

Relationship Between IAQ And Indoor Temperatures Of Different Dwellings In A Temperate Climate During A Pandemic Summer

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ABSTRACT

This paper investigates the relationship between indoor air quality (IAQ) and overheating in a temperate climate in Spain (Cfb attending to Koppen-Ggeiger classification), in dwellings located in residential buildings and without cooling systems. Twelve dwellings were selected among different Spanish building regulatory periods and quality of construction (before the first regulatory period, 1979; between 1980-2006; and after 2006 with the Spanish Building Code following the European Directive, and with the Passivhaus standard), and located in an intermediate floor and a top floor of residential buildings. Two spaces of each dwelling (living room and main bedroom) were monitored during three months from June to September 2021 (temperature, relative humidity and CO₂ concentration). Analysis of monitored data shows dwellings' performance during all summer where a heatwave took place and during the COVID pandemic, where ventilation was strongly recommended to the population to minimize infection risk at home. Results show a better IAQ in the newer dwellings built after 2006 (with vents or heat recovery ventilation systems) although less overheating was not observed in relation to the older ones, but with significant differences during the registered heatwave, and the relationship between IAQ and temperatures. More efforts are needed to improve the design of new and rehabilitated buildings for an optimal thermal and IAQ performance of dwellings, attending to warming conditions related to Climate Change.

KEYWORDS

Monitoring, IAQ, natural ventilation, heatwave, CO₂ concentration

1 INTRODUCTION

Different standards of new and refurbished residential buildings are being developed to improve energy performance, but in cold and temperate climates they are mainly focused on the reduction of energy demand and consumption related to heating systems. As a consequence, buildings are being designed and refurbished with high levels of thermal insulation, high performance windows and high standards of airtightness. However, some studies have found that these high insulated and air tightened envelopes can turn on overheating if other design strategies are not provided (Psomas et al., 2016)(A. Monge-Barrio & Sánchez-Ostiz Gutiérrez, 2018b).

Among other impacts, Climate Change is increasing temperatures in all climates and the frequency, duration and severity of heatwaves (HW) (see IPCC reports, AR6) and yet these new climate conditions are not in general well collected on standards or energy regulations of buildings that use typical climate conditions for the specific location. So, there is a need to raise

awareness in order to design and refurbish buildings with a relatively long life span that should be adapted to these new conditions (see IPCC reports, AR6).

On the other hand, the needed improvement of Indoor Air Quality (IAQ) on residential buildings is addressed in the new buildings mainly through mechanical systems, although standards as e.g. in Spain, allow in addition *hybrid* solutions with fixed vents on windows. Extant literature relates benefits of adequate IAQ with wellbeing and health, especially those more vulnerable. With the COVID pandemic, the need of air renovation has become a priority to reduce airborne infection risk transmission, mainly in overcrowded indoor spaces (Morawska et al., 2020) but also in all type of buildings even dwellings with lower occupation rates (Wargocki, 2021). Although there are some studies with recommendations of CO₂ concentration as an indicator of IAQ, ventilation performance and lower infection risk, they are still highly uncertain, and depend on different parameters to be studied including differences between pathogens (ASHRAE, 2022).

This study is based in the indoor temperatures and IAQ monitoring of twelve dwellings selected within different constructive periods in Spain, and differentiating them between those built before and after Spanish Building Code, CTE by its acronym in Spanish (CTE 2006). This is derived from the first Energy Performance of Buildings Directive, EPBD in 2002, and include IAQ requirements for the residential stock (Gobierno de España, 2017a) (Gobierno de España, 2017b). With these dwellings located in a temperate climate with traditionally mild summers and therefore with dwellings without cooling systems, the main objectives of this paper are to investigate:

- Differences of indoor temperature and IAQ between dwellings built in both periods
- Differences during heatwave events that harden outdoor conditions

2 METHODS

2.1 Context

This study of temperatures and IAQ in the residential sector was performed in twelve selected dwelling in a temperate climate in a location in the north of Spain (Pamplona, Cfb). Dwellings were selected in multifamily buildings constructed in different regulatory periods, affecting mainly the level of thermal insulation and ventilation systems. Although some new dwellings have AC, these systems are not common in the location, and therefore, the sample was selected without cooling systems.

In addition, the study was performed during the COVID pandemic (June-September 2021), where natural ventilation was encouraged in all kinds of buildings in order to reduce airborne infection transmission risk (Aurora Monge-Barrio et al., 2021). Outdoor conditions are normally temperate in the location of the case studies and make possible natural ventilation through windows, but heatwave events, that are unpredictable by definition can compromise this strategy.

