



HAL
open science

Does energy-efficient renovation positively impact thermal comfort and air quality in university buildings?

Keovathana Run, Franck Cevaer, Jean-François Dubé

► To cite this version:

Keovathana Run, Franck Cevaer, Jean-François Dubé. Does energy-efficient renovation positively impact thermal comfort and air quality in university buildings?. *Journal of Building Engineering*, 2023, 78, pp.107507. 10.1016/j.jobe.2023.107507 . hal-04458931

HAL Id: hal-04458931

<https://hal.science/hal-04458931>

Submitted on 15 Feb 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Does energy-efficient renovation positively impact thermal comfort and air quality in university buildings?

Keovathana Run*, Franck Cévaër, Jean-François Dubé

LMGC, University of Montpellier, UMR CNRS 5508, cc048, Place E. Bataillon, 34095 Montpellier cedex 5, France

Abstract

The University Institute of Technology (IUT) buildings in France were primarily built in the late 1960s without considering the energy issues that were not relevant at the time. At the IUT of Nîmes, during winter and summer, rooms within the same building can be either very hot or very cold, causing discomfort for the users. One of the solutions is the renovation of the building and its systems. This research aims to evaluate the energy-efficient renovation performance associated with thermal comfort and indoor air quality. Modifications to the building envelope and systems were recommended by thermal engineers based on simulations that did not consider the occupants' behavior and operational uncertainties. Therefore, this analysis relies on physical measurements of CO_2 concentrations, humidity, and temperature during the heating period, along with a thermal comfort survey. The analytical result showed no significant change in CO_2 level and humidity, but the temperature reduced up to $3^\circ C$ as a consequence of adjusting the heating temperature threshold. However, in certain post-renovation classrooms, the CO_2 concentrations increase by 11.7% with an incorrect airflow rate. Although there is no change in measured values, according to the French thermal building code for renovated buildings, these values are on the border of their comfort zone. Overall, thermal renovation saves 85 MWh while maintaining satisfactory thermal comfort and air quality. However, caution should be exercised regarding the air exchange rate.

Keywords: School buildings, Mediterranean weather, IEQ evaluation, Retrofitting, Energy conserving

1. Introduction

European policy currently aims to improve energy efficiency by 27% by 2030, which can be achieved through using energy-efficient materials when constructing new buildings and improving existing buildings [1, 2]. Renovation strategy could decrease EU energy use by 5-6%, but unfortunately, only 1% of the building stock is renovated annually [3, 4]. For educational facilities, such as the University Institute of Technology (IUT) buildings, ensuring energy

*Corresponding author. Tel.: (+33) 7 49 82 04 05.

Email address: keovathana.run@umontpellier.fr (Keovathana Run)

efficiency is vital not only for cost savings but also for the well-being and performance of students and other occupants. Over the past two decades, extensive research has shown a correlation between Indoor Environmental Quality (IEQ) and occupants' performance, health, and attitudes [5–11].

The IEQ factors are broad, but most literature focuses on four factors that can be measured and controlled actively: indoor air quality and ventilation, thermal comfort, visual comfort, and acoustic comfort [9]. Previous studies have individually examined the impact of these factors on human perception and performance, emphasizing the importance of maintaining optimal conditions in educational settings. For instance, a study by Clements-Croome [12] found that indoor air quality in school buildings, as assessed by short-term computer-based tests, is associated with poor student performance, mainly due to inadequate ventilation rates and high occupancy densities ($1.8\text{--}2.4\text{ m}^2/\text{person}$). Haverinen-Shaughnessy showed that the ventilation rate also plays an essential role in student academic performance [13] and reducing sick absences [14, 15]. Additional research [14, 16–19] also supports the previous findings emphasizing the importance of indoor air quality and ventilation factors. Other aspects were also extensively investigated: thermal comfort [20–27], visual comfort [28–32], and acoustic comfort [33–35], which demonstrate that each of them could have a significant impact on the overall comfort conditions. According to ASHRAE [36] and a previous review paper [10], among other components, thermal comfort and indoor air quality are the most significant in defining comfort. Nonetheless, more effort was put into investigating the combined effects of IEQ indicators [37–41] and suggested that the interaction effect could evaluate overall human comfort better when the single factor is still lacking.

IUT of Nîmes has undergone a significant renovation to enhance its energy efficiency, particularly targeting heating and ventilation energy. It is worth noting that acoustic comfort has not been a subject of concern or complaints from the users at the institution. Consequently, the aspects of visual and acoustic comfort have been excluded from the scope of this investigation, while the primary focus remains on evaluating thermal comfort and indoor air quality. By outlining the key priorities, the study seeks to provide valuable insights into the influence of energy-efficient measures on the indoor environment's thermal conditions and air quality. These two factors primarily depend on the outdoor meteorological condition [42], air exchange rate [43], and occupancy patterns [44, 45] for the same building envelope.

When the energy efficiency of school buildings is discussed, it is often relatively difficult to maintain excellent indoor climate conditions and cost-effectively, as indoor climate conditions and energy efficiency are conflicting objectives. Therefore it creates a problem in designing new and renovated buildings [46].

Recent cross-sectional investigations in classrooms at Danish and foreign schools have shown that CO_2 concentrations frequently exceed the maximum of 1000 ppm, which is usually advised by existing recommendations and building regulations in terms of classroom air quality [47, 48]. It has been reported to occur particularly often in classrooms where ventilation relies on the manual opening of windows, specifically during the heating season in regions with a temperate climate [18, 49–52]. Zhang and Bluysen [53] conducted an observational study of existing schools to determine potential correlations between energy consumption and building characteristics. During the in-

vestigation, they discovered that when the buildings consumed 71.9 MJ/m^2 of electricity and 358.8 MJ/m^2 of gas, the average indoor climate of classrooms is as follows, 23°C , 41%, and 1260 ppm. Almedia and Freitas [54] compared two non-retrofitted and seven retrofitted schools. Throughout the winter, the average temperature was 14.9°C and CO_2 of 1905 ppm in non-retrofitted buildings, while those of certain retrofitted buildings were 20°C and 1052 ppm. They inferred that non-retrofitted schools need to improve their indoor environmental conditions, and in renovated buildings, mechanical ventilation systems are not efficiently utilized, with significant consequences on indoor air quality. Zinzi et al. [55] did a case study on a school building in Italy. The deep renovation includes an insulated building envelope, installed mechanical ventilation, energy-efficient windows, and new sun shades. The results show that the IEQ indicators of the classroom can increase to 20°C from 18.5°C at 8 am in the early morning and remain below 1600 ppm with mechanical ventilation. However, it exceeds the recommended values, which are far lower than those without mechanical ventilation. A recent study by Mocová and Mohelníková [56], examined the renovated schools from the 1970s including the upgrading building fabrics, installing regulated heating systems, and renovating the water supply. The energy consumption reduced from 271 GJ/year to 105.8 GJ/year. However, an unexpected increase in CO_2 levels within the renovated classroom was observed. Zaeh et al. [57] have investigated seven school buildings in pre- and post-renovation states. The retrofitting strategy includes replacing windows and renewing the HVAC system. The study has revealed that, prior to renovation, a noteworthy proportion of indoor CO_2 measurements (more than 30%) and indoor temperatures (over 50%) exceeded the recommended guidelines. After the refurbishment, it was observed that 10% of CO_2 levels and 28% of temperatures deviated from the recommended ranges.

Despite solid theoretical and calculation evidence supporting the need for renovation to meet the required Indoor Environmental Quality values [47, 48, 54, 57], school renovation projects remain challenging due to multiple stakeholders and limited funding from local authorities. The existing literature on renovation's impact on IEQ remains inadequate, emphasizing the necessity for more case studies involving different school building types and climates. Moreover, previous research has predominantly focused on evaluating the renovation performance solely in classrooms, while higher education buildings accommodate various activities and functions, including offices, laboratories, workshops, and e-learning spaces [58]. Ensuring a healthy and comfortable environment in all the rooms within the building is of utmost importance.

To fill the gap in previous papers, the objectives of this study are to:

- 1) assess the renovation's impact on the thermal comfort and indoor air quality of the entire school building by incorporating classrooms, offices, and workshops in the analysis;
- 2) investigate the relationship between energy-efficient refurbishment measures and the tackled IEQ components;
- 3) analyze the level of user comfort during the heating period following the renovation.

