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Thermal comfort and air quality assessment in public schools in Madrid. Study of three cases during one year

Evaluación del confort térmico y la calidad de aire en centros docentes públicos en Madrid. Estudio de tres casos durante un año

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ABSTRACT

Thermal comfort and air quality in schools are two parameters that must be studied in depth. They have consequences on the health of people whose bodies are developing and on the learning outcomes obtained in educational spaces. To analyze the interior environmental quality, the main parameters to consider are: thermal comfort and air quality. In this paper, data on CO_2 concentration and temperature are taken in a total of nine classrooms belonging to three public schools during a year with the aim of analyzing the situation, determining the causes that influence the mentioned aspects and offering measures to correct the deviations recorded and improve the quality of the indoor environment in classrooms. The data obtained shows that CO_2 concentrations exceed the established limit values for one third of the teaching time and that the temperature values are outside the comfort zone for more than two thirds of teaching time.

Keywords*:* indoor environmental quality; indoor air quality; thermal comfort; school classrooms; educational buildings.

RESUMEN

El confort térmico y la calidad del aire en los centros docentes son dos parámetros que deben ser estudiados en profundidad. Tienen consecuencias en la salud de las personas cuyo cuerpo está en desarrollo y en los resultados de aprendizaje que se obtienen en los espacios educativos. En este trabajo se toman datos de concentración de CO_2 y temperatura en un total de ocho aulas que pertenecen a tres centros docentes públicos durante un año con el objetivo de analizar la situación, determinar las causas que influyen en los aspectos mencionados y ofrecer medidas para corregir las desviaciones registradas y mejorar la calidad del ambiente interior en las aulas. Los datos obtenidos muestran que durante un tercio del tiempo lectivo las concentraciones de CO_2 superan los valores límite establecidos y que durante más de dos tercios del tiempo lectivo los valores de temperatura se encuentran fuera de la zona de confort.

Palabras clave*: calidad ambiental interior; calidad del aire interior; confort térmico; aulas escolares; edificios educativos.*

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1. INTRODUCTION

Indoor Environment Quality (IEQ) attracts scientific interest especially when it concerns the health of vulnerable populations such as children. IEQ refers to the state of health and comfort conditions of the different elements that condition our life. The main aspects to be considered to ensure the IEQ must satisfy the conditions of thermal comfort, acoustic comfort, visual comfort, physical-chemical and microbiological contaminants in the air, and the electromagnetic environment (1). The indoor environment should not hinder the learning of the children, e.g. with high noise level, overheated rooms or inadequate lighting conditions or stuffy and unhealthy air. Unfortunately, many schools do not provide an adequate indoor environment. Air supply rate is insufficient and temperatures are too war during summer months (2).

In relation to thermal comfort, particularly in Spain and Portugal, but also in southern Europe, there is an alarming situation. The impacts of climate change are affecting and will affect all European cities but with regional and local differences. The regions of Southern Europe are already experiencing a marked increase in maximum temperatures and a consequent and marked decrease in rainfall. More frequent heat waves and changes in the distribution of infectious diseases sensitive to climate change are expected to increase, which will result in risks to human health and wellbeing (3). The month of June 2017 was marked by high temperatures across Western Europe with heat waves triggering national heat-health plans and wildfires requiring evacuations in Portugal and Spain, sending monthly mean temperatures about 3 degrees Celsius (4.8 degrees Fahrenheit) above normal levels (1981-2010) (4). The heat wave in 2017 highlighted the lack of adaptation strategies to climate change of educational buildings since it took place during the school period. Other heat waves have taken place on dates (5) when most of the educational centers are not occupied and data of indoor temperatures was not recorded.

During these heat waves, temperatures above 32ºC inside public education centers were reached. This problem has generated an important social alarm in the warmer regions of Spain; children went to school with water sprayers, extreme circumstances occurred in the warmest regions, and in large cities where the problem is accentuated by the thermal island effect (6, 7). Therefore the press in Spain echoes this pressing situation in educational centers on their covers. For example, the following press releases for this year 2017: The Andalucía Government gives permission to students to miss classes due to the heat wave with their parents' authorization (8). The Community of Madrid has announced that schools may shorten the day due to high temperatures (9). In Valdemoro (Madrid) five students were treated for symptoms of heat stroke, the rest of the students, as an emergency measure, were transferred to the mortuary of the municipality, being the nearest cool place, with vegetation and shade (10) The BBC's "Maximum temperature call for heatwave classrooms" shows a similar situation in other European Union countries (11).

Studies carried out conclude that there is an effect on student' performance as a result of anomalous temperatures inside their classrooms (12). Heat makes pupils lethargic, can affect concentration and lead to fainting. Warmer and more humid conditions generally seem to have a negative impact on learning; while in the early years specifically, poor air quality and high noise levels have a negative impact (13). A survey was performed (14) over 150 school buildings finding neutral and preferred operative temperatures were found to be about 22.5°C, which falls below predictions of both Predicted Mean Vote index (PMV) and adaptive models of thermal comfort. This finding reiterates the findings of other researchers (15, 16), but a coherent explanation of why children's thermal sensation and temperature preference fall 1-2°C below those of adults is yet to be developed. It is especially interesting that the student group exposed to more diverse indoor and outdoor thermal environment showed greater degrees of thermal adaptability.

Air quality is another factor that influences learning, the available research indicates that increased ventilation rates in classrooms are associated with reduced student absence, but the available data is limited (17). In the early years specifically, poor air quality has a negative impact. CO_2 concentrations seem to affect attendance. Based on a review of literature published in refereed archival journals a majority of the averages and medians of time-average concentrations also exceeded 1,000 ppm with maximum values ranging from 1,400 ppm to 5,200 ppm (18). Concentrations of CO_2 do not appear to be systematically higher or lower in naturally ventilated classrooms relative to mechanically ventilated classrooms. This CO_2 data indicates a widespread failure to provide the minimum amount of ventilation specified in standards for classrooms.

A 1,000 ppm-rise in CO_2 concentration leads to increased absenteeism of 10-20%and every increase of 100 ppm leads to a decrease in annual attendance of about 0,2% (19). If ventilation rates were increased over the recommended values (which in fact is not the case in many schools, as outlined above), the illness caused absence rate would seem to be reduced by about 11-17% (18). An earlier study of one hundred elementary schools from two school districts in the Southwest United States found that 87% of classrooms studied (one classroom per school) had ventilation rates below 7.1 l/s per person (20). The 7.1 l/s per person value was the minimum prescribed rate in the 2004 version of ASHRAE Standard 62, and is comparable to the 2013 version of the ASHRAE Standard. In addition, there was a linear association between classroom ventilation rates and students' academic achievement within the range of 0.9-7.1 l/s per person.

