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Encouraging natural ventilation to improve indoor environmental conditions at schools. Case studies in the north of Spain before and during COVID

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ABSTRACT

The COVID pandemic has strongly affected daily life both in Spanish schools and worldwide. Providing the best environmental conditions for children allowing face-to-face learning with healthy and safe indoor spaces is a challenge. In the present study, empirical research about how these environmental conditions change with COVID is presented comparing the situation from March 2020 to January 2021. The methodology combines surveys conducted in nine schools with a case study in a selected school where a detailed monitoring of the building was developed during both heating seasons. This data analyzes the impact of the new COVID prevention protocols on indoor environmental conditions (especially those related to natural ventilation). Results show a mean CO_2 reduction of 1,400 ppm, having in the second term values around 1,000 ppm, although temperatures diminished nearly 2 °C to mean values of 18 °C. Evolution of temperature and CO_2 concentration throughout the day was also analyzed, being these indoor conditions especially important for the children with poorer health. Mechanical ventilation with heating recovery should complement natural ventilation, at least during the coldest months or hours of the day, although systems have to be carefully designed and installed to work effectively.

1. Introduction and background

Studies all over the world have shown the need of creating a productive educational environment together with environmental awareness. Studies on educational buildings have proved that inadequate indoor environmental conditions of classrooms affect negatively the students' learning abilities and concentration [1–3], due to the time, one third of the day, they spend in indoor spaces [4,5], and taking into account that inadequate environments can generate or enhance health issues such as headaches, flue, asthma, etc. [6,7]. Some studies show the variation of the student's performance taking into account different temperatures ranges [8,9] and CO_2 concentration levels [10]. Both parameters do not seem to have a direct relationship even if they can both create a feeling of discomfort [11].

Children's thermal comfort has been studied and adapted to students' preferences [4,12], which are different to adultś. However, children show a wide range of adaptability and flexibility on indoor environments [4,13]. More research is recognized as necessary, not only on thermal comfort but also on other environmental parameters, in order to design and refurbish the best indoor spaces for children [7]. Through direct children responses of self-reported sensations related to thermal comfort, indoor air quality or tiredness, and other measured or monitored classroom data, parameters that predict those variables can be studied.

Natural ventilation is the more usual type of ventilation on educational buildings in Spain and in Europe [15–16]. There are other studies that deal with natural ventilation in schools in similar Southern European climates as Greece [17], Italy [12], Portugal [1,18] or Andalusia in Spain [19,20]. There are several studies that describe the relationship between CO_2 levels and window areas [21], ventilation rates [22] or the incidence of classroom orientation to enhance cross ventilation [23].

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Mechanical systems are slowly being introduced in schools in order to improve indoor environments by reducing heating energy consumption, in order to achieve high standards of energy efficiency and low emissions [24]. In Spain, mechanical ventilation systems are mandatory in schools since 2007, with the Standard for Regulation of Thermal Mechanical Systems (RITE, acronym in Spanish) [25], part of the Spanish Building Code (CTE). Mechanical ventilation is recommended to be combined with natural ventilation, although it still needs better design and operating practices [26], and it should be properly designed with an efficient building envelope in order not to increase energy consumption. Finally, it is not the unique preferred option by children as other studies suggest [27].

The emergence of COVID has created a critical point for the traditional school routine. In Spain, schools closed in mid-March 2020 and they re-opened in September 2020, having into account the advantages of the face-to-face learning in children [28]. However, a lot of countries maintained their schools closed with different socio-economic contexts and climate conditions, being estimated that globally 30% of children did not have the needed technology for on-line learning or were not reached by remote learning policies [29].

Ventilation has been broadly recognized as a means to reduce airborne transmission of SARS-CoV-2 and any other airborne virus-containing small micro-droplets, in addition to other measures (such as avoiding overcrowding, etc.), including building engineering controls that provide sufficient and effective ventilation, preferable with particle filtration and air disinfection, and avoiding air recirculation [30]. Also, the reconsideration of ventilation rates must include as an objective the need of removing airborne pathogens in order to design spaces with low risk of infection, which should be included in the standards in the following years [31,32].

Recommendations from general and regional administrations for the 2020–21 school course were implemented in Spain in relation to the mandatory use of masks (indoors and outdoors), distances between students, protocols of cleaning and disinfection, etc. [33]. Among all these measures, enhancement of natural ventilation was considered a key measure looking for a safe and healthy indoor space. Natural ventilation was prioritized over mechanical ventilation, and special measures should be taken with mechanical ventilation (filters, higher rates, etc.). The recommendation was at least to ventilate at the beginning and at the end of each class, during the break, and if possible, during the classes [34].

This natural ventilation measure is contrary to any concept of energy efficiency on the heating period [35,36], but governments have specifically prioritized health through natural air renewal over lower indoor temperatures and higher energy consumption during the pandemic [33], although ACH is difficult to control [30]. A balance should be found between energy consumption, thermal comfort and measures to be applied in the following years, not only through the installation of technology. As e.g. the study of *Korsavi et al* explains adaptive behaviors, and teachers' and children's engagement have the most impact on a better IAQ [37], above other parameters on heating and non-heating periods.

CO2 monitoring has been proposed as a low cost indicator to achieve low levels of transmission risk, and some schools have introduced these sensors throughout the year to help understand the efficiency of natural ventilation [38]. However, it can be misrepresentative when it is not calculated taking account specific calculations of SARS-CoV-2 transmission [31,39].

This study has been developed during the heating period in secondary/high schools located in Pamplona (north of Spain with temperate climate), before and during the pandemic, with the following research aims:

- To analyze energy efficiency and indoor environment of nine state schools, and assess architectural measures and limitations during the pandemic related to the buildings.

- To compare indoor environmental parameters in a selected Case Study (IES.N), before and during the pandemic (temperature and CO_2 concentration).

- To check and analyze personal, environmental and architectural parameters in a classroom, predict thermal sensation, sensation of stuffy environment (related to IAQ) and tiredness sensation, before the pandemic.

2. Methods

2.1. Context

This study is focused on the state secondary/high schools (with children between 12 and 17 years) located in Pamplona, in the north of Spain. In each school, architectural and constructive characteristics of the buildings and their facilities were studied, and surveys to the directors were carried out in December 2020-January 2021. Among these schools, an educational center (IES.N) was selected to be monitored and studied in detail in September 2019 and in March 2020 previously to the COVID lockdown in Spain. The building was continuously monitored from March 2020 to February 2021, during the pandemic. This study only analyses data from the heating seasons.

After reopening schools in September 2020, a special relevance is being given to the enhancement of natural ventilation. From the Government of Navarre (which regulates Education at regional level), the protocol of classrooms management establishes as a minimum, and in a prescriptive way, ventilation of 10–15 min before classes, during the break (30 min), and at the end of the school day [34].