2. Material and methods

This work employs a comprehensive approach encompassing physical measurements and subjective assessment to analyze indoor environment comfort. This approach is a well-established method used in prior literature to evaluate thermal comfort [21–23]. Student t-Test statistics were adopted and performed through “anova.test” in RStudio to compare the physical measurements, while questionnaire responses were compared directly by the percentage of votes. Simultaneously, heat demand was also calculated using a quasi-stationary monthly technique. This mathematical model is based on a monthly energy balance in steady-state conditions between heat gains and thermal losses according to EN ISO 52016-1 standard [59].

The research methodology for this study involved long-term data collection from two renovated buildings, as illustrated in Figure 1. Various data analysis techniques were employed to thoroughly assess the collected data and draw conclusive findings.

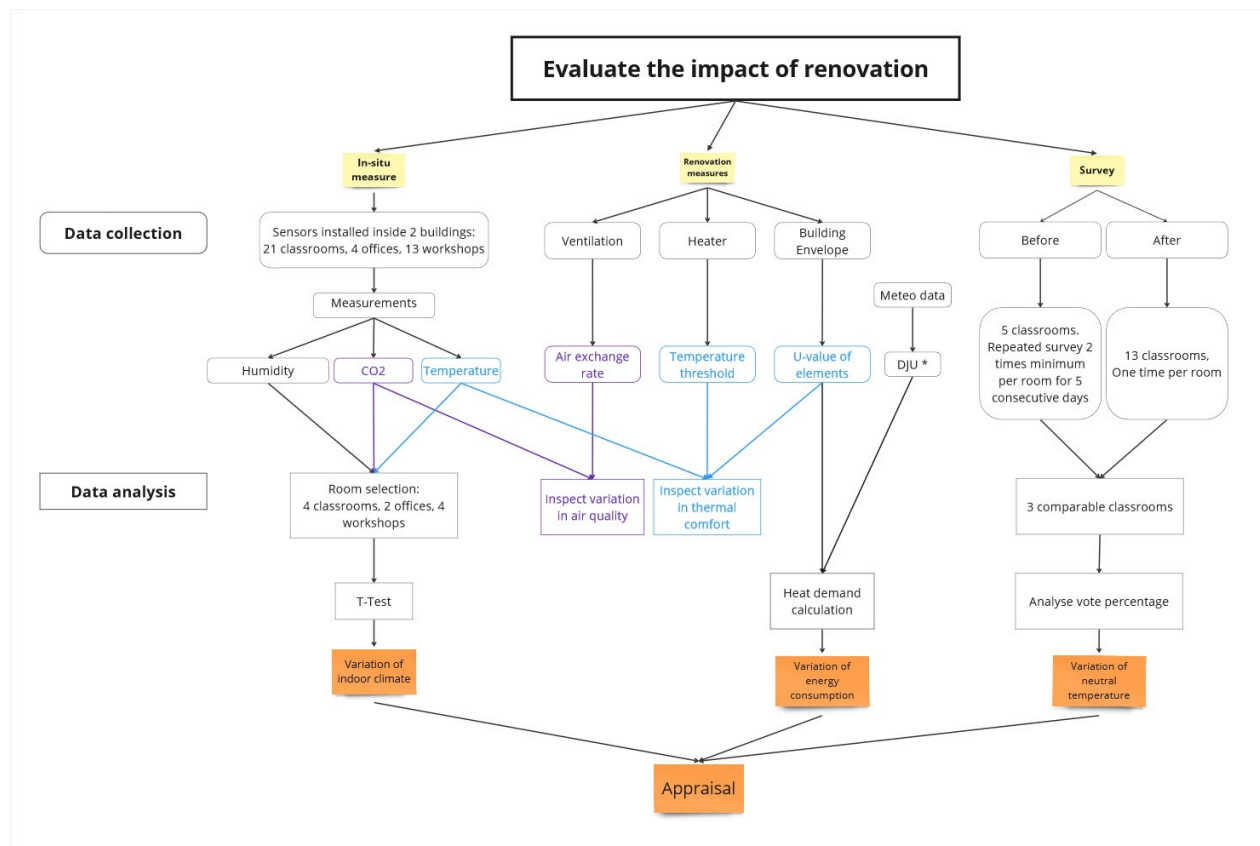


Figure 1: Research methodology

2.1. Description of the studied buildings

The studied buildings represent all French university buildings built during 1960-1979 when exterior structures, HVAC, and other technical systems did not meet today’s energy-efficient building standards. The IUT of Nîmes campus

is located in the south of France, Nîmes (Latitude 43.83. Longitude 4.36), under Mediterranean climate (C) by the Köpper-Geiger climate classification [60]. This weather is mild winter and hot summer, which makes thermal comfort during summer sensitive.

This campus comprises five buildings, as shown in Figure 2, representing a total SHON surface of 27 666 m². However, this study was conducted only on two renovated buildings, GC (BAT. 4) and GEII (BAT. 5), with the same floor plan layout consisting of two sections, later referred to as “North” and “Workshop”. Figure 3 is an elevation drawing of the GEII building demonstrating a two-level at the *North* (front) section and a one-level *Workshop* (back) section. The *North* dedicates to classrooms and offices while laboratories and workshop halls mostly occupy the *Workshop*. The details of the building’s usage are presented in Table 1.



Figure 2: IUT of Nîmes campus showcases studied buildings, BAT 4 (GC) and BAT 5 (GEII)

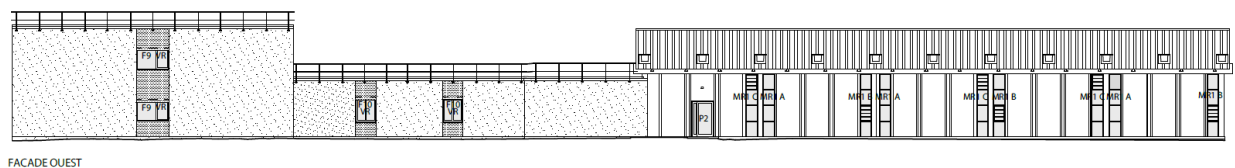


Figure 3: West elevation plan of GEII building

2.2. In-situ measurements

338 sensors of six types (Elsys, Class’Air, CM868LR, IR868LR, BT1-L, and Adeunis) have been placed on four buildings in IUT of Nîmes campus to measure continuously. These sensors use Node-RED to store data in the InfluxDB

Element		GC	GEII
Construction year		1969	
Renovation		May to October 2022	May to October 2021
Number of floors	North	2 (2.5m height each floor)	
	Workshop	1 (3.5m height)	
Floor area (m^2)		5467	4168
Net floor area (m^2)		4762	3627
Number of rooms	Classroom	19	14
	Workshop	26	20
	Office	7	7
	Others	7	4

Table 1: *Building characteristics and usage detail*

database. Grafana is a tool used to visualize and export data, which is then used in RStudio for analysis. In this paper, Elsys and Class’Air sensors that measure indoor air quality indicators (CO_2 levels) and hygrometer comfort indicators (relative humidity and air temperature) [61] were utilized. The data were collected from two buildings, GC and GEII, that underwent renovation. Rooms with available data both before and after refurbishment were selected for the analysis: 4 classrooms, 2 offices, and 4 workshops. To acquire the most accurate readings, the sensors were mounted at a height of 0.6 meters on the wall and a fair distance from the heat and CO_2 emission sources, following ISO standards [62].

Class’Air (± 0.1 °C, 1% and ± 50 ppm + 3% precision) is set to 60 minutes, whereas Elsys (± 0.2 °C, 2% and ± 50 ppm + 3% precision) is programmed to a 15-minute interval. The continuous measurements from January to March in each state result in data gaps. Approximately 20% of the collected data was missing due to data acquisition failure and power outage. Since this data is the primary source for this analysis, it is essential to interpolate the values every fifteen minutes to get the same time base and find missing values.

A weather station (Météo France) of Nîmes Courbessac monitored outdoor conditions and was used to calculate DJU (unified degree day) as detailed in Section 2.4.

2.3. Renovation measures

This case study adopts passive renovation strategies by replacing conventional single-glazed and double-glazed with low-emissivity double-glazed windows and adding exterior insulation. Such renovations are found to elevate the internal temperature by enhancing the air-tightness of buildings [63] and simultaneously lowering the overall energy consumption [64–66]. These measures were commonly used in residential [67–70] and school buildings [56, 71, 72]. Moreover, natural ventilation was replaced by single-flow mechanical ventilation. Some work has also been done on the heating system, such as installing a heat exchanger beneath each building and incorporating thermostats into new radiators.