The evidence of an association of increased student performance with increased ventilation rates is compelling. There is evidence of associations of reduced respiratory health effects and reduced student absence with increased ventilation rates (15). Whatsoever, this trend supports the importance of a proper design and operation of classrooms with respect to ventilation. In the AIRMEX study (21) Indoor VOCs were measured in 11 European cities, also in schools. All the measured substances were prevailing in the indoor environment, and seasonal variations were analysed due to changes in ventilation rates (20).

According to data provided by the Ministry of Education, Culture and Sport, in Spain, there are a total of 27,790 schools, of which 18,855 are public (22). Around 68% of Spanish students attend their studies in a center of public ownership while the average in Europe is 81%. The annual expenditure per pupil in Spanish public centers was €7,861 for the period 2013/2014, which exceeds the average of the European Union (€6,829). According to official data, as a general rule it can be said that the total energy consumption in schools is: heating (30%), air conditioning (35%) and lighting (35%) (23).

Table 1. Characteristics of the teaching centers.

	Educational Center A	Educational Center B	Educational Center C
Eduacational Level	Infant and Primary	High School	High School
District	Hortaleza	Chamberí	Chamartín
Average income of the neighborhood (€) (26)	36,691	59,459	62,635
Number of students	200	800	700
Class schedule	9:00 – 13:30 15:30 – 17:00	9:00 – 15:00	9:00 – 15:00
Construction year	1967	1965	2010
Area (m^2)	3,048	9,742	7,176
Opaque facade	Single layer ceramic wall without thermal insulation	No opaque parts. Glazing facade (curtain wall)	Two layer ceramic wall with thermal insulation
Window frame	Aluminum without thermal break	Aluminum without thermal break	Aluminum with thermal break
Window glass	Single glass 3mm	Double glazing 3/6/3	Double glazing 4/6/6

This work is based on the hypothesis that most educational centers in Spain do not comply with the minimum requirements of Indoor Environmental Quality. Temperature and CO2 concentration are measured. Temperature related to thermal comfort analysis, which has generated social alarm in Spain since the heat wave in 2017 and CO2 related to Air Quality analysis is not an issue that has aroused social alarm. Therefore, in Spain, despite the increasing number of energy studies on educational centers, there is not yet a characterization of educational buildings developed but studies of several buildings. One study approximates the need to characterize school buildings by using previous classifications made for residential buildings (24). Most of the existing residential buildings in Spain have been built after the 2nd half of the 20th century (circa 90%). Parallel to housing construction, schools where built, even though there is no characterization available, the bigger amount of school buildings were built before the 2006, when building regulations did not consider mechanical ventilation. Generally, educational centers do not have mechanical ventilation and do not have any ventilation protocols, in Mediterranean climate there is the possibility to regularly ventilate but this act depends on the teachers' habits and perception, so it is proposed to monitor this parameter to determine what the situation is.

The objective of this work is, therefore, to analyze the situation, determine the causes that influence the aforementioned aspects and offer measures to correct the deviations recorded and improve the quality of the Indoor Environment of classrooms.

2. METHODOLOGY

2.1. Case studies

The study was carried out in three educational centers located in Madrid whose characteristics are shown in table 1. The intention is to analyze buildings prior to 1979, as they are a cluster of inefficiency in Spain, since they lack thermal insulation (25). However, a recently constructed building was included in the sample, to analyze the possible influence of the newest regulations. None of the educational centers have mechanical ventilation. In all cases ventilation is done manually by opening windows.

Three spaces were selected in each educational center. Different orientations were taken in order to include possible variations in wind and solar incidence.

2.2. Data collection

Data of CO2 concentration and temperature are registered in the selected buildings as case studies. Data is obtained

Table 2. Characteristics of the spaces in which the recorders have been installed.

	Educational Center A		
Designation	A1	A2	A3
Device	CAI5	CAI6	CAI7
Use	Classroom	Gym	Classroom
Student´s age	11 years old	6–11 years old	5 years old
Mean occupation	15	18	10
Floor	Highest	Ground	Intermediate
Orientation	E	NW	E
	Educational Center B		
Designation	B1	B2	B3
Device	CAI1	CAI3	CAI4
Use	Classroom	Classroom	Classroom
Students age	14-18 years old	14-18 years old	14-18 years old
Mean occupation	22	22	22
Floor	Intermediate	Intermediate	Intermediate
Orientation	E	S	N
	Educational Center C		
Designation	C1	C2	C3
Device	CAI9	CAI10	CAI11
Use	Classroom	Classroom	Classroom
Students age	12-18 years old	12-18 years old	12-18 years old
Mean occupation	16	34	29
Floor	Intermediate	Over outer space	Intermediate
Orientation	N	W	S

with Wöhler CDL 210 data recorders (27). They offer a CO2 measurement range between 0 and 2,000 parts per million (ppm), with an accuracy of 50 ppm ± 5% and a resolution of 1 ppm. They use the NDIR procedure (non-dispersive infrared absorption analyzer) as a measurement principle. They offer a range of temperature measurement between -10ºC and + 60ºC with an accuracy of ± 0.6% and a resolution of 0.1ºC.

Data has been taken every 15 minutes during one year, between the months of October 2017 and September 2018.

The recorders are installed in the classrooms on the outside wall, one meter from the ground, with the characteristics shown in table 2.

2.3. Indicators

The aim is to evaluate thermal comfort and air quality, comparing the data obtained with the recommended values. To study the indoor air quality, the CO2 concentration data is considered. This is one parameter used by the Spanish Building 2017 (Code Document Base HS-3) (28), hereinafter DB HS-3 and by the Regulation of Thermal Installations in Buildings, (29) from now on RITE. This parameter is chosen because the adequate instrumentation to obtain its value is available and because it is a good indicator to observe the amount of air renovation in spaces with human presence. Indirectly, the higher or lower rate of ventilation influences to maintain better or worse indoor air quality.

RITE sets a CO2 concentration for classrooms of 500 ppm above the concentration in outside air. Regarding the concentration of CO2 in outdoor air, the value of 400 ppm is adopted (28, 30), so the value measured inside the classroom should not exceed 900 ppm. This value is similar to the expressed in DB HS-3 "Air Quality", where it is stated that: "In habitable rooms of the dwellings, a sufficient external air flow must be provided to ensure that in each location the average annual concentration of CO2 is less than 900 ppm and that the accumulated annual CO2 that exceeds 1,600 ppm is less than 500,000 ppm · h" (30). Although this limitation only applies to housing, it offers a second reference value to guarantee the health of people. The standard UNE-EN 013779: 2008 "Ventilation for non-residential buildings - Performance requirements for ventilation and room-conditioning systems" (31) also matches this value by marking in its table A.10 the value of 900 ppm to activate ventilation systems that are responsible for ensuring air quality.

