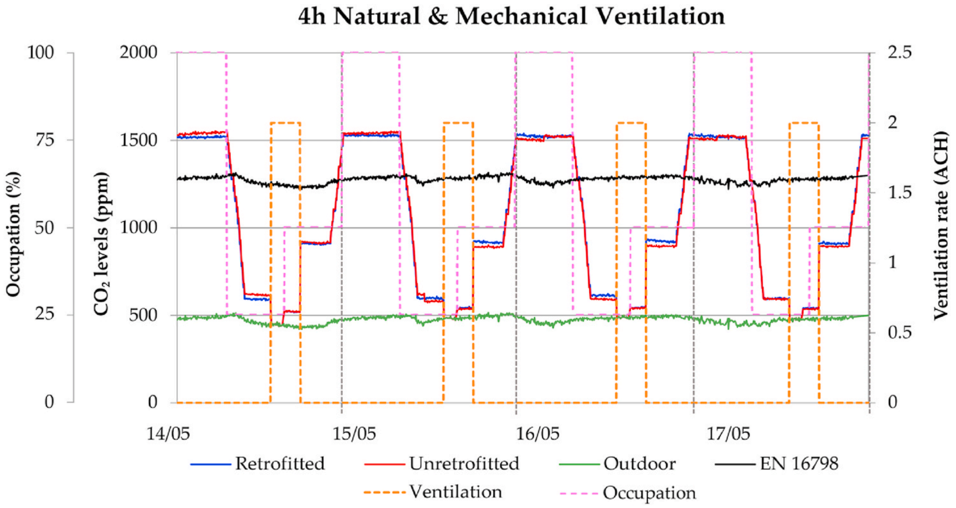

Fig. 4. CO_2 levels during the 4-h natural and mechanical ventilation protocol.

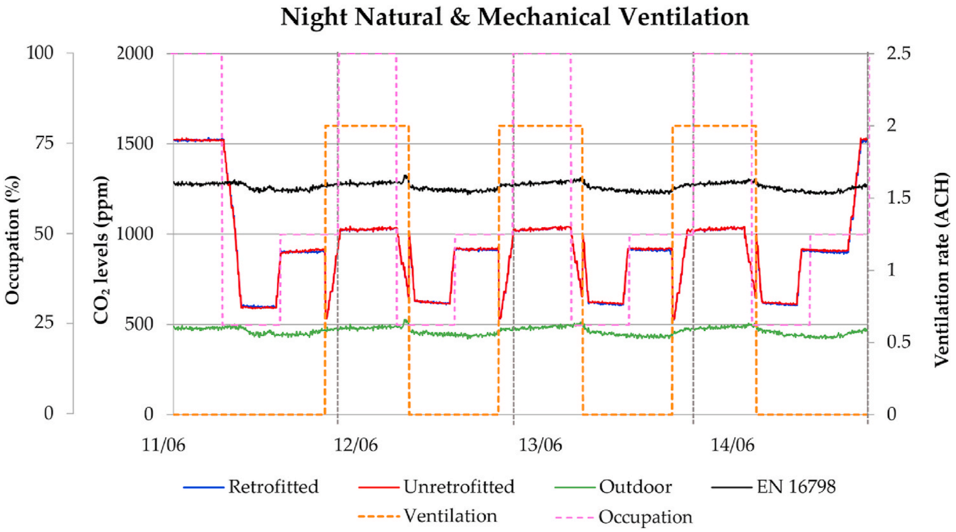

Fig. 5. CO_2 levels during the night natural and mechanical ventilation protocol.

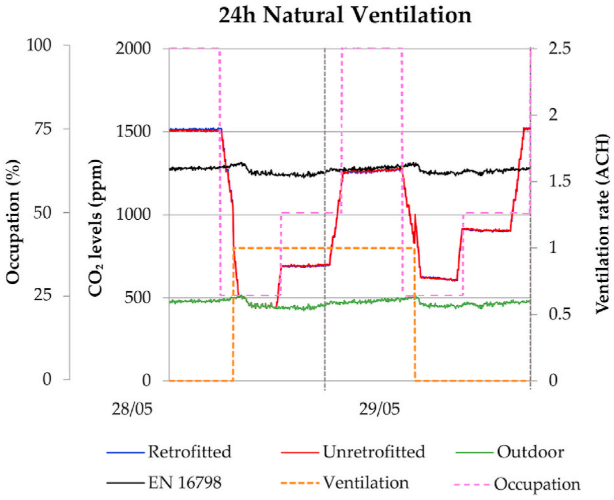

Fig. 6. CO_2 levels during the 24-h natural ventilation protocol.