2.2 Climate and heatwave events

Pamplona is a Spanish city with a Cfb climate according to Köppen-Geiger classification, that is a temperate “*oceanic*” climate (without a dry season) and D1 climate classification according to the Energy Saving document of the Spanish Technical Building Code (CTE, according to its acronym in Spanish). According to climate series 1980-2010 of Spanish State Meteorological Agency (AEMET, for its acronym in Spanish. See: www.aemet.es), mean, mean of maximum,

and mean of minimum of summer months (June, July, August and September) are: 19,85°C, 26,55°C and 13,15°C. The monitored exterior data of these months during the year 2021 are: 19,88°C, 26,32°C and 14,85°C; therefore, typical data for the location, except minimum that is on average more than 1,5°C higher.

A heatwave (HW) is defined by AEMET as an episode of at least three consecutive days where a minimum of 10% of the given weather stations register maximum temperatures over the 95% percentile of its 1971-2000 climate series during July and August. (AEMET, 2020), although there are other definitions (Zuo et al., 2015). Other authors have recently proposed to study *heatwaves* in relation to their impacts on buildings. (Ramallo-González et al., 2020).

There were two heatwaves in Spain in 2021, and both of them affected the community of Navarre (21-23/7/2021 and 11-16/8/2021) (AEMET, 2021a). The second one stands out for its extension over 33 provinces, therefore affecting almost all the Iberian Peninsula and Balearic Islands, and its intensity (AEMET, 2021b)

Only the second HW of 2021 affected Pamplona. In this case study, indoor environmental conditions of dwellings during the HW are studied only during the days with maximum temperatures above the thresholds of the HW definition for the location; therefore, those days in Pamplona with maximum daily temperature higher than 36°C, that were specifically 12-14/8/2021. Mean, mean of maximum, and mean of minimum of those three specific days are: 25,65°C, 38,13°C and 17,87°C.

2.3 Selected Case Studies. Dwellings

Twelve dwellings were selected according to different regulatory periods in Spain according to their energy performance:

- Prior to 1979, without energy regulations in dwellings
- After 1979 and before 2006, NBE-CT-79 (Ministerio de Obras Públicas y Urbanismo, 1979), first energy regulation in Spain as in other countries after the 1970s energy crisis
- After 2006, Spanish Building Code (CTE, according to its Spanish acronym). In addition to the fulfilment of the official regulations, some of the dwellings are labelled as *Passivhaus*

The global transmission coefficient calculation of the building, “Kg”, in NBE-CT-79, had to be under a certain value, depending on its location and its compacity. The limitation of the energy demand, CTE-HE1 in 2006, asked for an envelope able to reach a thermal comfort as a function of the climate, the use and the building regime, as well as the characteristics of its insulation and inertia, air tightness and solar radiation. The main differences between both regulations are that the later includes the sun radiation and considers the internal load as a key parameter to define the thermal characteristics of the building envelope.

The approval of CTE-HS3 in 2006 was a novelty in Spain, because it quantified air flow renovation in housing units, establishing inlet and outlet conditions, and considering either mechanical or hybrid systems. Previous regulations demanded only construction provisions, like providing windows in habitable spaces or vertical ducts in bathrooms and kitchens, but not offering a real number for air renovation.

For the purpose of this study, dwellings were classified as two main periods, prior and after CTE (2006), since this normative follows Energy Performance of Buildings Directive (EPDB).

CTE has different updates, and it officially includes a Spanish nearly Zero Energy Building (nZEB) definition in 2017 with the 2013 version (Gobierno de España, 2017a). Two dwellings were selected in each same multifamily building (except 5&6 cases studies): one of them located in an intermediate floor and the other one in the upper floor, the latter studied for its higher risk of overheating as other studies have found (A. Monge-Barrio & Sánchez-Ostiz Gutiérrez, 2018a)(Sharifi et al., 2019).

Ventilation in the different apartment units is also presented, but only as a descriptive characteristic. The situation before CTE is difficult to quantify, as no mechanical ventilation was required. Air change was generated by manual windows opening, high level of infiltrations, and, in some cases, the existence of vertical ducts in bathrooms and kitchens.

After the CTE-HS3 approval, hybrid or mechanical ventilation was compulsory, as explained previously. It consisted in air intake in bedrooms (5 l/s per person) and living rooms (3l/s per person) and outtake in bathrooms (15 l/s per unit) and kitchens (2 l/s per net surface). As a result of an equilibrium between intake and outtake, units 7, 8 and 9 have a total flow of 177,91 m³/h.