To study thermal comfort, temperature data is taken, as contemplated in several studies (32, 33, 34, 35). Thermal comfort depends on various factors such as the characteristics of the users (age, sex, level of clothing...), the shape of the building, the thermal facilities, as well as the ability to be controlled by the users and the external climate, among others. So humans have an adaptive capacity to feel comfort within varied thermal conditions (36).

RITE establishes, as a requirement for thermal quality of the environment, a temperature range of 21ºC to 23ºC in winter and 23ºC to 25ºC in summer, when metabolic activity is maintained in a classroom (1.2 met) and clothing is usual for the season (0.5 clo in summer and 1.0 clo in winter).

For a gym, the comfort temperature drops to 17-19ºC in winter and 19-21ºC in summer, given that the metabolic activity is greater even though the clothing is lighter (37). Nevertheless, Givoni (38) establishes as a comfort zone, the one comprised between values of 21ºC and 26ºC.

To study the quality of the interior environment and its effect on the wellbeing and comfort of the occupants, we proceed to compare the data obtained with the aforementioned reference values.

3. RESULTS

The collected data on CO2 concentration and temperature is summarized.

3.1. CO2 concentration

Mean monthly data is represented in figure 1.

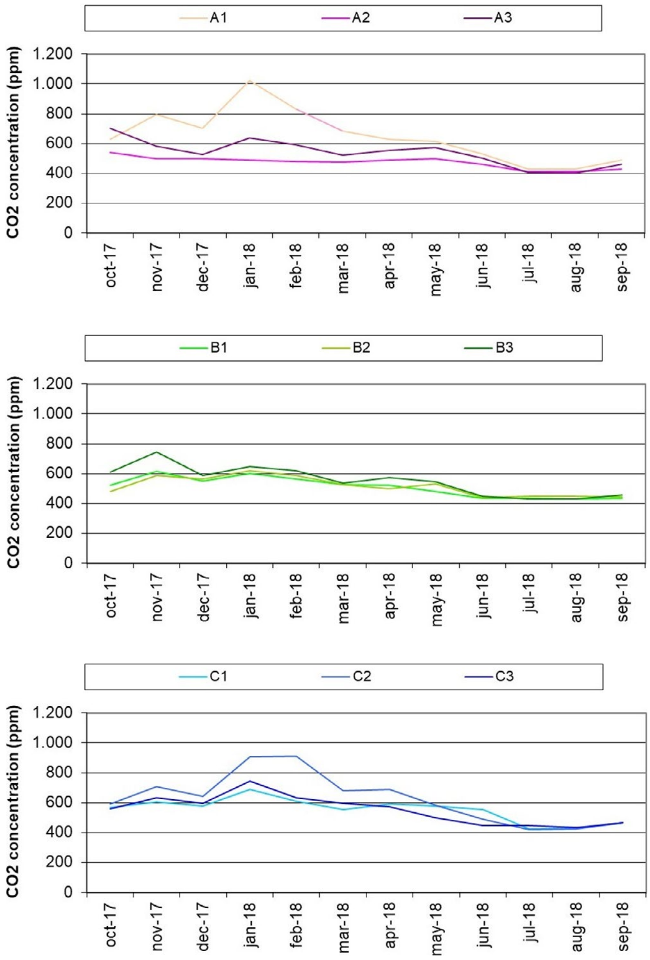

Figure 1. Mean monthly CO2 concentration in each classroom (ppm)

The highest monthly average values are obtained in the month of January, while the lowest values are obtained in May. These values do not take into account the months of July and August that are not academic and the months of June and September in which the academic activity starts and ends.