where:

$C_{(t)}$: final indoor CO_2 concentration in the building (mg/m^3).
$C_{(0)}$: initial indoor CO_2 concentration in the building (mg/m^3).
S: source emission rate (mg/h).
V: volume of conditioned space in the building (m^3).
C_a: outdoor CO_2 concentration (mg/m^3).
I: air exchange rate (ACH).
K: pollutant decay rate of reactivity (1/hr), assumed to be 0 [40].

According to Emmerich et al. [42], the source rate of CO_2 emitted by one person (S) may be set at 800 mg of CO_2 per minute, considering a metabolic rate of 1.2 met and a clothing insulation value of 1.0 clo. This source rate is equivalent to that established by the Spanish Technical Building Code CTE DB-HS3 [29], which contemplates a emission of 19 l/h of CO_2 per occupant; and to that indicated in ASHRAE 62.1:2013 [30], where a CO_2 emission rate of 0.0052 l/s per occupant is set, taking into consideration a metabolic rate of 1.2 met.

The occupancy scenario considered for the calculation of the CO_2 emission rate due to human activity is that included in the Spanish

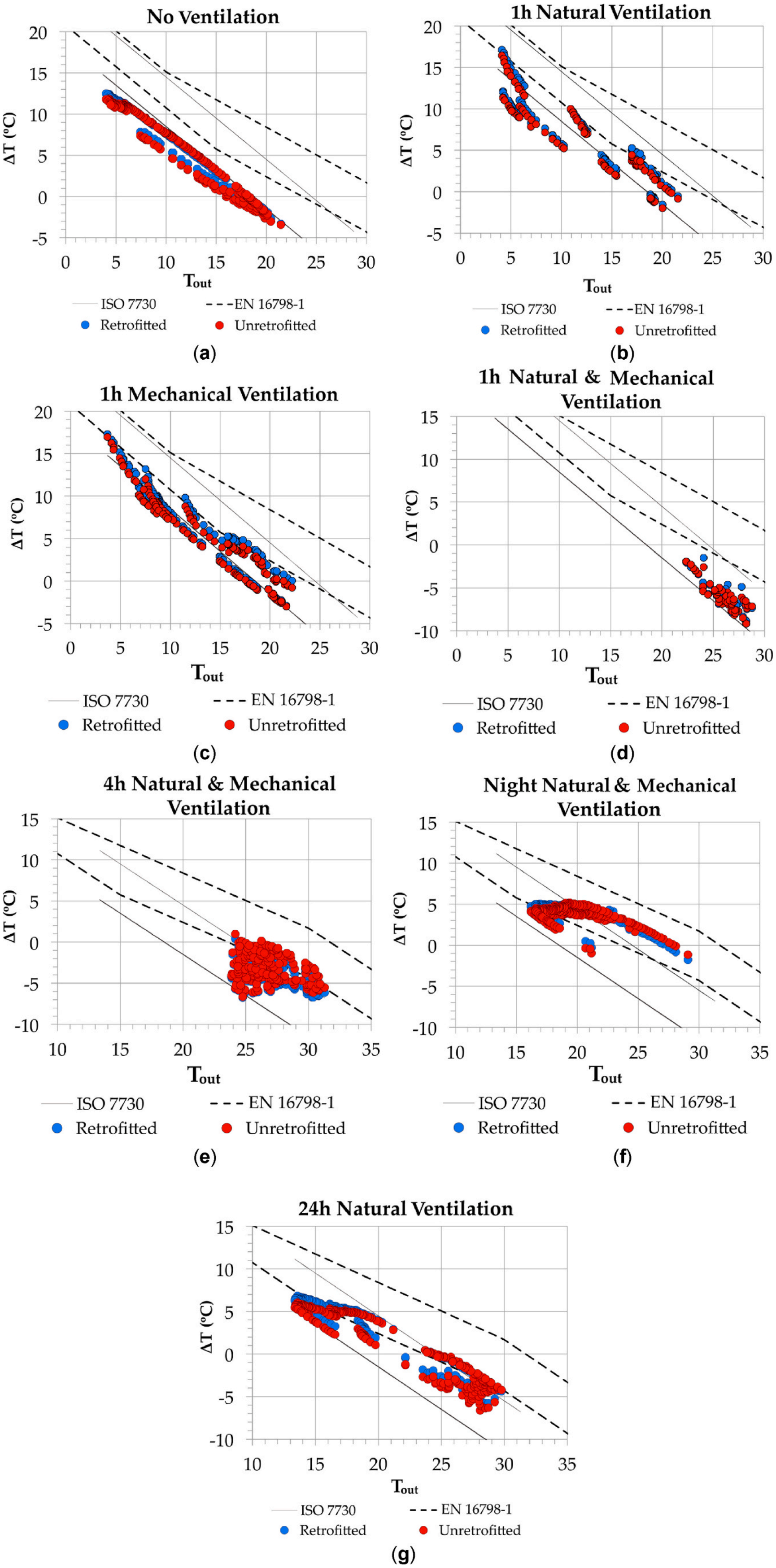

Fig. 7. Temperature recorded during the periods analysed.

Table 4
Percentage of thermal comfort hours in the retrofitted (cell 1) and un-retrofitted (cell 3) cells for each ventilation protocol. Comparison of steady-state and adaptive comfort models.

Ventilation type	Ventilation period	% Comfort Hours (ISO 7730)		% Comfort Hours (EN 16798–1)	
		Retrofitted	Un-retrofitted	Retrofitted	Un-retrofitted
No Ventilation		0.0	0.0	0.0	0.0
Natural	8:30-9:30 & 13:00-14:00	49.5	44.8	9.1	2.0
Mechanical	8:30-9:30 & 13:00-14:00	57.0	46.8	9.6	0.0
Natural and Mechanical	13:00-14:00	100.0	100.0	0.0	0.0
4h Natural and Mechanical	13:00-17:00	74.0	59.7	21.9	33.7
Night Natural and Mechanical	21:00-8:30	78.4	80.8	77.9	61.2
24h Natural	8:30-8:30	76.8	78.6	65.4	58.5

Technical Building Code CTE DB-HS3 [29]: an occupant per test cell (since the cell reproduces a living space typical of Andalusian social housing) and an occupancy profile of a residential building with sleep-time periods from 0:00 to 8:00.

4. Results and discussion