2.2. Climate

The study analyses indoor environmental conditions of schools located in Pamplona, in the North of Spain (42.5°N, 1.4°W, 459 m altitude), with a temperate climate without a dry season, Cfb "*oceanic*" according to Köppen-Geiger classification. Following data from the 1980–2010 climate series of the Spanish State Meteorological Agency, AEMET [40]: average annual temperature is 12.7 °C; January is the coldest month of the year, with a monthly average of 5.2 °C and a monthly average minimum of 1.4 °C; and March has a monthly average of 9.1 °C, and a monthly average minimum of 3.7 °C.

2.3. Selected educational centers and surveys

Nine of the eleven secondary/high state educational centers located in Pamplona were studied. Schools were visited and directors interviewed by the research team. Information was collected about facilities and constructive and architectural characteristics of the buildings related to energy efficiency and indoor environmental conditions (summarized in Table 1) and about measures, perceptions and limitations in the classes during COVID, regarding ventilation, perception of IEQ, energy consumption, etc.

Building typologies are related mainly to classroom arrangement (see Fig. 1). In linear block and spinal typologies, classrooms have mainly orientations facing North and South or Southwest (S or SW in T4.1). In square with courtyard and U-shaped typologies, classrooms face different orientations with different associated performance.

Selected schools were built in different construction periods. Four of them were built before the first Spanish energy normative

Table 1
Summary of more relevant characteristics of the studied educational centers in Pamplona (Spain).

School	1	2	3	4	5	6	7	8	9
Year construction	1944(A)	P1: 1950 (A) P2: 2005 (B)	1971(A)	1972(A)	1980 (A*)	P1: 1987(B) P2: 2015(C)	1989(B)	P1 2007(B*) P2 2011(C)	2018(C)
Rehabilitation works	W, 70% from 2012 RTI 2018–19	FTI-RTI-W 1995 B 2015	W 100% from 2012	RTI 2013–20 W 2013–20 B 2018	W	W (South F from 2015)	W GF 100%, F1&F2, 50%	–	–
Classroom typology (Fig. 1)	T1. Square-shaped & courtyard	T2. Linear block	T4.1.Spinal	T3. U-shaped block	T2. Linear block	T2. Linear block	T1. Square-shaped & courtyard	P1. T4.2 Spinal P2. Linear	T2. Linear block
Heated area (m^2)	9583	4572	5749	5448	5534	5085	4681	7333	4375
U façade(W/m^2 K)	1.62**	0.58	1.74	0.58**	0.61	0.58–0.22**	0.58	0.51–0.35	0.20–0.34
U roof(W/m^2 K)	0.50**	0.50	1.00	0.50**	0.53	0.53–0.27**	0.53	0.55	0.19–0.36
W. Frame/Glazing	Old: T/SG New: Al/DG	T/DG	Al/DG	Old: Al/SG New: Al/DG	Old: Al/SG New: Al/DG	Al/DG	Al/DG	Al/DG	Al/TG
Energy H. system	N. Gas	Oil	Oil	N. Gas	N. Gas	N. Gas	N. Gas	N. Gas	N. Gas
Heating S.	WR	WR	WR	WR	WR	WR	WR	WR	WR
Mechanical Ventilation	No	No	No	No	No	P1: no P2: yes. HRV (– –)	No	P1: no P2: yes HRV (-)	Yes: HRV (-)
Air Conditioning	No	No	No	No	No	No	No	P1: no P2: yes (– –)	Yes (– –)
Occupation (m^2/student)	3–2.3	2	1.7–2.3	2.9	2.4	2.9	2.2–2.9	P1: 2.3–2.7 P2: 2.8	2.3
Main Orient. Classrooms	NE, SE, SW	S, N	SW	SE	NW, SE	NE, SW	NE, NW, SE, SW	P1: NE, SW P2: E, W	NW, SE

Legend:Period of construction: A, before 1979; B, between 1980 and 2006; and C, after 2006 (those marked with * means that although the building was finished in one period, it was constructed with the previous normative
P, phase; GF, Ground Floor; F1, First Floor; F2, Second Floor
W, windows; RTI, Roof Thermal Insulation; FTI, Façade Thermal Insulation; B, Boiler
** Specific data is not available, so U is estimated according to the built period and visual observation
T, Timber; Al, Aluminum; WR, Water radiators; SG, simple glazing; DG, double glazing; TG, triple glazing
(-) Not used. Too much noise(– –) Not used. It is not necessary or it does not work

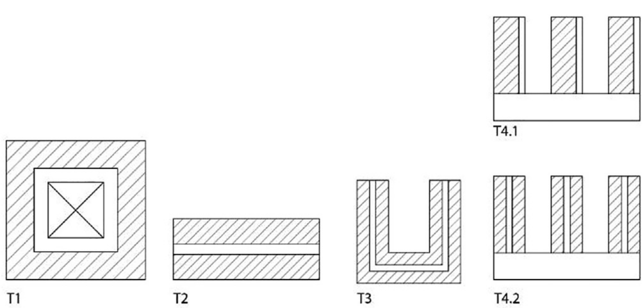


Fig. 1. Sketches of classrooms typologies (scratched area means classrooms): T1, Square-shaped with courtyard; T2, linear block; T3, U-shaped block; T4.1, Spinal with 1 orientation; and T4.2, Spinal with 2 orientations.

on buildings of 1979, three of them were constructed between 1979 and 2006, and two of them were constructed after 2006, with the Spanish Building Code, CTE [41] (Standard derived from the European Directive on Energy performance of buildings) and the approval of RITE in 2007.

Therefore, most of the buildings are naturally ventilated (NV), and only the last two have mechanical ventilation with heating recovery ventilation (HRV). However, those new schools surveyed do not use these systems due to the noise and in one case, additional energy consumption. In all cases, heating systems have boilers of natural gas, except two oil boilers, and radiators. In relation to the thermal envelope, specific U data is included in Table 1. Buildings constructed before 1979 were built without insulation (five of the studied schools). As an example, schools constructed in England prior to the first energy regulations in 1976 represent 81% of the total stock. [16]. Buildings constructed after 2006 are two of the schools, and the second phase of one of them). Main rehabilitations have supposed the substitution of windows (aluminum frames with thermal bridge, double glazing and tilt and turn), the replacement of the boiler, and the placement of insulation on the roof and in one case, also in the facade. All school roofs have insulation except in school 3.

Mean area per student in the classrooms (occupancy) is<3 m^2/student in all schools, even in the new ones. Previous to the opening of schools, a reduction of occupancy to maintain distances was proposed to lower the risk of COVID (avoiding overcrowding) with a maximum of 15 children per classroom, but finally the ratio of occupancy was maintained as it was (25–30 students per class), due to the impossibility to operate with lower ratios.