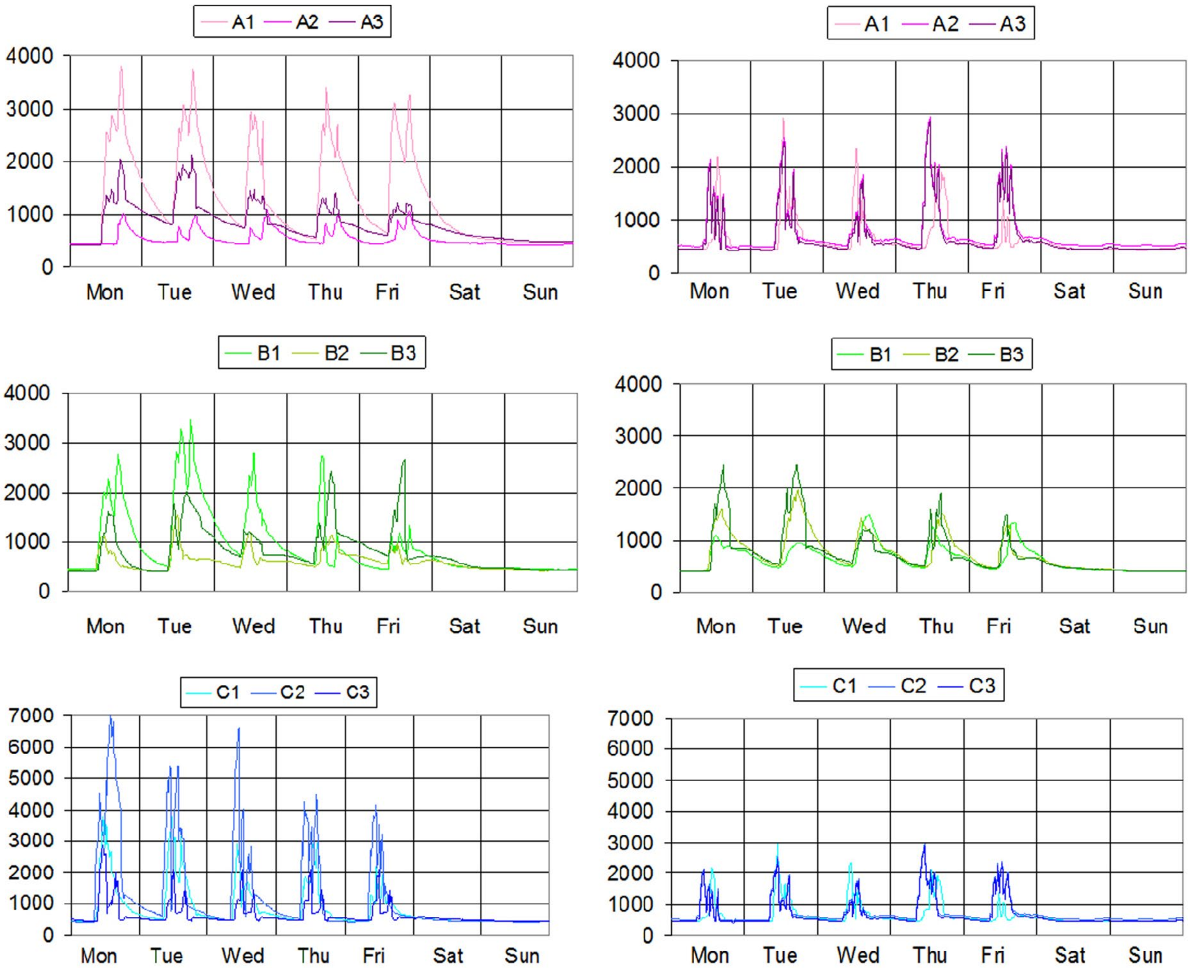

Figure 2. CO_2 concentration (ppm) for each building for the best and worst weeks. From Jan 22nd to Jan 28th (left column) and from May 20th to May 26th (right column).

In Figure 2, the evolution of CO_2 concentrations during the worst and best week in each building is shown. The week from 22nd Jan. to 28th Jan. stands for the worst performance, while the week of May 20th to May 26th stands for the best performance.

Table 3 shows the annual indicators for CO_2 concentration.

Table 3. Indicators of CO_2 concentration during one year.

Class-room	Mean CO_2 concentration (ppm)	Percentage of hours with CO_2 > 900 ppm (%)	Annual aggregate of CO_2 > 1,600 ppm (ppm·h)
A1	640	13%	411,059
A2	468	2%	1,561
A3	524	5%	1,778
B1	509	5%	35
B2	514	5%	2,294
B3	549	8%	32,697
C1	553	8%	93,492
C2	624	8%	431,819
C3	552	8%	114,770

The classrooms are occupied 6 hours a day, and the annual occupation period is 175 days according to the school calendar. This implies that the classrooms remain occupied 12% of the hours throughout the year. Therefore, Table 4 shows the CO_2 concentration data obtained only during school hours.

Table 4. Indicators of CO_2 concentration during school hours throughout a year.

Class-room	Mean CO_2 concentration (ppm)	Percentage of hours with CO_2 > 900 ppm (%)	Annual aggregate of CO_2 > 1,600 ppm (ppm·h)
A1	1,460	64%	333,630
A2	535	6%	1,528
A3	791	31%	1,763
B1	769	32%	35
B2	766	31%	2,234
B3	936	46%	27,766
C1	893	36%	55,584
C2	1,262	49%	281,833
C3	830	30%	57,138

3.2. Temperature results

The obtained average monthly values are shown in Figure 3. These values are compared to the average monthly outside temperature (39).

The highest average monthly values are obtained in the month of October, while the lowest values are obtained in January, if we do not take into account the months of June, July, August and September. Figure 4 shows the temperature evolution in each teaching center during the week of January 22 to January 28, the coldest month.

Figure 5 shows the temperature evolution in each teaching center during the week October 23 to 29 are represented, the hottest month.

Figure 6 shows the percentage of hours in which each classroom is below/above or within the comfort temperature marked by RITE. Winter season and summer season are differentiated since the RITE identifies different comfort temperature values for each season. It is considered the winter season when the heating system is operating from November to April. The one in which the heating system is not working, from May to October, is considered the summer season. The comfort temperature in winter is 21-23ºC for the classrooms and 17-19ºC for the gym, and in summer is 23-25ºC for the classrooms and 19-21ºC for the gym.

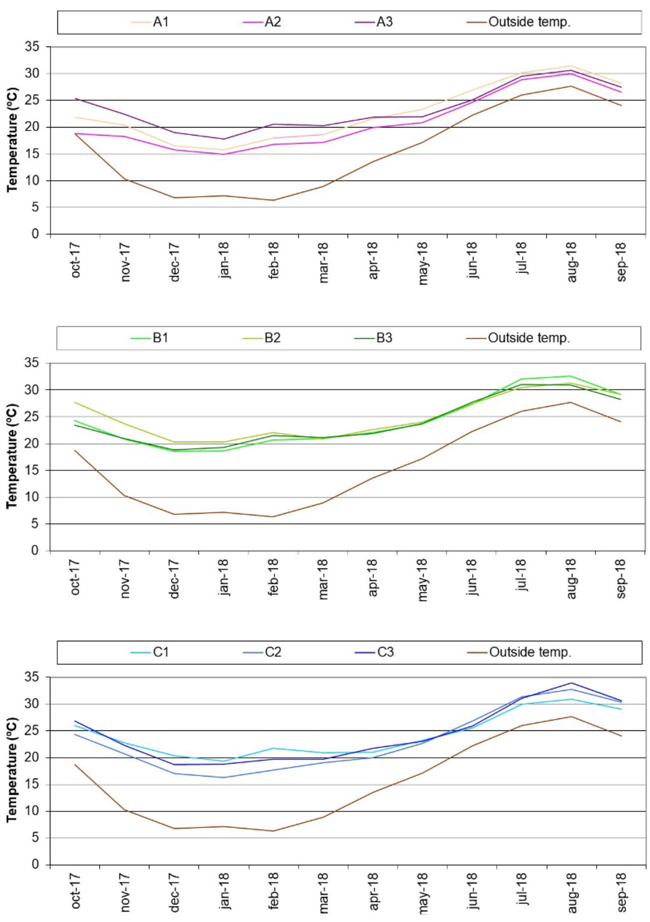

Figure 3. Average monthly values of temperature in each classroom.

As previously mentioned, the classrooms remain occupied for 12% of the hours throughout the year. Therefore, the temperature data is obtained only during the moments in which the classroom remained occupied and shown in figure 7.

4. DISCUSSION

Discussion is set under the two main subjects addressed during the research: indoor concentration of CO2 and temperature results. At the end of this chapter, some considerations about the overall behaviour of each one of the monitored schools are included.

4.1. Indoor CO2 concentration

The limit set by the current housing regulations in Spain for the annual cumulative CO2 that exceeds 1,600 ppm is 500,000 ppm h. To set this limit, a scenario of occupation of the dwelling in which users remain outside for 8 hours on weekdays and 2 hours on weekends is established. This scenario implies that users stay in the house 6,464 annual hours.