Table 2 displays the U-values of the building envelope, along with a short description of the ventilation and heating system, for both the pre-building and post-building phases. The installation of mechanical ventilation and thermostats

Element		Materials		U-value ($W/m^2.K$)	
		Before	After	Before	After
Floor		Concrete	Unchanged	3.08	3.08
Roof	North	Concrete + polyurethane foam 40 mm	Unchanged	0.51	0.51
	Workshop	Concrete + mineral wool 120 mm	Unchanged	0.25	0.25
Wall		Hallow brick	Hallow brick + rock wool insulation 120 mm	3.52	0.27
Window		Single-glazed / Double-glazed	Double-glazed argon 16mm	3.6	1.5
Building information				Program	
Ventilation		Natural (0.5 vol/h)	Mechanical extract ventilation (0.23 vol/h)	Permanent	6h00-20h00
Central heating system	North	District heating + Convection heater	District heating + Radiator + Thermostat control	7h00 - 18h00	7h00 - 18h00
	Workshop	District heating + Unit heater	Unchanged		

Table 2: Thermal properties of building envelope and a short description of ventilation and heating systems before and after renovation

were limited to the *North* section. Before the refurbishment, the heating system was controlled manually, in contrast to its current state of operation, which is managed and operated through a computer program.

2.4. Heat demand calculation

This study utilized a quasi-stationary monthly calculation of heat loss and usable heat gains for the building [73]. The calculation expressed in equation 1 is made only for this case study's potential heating season from January to March.

$$Q_h = Q_1 - \eta \times Q_g \quad (1)$$

Where:

Q_h : total heat demand (kWh)

Q_1 : total heat loss (kWh), defined in equation 2

Q_g : total heat gain (kWh), defined in equation 6

η : overall production efficiency monthly (generation, distribution, transmission, regulation), defined in equation 9

Total heat loss Q_1 of a national level that incorporates the use of degree days is:

$$Q_1 = H \times DJU \times 0.024 \quad (2)$$

Where :

H : total heat loss coefficient of the building (W/K)

$$H = H_T + H_V$$

H_T is the specific transmission loss through each building fabric (W/K) namely, walls, windows, roofs and floors. It is calculated as:

$$H_T = \sum b_i \times U_i \times S_i + \sum b_i \times \Psi_i \times l_i \quad (3)$$

where b_i is the reduction factor of fabric's temperature depending on the condition that the element is exposed to, $b = 1$ for exterior, and $b < 1$ for non-heating space, i.e., crawl space. U_i is the transmission coefficient ($W.m^{-2}.K^{-1}$) and S_i is the transmission surface area (m^2). Ψ is the thermal bridge coefficient ($W.m^{-1}.K^{-1}$), and l is the transmission length (m).

H_V is the specific heat loss through ventilation (W/K), calculated as follows:

$$H_V = \dot{V} \times \rho_a \times c_a \quad (4)$$

where \dot{V} is the air flow rate through the building ($m^3.h^{-1}$); including air flow through unheated space, and $\rho_a c_a$ is the heat capacity per volume = $0.34 (Wh.m^{-3}.K^{-1})$.

DJU : average unified degree day ($^{\circ}C.day$) defined in equation 5.

DJU is the unified degree day on a base of $18^{\circ}C$ of the Nîmes Courbessac region during the heating period from January 1st to March 31st.

$$DJU_{18} = \int_{jan}^{mar} \left(18 - \frac{T_{ej_{max}}(t) + T_{ej_{min}}(t)}{2} \right). dt \quad (5)$$

where $T_{ej_{max}}$ is the maximum daily outdoor temperature ($^{\circ}C$), $T_{ej_{min}}$ is the minimum daily outdoor temperature ($^{\circ}C$) and t is time (day).

Available heat gains Q_g are the combination of solar heat gain through windows Q_s (kWh) and internal heat gain Q_i (kWh) released by human body heat, thermal machines, computers, servers in educational buildings, etc. The Q_s and Q_i are evaluated monthly during heating.

$$Q_g = Q_s + Q_i \quad (6)$$

Where:

Q_s : solar gains for each individual window facing different orientations (kWh).

Q_s for a window is calculated from the solar incident through a type of window glass, a free horizon, and the same orientation of the corresponding windows as

$$Q_s = F \times S_i \times I_s \quad (7)$$

where F ($F = F_s F_a F_g$) is the reduction factor of the insulation through the actual window anticipates the effect of

shadows F_s , the area the frame F_a and the glass type F_g . S_i is the transmission surface area (m^2) and I_s is the insulation through the reference pan ($kWh.m^2$).

Q_i : internal heat gain (kWh)

Q_i for each month over the heating period is calculated as:

$$Q_i = 0.024 \times D \times S_e \times \Phi_i \quad (8)$$

where D is the number of days of the month, S_e is the total heated floor surface area of the building (m^2), and Φ_i is the average internal heat gain ($W.m^{-2}$).

Not all the free gains that are available can be effectively utilized for heating the building. This is attributed to an excess of temperatures in certain periods, which can often be traced back to the substantial solar gains in periods with elevated external temperatures. The utilization of the heat gained in the course of the heating season depends on the time constant of building τ and the total heat gain as a ratio of the total heat loss, γ . The utilization factor for the heat gain η indicates how big a part of the potential heat gain can be utilized. The residual heat gain is mitigated through implementing solar shades and curtains, accompanied by enhanced ventilation. Typically, the model calculates the utilization factor η for the free gain as:

$$\eta_1 = \frac{1 - \gamma^a}{1 - \gamma^{a+1}} \quad (9)$$

$$\eta_2 = \frac{a}{1 + a}$$

where γ is the relative heat gain ($\gamma = \frac{Q_g}{Q_l}$). For $\gamma \neq 1$, apply η_1 and for $\gamma = 1$ and apply η_2 . τ is the building's time constant in hours ($a = 1 + \frac{\tau}{16}$).

3. Results

3.1. Energy consumption

For this study, the usable free heat gains Q_g are considered to remain the same between the pre-building and the post-building. Therefore, the changes before and after in heat demand Q_h are placed on the difference in total heat loss Q_l . The equation of heat demand saving ΔQ_h is expressed in equation 10.

$$\Delta Q_h = \Delta H \times DJU \times 0.024 \quad (10)$$

The calculation is applied to ventilation and upgraded building envelopes: walls and windows. Table 3 presents the inputs and outputs of heating saving ΔQ_h . The total saving was 85 MWh during the studied period.

Through the implementation of single-flow ventilation and the removal of permanent openings, heating conserved from ventilation contributes 9% of the total savings. In natural ventilation schools, air renewal relies on manually

Type of heat loss	Element	$\Delta H(W/K)$	DJU ($^{\circ}C.day$)	Heat saving (MWh)	Saving shares (%)
Envelope	Wall	2640	784.67	50	59
	Window	1440		27	32
Ventilation		413	-	8	9
Total		4822	-	85	-

Table 3: Calculated heating requirements saving before and after renovation of the GEII building during studied period from January to March

opening of windows and doors in classrooms [52]. In winter, it can be observed that both teachers and students exhibit a lack of motivation to manually open windows, as reported in academic studies [49, 74]. Consequently, retrofits incorporating automatically controlled ventilation have been found to present greater dependability than traditional window opening methods when enhancing the quality of air within the classroom [50].

Hence, the ventilation system implemented in the present study serves the dual purpose of diminishing thermal dissipation and regulating air permeation. The mechanism ensures a consistent and ample airflow supply in compliance with the recommended healthy regulation value of $18 m^3/h.per$ throughout occupied periods and stops utterly when unoccupied. When considering the building envelope, incorporating insulation within the walls constitutes the most significant means of reducing heat loss, up to 59%.

3.2. Results of monitoring of indoor climate

Continuous measurements of CO_2 concentrations, relative humidity (HR_{in}), and indoor temperature (T_{in}) were carried out in two classrooms, one office, and two workshops of each studied building before and after renovation, from January to March. The cumulative percentage distribution of the measured values of CO_2 , HR_{in} , and T_{in} is shown in Figure 4.