Passivhaus standard requires a flow of 20-30 m³/h per person, but at least 0,30-fold air change (Passive House Institute, 2013). Considering the real number of occupants in units 10, 11 and 12 and an average of 25 m³/h we obtain rates between 75-150 m³/h per unit, in all of them over the minimum of 0.30-fold air change.

All these main parameters of the dwellings for the purposes of this study is summarized in Table 1.

Table 1. Main characteristics of the 12 selected dwellings for the purposes of this analysis

Dwelling	Year of Const.	Construction Regulatory Period	Area (m ²)	Real occupation (m ² /pers)	Ventilation (*)	Air Flow m ³ /h (**)	Air Flow (CTE) per area m ³ /h m ²	Orientation of monitored rooms (LR-BR)***
1	1964	pre-CT-79	58,25	29	NV_C	-	-	W-E
2	1964	pre-CT-79	58,25	29	NV_C	-	-	W-E
3	1967	pre-CT-79	63,85	32	NV_C+VD	-	-	SE-NW
4	1967	pre-CT-79	54,5	9	NV_C+VD	-	-	E&W-N
5	1990	CT-79	65,0	16	NV+VD	-	-	W
6	1990	CT-79	82,5	28	NV_C+VD	-	-	E&SE-E
7	2018	CTE	85,81	86	Vents +VD	177,91	2,07	SW-NE
8	2018	CTE	85,81	29	Vents +VD	177,91	2,07	SE-NE
9	2018	CTE	84,11	42	Vents +VD	177,91	2,12	NW-SW
10	2018	CTE+passivhaus	96,51	24	HRV	118,8/100*	1,23	NW-NE
11	2018	CTE+passivhaus	87,49	29	HRV	118,8/100*	1,36	SW-NE
12	2021	CTE+passivhaus	108,23	18	HRV	118,8/100*	1,10	SE-NE

Legend:

(*) NV: natural ventilation; NV_C: natural and cross ventilation; Vents: fixed vents in addition to openable windows; VD, ventilation ducts in wet rooms (kitchen and bathrooms); and HRV: mechanical and heat recovery ventilation, in addition to openable windows

(**) Air flow according to *Passivhaus* standard

(***) All rooms have roller blinds and according to questionnaires they were used during all summer

2.4 Monitoring of indoor environmental parameters

Dwellings were monitored with *Mica Desk* sensors of *Inbiot* that can be managed on line. These sensors were calibrated *on purpose* for this study by the company (*Inbiot*), to check the comparability of the sensors with the adequate range of accuracy. These sensors were located in the living room and in one bedroom located preferably in an opposite orientation (see Table 1). Ten-minute data from June to September 2021 was registered for indoor temperature (accuracy $\pm 0,5^{\circ}\text{C}$), relative humidity (accuracy $\pm 3\%$), CO_2 concentration (accuracy $\pm (30 + 3\%)$ ppm), and formaldehyde and VOCs (these two parameters were not included in the study).

Occupants fulfil some questionnaires about typical usage pattern of each dwelling throughout the summer (natural ventilation at night, shading systems, etc.) showing typical and comparable uses for the purpose of this study. Registered data of those days when there were no occupants at home during all day, were not studied in this analysis. In addition, dwellings 6 and 7 had no occupation during the HW, so their data is not included in the study of the HW period.

2.5 Data analysis

Hourly data per room (averaging ten-minute data) of the 12 dwellings were studied grouping them as mean values per group attending to their year of construction and regulatory period (pre and post CTE, according to paragraph 2.3). Box-plot graphs and statistics study analyse temperatures and CO_2 concentration during all summer and during the HW event.

3 RESULTS

Temperature conditions of summer 2021 in Pamplona were in general temperate and similar to the 1980-2010 climate series (see paragraph 2.2) unlike previous years of the XXI century. However, the second HW affected the studied dwellings that registered indoor temperature differences of $5\text{-}7^{\circ}\text{C}$ among them, with indoor temperatures reaching more than 30°C (Figure 2).