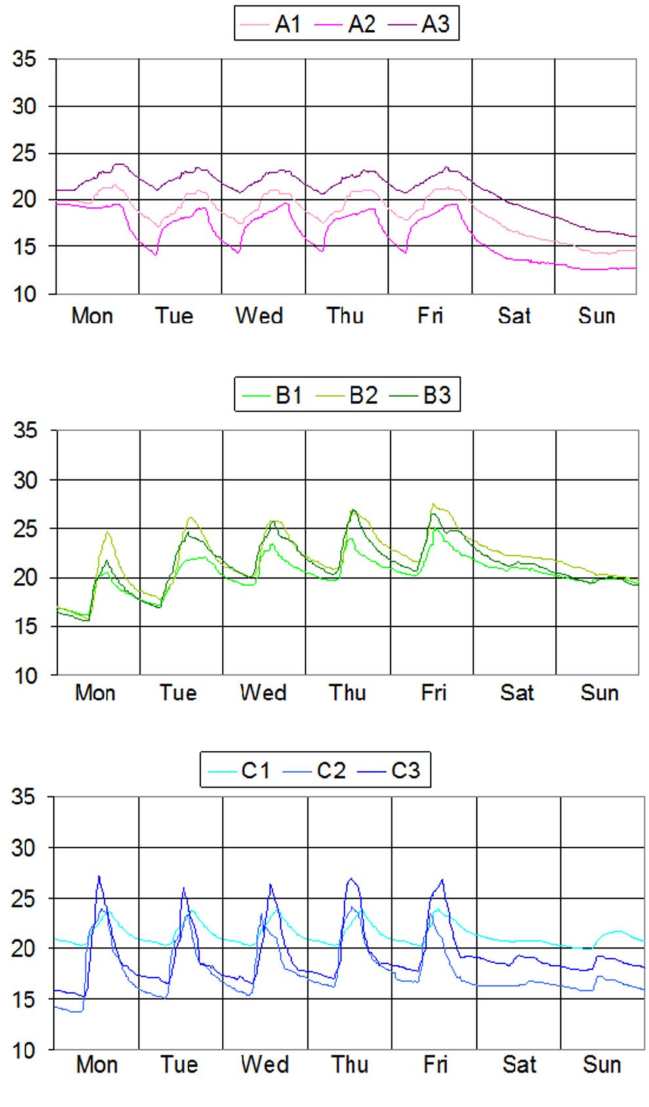

Figure 4. Temperature per teaching center during the week of Jan 22 to Jan 28

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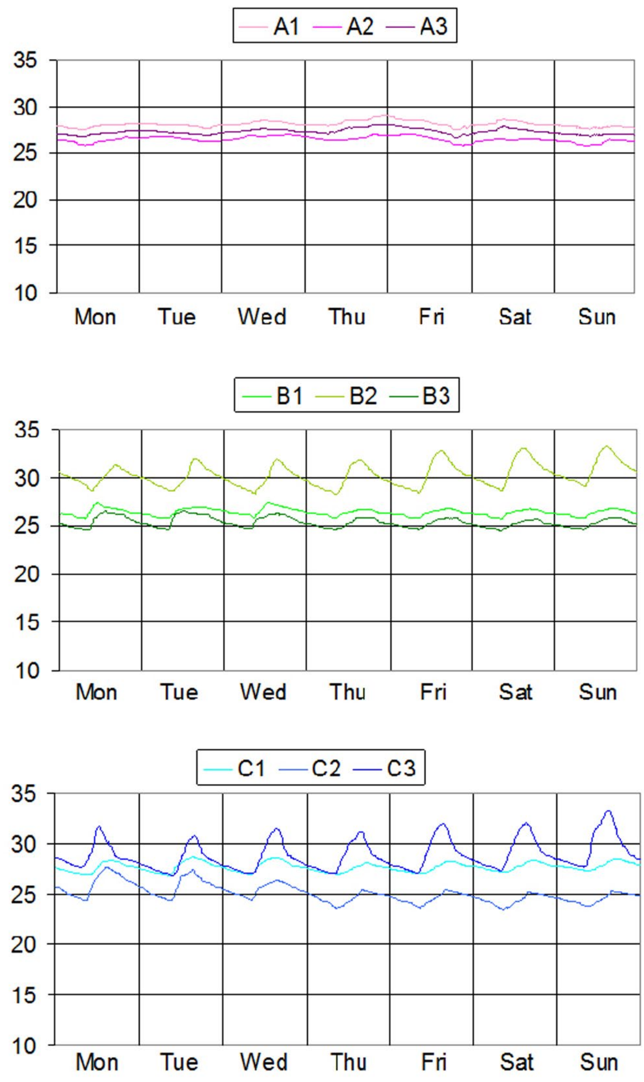

Figure 5. Temperature per teaching center during the week of Oct 23 to Oct 29

In the case of schools, the time spent in a classroom is 6 hours for 175 school days, which is 1,050 hours per year. The equivalent limit for the annual accumulated CO2 that exceeds 1,600 ppm in classrooms, to maintain the same level of health, would be set at 81,219 ppm · h. This value represents 16.2% of the limit marked on housing, since the annual time spent in the classroom is 16.2% of the time spent in the home.

Table 5 shows that classrooms A1 and C2 exceed the equivalent limit value for the annual cumulative CO2 that exceeds 1,600 ppm between 3.5 and 4 times, which means that students are exposed to high concentrations of CO2 accumulated during the period of occupation of classrooms. While the next two classrooms, C3 and C1 have values 0.7 times below the limit value, class B3 has a value 0.35 times below the limit value and the rest of the classrooms, values below 0.05.