In both buildings and states, the CO_2 trends concave up nearly vertically at 500 ppm and then remain at the same level horizontally from 750 ppm to 1500 ppm or more. This means that approximately 75% of CO_2 data are lower than 500 ppm, another 20% is between 500 ppm and 750 ppm, and the rest of the data less than 5%, are higher than 750 ppm. On the other hand, the level of HR_{in} differs remarkably in the GEII building after renovation. The data initially concave upwards simultaneously at 20% HR_{in} for all cases. But while the others continue to increase to 50% gradually, the HR_{in} of GEII in the after state increases more rapidly from 40% to 65%, surpassing that of the others. As the rise is rather loose (diagonally), the interpretation of that variation is that after renovation, the HR_{in} level of GEII appears to be higher than in another state casually from time to time. On the other hand, the temperature's frequency evolves differently in all cases. In post-GEII building, the data quickly moves from $10^{\circ}C$, horizontally, to $18^{\circ}C$ then proceeds to concave upward vertically between $18^{\circ}C$ and $20^{\circ}C$. Whereas it is of pre-GEII building, concaves up slower and further from $18^{\circ}C$ to $24^{\circ}C$. This demonstrates that the majority of temperature in the post-building ranges from $18^{\circ}C$ to $20^{\circ}C$ and is cooler than the temperature in the pre-building, explaining the rise of HR_{in} level as previously stated. GC buildings have a more diagonally rise in temperatures, especially in the post-state showing that the temperature

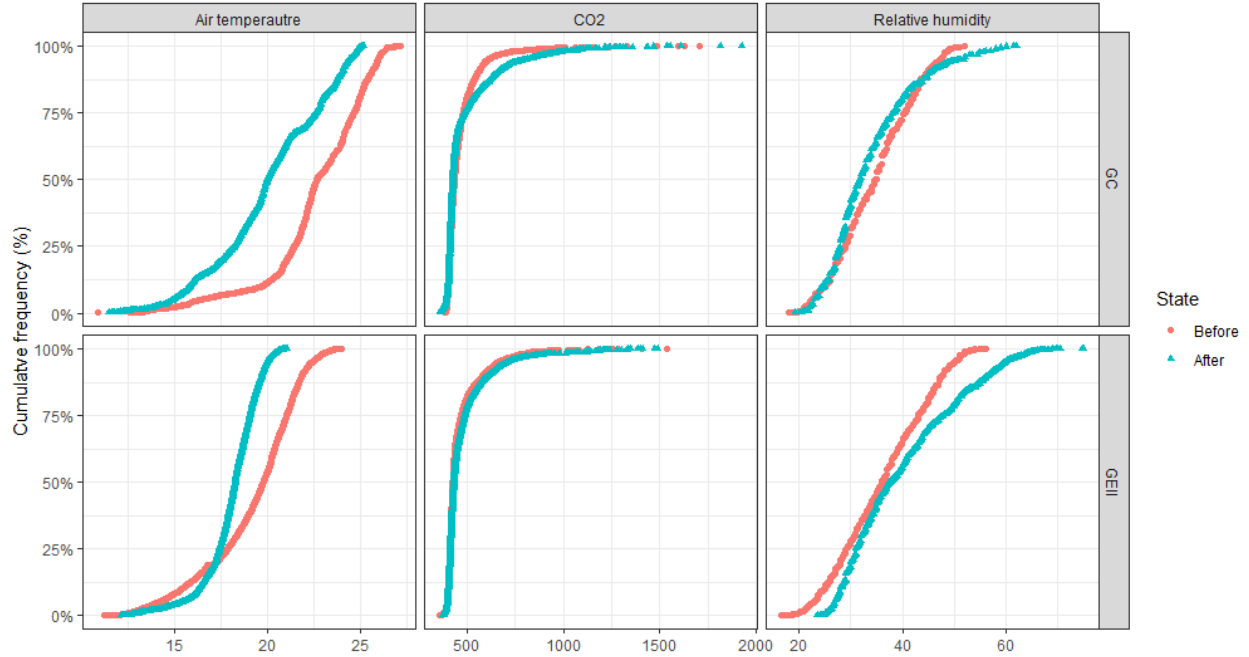


Figure 4: Overall cumulative frequency of the indoor climate in each building

varies a lot more during the studied period. By comparing the temperature curves before and after renovation, it can be concluded that the renovation overall led to a reduction in indoor temperature, which translates into heating savings.

A study in 2015 by Almeida [75] determined that the occupancy levels of educational institutions may significantly surpass those found in conventional office buildings, with up to four times more individuals occupying a given area per square meter. Therefore, a prominent focus of previous research has been the examination of classroom indoor climates as they are particularly susceptible to the impact of CO_2 levels. However, universities possess various functions and activities, including administrative units, lecture halls, classrooms, e-learning, laboratories, and workshops [58]. They are differentiated regarding spatial requirements, building equipment, and occupancy rate. The study of classrooms alone is insufficient to evaluate the overall efficacy of a building's renovation; all spaces must adhere to the appropriate health-related standards for each IEQ indicator.

This paper integrates room types into the analysis in order to undertake discrete evaluations and attain a greater comprehension of statistical accuracy. Figure 5 presents a boxplot of classrooms, offices, and workshops featured by indoor climate during school hours from 8h00 to 18h00 over the weekdays. In France, according to regulations, EN 15251 [76], the acceptable indoor environment of school buildings for category II (Renovated buildings) and category III (Existing buildings) are the following, respectively, indoor temperature ranges for heating: $20^{\circ}C - 24^{\circ}C$ and $19^{\circ}C$ to $25^{\circ}C$, CO_2 concentrations: 500 ppm and 800 ppm, relative humidity range: 25% to 60% and 20% to 70%. ASHRAE's journal just published a summary article by Stumm et al. [77], which takes a fresh look at the guideline of 1000 ppm of CO_2 as an upper limit in indoor environments. Based on that, the average values of CO_2 and HR_{in} in both buildings and

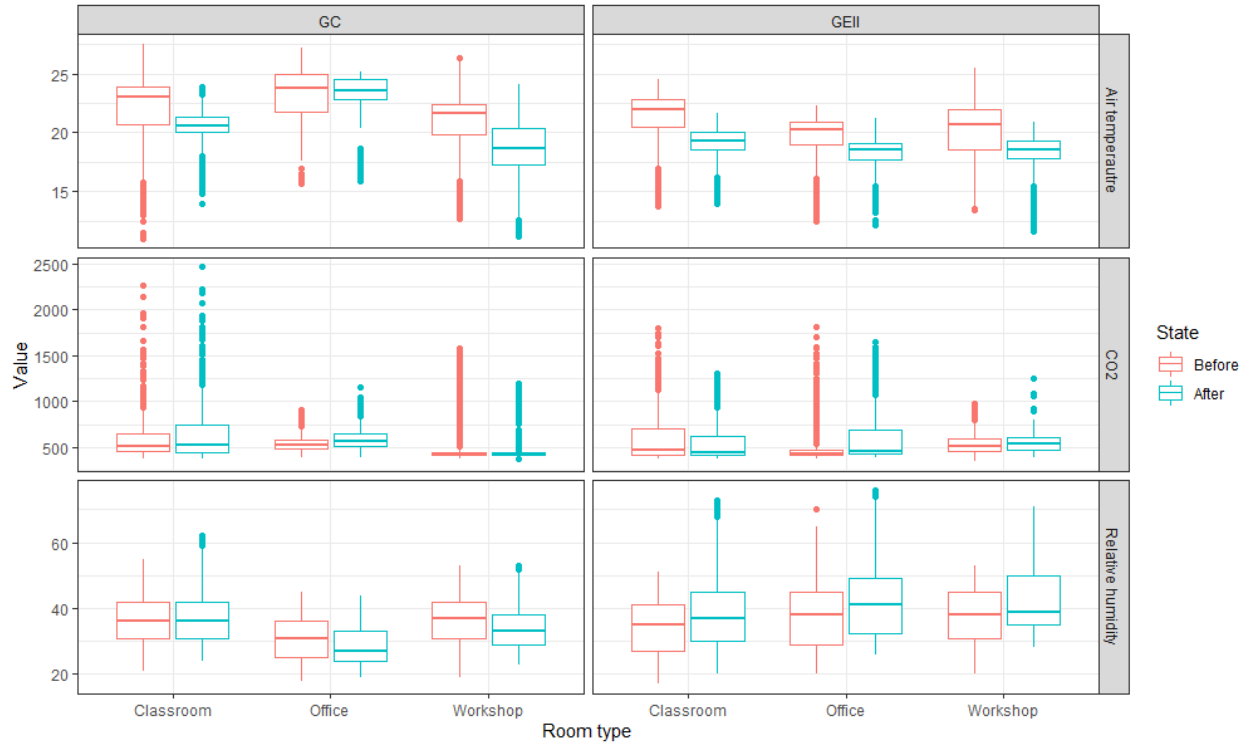


Figure 5: Boxplot of the indoor climate in different room type on weekdays during the occupied hours from 8h00 to 18h00

states conformed to the recommended values. Nevertheless, extreme values are surpassing 1000 ppm in most cases, together, taking 1.3% of the studied data. Notably, GC and GEII's temperatures drop out of prescribed ranges by 25% and 25% in the existing state and 53% and 90% in the renovated state. While the temperatures were generally warmer than wanted in the old buildings, the retrofitted buildings, particularly GEII, got cooler than the comfort temperature. These are due to the lack of energy control in the pre-state and the rise of energy prices in the post-state. In the previous state, indoor temperature accumulated per day takes into account the heat by heaters and available internal heat gain. Although some internal heat gains compensate for heat loss, solar radiation in the Mediterranean region is relatively robust even in winter making rooms facing south sensitive to the solar gains. Without indoor regulator valves, these internal heat gains are ignored and heaters usually waste energy on unnecessary heating making the indoor temperature warmer than the threshold. In 2023, corresponding to the after-state, the energy price surged enormously. To reduce energy bills, the new temperature threshold during occupied hours is lowered to 18°C. When coupled with the available thermostats, the indoor temperature is maintained at 19°C after including the internal heat gain.