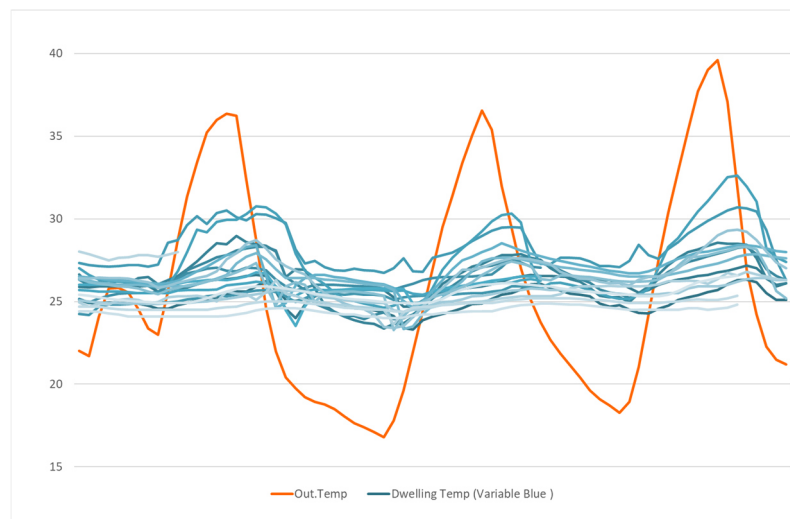


Figure 2. Indoor temperatures during HW that takes place during 12-14/8/2021. Ten-minute temperature per dwelling in blue, from the oldest ones (the darkest) to the newest ones (the clearest)

Comparing indoor temperatures between both main constructive periods (pre and post CTE), through a TTest, differences between both samples were not found statistically significant. However, temperature difference was found significant ($p < 0.001$) during the HW event with

a mean difference of 0,61°C, the newest dwellings having the lower indoor temperature (see Figure 3 and Table 2).

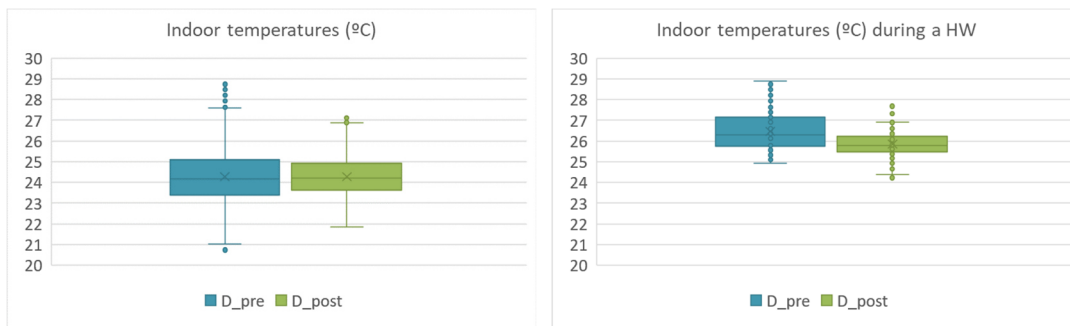


Figure 3. Box-plots showing differences of temperature (°C) between rooms of dwellings built before and after CTE, during all the campaign (left) and during the heatwave event (right). Hourly mean temperature per group data

Table 2. Differences in indoor temperatures (°C) between rooms of dwellings constructed pre and post CTE, during a heatwave event (12-14/8/2021). Mean hourly data per group

Group	Observations	Mean temperature (°C)	p value
HW. D_Pre-CTE	73	26,46 (SD.0,97)	
HW. D_Post-CTE	73	25,85 (SD.0,68)	
HW. Diff.		0,61 (0,47-0,74)	< 0,001

Although there are not significant differences in indoor temperatures, Figure 4 shows in a descriptive way how new buildings present more stable indoor temperatures in relation to outdoor temperatures than older ones.

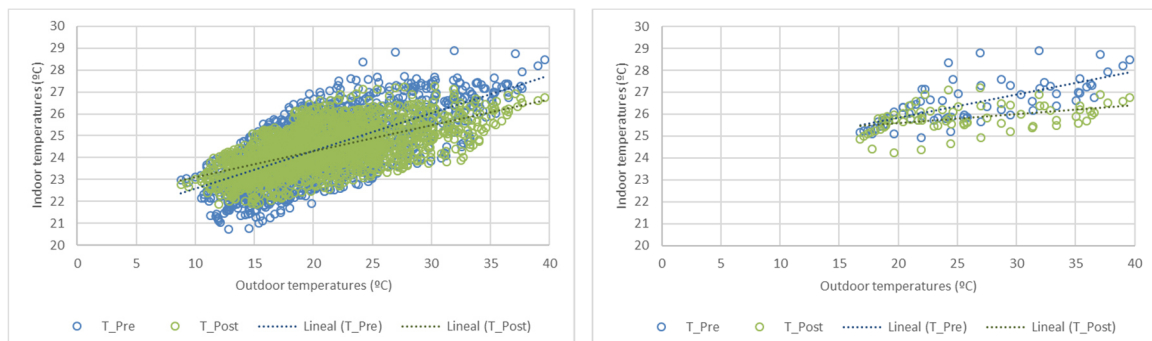


Figure 4. Relation between daily mean outdoor temperatures (°C) and mean indoor temperatures (°C) considering all rooms of dwellings built before (T_Pre) and after (T_Post) CTE, during all the campaign (left) and during the heatwave event (right). Mean hourly data per group