Regarding the percentage of hours in which the classrooms have a CO2 concentration above 900 ppm, Table 5 shows that classrooms A1, C2 and B3 exceed this concentration between 46% and 64% of the time in which they remain busy. The same classrooms have an average CO2 concentration value

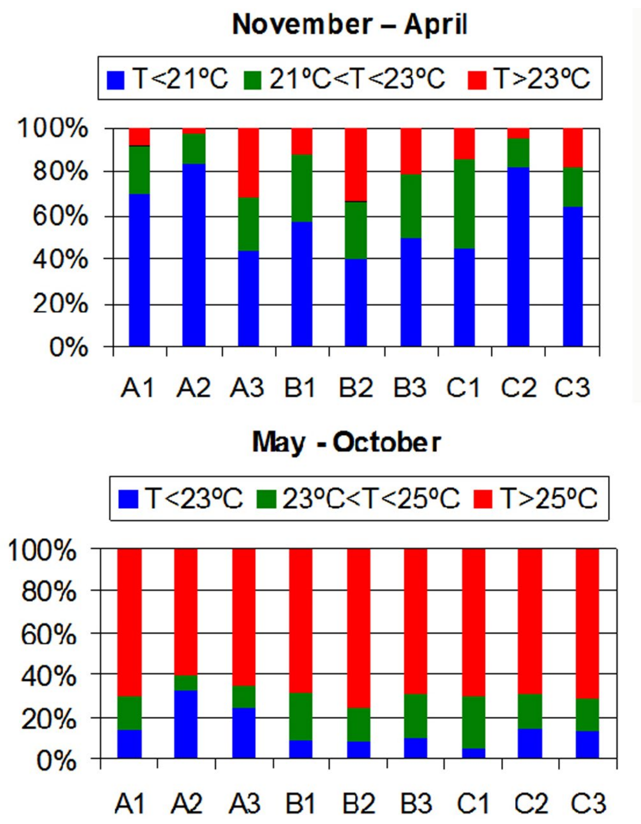

Figure 6. Percentage of hours below the comfort temperature, within the comfort temperature and above that temperature throughout the year.

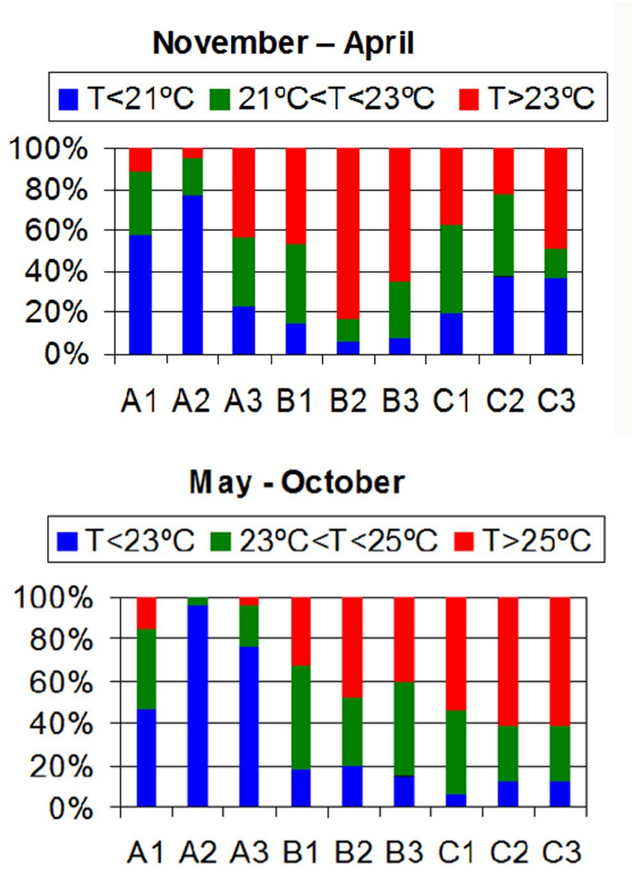

Figure 7. Percentage of hours below the comfort temperature, within the comfort temperature and above that temperature.

above 900 ppm, exceeding this value 1.6 times in the case of classroom A1. Table 5 shows the different classrooms ordered according to how they exceed the limit values of the different CO2 concentration indicators.

Table 5. Classrooms ordered according to how they exceed the limit values of the different CO2 concentration indicators.

Class-room	Annual aggregate of CO2 > 1,600 ppm over the limit value of 81,219 ppm·h	Class-room	Percentage of hours with CO2 > 900 ppm (%)	Class-room	Average concentration of CO2 over the limit value of 900 ppm
A1	4.1	A1	64%	A1	1.6
C2	3.5	C2	49%	C2	1.4
C3	0.7	B3	46%	B3	1.0
C1	0.7	C1	36%	C1	1.0
B3	0.3	B1	32%	C3	0.9
B2	0.03	A3	31%	A3	0.9
A3	0.02	B2	31%	B1	0.9
A2	0.02	C3	30%	B2	0.9
B1	0.00	A2	6%	A2	0.6

First of all, the good behavior that the gym offers in comparison of the classrooms should be highlighted. The value in which it shows the best performance is in Percentage of hours with CO2> 900 ppm (%), whose results are between 5 and 11 times lower than the classrooms. Despite the fact that in the gym, due to more intense metabolic activity than in the classroom, the emission of CO2 by the students increases, its greater volume makes the CO2 concentration lower than that achieved in the classrooms.

It can be observed that the same educational center has some classrooms with very unfavourable air quality conditions, and other classrooms with very favourable conditions regarding the concentration of CO2.

However, school C obtains the worst results, while the other two schools obtain slightly better results. This could be due to two reasons. School C was built in 2010 and has window framing which present more tightness than other schools, this circumstance limits air infiltration. On the other hand, the classrooms studied in case study C have an average occupation of 26.3 students compared to 22 and 14.3 students in cases B and A respectively. Taking into account that the generation of CO2 is 19 l / h · occupant, the generation of CO2 in school C is 20% higher than in school B and 80% higher than in school A. So, since more CO2 is generated and less dissipated, school C presents the worst results as a whole. The SINPHONIE report: Schools Indoor Pollution & Health Observatory Network in Europe (40) studies air quality in 23 European countries among which Spain is not included. The average value of CO2 concentration in the 114 schools studied in this report is 1,433 ppm, while the average value obtained in the 3 Spanish schools studied in this article is 916 ppm. In spite of being a value higher than 900 ppm, only Norway with 686 ppm and Sweden with 657 ppm have lower average concentrations.

Finally, it should be noted how the studied gym achieves very low results. This is due to the fact that, despite that the metabolic activity that takes place in it implies a greater emission of CO2 by the students, as it has a larger volume than a classroom, the CO2 concentration does not reach the values obtained in smaller spaces.

4.2. Indoor temperature aspects

Table 6 shows different classroom analysis according to the comfort temperature for the winter season with space heating, and summer season, during the annual occupation period of the classrooms.

It can be observed that the highest temperature during the heating period is school B (table 6), while school C has the

Table 6. Classrooms arranged in the comfort temperature ranges for the winter season and the summer season.