3.2.1. T-Test comparison of before and after renovation

The ANOVA test (one-way analysis of variance) is employed to compare data points before and after renovation. This statistical test is an extension of the independent two-sample t-Test and is specifically designed to compare the means of multiple groups. As such, ANOVA is the appropriate technique for this case study, where the means of three

groups of room types are compared. The ANOVA of “rstatix” package of RStudio [78] takes into account two types of variations - the SS_n Sum of Squares in the numerator (i.e., SS effect), the SS_d Sum of Squares in the denominator (i.e., SS error). The ANOVA test also calculates effect sizes *ges* by dividing SS_{effect} by SS_{total} as follows:

$$ges = \frac{SS_{effect}}{SS_{effect} + SS_{error}} \quad (11)$$

Table 4 summarizes the t-Test results of the pre-buildings and post-buildings of each room type. The p-value is the significant value if it is less than 0.05 and is denoted with a star “*”. The *ges* value (generalized eta squared) is the level of significance with three ranges, namely, “0.2” for small and not noticeable by experts, “0.13 +” for medium and noticeable to the expert eye, and “0.26 +” is large and noticeable even to the untrained eye. This t-Test is vital to determine the degree of change in indoor climate, whether remarkable or subtle.

Indicators	Type	Effect	p-value	p < 0.05	ges
CO ₂	Classroom	State	3.05e-05	*	0.021
	Office		1.75e-13	*	0.072
	Workshop		2.86e-01		0.002
Temperature	Classroom		1.00e-17	*	0.084
	Office		1.20e-02	*	0.009
	Workshop		2.06e-17	*	0.094
Humidity	Classroom		2.06e-16	*	0.078
	Office		1.91e-04	*	0.019
	Workshop		7.31e-06	*	0.027

Table 4: Relationship between pre- and post-renovation states of indoor climate in different room types of studied buildings

As a result of both buildings combined, a statistically relevant relationship between renovation and indoor environmental quality is found for a p-value lower than 0.05 except for CO₂ of the workshop with p-value = 2.86×10^{-01} in consequence of unchanged ventilation in the workshop section. Drawing on *ges* values, this degree of significance is relatively minimal, for they are inferior to 0.2. Globally, this denotes that the pre-building and post-building progress in similar patterns, if not the same, for each indicator. The most prominent changes, according to *ges* values, are the temperature of the workshop (0.094) and of the classroom (0.084), attributed to a change in temperature threshold.

3.2.2. Investigation of indoor air quality indicators

Ventilation inside schools is vital for at least two reasons. One is the question of air quality and its impact on well-being and performance. And second, it is a heat loss path. There is varying evidence about the effect of low ventilation rates on performance and health [79, 80]. The role of ventilation as a heat loss path in school classrooms is sometimes misconstrued. The occupation rate in a classroom is commonly exceptionally high, and thus, the metabolic gains are also high. Modern designs incorporate typical gains to compensate for fabric losses, even in winter. This means modest ventilation levels are unlikely to imply a load on the heating system [81].

Figure 6 illustrates the evolution of the average hourly CO₂ levels on weekdays during the pre and post-renovation

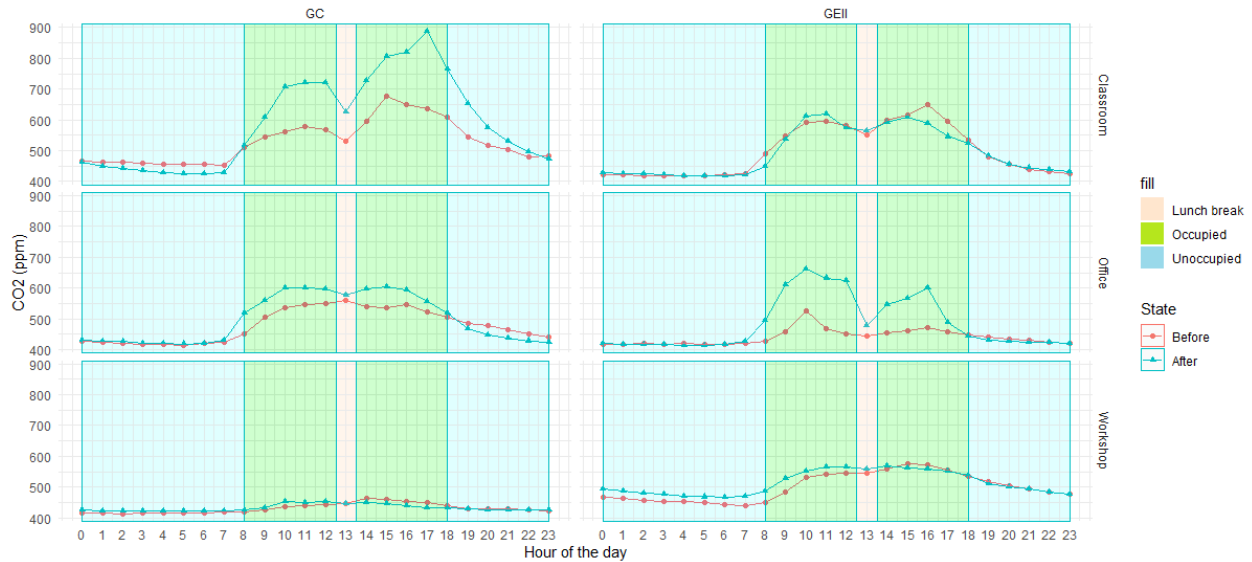


Figure 6: Mean CO_2 concentrations over the studied period on weekdays from January to March of Before (2021) and After (2023) renovation. The filled color represents the global lunch break that usually takes place between 12h30 and 13h30, a typically occupied period of school hours and typical non-occupied periods

period. It incorporates an unoccupied period at nighttime, an occupied period from 8h00 to 18h00, and a lunch break from 12h30 to 13h30. Surprisingly, the concentration of CO_2 in the GC building is higher after retrofitting than before, particularly in the classroom and office, by 11.7% and 3.8%, respectively. When non-ventilated, enclosed spaces are subjected to elevated concentrations of metabolically produced carbon dioxide emissions from the occupants' breathing [82]. A lower CO_2 level indicates the indoor air quality's freshness. This depends on the implementation of an appropriate ventilation strategy. Insufficient ventilation in buildings is a prevalent cause leading to a potential risk of sick building syndrome [83]. A test was conducted to assess the mechanical ventilation system's efficacy through airflow rate measurements. The results indicate that the extraction rate of each ventilation outlet is 50% lower than the proposed design value of $90m^3/h$. This design value conforms to the regulatory requirement for ventilation rates of $18m^3/h.per$. When it is not respected, excessive CO_2 levels happen, and more seriously for renovated buildings when they are more air-tightness following the renovation of windows and walls.

As for the GEII building, it was observed that the single-flow ventilation rate is correct, prompt to similar patterns of CO_2 evolution trends, except for the office. Nonetheless, this is not a problem caused by inefficient ventilation but rather by the change in room function. After renovation, this office was altered into a classroom, increasing the average CO_2 abruptly. This effect emphasizes previous findings that the CO_2 levels of the school are more important than the office's for it has higher occupant density.

Although the average CO_2 concentrations have worsened due to a defective ventilation system and a change in room utilization, they remain below 1000 ppm, with the highest peak at 900 ppm in the GC classroom at 17h00. The rest of the renovated buildings, which differ from the existing ones, reach a maximum of 700 ppm for the GC classroom

at 10h00, 600 ppm for the GC office at 10h00 and 15h00, and 650 ppm for the GEII office at 9h00.