2.4. Selected case study IES.N

IES.N (number 3 in Tables 1 and 3) was selected to be studied in detail, due to classroom arrangement (typology, in Spinal with two wings, and classrooms with main orientation facing south-west), thermal envelope without any insulation, and also due it is naturally ventilated. The school was constructed in 1971 and it has three floors. Windows have been changed through the years to tilt and turn ones of aluminum with thermal bridge the newer ones, and with glazing with thermal transmittances from 2.7 to 1.1 W/m^2 K.

The school has a heating system with an oil boiler and radiators, and the system is only regulated by on/off with a schedule per circuit (6 circuits, one per each main wing of classrooms), and there are no thermostatic valves on the radiators. The staff collects manually monthly oil consumption.

The school receives almost 1000 adolescents from 12 to 17 years old (4 courses of ESO and 2 courses of BAC, acronyms of secondary and high school courses in Spain).

2.5. Surveys to children of the case study IES.N

Surveys *in time* were conducted *on line* during March 2020 in three different classrooms (see Table 2), to study *Thermal Sensation Vote* (TSV) [42,4], *Sensation of Stuffy Environment* (called SSE in this study), and *Tiredness Sensation* (called TS in this study) TSV follows an ASHRAE 7-point Likert Scale (cold, cool, slightly cool, Ok, slightly warm, warm, and hot), Questions for SSE and TS were chosen to go in deep with perceived IAQ and their relation to tiredness as an indirect indicator of students concentration, and they were based in 3 responses (Yes, a lot; yes, a little bit; and It is OK / I am OK), both indicators based on previous studies in schools [36,43,44].

Surveys were carried out to 67 different adolescents in different moments of the school day named in this study as: i) *Hour:* First class of the day (8:30–9:25 h); class after the break (11:45–12:40 h); and last class of the school day (13:35 14:30 h); and ii) *Time:* Start and End of each class (of the previously selected *Hours*).

Questions in the surveys in addition to TSV, SSE and TS were related to gender, classroom (age), seating location, clothing, previous activity, meal, and auto-perceived health. Self-reported sensations were prepared according to standards, previous literature and adapted to adolescents [43,45,46].

2.6. Monitoring of indoor environmental parameters in case study IES.N

Data in this study was registered on March 3-13th 2020 (8 school days) before Spanish COVID lockdown, and January 11-22th 2021 (10 school days) during pandemic. Only data during school hours were analyzed, from 8:30 to 14:30 h, to analyze IAQ and COVID risk during the hours that children attend school.

Data of air temperature (T_a), relative humidity (HR), and CO_2 ppm concentration were registered each ten minutes. T_a and HR were registered in the first campaign with mini data loggers *MadgeTech* (accuracy ± 0.5 °C in temperature and ± 3% in RH). In the second campaign were registered with *Sensonet* data loggers with *Sensirion* components (accuracy ± 0,3°C in temperature and ± 3% in RH), that provided *on line* data. They were located in the opposite wall to the main windows, to ensure that the sensors were not affected by solar radiation and children's actions, and thus allow normal operation of the classes, as other studies also justify [4].

CO_2 concentration data loggers were located in the teacher's table, due to the small size of the classrooms (even 1.65 m^2/student), and to ensure reliable and consistent data was not influenced by children's actions. They were registered by *Extech* data loggers (accuracy ± 50 ppm) in the first campaign, and with *Sensonet* data loggers with *Sensirion* components (accuracy ± 30 ppm) in the second, which provided *on line* data.

Both types of data loggers (temperature and CO_2 concentration) were tested together showing errors lower than the device's error, and reliable comparability for the objectives of this study.

As a weather meteorological station was not available in that moment, indoor monitoring data were analyzed with data from a meteorological weather station of the Government of Navarra, located in the city center in a cleared area similar to the school area. It offers free *on-line* ten-minutes and daily data [47].

In addition, other IAQ parameters were measured in the outdoors (PM, O_3, and NO_2) and indoors (PM) of the building, having lower values than recommended by WHO and Ventilation Standards [48], showing only punctually high values out of the school schedule.

2.7. Data management and analysis

A descriptive analysis was done with the surveys and interviews made to nine secondary/high educational centers in Pamplona, about measures and limitations related to energy efficiency and assessment of ventilation related to the COVID pandemic.

Indoor environmental conditions in the Case Study (IES.N) have been studied during March 2020 and January 2021 (before and during pandemic), the main difference being the relevance that natural ventilation has in the second period to ensure healthy and safe environments on classrooms. Data of occupied school periods from environmental monitoring was analyzed per class and also as average per all ten-minute data (temperature and CO_2 concentration). Significant differences between periods were found through statistical tests.

In relation to indoor temperatures, Spanish RITE [25] recommends a heating set point for new schools of 21 °C. European standard UNE EN EN16798-1 [48] in Tables B.2 and B.5, recommends, for classrooms, the following minimum operative temperatures for heating seasons: 20 °C (with temperature ranges of 20–24 °C) for Category II which refers to new and rehabilitated buildings, with medium level of expectation); and 19 °C (with temperature ranges of 19–25 °C) for Category III that refers to existing buildings, with moderate expectation).

In relation to CO_2 concentration, both Spanish RITE and UNE EN EN16798-1 recommend for classrooms 500 ppm above outdoor concentration (400 ppm, if there are no measured data). The latter recommends the following CO_2 default limits based on building categories (Table B.9)

800 ppm above outdoor concentration for Category II, and 1,350 ppm above outdoor concentration for Category III.

Table 2
Main constructive and *in use* characteristics of selected classrooms for *Surveys in Time*.

Classroom	Floor	Wing	Orientation	Repre.	WWR (%)	Area (m^2)	N° students	Occ.Ratiom²/student
2°ESO B	GF	B	SW	yes	46	52.81	25	2.11
1°BAC D	2F	B	SW	yes	46	52.88	32	1.65
2°BAC B	2F	A	SW/SE	no	25	69.94	31	2.26

Legend:
- Courses: 2ºESO (13 years old), 1ºBAC (16 years old), and 2ºBAC (17 years old)
- Floors: GF, ground floor; 2F, 2º floor
- Main Wings of the building for classrooms: Wing A (unshaded) and Wind B (shaded).
Repre.: means if the classroom is representative of the other classrooms for the same course
- WWR: Window to Wall ratio (%)
- Occ. Ratio: means Occupancy Ratio (m2/ student)

Finally, univariate and multivariate analysis were made with software Stata v.15.0, with data collected on March 2020 before the pandemic. As dependent variables were studied

1) Thermal Sensation, 2) Sensation of Stuffy Environment, and 3) Tiredness Sensation, all of them as dichotomous variables (yes/no). Taking into account repeated measures, generalized mixed models were used, which allowed control for intra-cluster correlation. In multivariate models, those independent variables that have shown a significant statistical association in the univariate models were included. All tests are two sided. Statistical significance was fixed *a priori* with the value $p < 0.05$.