November – April						May – October					
Classroom	Below C. T.	Classroom	Comfort temperature	Classroom	Above C. T.	Classroom	Below C. T.	Classroom	Comfort temperature	Classroom	Above C. T.
A1	58%	C1	43%	B2	83%	A3	76%	B1	49%	C2	61%
C2	37%	C2	41%	B3	66%	A1	47%	A2	46%	C3	61%
C3	36%	B1	39%	A2	51%	B2	20%	B3	45%	C1	54%
A3	23%	A3	34%	C3	48%	B1	18%	C1	40%	B2	48%
A2	20%	A1	31%	B1	46%	A2	17%	A1	38%	B3	40%
C1	19%	A2	29%	A3	43%	B3	15%	B2	32%	A2	37%
B1	15%	B3	28%	C1	37%	C2	12%	C2	27%	B1	32%
B3	7%	C3	15%	C2	22%	C3	12%	C3	27%	A1	15%
B2	6%	B2	11%	A1	11%	C1	6%	A3	19%	A3	4%

highest percentage of hours inside the comfort temperature, and school A is the one that presents cooler temperatures.

However, in the periods when heating installations are not working, the warmest case is School C, which is the school with the longest period of comfort, and the coldest is case A. In this last period, thermal behaviour of the building is analysed in free oscillation (without an external incorporation of energy), since it is not affected by the operation of heating appliances.

None of the centers have shading devices such as blinds or horizontal overhangs that allow the entry of natural light while protecting windows from direct solar radiation. In all cases, the entry of direct solar radiation can be blocked deploying the blinds, but this forces the use of artificial lighting when protection from direct solar radiation is needed.

Summer season

Table 7 shows the classrooms ordered according to the percentage of hours that they are above the comfort temperature, compared to the rest of the data that influences the heat gains during the summer period.

In School B, the number of students is similar in the classrooms, as well as its situation in the middle floor. The only difference is the orientation. A greater number of hours are observed above 25ºC in classroom B2 that has a south orientation. Next is classroom B3 with northern orientation and with more hours than classroom B1 with east orientation. However, if we observe the evolution of the temperatures over a typical week shown in figure 6, we can see how classroom B1 presents about one more degree of temperature than classroom B3. Even presenting better behaviour than school C, the temperature at which the three classrooms are located is excessive.

Classrooms and gym in school A profit from orientations with low thermal gains caused by solar radiation, low number of students. Only the gym A2 has 37% of hours above comfort temperature. The classrooms barely exceed these values.

Winter season

Table 8 shows the classrooms ordered according to the percentage of hours below comfort temperature, together gains and losses of heat during the winter period-related data.

Table 7. Classrooms ordered according to the percentage of hours of overheating during the summer season.

Class-room	Above C. T.	Floor	Orientation	Students
C2	61%	Over outer space	W	34
C3	61%	Highest	S	29
C1	54%	Intermediate	N	16
B2	48%	Intermediate	S	22
B3	40%	Intermediate	N	22
A2	37%	Ground	NW	18
B1	32%	Intermediate	E	22
A1	15%	Highest	E	15
A3	4%	Intermediate	E	10

Table 8. Classrooms ordered according to the percentage of hours below comfort temperature during the winter season.

Class-room	Below C. T.	Floor	Orientation	Students
A1	58%	Highest	E	15
C2	37%	Over outer space	W	34
C3	36%	Highest	S	29
A3	23%	Intermediate	E	10
A2	20%	Ground	NW	18
C1	19%	Intermediate	N	16
B1	15%	Intermediate	E	22
B3	7%	Intermediate	N	22
B2	6%	Intermediate	S	22

In case C, a similar behaviour is observed in classrooms C2 and C3. The same number of hours is maintained above comfort temperature. Analysing the evolution of temperatures during a typical week shown in figure 6, we note that classroom C3 suffers the highest temperatures. This is because it receives heat gains through the roof and solar gains through the windows (in spite of its protection) facing south. One might think that the west orientation of the classroom C2 could be more unfavourable, but it receives the highest heat gains when the classroom is unoccupied. The greater number of students in classroom C2 compensates for its better location and orientation with respect to classroom C3. Class C1, due to its better orientation and location and its smaller number of students, behaves better than the rest of the classrooms. Although the temperature at which the three classrooms are located is excessive.

School A has the best behaviour in summer. However, in winter it presents the worst conditions, which implies that the use made of the heating installations is insufficient to maintain an adequate indoor temperature. In spite of this, classroom A3 exhibits behaviour 2.5 times better than the other classroom in the same school. No factors that explain this difference are found, so it is considered that the heating installation could present imbalances in its regulation.

The worst behaviour in school C compared to school B is repeated both in winter and in summer. This circumstance may be due to the fact that its thermal envelope has worse performance. Given that building B was built before the first regulation, limiting energy demand in Spain (NBE-CT79) and building C is constructed according to this regulation; the worst behaviour of the envelope could be explained by the higher percentage of glazing surface in building C, which increases the global transmittance of its facade.

The only school that shows good behaviour in winter is B, although when analysing figure 6, it is observed that on Mondays the educational center has a hard time reaching 21ºC because during the weekend the heating installation is off.

Table 9 shows the classrooms in order according to the percentage of hours above comfort temperature, together with the rest of the data that influence the gains and losses of heat during the winter period in which the heating installation is operating.

The large number of exceptions that are presented before the general criteria of expected behaviour, indicate, once again, that the regulation capacity of the heating systems are not able to adequately avoid the excess of energy consumption once the comfort temperature has been reached. The waste of energy that has been verified does not reflect the extra energy consumption that could actually have been produced, given that only temperatures have been measured and the time in which the classroom windows have been opened to relieve the excess heat that has been recorded is unknown. The thermal amplitude (difference between maximum and minimum daily temperature) of the different classrooms throughout the day, including school hours and closing hours, are shown in table 10 for the winter and summer seasons.

Table 9. Classrooms ordered according to the percentage of hours whose temperature is above comfort temperature during the winter season.

Class-room	Above C. T.	Floor	Orientation	Students
B2	83%	Intermediate	S	22
B3	66%	Intermediate	N	22
A2	51%	Ground	NW	18
C3	48%	Highest	S	29
B1	46%	Intermediate	E	22
A3	43%	Intermediate	E	10
C1	37%	Intermediate	N	16
C2	22%	Over outer space	W	34
A1	11%	Highest	E	15

Table 10. Thermal amplitude of the classrooms in summer and winter.

Classroom	Orientation	Winter amplitude (ºC)	Summer amplitude (ºC)
A1	E	7.2	1.3
A2	NW	4	1.4
A3	E	7.7	1.4
B1	E	9	1.7
B2	S	11.8	5
B3	N	11.3	2.2
C1	N	4.1	1.9
C2	W	10.5	4
C3	S	12	6.5

Registered data shows that 89% of the classrooms and the gym remain more than 20% of the time above the maximum comfort temperature. Such overheating may be due to the fact that the heating installations in the schools suffer from an adequate regulation system, which is capable of stopping the heat emissions when the set point temperature is reached.