Differences between both periods of construction regarding CO₂ concentration are statistically significant, considering both all summer period and only the HW event (Figure 5 and Table 3). Through the TTest, CO₂ difference considering all summer were 76 ppm and considering the HW were 66 ppm, newer dwellings having the best performance. It is worth noting that average registered CO₂ data of all dwellings was in general lower than recommended values: 1200ppm following EN-16798 for a medium or normal Category of IEQ (UNE-EN-16798-1, 2020); 900ppm, following Spanish normative, CTE-HS3 (Gobierno de España, 2017b) and being the recommended values to minimize COVID transmission according to Kurnitski (Kurnitski et al., 2021). These thresholds suppose an outdoor level of 400ppm, values suggested by CTE-HS when outdoor levels are not available.

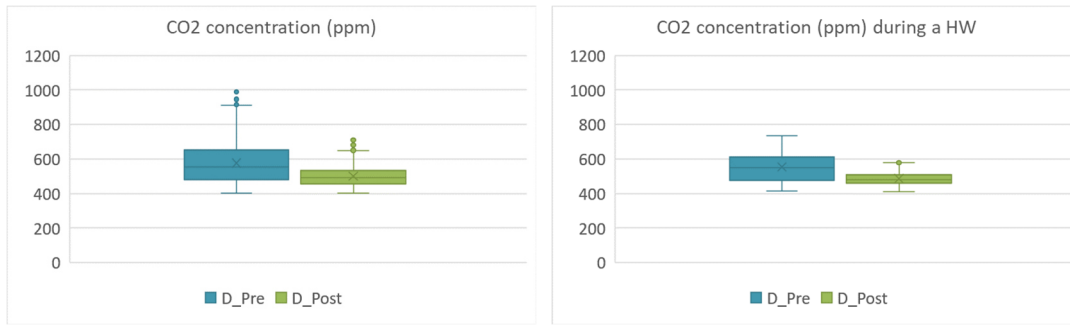


Figure 5. Box-plots showing differences of CO₂ concentration (ppm) between rooms of dwellings built before (D_Pre) and after (D_Post) CTE, during all the campaign (left) and during the heatwave event (right). Mean hourly data per group

Table 3. Differences in CO₂ concentration (ppm) between rooms of dwellings constructed pre and post CTE, during all summer (June to September 2021) and only considering a heatwave event (12-14/8/2021). Mean hourly data per group

Group	Observations	Mean CO ₂ concentration (ppm)	p value
All summer. D_Pre-CTE	2233	576 (SD.119)	
All summer D_Post-CTE	2233	500 (SD.59)	
All summer. Diff.		76 (71-80)	< 0,001
HW. D_Pre-CTE	73	553 (SD.88)	
HW. D_Post-CTE	73	486 (SD.37)	
HW. Diff.		66 (44-89)	< 0,001

Finally, correlation between indoor temperature and CO₂ concentration shows in both cases that when indoor temperature increases there is a slight decrease in CO₂ concentration, that could suggest a higher level of ventilation (Figure 6). However, during HW events and in the oldest dwellings the trend is the opposite with an increase in CO₂ concentration.