Eighteen selected predictive parameters (independent variables) have been grouped in three categories: personal parameters of the student (6), temporal environmental parameters (6), and architectonic parameters of the classroom (6). A description of the sample is included in Table 7.

Personal parameters are based on surveys and they are as follows: gender, age, clothing, previous activity, previous meal, and

Table 3
Public Secondary/High Educational Centers in Pamplona, during COVID Pandemic.

School	1	2	3	4	6	7	8	9
Scholar schedule (h)	8:30–15 16:50–21:30 N	8:15–15:10	8:30–14:30 17:15–22:15 N	8–15	8–15	8:15– 15:10	8:30–15:20	8:15–14:15
Heating Schedule (h)	6–13:30 15–20:30 N	7:10 to 13 h	7–13 17–20 N	5–12	7–13	7:10–10:30 11:30–14	6:30–12	7–14:15
Ventilation protocol	1	2	1	1	1	1	1	1
Type of windows op.	Old: C New: TT	C	TT	TT	Old: S New: TT	TT	P1: S P2: TT	TT
Outdoor noise level (1)	65–70 dBA	55–65 dBA	<55 dBA	55–60 dBA	55–65 dBA	55–65 dBA	P1:<55 dBA P2:55–65 dBA	55–65 dBA
Discomfort due to temp (2)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Performance affection(3)	No	No	No	No	No	No	No	No
COVID transmission in classrooms (4)	No	No	No	No	No	No	No	No
Monitoring of Temp and CO_2	No	No	Yes	No	No	Yes	No	Yes (only temp)

Legend:
- N in schedules means evening scholar schedule
- Ventilation protocol: 1, After each class, at the break (30') and at the end of the day; 2, At the beginning of the day, at the break (30') and at the end of the day
- Type of window opening: C, casement; TT, tilt and turn; S, sliding
(1) Outdoor noise level (total diurnal: from road, air and rail traffic, and industry) used also as an indicator of outdoor IAQ. Source: http://www.navarra.es/home_es/Temas/Medio+Ambiente/Ruido/Mapas+del+ruido.htm
(2) Have students expressed discomfort by temperatures?
(3) Do you think that indoor temperatures in classrooms have reduced children attention?
(4) Do you have evidence of COVID infections within the classrooms of your school?
Questions (2-4) are self-declared by schooĺs director

Table 4
Heating energy consumption in surveyed schools.

School	School year	Heating consumption (kWh/m^2)	Heating consumption per degree day (kWh/m^2)	Heating consumption normalized by HDD (kWh/m^2)	Increase in Heating consumption (A, %)
1(N)	Year 2018/19	58.98	0.04	62.03	
	Year 2019/20	39.77	0.03	47.60	
	Year 2020/21	56.89	0.04	59.92	−3%**
2	Year 2019/20	50.8	0.03	52.54	
	Year 2020/21	49.7	0.03	52.34	
3(N) (IES.N)	Year 2018/19	68.4	0.05	70.74	
	Year 2019/20	50.4	0.04	60.32	
	Year 2020/21	88.3	0.06	93.00	+31%
4	Year 2018/19	70.9	0.05	73.32	
	Year 2019/20	52.3	0.04	62.59	
	Year 2020/21	75.7	0.05	79.73	+9%
6*	Year 2018/19	36.95	0.03	45.79*	
	Year 2019/20	20.96	0.02	27.52*	
	Year 2020/21	50.86	0.04	64.09*	+40%
7	Year 2018/19	61.20	0.04	63.29	
	Year 2019/20	48.07	0.04	57.53	
	Year 2020/21	41.23	0.03	43.42	−31%**
8	Year 2018/19	52.90	0.03	54.71	
9	Year 2020–21	47.90	0.03	49.54	

Notes: HDD 2018-19 = 1516; HDD 2019-20 = 1310; HDD 2019-20 = 1489 (October-May, Base 15ºC
A = Increase in Heating Consumption adjusted by HDD, between Year 2018-19 (previous pandemic) and Year 2020-21 (during pandemic, but with face to face education)(N) The school offers evening scholar schedule
* School 6 only has available data from October to March of the 3 courses
** The school has removed extracurricular classes in the afternoon

self-reported health. Clothing and previous activity were calculated according to the standards [41], and grouped for the analysis. Self-reported health was also grouped for this analysis in three categories (bad-regular, well, and very well-excellent).

Temporal environmental parameters correspond mainly to measured values in the moment of the survey: indoor temperature, RH and CO_2 concentration, and outdoor temperature. In addition, *Hour* and *Time* of each response were considered (described in paragraph 2.5).

Architectural parameters of the classroom are the same for all the students of each classroom (wing, floor, orientation, WW and occupant ratio, described in Table 3), except for the seating location of each student, that was grouped in two for the purpose of this study: near the windows or near the opposite wall.