This section presents the results of the assessment of ambient quality and thermal comfort in the test cells during the different ventilation protocols considered. In general, monitored data in the retrofitted cell (cell 1) is indicated in blue, while measurements from the un-retrofitted cell (cell 3) are shown in red. Comfort bands or maximum recommended values are shown in black.

4.1. Indoor air quality assessment

Results from the assessment of indoor air quality in both cells during the ventilation protocols are shown in this section. CO_2 (ppm) levels for the retrofitted cell (cell 1) are shown in blue; CO_2 levels of the un-retrofitted cell (cell 3) appear in red; outdoor CO_2 levels are in green and, finally, maximum indoor CO_2 concentrations recommended in EN 16798–1:2019 [24] appear in black. The ventilation schedules and rates (ACH) used in each protocol are coloured in orange.

Fig. 3 shows both the natural and mechanical ventilation protocols, implemented from 8:30 to 9:30. Fig. 4 includes the CO_2 levels calculated for the 4-h natural and mechanical ventilation period, from 13:00 to 17:00. CO_2 concentrations obtained during the night ventilation period (from 21:00 to 8:00) and during the continuous ventilation period (24 h), are shown in Figs. 5 and 6 respectively.

Figs. 4–6 show indoor CO_2 levels within the maximum recommended values during all ventilation protocols, with a significant decrease of CO_2 values inside both cells. When considering indoor air quality, there are barely noticeable differences between the retrofitted cell (cell 1) and un-retrofitted cell (cell 3). In fact, these differences are barely visible during long-term ventilation periods, when only small variations in the 1-h to 4-h ventilation periods can be observed.

Some of the cases analysed include time slots where indoor maximum CO_2 recommended levels are exceeded, corresponding to unventilated periods. This occurs during night periods, when the cell is 100% occupied, according to the occupancy pattern established in the applicable legislation (see subsection 3.4). This is not observed during night and 24-h protocols, since both of these consider ventilation rates in the high-occupancy time slot.