3.2.3. Investigation of thermal comfort indicator

In both states, the heating control system consists of two operational modes. The first mode referred to as “*Comfort*” operates from 7h00 to 18h00. The second mode, known as “*Eco*” is intended for night-time use and on weekends. Following the renovation, it was decided to reduce the established temperature threshold in the *Comfort* mode from 20°C to 18°C for financial reasons. Nonetheless, it is essential to note that the actual temperature development may diverge from the pre-established setting as a consequence of the inefficient controlling system. An occurrence is observable occasionally wherein radiators maintain a consistent temperature at the designated comfort mode across the entire day, which may persist for several weeks.

Figure 7 presents the average hourly indoor temperature on weekdays of the two buildings in each state. The temperature in the pre-GC building appears to be higher than in pre-GEII. This is associated with the heat exchanger that is now installed beneath the individual building. Prior to that, the heat energy came from the GC sub-station, which benefits one of the two. This means that if the optimal temperature requested in GC is between 19°C and 25°C, depending on the set temperature, the temperature supplied in GEII tends to be lower due to distribution energy loss. Since the installation of separate heat exchangers, the transmitted energy is consistent with the energy needed in both buildings.

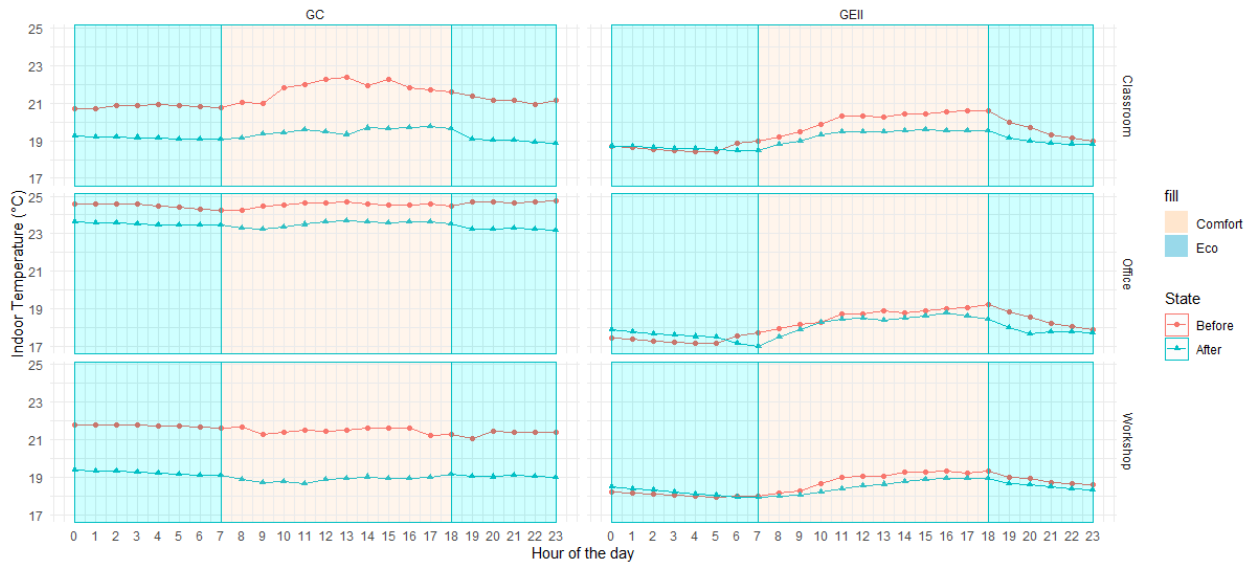


Figure 7: Mean indoor temperature over the studied period on weekdays from January to March of Before (2021) and After (2023) renovation. The filled color represents two heating operation modes, namely ‘*Comfort*’ that maintains a comfortable room temperature and ‘*Eco*’ that economizes energy during nighttime and on weekends

The historical distribution of heat has been found to significantly influence the fluctuation of temperature experienced by the GEII and GC buildings. Given the new interior temperature setpoint at 18°C, the temperature variation of

the GEII building is less severe than that of GC because its final temperature was close to 19°C. Meanwhile, in the GC building, it is apparent that the temperature differences between before and after renovation are more prominent, with a maximum decrease of 3°C.

The temperature trends in GC are steady all day, unlike the progressions of GEII. Upon verification with GC's heating control, the supplied energy was consistently at the same level across all modes of operation. Another issue is related to continuous nighttime heating requested by an energy company in 2021 to avoid the energy spike that could cause temporary shutdowns. Since the GC's office space area is relatively small, this results in consistently elevated temperatures at 24.5°C and 23.5°C in the pre-state and post-state.

As the number of individuals within the classroom increases, there is a direct proportional rise in temperature. In contrast, the temperature decreases when students are absent, end-of-activity, or depending on the type of ventilation employed [84]. Based on the aforementioned studies, the discernible surge observed in GC's classroom before the renovation, between 10h00 and 13h00, may be attributed to the occupants' heat release.

In the GEII, the typical temperature peaks can be observed at 11h00 in both states when provided with appropriate heat supply and scheduling as per demand. Besides occupancy density, numerous other factors significantly contribute to the fluctuations in average indoor temperature following retrofitting. These may encompass outdoor conditions, room characteristics such as size, orientation, and the surface of external walls, and the type of ventilation system employed, such as natural or mechanical ventilation with extraction. The enhancement of thermal insulation and implementation of new airtight windows serve as measures for reducing external influence on measurements, thereby decreasing the observed differences following retrofitting. Following the refurbishment, the disparities in the temperature range of GEII have been mitigated, indicating the efficacy of the restoration in preserving thermal energy. Maintaining consistent temperatures during both nighttime and daytime periods results in effective energy conservation for subsequent heating purposes.

3.3. Thermal comfort survey

Students of the GC building were asked to fill out a questionnaire in two periods, before and after renovation. The main question is, "How do you perceive the indoor temperature at this instant?". The answer is on a scale of five, from "Cold" to "Hot". In the pre-state, the survey was conducted in two classrooms repeatedly, at least twice a day, for five consecutive days giving 159 responses in total. However, using this longitudinal survey, students tend to lose interest in answering, making certain votes unreliable. Therefore, the survey conducted in the post-state was limited to a single day and a single time per classroom, yielding a total response of 50. Figure 8 A) illustrates the distribution of thermal sensation vote (TSV) in percentages. Before the implementation of retrofitting measures, a small fraction of the survey participants, 2.6%, reported experiencing indoor temperatures that were deemed extremely cold and hot. In the after stage, the response rate for the "Neutral" category demonstrated a statistically significant increase, with a recorded

rate of 76% compared to 57.2% in the before stage. When comparing the TSV to the actual indoor temperature, as

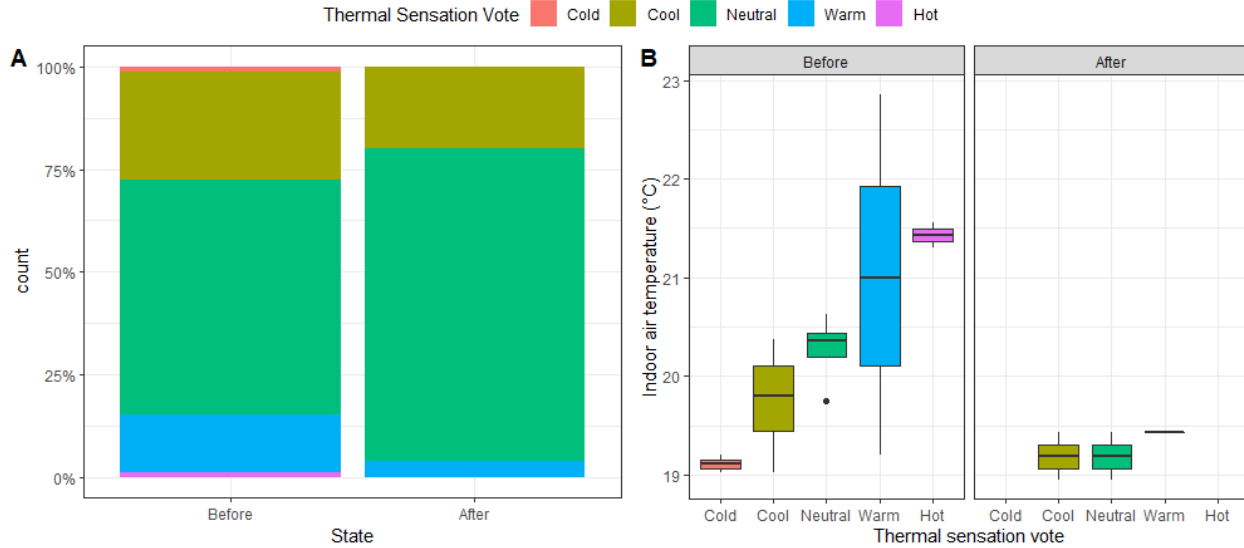


Figure 8: Distribution of thermal sensation vote in GC building before (from February 17th to 23rd, 2022) and after (March 7th, 2023) renovation: A) frequency distribution; B) correlation between perception vote and measured indoor temperature

shown in Figure 8 B), it is interesting to see that in pre-building, the distribution of votes correlates to the temperature distribution. For instance, users in pre-renovation buildings evaluate the rooms as cool at an average temperature below 20°C, neutral at 20.4°C, and warm at 21°C or higher. On the contrary, after renovation, as revealed in Section 3.2.3, the air temperature is constantly lower than 20°C due to heating regulations. As a result, for the same temperature range, 76% of responses are neutral, and another 20% find it cool. Herewith suggests that reducing the temperature for energy-efficient purposes is still statistically comfortable for occupants.