3. Results

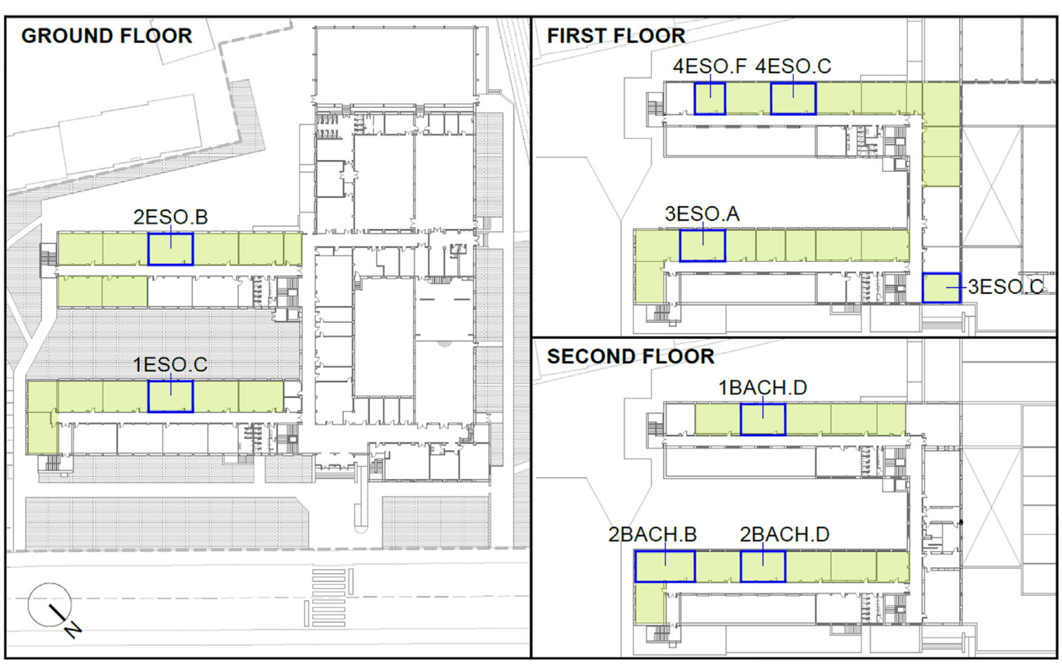
3.1. Studied schools

A summary of surveyed schools' data is shown in Tables 3 and 4. All schools showed a clear involvement of teachers in providing the best safe space for children. None of the schools self-reported COVID transmission in the classrooms. Although temperatures were low and uncomfortable, and children wear coats (even blankets) in class during the coldest days, a diminishing on concentration and performance of the students has not been observed, according to director perceptions. These questions are self-declared by the director, therefore an *unacceptability bias* could happen.

Ventilation routines follow governmental recommendations at the end of each class and during the break (30 min), opening all windows and doors to allow cross ventilation. During classes, ventilation depends on teacher's criteria, with windows mainly closed or slightly opened depending on outdoor temperatures and type of openings, and classroom's doors are opened in some classes. In relation to the openings of windows, most of them have been substituted through the years for tilt and turn ones that allow secure openings. Some of the older ones have sliding ones, that although with poor energy performance allow a safe ventilation.

Most of the buildings have an outdoor private space that limits with traffic lanes. Only one (the older one) has all facades facing traffic lanes. In Table 3, this issue is collected with the indicator of outdoor noise level in the classrooms' facades. If natural ventila-

(a)



(b)

Fig. 2. a. Images of the building IES.N. **b.** Plants for the Ground, First and Second floor.

tion has to be promoted, noise and polluted outdoor environment should be controlled.

All schools have increased the heating schedule to try to obtain better temperatures during the school hours, although school 1 and 7, have removed extracurricular classes in the afternoon (schools 1 and 3 also offers evening scholar schedule. Only three schools had monitoring system of CO_2 and temperature to control the efficiency of the ventilation measures, at the moment of this study. Schools 3 (IES:N) and school 6 have increased 31% and 40% their heating consumption to improve the effect of natural ventilation over indoor temperatures, and in school 4 is estimated in 9% (Table 4). Schools 1 and 7 have reduced their heating consumption due to the elimination of extracurricular hours.

3.2. Changes and evolution of temperature and CO_2 Concentration, before and during COVID in selected case study

3.2.1. General comparison of CO_2 concentration

Both monitored moments (March 2020 and January 2021) were typical for the heating period in Pamplona. Although there are differences among different classes at the same campaign (Fig. 3), in March 2020 there is a special concern about achieving good temperatures by mainly maintaining the windows closed with the lowest energy consumption and with low rates of ventilation. However, in January 2021 during COVID, the main concern was to ensure students health promoting natural ventilation, in spite of lower temperatures and higher energy consumption. Fig. 4 shows box-plot of average CO_2 values per ten minutes of all monitored classrooms, comparing results of both campaigns. Through a TTest (Table 5), differences between both samples were found statistically significant ($p < 0.001$), with a mean difference of 1,373 ppm (1,280–1,466 ppm).

3.2.2. General comparison of temperatures

Figure 5 shows temperatures box-plot per classroom on both monitored moments. In March 2020, when the classrooms were naturally ventilated only for short periods of time, temperatures vary according mainly to the situation of either Wing-A or Wing-B (being the coldest, those located on Wing-B) and height (the coldest those located on the upper floor). In January 2021, and in spite of the increase on heating consumption, there are lower differences among classrooms, because the influencing factor is mainly a common pattern of ventilation. Differences between both moments have been analyzed, considering mean temperature values of ten-minutes data in all classrooms, and they are shown through a box-plot in Fig. 6. On March 2020, temperatures are mainly over 19 °C, and on January 2021, temperatures are mainly below 19 °C.

As indoor temperatures are closely related to outdoor temperatures mainly due to the classrooms being NV, regressions were made in both cases to estimate the dependency of both values (see Fig. 7). Adjusting by outdoor temperatures, a difference of 1.95 °C (1.80–2.09 °C) was found between indoor temperatures on both campaigns (Table 6). According to Fig. 7 and data of this study, In January 2021 with outdoor temperatures lower than 12 °C, indoor temperatures are lower than 19 °C (and when outdoor temperatures are lower than 9.4 °C, indoor temperatures are lower than 18 °C), and therefore only NV is not providing adequate ranges of indoor temperatures.

3.2.3. Analysis of CO_2 concentration evolution throughout the day (Hour and Time)

The evolution of CO_2 concentration goes upward throughout the day in *Hour* and in *Time* in March 2020 (Fig. 8 and Fig. 9). Nor in the first class nor at the beginning of each class (considering mean values of all monitored classrooms) mean values are lower than 1,000 ppm. However, in January 2021 values are more stable and closer to 1,000 ppm. In March 2020, the mean increase per *Hour* is 857 ppm (719–995 ppm), however in January 2021, the mean increase is only 135 ppm (81–189 ppm), as shown in Table 7.

3.2.4. Analysis of temperature evolution throughout the day (Hour and Time)

Temperature throughout the day follows a different evolution in Hour and Time in March 2020 in relation to January 2021 (see Fig. 10 and Fig. 11). In March 2020 evolution of temperature in *Hour* is ascendant with mean values higher than 20 °C from the second hour after the break. However, in January 2021, temperatures are most stable, showing even a reduction after the break,