In the cases where indoor CO_2 levels exceed maximum recommended values, it becomes necessary to establish a minimum ventilation rate of 1 ACH (between 0.92 and 0.96 ACH), obtained from the application of Equation (4). In the case study in this research, this ventilation rate corresponds to 5.75 l/s, slightly above the rate of 4 l/s established in the Spanish Technical Building Code CTE DB-HS3 [29] for bedrooms in dwellings.

4.2. Thermal comfort assessment

Fig. 7 provides a summary of the thermal comfort results obtained, comparing the retrofitted (cell 1) and un-retrofitted cells (cell 3), in each ventilation protocol. Measurements are shown in dispersion diagrams: the X axis indicates outdoor temperature (T_{out}) and the Y axis represents indoor-outdoor thermal differences ($\Delta T = T_{in} - T_{out}$).

Table 4 shows the percentage of thermal comfort hours recorded in each protocol and cell, according to the steady-state (ISO 7730:2005 [34], black continuous lines) and adaptive (EN 16798–1:2019 [24], dashed black lines) comfort bands.

In the unventilated protocol, none of the cells meet the comfort requirements of the international standards considered, given that indoor temperatures are lower than the comfort bands. The implementation of natural and mechanical ventilation in both cells clearly improves the percentage of comfort hours established in ISO 7730, with values around 50% of the hours in comfort. The differences in the percentage of comfort hours between the retrofitted and the un-retrofitted cell are more noticeable when applying mechanical ventilation than when using natural ventilation systems, with a higher percentage of comfort hours in the retrofitted cell.

When natural and mechanical ventilation are combined, the percentages of comfort hours increase significantly: with ventilation periods from 13:00 to 14:00, the cells reach comfort conditions during 100% of the hours, whereas with long-term ventilation (13:00 to 17:00) the percentage of comfort hours decreases slightly due to indoor-outdoor thermal differences.

A noteworthy aspect is the higher percentage of comfort hours achieved in the un-retrofitted cell compared to the retrofitted one, during night and 24-h ventilation protocols: indoor temperatures in the retrofitted space are generally higher than in the un-retrofitted cell, and above the comfort band. This is due to the fact that the construction solution of the retrofitted cell (thermal insulation on the external layer of the vertical envelope) hinders thermal dissipation, unlike the un-insulated façade of the un-retrofitted cell (Table 1).

The values in Table 4 show that the percentages of thermal comfort are higher when the steady-state comfort band is considered (ISO 7730) in both cells, compared to the adaptive model (EN 16798–1), with the sole exception of night ventilation. This is due to slightly high outdoor temperatures and a positive indoor-outdoor thermal difference during that period. In other words, the indoor temperatures of the cells are usually higher than the outdoor temperatures. When both cells are analysed under adaptive thermal comfort conditions, it is observed that the percentage of comfort hours is higher in the retrofitted cell than in the un-retrofitted space in almost all the protocols. This is caused by the adaptive comfort band being more permissive than the steady-state comfort model when higher outdoor temperatures are considered. In contrast, if outdoor temperatures are low, the steady-state comfort band is more permissive.

Fig. 8 shows dispersion diagrams with the relative humidity values recorded in the retrofitted (cell 1) and un-retrofitted cells (cell 3) in each