4. Discussion

After investigating two renovated buildings, there are several factors to take into account for a better assessment. The heating system in a school building differs from those in residential and office buildings since individuals, such as students and teachers, lack the capacity to regulate it. Unless their impact pertains to the opening and closing of windows or doors. But it has been studied and proved by Gao et al. [49] that it is rare for users to change them manually during the winter. Therefore, the change in the heating system relies heavily on the management strategy and its efficiency. In this case study, results have found that the supplied energy in one of the buildings, GC, does not conform to the energy demand by overheating predominantly. This effect not only jeopardizes energy consumption but also the occupant's comfort.

Furthermore, the new heating temperature threshold was reduced to 18°C to conserve energy. This effect leads to 90% of the temperature data falling into the uncomfortable zone with respect to the recommended temperature range

of the thermal guidelines for renovated buildings. Nevertheless, concerning the thermal comfort vote, occupants tend to be less affected by the renovation. According to the survey results, at approximately 19.5°C, 20% of participants rated the post-classrooms as cool, and the other 76% voted for the neutral temperature. The evidence suggests that individuals have the capacity to acclimate and exhibit an increased level of acceptance toward unfamiliar temperature settings. Similar situations were already reported in other studies [17, 52] and reinforce the idea that satisfactory comfort levels can be attained through internal heat gains and a thermally efficient building envelope.

Nonetheless, the designated temperature threshold may not be optimal for the workshops and the offices, where the number of occupants is minimal. After renovation, the average temperature of these two room types is as low as 18°C is equal to the threshold temperature since the internal heat gains are unavailable. Hence, it is crucial to maintain a delicate equilibrium between the user's comfort in different room types and overall energy saving. For instance, supplementary heating devices such as portable heaters or convertible air-conditioners may be installed within office spaces. In the workshops, students are advised to put on additional clothing to decrease personal heat loss.

Regarding the modification in temperature consequent to the transition from the *Comfort* to *Eco* heating mode, it has been observed that the temperature experiences a more rapid and abrupt decline prior to the retrofitting measures. The findings indicate that the upgrade of the envelope has led to a decrease in heat dissipation through both the fabrics and the ventilation system, resulting in prolonged conservation of heat and a reduction in the variance between nocturnal and diurnal temperatures.

Relevant to single-flow ventilation systems, the exchange air rate has become more vital in the post-building than it is in the pre-building. In extremely air-tight rooms, indoor air quality is at risk if the air-flow rate does not meet the design value of 18 $m^3/h.per$, primarily for classrooms. The analyses in Section 3.2.2 have proved that when the exchange air rate is incorrect, the CO_2 levels on average can increase up to 11.7% more than the typical CO_2 values of the pre-state. Consequently, regular checks and maintenance of the ventilation system are mandatory.

Overall, the t-Test statistics have shown a slight significance between indoor climate before and after renovation for ges values less than 0.2. Suggesting that this retrofitting strategy maintains the IEQ at roughly the same range, without any noticeable improvement or deterioration. Although the CO_2 concentrations, HR_{in} , and T_{in} values are acceptable by remaining the same, they are sitting on the edge of the recommended zone according to the thermal benchmark of renovated buildings.

The results also show that during the occupied period of the heating season, the CO_2 levels exceeding 1000 ppm is only 1.3% of measured data in both states. However, occasional spikes can reach up to 3000 ppm within a brief 15-minute. The analysis was carried out during a period of use, but the rooms are not always occupied. Thus, the analysis presented in Figure 6 smoothes out the average hourly rate of CO_2 . Previous research has found similar patterns. For instance, Ramalho et al. (2013) [85], investigated 108 campus buildings in France and revealed that in the occupation period, 33% of the schools revealed CO_2 concentrations above 1700 ppm in more than 66% of the

records. Santamouris et al. (2008) [86], monitored the indoor air quality in 27 naturally ventilated schools in Athens. The measurements were taken in the spring and fall seasons when window opening is the main ventilation procedure. The finding indicates that 52% of the classrooms presented CO_2 concentrations greater than 1000 ppm with a median of 1070 ppm. At the end of the class period, there was a maximum concentration of 3000 ppm with a median of 1650 ppm. Similarly, a study by Almeida found a marginal enhancement in indoor environmental conditions following the retrofitting process compared to the pre-existing state, albeit still falling short of the recommended criteria [54, 56, 57].

These similarities with previous research highlight the importance of ongoing efforts to improve indoor air quality, especially during peak occupancy periods, in order to enhance the occupants' health and comfort within the building premises.

5. Conclusions

Students spend most of their time in school. Therefore good indoor environmental quality must be provided. With the current trend of low-energy consumption buildings, university buildings, like many others, have undergone energy-efficient renovation. This renovation, however, does not guarantee better indoor environmental quality. This study is designed to comprehensively analyze the impact of refurbishment on thermal comfort and indoor air quality.

The key outcomes of the research revealed substantial reductions in heating consumption, amounting to 85 MWh over the studied period, as a result of the retrofitting efforts. Through t-Test statistics, the study identified subtle but significant changes in indoor climate parameters, including CO_2 levels, temperature, and humidity. However, these changes were not discernible to the occupants or experts.

Specifically, the detailed analyses yielded several noteworthy findings:

- In Mediterranean weather conditions, considering usable internal heat gain is crucial for retrofitted buildings. Accounting for heat release from occupancy and solar radiation in heating design and control strategies, such as thermostats, can prevent unnecessary energy wastage on heating;
- The adjustment of heating set points to 18°C post-renovation did not impact the thermal comfort perception of occupants in classrooms. Surprisingly, occupants displayed an increased tolerance towards cooler environments compared to their pre-existing attitudes. However, this threshold was suboptimal for offices and workshops, given their relatively low occupancy rates, limiting available internal heat gain. As a result, supplementary heating devices should be provided in these room types;
- Exchange air rate is more vital in the renovated building with extreme air-tight than in the existing building. This case study proves that defective ventilation systems led to a significant 11.7% increase in CO_2 concentrations, emphasizing the need for regular verification and maintenance to meet regulatory standards and prevent building sick syndrome.

The research confirms that the retrofitting of buildings using energy-efficient methods offers substantial benefits, as it significantly reduces heating demand and overall energy consumption without compromising indoor climate condi-

tions. While values of certain indoor environmental quality indicators may sit on the edge of the comfort zone defined by building thermal regulations for renovated buildings, they remain within acceptable limits. Future studies should confirm heat demand assessments through measurements of heating energy supplied by the building's substation, which will be accessible for the next heating campaign. Additionally, further investigations should explore combined effects, incorporating user comfort surveys in similar or mid-season periods, and consider visual comfort and indoor air quality, including odor comfort. These endeavors will contribute to a more comprehensive understanding of the impact of energy-efficient renovations on indoor climate and occupant comfort.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Keovathana Run reports financial support was provided by regional scholarship and the University of Montpellier.

Acknowledgement

The authors gratefully acknowledge the support from the OEHM project supported by Occitanie region and Europe.