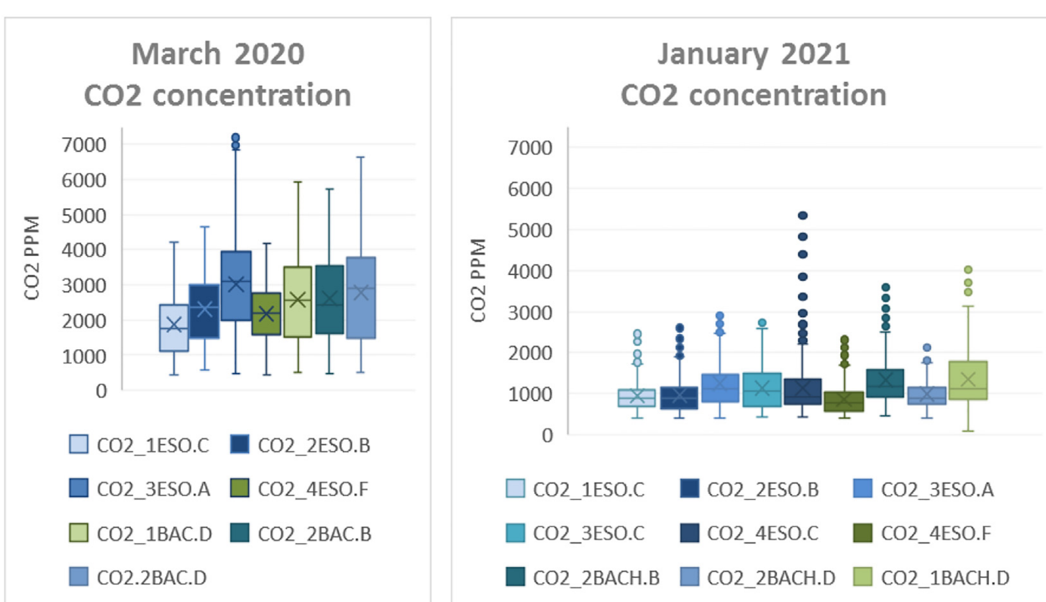


Fig. 3. Comparative of CO_2 concentration between March 2020 and January 2021. Boxplot of all monitored classrooms.

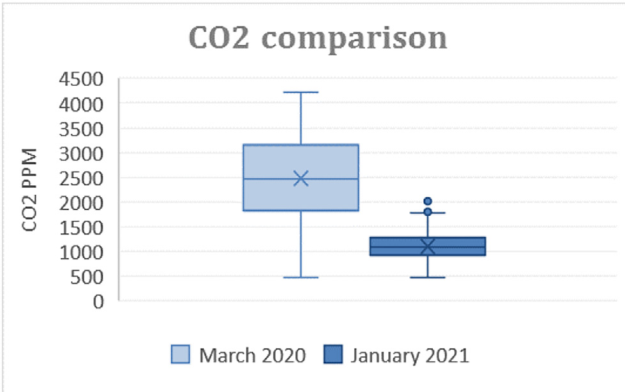


Fig. 4. Comparative of CO_2 concentration between March 2020 and January 2021. Boxplot of average measurements of all classrooms.

Table 5
Differences in CO_2 concentrations (ppm) between January 2021 and March 2020.

Group	Obs.	Mean	p value
March 2020	296	2478 (SD.852)	
January 2021	370	1105 (SD. 295)	
Diff		**1373 (1280–1466)**	**<0.001**

and with mean values lower than 18 °C during the three studied hours.

3.2.5. Multivariate statistical analyses. Predictive parameters

Through univariate and multivariate analyses, those factors that predict thermal sensation (TSV), sensation of stuffy environment (SSE), and tiredness sensation (TS) have been analyzed in March 2020, considering all of them as independent variables. For each dependent variable (TSV, SSE and TS), univariate statistical analysis was made, with all the parameters described in Table 8. For the multivariate analysis, only independent variables that were statistically significant ($p < 0.05$) were selected, and multivariate analysis was done for each one of the three dependent variables. Table 9 shows results of these multivariate analysis.

In the model of predictive parameters for the TSV, variables with a higher likelihood of being dissatisfied were Indoor Temper-

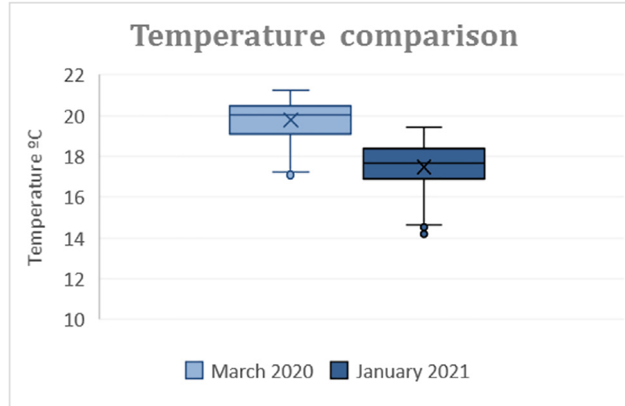


Fig. 6. Comparative of registered temperatures between March 2020 and January 2021. Boxplot of average measurements of all classrooms.

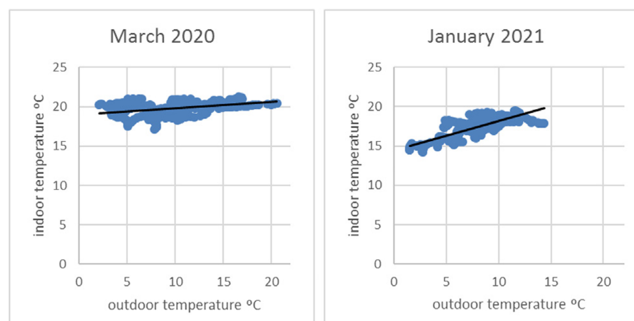


Fig. 7. Comparative of registered temperature according to outdoor temperature on March 2020 and January 2021.

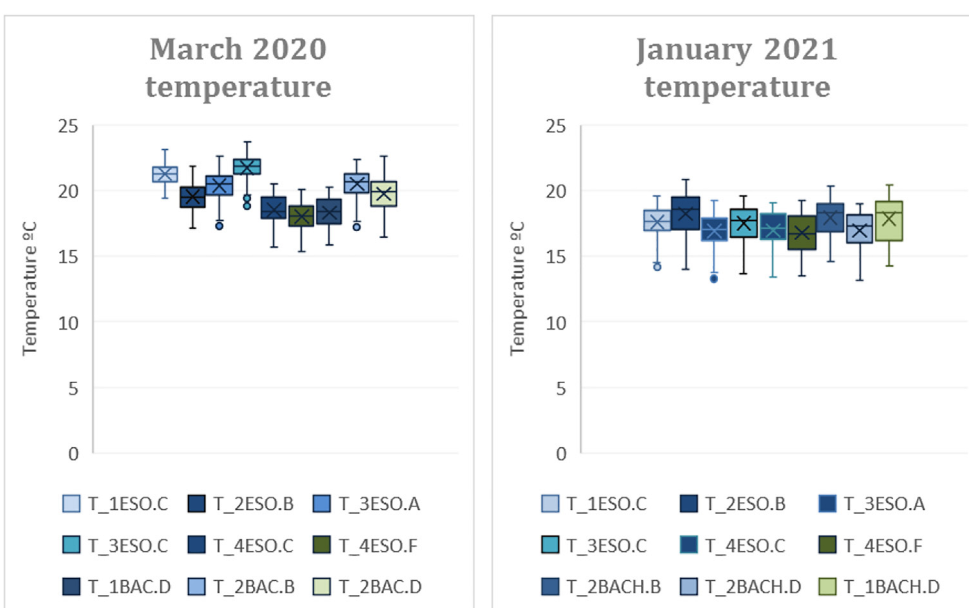


Fig. 5. Comparative of temperatures between March 2020 (left) and January 2021 (right). Boxplot of all monitored classrooms.