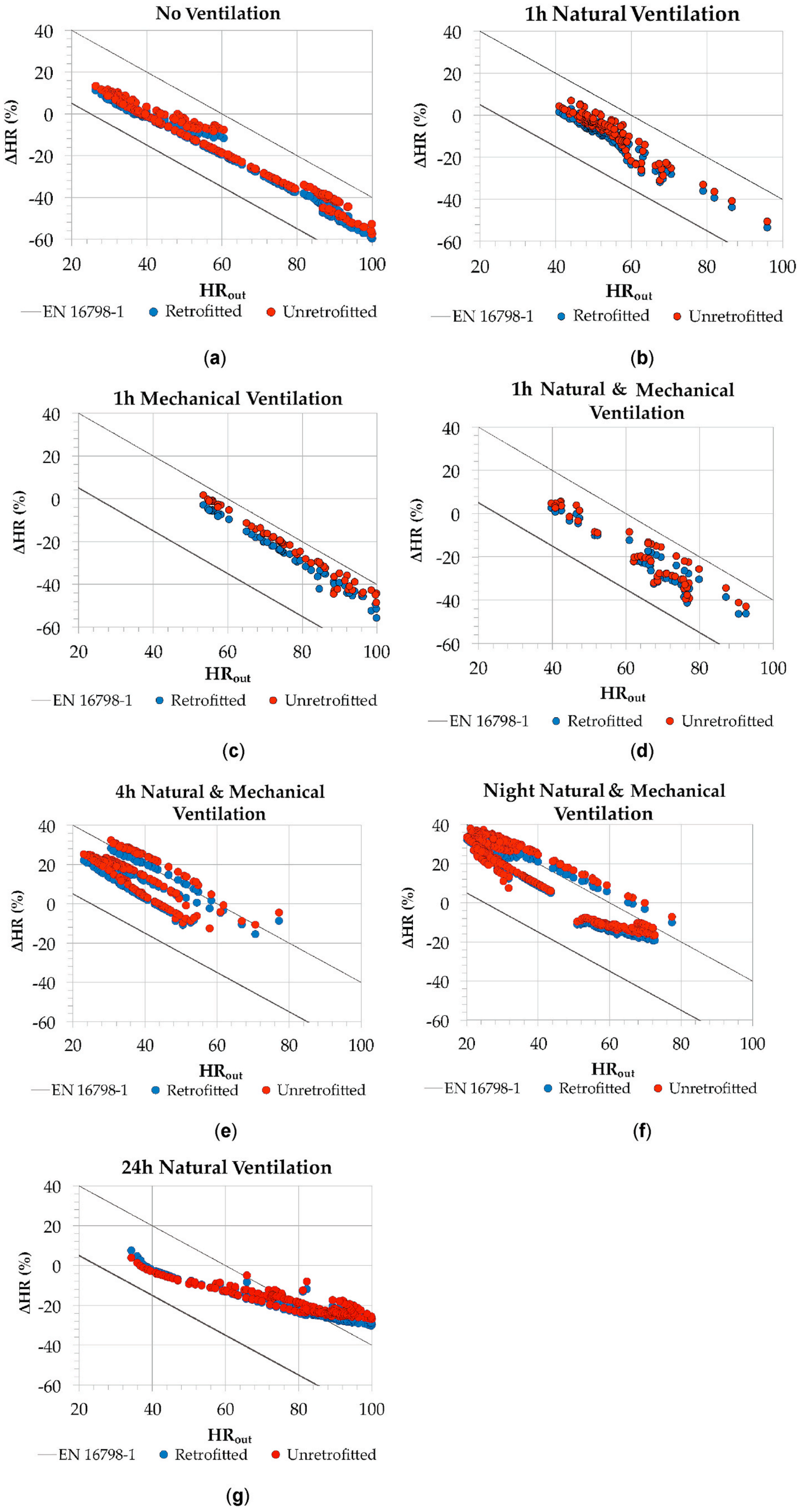

Fig. 8. Relative humidity recorded during the periods analysed.

Table 5
Percentage of hours with relative humidity values within the comfort band in the retrofitted (cell 1) and un-retrofitted (cell 3) cells, for each ventilation protocol.

Ventilation type	Ventilation period	% Comfort Hours (EN 16798–1)	
		Retrofitted	Un-retrofitted
No Ventilation	-	100.0	100.0
Natural	8:30-9:30 & 13:00-14:00	100.0	100.0
Mechanical	8:30-9:30 & 13:00-14:00	100.0	100.0
Natural and Mechanical	13:00-14:00	100.0	100.0
4h Natural and Mechanical	13:00-17:00	89.3	78.0
Night Natural and Mechanical	21:00-8:30	92.8	82.7
24h Natural	8:30-8:30	37.7	29.0

ventilation protocol: the X axis indicates outdoor relative humidity (HRout) and the Y axis represents indoor-outdoor relative humidity differences ($\Delta HR = HRin - HRout$). The percentage of hours when indoor relative humidity is within the comfort band (continuous black lines) is included in Table 5, for each cell and protocol.