It is noticed that school A, which has a more limited use of its heating installation and keeps its classrooms and gym below the comfort temperature for more hours during school hours, the A3 classroom is above the comfort temperature for 43% of the time.

Classrooms and gym that show better behaviour against energy waste exceed the comfort temperature, and are those that are on more exposed floors, have a smaller number of students and have orientations east and south with greater sunlight during the school day. It should be noted that the results reflect exceptions tothis criteria. Classroom A3 with the largest number of students, presents the third best behaviour. Classroom C3 has the third worst result. Classroom B3 faces north, so it does not receive solar radiation, presents the second worst result.

During the periods in which the heating is off, the classrooms maintain a general thermal amplitude between 1.3 and 2.2ºC, except for the classrooms with west and south orientations, whose thermal amplitude increases to values between 4 and 6.5ºC.

In the periods in which the heating is on, the thermal amplitude stays around 4ºC in classrooms A1 and C1 with north-west and north orientations, given that they do not receive sunlight. In schools A and C, classrooms and gym that receive solar gains, present a thermal amplitude between 2 and 3 times higher, as this occurs during the summer. However, school B does not show a significant difference in thermal amplitude between classrooms that receive sunlight and the one that faces north. This may be due to the fact that the classrooms in school B reach higher temperatures in winter thanks to the contribution of energy by the heating system, which increases its thermal amplitude and reduces the influence of solar gains.

4.3. Global behaviour by schools

Table 11 shows schools ordered from best to worst behaviour with respect to the different parameters studied.

Table 11. Schools ordered according to behaviour.

Order	CO2	Winter T	Summer T
Best	A-B	B	A
Intermediate		C	B
Worst	C	A	C

It can be observed that case C, despite being in the neighbourhood with the highest average income and being of more recent construction, shows the worst behaviour.

As previously indicated, greater air tightness of windows in case C and the high occupancy of its classrooms are causing high concentrations of CO2. Also the fact of having opaque enclosures and glazing, both with lower thermal transmittances, together with their higher occupancy, are causing overheating in summer. Although, due to these circumstances, it would be foreseeable that school C presented the best temperature comfort in winter, this is not the case. This may be due to the fact that the heating installation in School B, which presents better comfort in winter, contributes with much more energy consumption, despite the fact that it has greater losses.

5. CONCLUSIONS

5.1. Concentration of CO2

The results of concentration of CO2 in the different classrooms lead us to the conclusion that the determining factor is not so much the constructive characteristics of the educational center or the number of students present in each classroom, which undoubtedly have an influence, but the use of natural ventilation by opening the windows which is done in each classroom. Since the CO2 concentration of the outdoor air is lower than the CO2 concentration of the indoor air, when the windows are opened, the CO2 concentration is reduced.

The worst values are obtained in a classroom from each school, while other classrooms in the same center obtain better results.However, school C built in 2010 whose window framing has greater tightness and whose occupancy by classroom is higher, gets worse results against CO2 concentrations, while the other two schools whose window framing is less tight and their classrooms are less busy, get better results.

It is concluded, therefore, that natural ventilation by opening the windows in the classrooms in the breaks between classes can be a sufficient measure to guarantee air quality in classrooms, but this is not carried out adequately in most cases. To avoid this situation and ensure adequate air quality, it is advisable to carry out a protocol in which someone is responsible for opening and closing the windows during the changing of class. The air quality delegate could be entrusted to supervise, for the good of all, that the classroom is adequately ventilated. Since opening windows in winter improves indoor air quality, but reduces thermal confort, it would be desirable for classrooms to have CO2 and temperature meters to manage window opening times so that neither of the two parameters were not compromised.

However, this form of ventilation is less energy efficient than double flow mechanical ventilation with heat recovery. Furthermore, with mechanical ventilation, adequate air renewal flow rates are guaranteed regardless of whether correct manual ventilation management is carried out.

Regarding the seasons, the highest concentrations of CO2 are reached in winter, which is when the windows are least opened due to the low outside temperatures.

5.2. Temperature

The temperature results obtained show us that the classrooms meet comfort temperature only for 30% of teaching hours.

Summer season

During the summer season in which the buildings operate in free regime, since the heating system remains off and there is no refrigeration installation, in each school the south-facing classrooms are the ones with the highest temperatures. This is because the east-facing classrooms receive solar radiation in the morning when the outside temperature is still low. While the classrooms facing west, which receive solar radiation in the afternoon when the outside temperature is higher, are unoccupied at that time of day.

It is concluded that it is more relevant to avoid the south orientation or to place external solar-luminance control devices, to reduce overheating during the summer in the classrooms, since they do not have a cooling installation.

Winter season

During the winter season, it is observed that in school C, contrary to what would happen in the case that the building operated in free regime, the classroom facing north behaves better than the one oriented to the south. It is also observed that in school A, a classroom oriented to the east maintains cooler temperatures for 3 times longer than another classroom with the same orientation.

During the winter season, the installation of heating can limit the differences in behaviour due to orientation, as long as there is the possibility of selectively controlling the spaces according to the different orientations.

It is observed that 30% of the winter season time the classrooms are within the comfort temperature, while 30% of the time they are cold and for 40% they are hot. During this period, school A has low temperatures between 47% and 96% of teaching hours.

It is concluded that the regulation of the operation of the heating installation is inadequate to maintain comfort conditions. It should come into operation beforehand, so that the first hours of the day enjoy a higher temperature and should have regulation capacity that would enable centers to stop emitting heat in the classrooms before entering the overheating situation. To avoid overheating it would be desirable for the radiators to have thermostatic regulation valves that stop the emission of heat inside the classrooms once the comfort temperature has been reached. On the other hand, school A should extend the period of operation of the heating installation to overcome the low temperatures it presents once the heat supply stops working.

5.3. General conclusion

The bad situation of air quality and thermal comfort in the public schools analysed in Madrid is noted. Adequate air quality is achieved for 64% of teaching time. Appropriate temperature conditions are achieved during 30% of teaching time. It is necessary to carry out an investigation of thermal comfort and air quality on a larger sample of schools in Madrid and other regions in Spain, in order to obtain a more accurate diagnosis, depending on the year of construction, the climatic zone in which it is located and other variables that can be identified, as building materials, location of the most polluted school zones, treatment of CO2 as a tracer gas, etc.

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