Table 6
Differences of temperature between January 2021 and March 2020, adjusting for outdoor temperature.

	Coef	p	(95% Conf. Interval)	
Var	**−1.95**	**0.000**	**−2.09**	**−1.81**

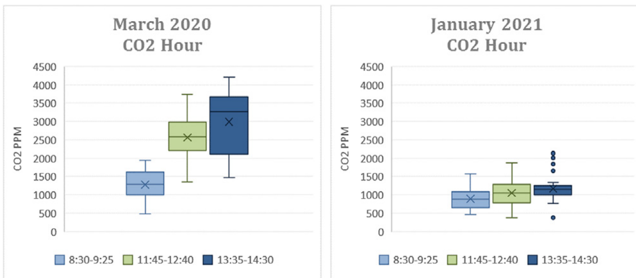


Fig. 8. Comparative of CO_2 evolution through the day (*Hour* in this study: first class, after the break and last class) during March 2020 and January 2021.

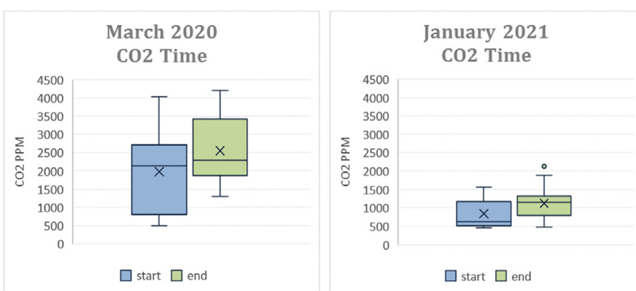


Fig. 9. Comparative of CO_2 evolution at the start and end of each class (*Time* in this study) during March 2020 and January 2021.

Table 7
Regression applied to CO_2 concentration per *Hour* in March 2020 and January 2021 (*Hour* in this study: first class, after the break and last class).

	Coef	p	(95% Conf Interval)	
March 2020 Hour	**857**	**0.000**	**719**	**996**
January 2021 Hour	**135**	**0.000**	**81**	**189**

Fig. 10. Comparative of temperature evolution throughout the day (*Hour* in this study: first class, after the break and last class) during March 2020 and January 2021.

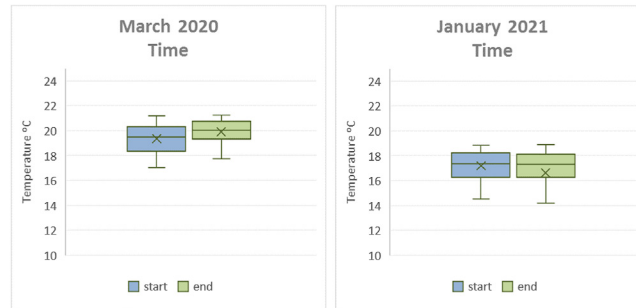


Fig. 11. Comparative of temperatures at the start and end of each class (called *Time* in this study) during March 2020 and January 2021.

Table 8
Descriptive summary of studied parameters of 202 responses from 67 different adolescents on March 2020 (number of participants and percentages). (* categories used as the reference category in the generalized mixed models).

PERSONAL PARAMETERS OF THE STUDENT (6)			
Gender	Boys * 122 (60,4%)		Girls 80 (39,6%)
Age	13y* 92 (45,5%)	16y 21 (10,4%)	17y 89 (44,1%)
Clothing (clo)	A (<1clo) * 46 (22,8%)		B (≥1clo) 156 (77,2%)
Previous activity (met)	1-1,4met * 173 (85,6%)		2met 29 (14,4%)
Previous meal	No * 94 (46,5%)	Yes, a little 82 (40,6%)	Yes, a lot 26 (12,7%)
Self-reported health	Bad-Regular 17 (8,4%)	Well 47 (23,3%)	Very W –Excel * 138 (68,3%)
TEMPORAL ENVIRONMENTAL PARAMETERS (6)			
Indoor temperature (°C)	<19°C * 54 (26,7%)	≥19 y <20°C 55 (27,2%)	≥20°C 93 (46,0%)
Indoor Relative Humidity (%) *Tertiles*	1 *(<55%) 80 (39.2%)	2 (55-70%) 58 (28.4%)	3 (>70%) 66 (32.4%)
Indoor CO_2 concentration (ppm)	<1200 * 36 (17,8%)		≥1200 166 (82,2%)
Outdoor temperature (°C)	<5 °C * 61 (30,2%)	≥5 y <10 °C 83 (41,1%)	≥10 °C 58 (28,7%)
Hour	1^{st} * 64 (31,7%)	2^{nd} 63 (31,2%)	3^{rd} 75 (37,1%)
Time	Start * 119 (58,9%)		End 83 (41,1%)
ARCHITECTONIC PARAMETERS OF THE CLASSROOM (6)			
Wing (A/B)	A-Unshaded * 89 (44,1%)		B-Shaded 113 (55,9%)
Floor	Ground floor * 92 (45,5%)		2° Floor 110 (54,5%)
Orientation	SW * 113 (55,9%)		SW/SE 89 (44,1%)
Window to Wall Ratio (WWR)	<45 * 89 (44,1%)		≥45 113 (55,9%)
Area per child (m^2/child)	<2 * 21 (10,4%)		≥2 181 (89,6%)
Seating location	A-B-C (wall) * 146 (72,3%)		D-E-F (window) 56 (27,7%)

ature and *Time*. Temperatures of 19–20 °C and the *End of each class* were found significant and protective (OR = 0–1), predicting better TSV. In the model of predictive parameters for the SSE (related to IAQ), *Hour* was found as a significant predictor. *The 3rd hour* of this study at the *End of the day* was a clear predictor (in accordance with values in Fig. 8). Finally, in the model of predictive parameters for the TS (tiredness), variables found predictive were *Self-Reported Health* and Indoor Temperature. Students with Bad-Regular Health and Indoor Temperatures higher than 20 °C (in winter) predict higher tiredness sensation.