In general, the percentage of comfort hours is quite high in both cells, with values slightly higher in the retrofitted one. Both cells reach 100% of hours in comfort conditions during the unventilated, natural ventilation (8:30 to 9:30 and 13:00 to 14:00) and combined natural + mechanical ventilation (13:00 to 14:00) protocols. When longer-term ventilation protocols are considered (4-h, night and 24-h), the percentage of comfort hours decreases in both cells, given that indoor relative humidity values exceed the comfort band.

5. Conclusions

This paper presents a statistical analysis of the impact of different ventilation scenarios commonly implemented in Mediterranean social housing buildings in southern Spain, on several ambient variables. The aim is to assess indoor thermal comfort and air quality conditions, using monitoring techniques through test cells which recreate living spaces typical of social housing buildings in southern Spain (Mediterranean climate), with real-time simultaneous analysis comparing a retrofitted and an un-retrofitted space. Indoor air temperatures, relative humidity and CO_2 levels have been recorded and outdoor values have been monitored by a local weather station. The conclusions reported include the significant influence of ventilation protocols on indoor air temperatures and CO_2 concentrations, with lower impact of ventilation on indoor relative humidity values, considering the assessment of thermal and ambient comfort.

5.1. Research limitations

Among the limitations of this research, it is worth mentioning the impossibility of considering occupant loads in the case study during the ventilation protocols analysed, so that results obtained correspond to unoccupied periods. Therefore, especially considering indoor air quality assessment, these aspects had to be recreated through numerical models.

Likewise, as the analysis of each ventilation protocol is conducted through on-site monitoring under different outdoor conditions, concluding which would be the most beneficial for both indoor air quality and thermal comfort is a complex task. The comparison of all ventilation scenarios under the same outdoor climatic conditions may be only addressed through energy simulation models.

5.2. Main conclusions

When comparing the indoor ambient of a retrofitted and an un-retrofitted housing space, with identical orientation and geometrical characteristics, it should be noted that indoor relative humidity and CO_2 levels report similar results, with more noticeable differences in indoor air temperatures under thermal comfort conditions.

Even though it was proven that implementing short-term ventilation periods is useful for mitigating high CO_2 levels, in order to guarantee minimum air quality levels according to international standards, continuous ventilation rates (long-term periods) that are substantially low (around 1 ACH), during high and 100% occupancy periods (night periods) should be applied. It should be noted that these ventilation rates are higher than the minimum values established by the Spanish Technical Code regulations to promote air renovation during occupied periods. Moreover, continuous ventilation during high occupancy periods guarantees the achievement of adequate indoor air quality conditions, but it negatively affects thermal comfort, especially if indoor-outdoor thermal differences are positive and outdoor temperatures are significantly high (over 25 °C). To ensure that both thermal comfort and air quality are reached, the implementation of continuous ventilation is recommended with specific thermal conditions: when outdoor temperatures are 10–15 °C, with positive indoor-outdoor thermal differences of 8–10 °C; when outdoor temperatures are 15–20 °C, with positive indoor-outdoor thermal differences of 3–5 °C; when outdoor temperatures are 20–25 °C, with negative indoor-outdoor thermal differences up to 2 °C; and when outdoor temperatures are 25–30 °C, with negative indoor-outdoor thermal differences between 3 and 7 °C. Nonetheless, it should be noted that these conclusions were experimentally reported in a non-internal gains scenario. Hence, future considerations of internal human and equipment gains ought to be considered.

In addition, the difference between implementing natural and mechanical ventilation in spaces with low thermal inertia (un-retrofitted cell) is barely noticeable in terms of thermal comfort, with the clear advantage of consumption saving of natural ventilation.

5.3. Future research

Contrasting and validating these theoretical models with measurement data from field studies would provide interesting conclusions to support the effectiveness of these numerical models. Additionally, extensive research should focus on the assessment of indoor thermal comfort and air quality during longer-term periods, when outdoor temperature fluctuation is more significant (outdoor temperatures above 30 °C). Likewise, introducing the assessment of different ventilation protocols under future climate change scenarios in the Mediterranean area is also a topic worthy of analysis. Finally, incorporating variable flow mechanisms for mechanical ventilation assessment (manual control and/or automatic control with sensors) is another appealing aspect to be evaluated, as well as incorporating other air pollutants into the analysis or the effect of human and equipment internal gains.

Author contributions

All authors have conceived, designed and performed the experiments; analysed the data; have written, reviewed and approved the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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