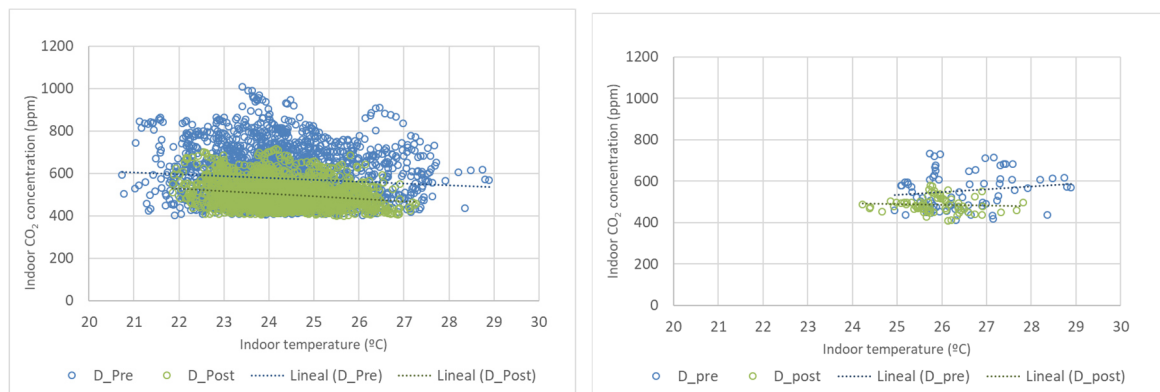


Figure 6. Relation between mean indoor temperature (°C) and average CO₂ concentration (ppm) considering all rooms of dwellings built before (and after CTE, during all the campaign (left) and during the heatwave event (right). Mean hourly data per group

4 DISCUSSION

Consecutive standards and normative related to reduction on energy heating consumption of residential buildings are having proven energy reductions that are being tested and collected at different levels (from literature based on energy simulations and/or post-occupational studies, to governmental reports, etc.). However, new and refurbished design are not proportionally having the expected or desirable same response on the reduction of cooling consumption or overheating risk in naturally ventilated dwellings. In general, cooling consumption in dwellings

is increasing also due to warming temperatures, increase on quality of life and expectations, or technological development of cooling systems. There are even studies that report an increase in the risk of overheating in these new residential buildings as e.g. (Psomas et al., 2016) (Hamdy et al., 2017).

This study shows no significant difference on indoor temperatures between dwellings constructed prior and after CTE, when a better performance should be expected in new and refurbished buildings not only in winter conditions but throughout the year. However, during a heatwave event new dwellings show slightly lower temperatures.

Further research should continue studying indicators and parameters that involve overheating in real case studies, clarifying parameters and strategies from design to occupants' use that help improve thermal conditions throughout the year and adapt these buildings to the future. Overheating during night hours is especially relevant for its impact on wellbeing and health therefore further research based on monitoring data should include analysis differentiating day and night hours.

CO₂ concentration as an IAQ indicator shows a slightly better performance in new homes in both scenarios (all summer, or only considering the HW event), although it is worth noting in the sample of this study, both the low values of CO₂ concentration and the low occupancy in dwellings. Natural ventilation especially at night is widely used by dwellers in Spain (although with some concerns in big cities due to unfavorable outdoor environmental conditions, especially those with more severe climate conditions), and its use has been checked in both old and new case studies of this sample (in addition to HRV or vents) through questionnaires. Finally, benefits and challenges of natural ventilation in addition to mechanical ventilation should be further studied in residential buildings.

5 CONCLUSIONS

This study analyses thermal and IAQ monitoring data of twelve dwellings during summer 2021 therefore during the COVID pandemic, in a location in the north of Spain (Cfb climate). Summer conditions were temperate according to climate series but one heatwave was registered. The study compares mainly indoor temperature and CO₂ concentration in these dwellings selected without cooling systems, and constructed prior and after the 2006 Spanish energy and IAQ regulations (CTE, *Spanish Building Code*; specifically CTE-HE: *Energy Saving* and CTE-HS: *Indoor Air Quality*) related to EPDB in Europe. CO₂ concentration was studied as a common indicator of IAQ, ventilation performance, and increased risk of airborne virus transmission. Natural ventilation has been highly recommended to minimize risk on indoor ambient during the pandemic, but taking into consideration dwelling rates of occupation (m²/person) that are less crowded than other public spaces as classrooms or offices.

Results show how considering data of all summer there are no significant differences on indoor temperatures between both groups of dwellings. However, and considering CO₂ concentration was generally lower than recommended values for residential spaces, difference of values in dwellings constructed prior and after CTE is statistically significant, having the latter ones a better performance. On the other hand, during the heatwave (event being by definition unpredictable and being its higher severity and frequency related to Climate Change impacts), both indoor temperatures and CO₂ concentration values were significantly lower on the new dwellings, with slight differences of 0,61°C and 66ppm respectively.

Although results of this study reveal a slightly better thermal and IAQ performance of the post-CTE dwellings, much more design efforts and research is needed to improve dwellings adaptation and liveability to warming conditions and heatwaves, specially taking into consideration the opportunity given by the *Renovation Wave* efforts in Europe and all over the world.

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