Table 9
Personal, environmental and architectonic predictors of Thermal Sensation (TSV), Sensation if Stuffy Environment (SSE), and Tiredness Sensation (TS) in 202 responses from 67 different adolescents, on March 2020 (Results from multivariate** multilevel mixed-effects logistic regression) (* categories used as the reference)

THERMAL SENSATION, TSV					
		Odds Ratio	P value	[95% Conf. Interval]	
Indoor Temperature	<19 °C *	1 *			
	≥19 y < 20 °C	0.05	**0.012**	0.01	0.52
	≥20 °C	0.32	0.193	0.06	1.79
Time	Start*	1*			
	End	0.21	**0.045**	0.04	0.97
*Adjusted for those variables with statistical significant results in the univariate analyses: indoor temperature and Time					

SENSATION OF STUFFY ENVIRONMENT, SSE					
		Odds Ratio	P value	[95% Conf. Interval]	
Hour	1st *	1 *			
	2nd	5.73	0.196	0.41	80.86
	3rd	51.67	**0.013**	2.28	1169.14
*Only Hour was statistical significant in the univariate analysis					

TIREDNESS SENSATION, TS					
		Odds Ratio	P value	[95% Conf. Interval]	
Self-reported health	Very Well-Excellent	1 *			
	Well	0.14	0.074	0.02	1.21
	Bad-Regular	15.94	**0.041**	1.13	225.82
Indoor Temperature	<19 °C *	1 *			
	≥19 y < 20 °C	2.11	0.392	0.38	11.68
	≥20 °C	5.41	**0.031**	1.16	25.18
*Adjusted for those variables with statistical significant results in the univariate analyses: indoor temperature, hour and floor					

Therefore, adequate ranges of temperatures are related to thermal comfort and tiredness, and it is especially important for the children with poorer health. In addition, special attention should be paid to the evolution of indoor parameters of Time and Hour, so children performance does not worsen throughout the day.

4. Discussion

Face to face education is considered the preferable one for children [28], therefore in addition to ensuring adequate ranges of temperatures and IAQ, the school year 2020–21 faced the challenge of promoting natural ventilation (NV) as one of the ways to minimize risk of infections. In Spain, all schools re-opened their classrooms on September 2020. The majority of them are naturally ventilated (NV) as in the rest of Europe [14,15], therefore, indoor temperatures and air quality are closely related to outdoor conditions.

The awareness of direct relation of NV on health has derived on clear protocols of ventilation in the classrooms. They involve window opening protocols (at least at the end of each class and during the break), someone in charge (generally the teacher), use of types of windows openings that allow safe ventilation (tilt and turn, sliding, etc.), type of openings that allow cross ventilation, and when possible, measurements of CO_2 concentration and temperature. A clear improvement of IAQ has been observed, although with low or very low temperatures, especially the coldest days and hours of the winter season. As reported in this study, children have gone with relative normality to the schools, with no known infections in the classrooms, and with no influence on the concentration and school performance of children.

Natural Ventilation has been shown effective on the improvement of IAQ, although it should be combined with mechanical systems with heating recovery (HRV), at least when temperatures are too low and when the classroom's design cannot guarantee an adequate rate of ventilation [39]. However, mechanical ventilation as a unique option is not the preferable one for children, as previous studies found, having problems like noise or excessive energy consumption (as has been reported in this study in some of the studied schools) that should be carefully addressed to obtain the desirable performance [7]. A study of school archetypes in England found a higher discrepancy between simulated and real consumption in the schools with mechanical ventilation (4–25%) in respect to those naturally ventilated, although these kind of schools only represent a 3% of the studied stock [16].This study only analyzes winter conditions, therefore performance and measures for the warm period in COVID times are not considered in this study, and should be further investigated in order to have data of the buildings' performance and its relation with children's wellbeing throughout the school year. Further research should deepen on assessing and validating measures in existing and refurbished educational buildings *in use* in different contexts, climates and kind of schools (construction periods, layout of the classrooms, etc). As natural ventilation is an option to be optimized and enhanced in the future, outdoor environment around schools should be further investigated [7,11] to apply convincing urban measures that reduce or definitely eliminate traffic in the surroundings of schools, especially those affecting the most vulnerable populations [49].

All schools should be prepared for the following years, with a progressive plan of measures to apply which improve indoor environmental conditions, because indoor school spaces should be safe and healthy for children. Education is one of children's main rights and a *lost COVID generation* must be avoided [29].

5. Conclusion

This research is based on the energy efficiency study of nine secondary/high schools in Pamplona (north of Spain) and the monitoring and surveys of one of them in detail. The study has taken place before and during the COVID pandemic.

The schools studied were varied in typology, construction time, thermal envelope, and facilities, but all of them were naturally ventilated before and during COVID. Schools with mechanical ventilation did not use it because it produces too much noise and energy consumption. All surveyed schools reported a great teacher's involvement, clear protocols of natural ventilation, and low or very low indoor temperatures. Classes took place normally, and concentration and school performance were not lower than previous years, according to the directors' responses.

The selected school was monitored before and during pandemic on the heating season (March 2020 and January 2021), and some surveys *in time* were made to students on March 2020. A multivariate analysis with data previous to the pandemic predicted as main significant predictors: i) for a better Thermal Sensation, indoor temperature (when temperature 19–20 °C) and *Time* (end of the day); ii) for Sensation of Stuffy Environment, the *Hour* (mainly, the last hour of the school day); and iii) for Tiredness Sensation, self-reported health (when being bad-regular) and indoor temperature (where higher than 20 °C). Therefore, students have clear preferences on indoor temperatures (although in COVID times they were colder than desired due to the health emergency), and indoor environmental conditions should be taken care of throughout the day, especially for the children with poorer health.

In the selected school, CO_2 concentration had a mean difference of around 1,400 ppm between both monitored campaigns, having in January 2021 mean values of around 1,000 ppm. In March 2020, there were concerns about adequate ranges of temperature with the lower energy consumption, while in January 2021 the main concern was to ensure adequate ventilation to minimize risks. Clear protocols of natural ventilation at the end of each class, and during the break with a person in charge, had reduced the increase of CO_2 concentration per studied *Hour* throughout the day (first, after the break, and last hour of the school day) from around 850 ppm to only 135 ppm. Mean temperatures were nearly 2 °C lower in January 2021 than in March 2020 (adjusted by outdoor temperatures). They were mainly around 18 °C in January 2021, in spite of an increase on heating energy consumption of around 31%. To achieve adequate levels of CO2 concentration in a naturally ventilated school supposes low ranges of indoor temperatures in the heated period, that are admissible in a pandemic situation until the availability of vaccines but not as a general rule.

All schools should prepare a plan to progressively improve indoor environment of the schools, through the upgrade of windows openings and allowing natural cross ventilation in the classrooms, the installation of a monitoring system to check CO_2 and temperature at least in some representative classrooms, and the installation of Heating Recovery Ventilation in addition to the improvement of the thermal envelope when outdoor temperatures requires it. In this way, schools will be able to provide safe and healthy spaces for the education of children, with the lowest energy consumption and CO_2 emissions for the following years.

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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