References

- [1] I. Artola, K. Rademaekers, R. Williams, and J. Yearwood. *Boosting Building Renovation: What Potential and Value for Europe?* European Parliamentary Research Service, Oct. 14, 2016.
- [2] G. Trotta, J. Spangenberg, and S. Lorek. "Energy efficiency in the residential sector: identification of promising policy instruments and private initiatives among selected European countries". In: *Energy Efficiency* 11.8 (Dec. 1, 2018), pp. 2111–2135. doi: [10.1007/s12053-018-9739-0](https://doi.org/10.1007/s12053-018-9739-0).
- [3] D.-G. for Energy. *New rules for greener and smarter buildings will increase quality of life for all Europeans*. Apr. 15, 2019.
- [4] J. Jens Laustsen, P. Ruyssevelt, D. Staniaszek, and D. Strong. *Europe's Buildings under the Microscope: A country-by-country review of the energy performance of buildings*. Report. Num Pages: 132 Publication Title: Buildings Performance Institute Europe (BPIE): Brussels, Belgium. Brussels, Belgium: Buildings Performance Institute Europe (BPIE), Oct. 2011.
- [5] V. De Giuli, O. Da Pos, and M. De Carli. "Indoor environmental quality and pupil perception in Italian primary schools". In: *Building and Environment* 56 (Oct. 1, 2012), pp. 335–345. doi: [10.1016/j.buildenv.2012.03.024](https://doi.org/10.1016/j.buildenv.2012.03.024).

- [6] L. Dias Pereira, D. Raimondo, S. P. Corgnati, and M. Gameiro da Silva. “Assessment of indoor air quality and thermal comfort in Portuguese secondary classrooms: Methodology and results”. In: *Building and Environment* 81 (Nov. 1, 2014), pp. 69–80. doi: [10.1016/j.buildenv.2014.06.008](https://doi.org/10.1016/j.buildenv.2014.06.008).
- [7] Y. Geng, W. Ji, B. Lin, and Y. Zhu. “The impact of thermal environment on occupant IEQ perception and productivity”. In: *Building and Environment* 121 (Aug. 15, 2017), pp. 158–167. doi: [10.1016/j.buildenv.2017.05.022](https://doi.org/10.1016/j.buildenv.2017.05.022).
- [8] Y. Al Horr, M. Arif, A. Kaushik, A. Mazroei, M. Katafygiotou, and E. Elsarrag. “Occupant productivity and office indoor environment quality: A review of the literature”. In: *Building and Environment* 105 (Aug. 15, 2016), pp. 369–389. doi: [10.1016/j.buildenv.2016.06.001](https://doi.org/10.1016/j.buildenv.2016.06.001).
- [9] I. Mujan, A. S. Anelković, V. Munćan, M. Kljajić, and D. Ružić. “Influence of indoor environmental quality on human health and productivity - A review”. In: *Journal of Cleaner Production* 217 (Apr. 20, 2019), pp. 646–657. doi: [10.1016/j.jclepro.2019.01.307](https://doi.org/10.1016/j.jclepro.2019.01.307).
- [10] M. Frontczak and P. Wargocki. “Literature survey on how different factors influence human comfort in indoor environments”. In: *Building and Environment* 46.4 (Apr. 1, 2011), pp. 922–937. doi: [10.1016/j.buildenv.2010.10.021](https://doi.org/10.1016/j.buildenv.2010.10.021).
- [11] M. Turunen, O. Toyinbo, T. Putus, A. Nevalainen, R. Shaughnessy, and U. Haverinen-Shaughnessy. “Indoor environmental quality in school buildings, and the health and wellbeing of students”. In: *International Journal of Hygiene and Environmental Health* 217.7 (Sept. 1, 2014), pp. 733–739. doi: [10.1016/j.ijheh.2014.03.002](https://doi.org/10.1016/j.ijheh.2014.03.002).
- [12] D. Clements-Croome, H. Awbi, Z. Bakó-Biró, N. Kochhar, and M. Williams. “Ventilation rates in schools”. In: *Building and Environment* 43.3 (Mar. 2008), pp. 362–367. doi: [10.1016/j.buildenv.2006.03.018](https://doi.org/10.1016/j.buildenv.2006.03.018).
- [13] U. Haverinen-Shaughnessy, D. J. Moschandreas, and R. J. Shaughnessy. “Association between substandard classroom ventilation rates and students’ academic achievement”. In: *Indoor Air* 21.2 (2011), pp. 121–131. doi: [10.1111/j.1600-0668.2010.00686.x](https://doi.org/10.1111/j.1600-0668.2010.00686.x).
- [14] M. J. Mendell, E. A. Eliseeva, M. M. Davies, M. Spears, A. Lobscheid, W. J. Fisk, and M. G. Apte. “Association of classroom ventilation with reduced illness absence: a prospective study in California elementary schools”. In: *Indoor Air* 23.6 (2013). eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1111/ina.12042>, pp. 515–528. doi: [10.1111/ina.12042](https://doi.org/10.1111/ina.12042).
- [15] U. Haverinen-Shaughnessy, R. J. Shaughnessy, E. C. Cole, O. Toyinbo, and D. J. Moschandreas. “An assessment of indoor environmental quality in schools and its association with health and performance”. In: *Building and Environment*. Special Issue: Indoor pollutants, chemistry and health- Selected papers presented at Indoor Air 2014 conference in Hong Kong 93 (Nov. 1, 2015), pp. 35–40. doi: [10.1016/j.buildenv.2015.03.006](https://doi.org/10.1016/j.buildenv.2015.03.006).

- [16] S. Langer and G. Bekö. “Indoor air quality in the Swedish housing stock and its dependence on building characteristics”. In: *Building and Environment* 69 (Nov. 1, 2013), pp. 44–54. doi: [10.1016/j.buildenv.2013.07.013](https://doi.org/10.1016/j.buildenv.2013.07.013).
- [17] S. Ezzeldin and S. J. Rees. “The potential for office buildings with mixed-mode ventilation and low energy cooling systems in arid climates”. In: *Energy and Buildings* 65 (Oct. 1, 2013), pp. 368–381. doi: [10.1016/j.enbuild.2013.06.004](https://doi.org/10.1016/j.enbuild.2013.06.004).
- [18] J. Toftum, B. U. Kjeldsen, P. Wargocki, H. R. Menå, E. M. N. Hansen, and G. Clausen. “Association between classroom ventilation mode and learning outcome in Danish schools”. In: *Building and Environment* 92 (Oct. 1, 2015), pp. 494–503. doi: [10.1016/j.buildenv.2015.05.017](https://doi.org/10.1016/j.buildenv.2015.05.017).
- [19] K. W. Tham. “Indoor air quality and its effects on humans—A review of challenges and developments in the last 30 years”. In: *Energy and Buildings* 130 (Oct. 15, 2016), pp. 637–650. doi: [10.1016/j.enbuild.2016.08.071](https://doi.org/10.1016/j.enbuild.2016.08.071).
- [20] A. M. Bueno, A. A. de Paula Xavier, and E. E. Broday. “Evaluating the Connection between Thermal Comfort and Productivity in Buildings: A Systematic Literature Review”. In: *Buildings* 11.6 (June 2021). Number: 6 Publisher: Multidisciplinary Digital Publishing Institute, p. 244. doi: [10.3390/buildings11060244](https://doi.org/10.3390/buildings11060244).
- [21] J. Jiang, D. Wang, Y. Liu, Y. Xu, and J. Liu. “A study on pupils’ learning performance and thermal comfort of primary schools in China”. In: *Building and Environment* 134 (Apr. 15, 2018), pp. 102–113. doi: [10.1016/j.buildenv.2018.02.036](https://doi.org/10.1016/j.buildenv.2018.02.036).
- [22] A. Kaushik, M. Arif, P. Tumula, and O. J. Ebohon. “Effect of thermal comfort on occupant productivity in office buildings: Response surface analysis”. In: *Building and Environment* 180 (Aug. 2020), p. 107021. doi: [10.1016/j.buildenv.2020.107021](https://doi.org/10.1016/j.buildenv.2020.107021).
- [23] A. Lipczynska, S. Schiavon, and L. T. Graham. “Thermal comfort and self-reported productivity in an office with ceiling fans in the tropics”. In: *Building and Environment* 135 (May 1, 2018), pp. 202–212. doi: [10.1016/j.buildenv.2018.03.013](https://doi.org/10.1016/j.buildenv.2018.03.013).
- [24] D. Wang, Y. Xu, Y. Liu, Y. Wang, J. Jiang, X. Wang, and J. Liu. “Experimental investigation of the effect of indoor air temperature on students’ learning performance under the summer conditions in China”. In: *Building and Environment* 140 (Aug. 1, 2018), pp. 140–152. doi: [10.1016/j.buildenv.2018.05.022](https://doi.org/10.1016/j.buildenv.2018.05.022).
- [25] W. Cui, G. Cao, J. H. Park, Q. Ouyang, and Y. Zhu. “Influence of indoor air temperature on human thermal comfort, motivation and performance”. In: *Building and Environment* 68 (Oct. 1, 2013), pp. 114–122. doi: [10.1016/j.buildenv.2013.06.012](https://doi.org/10.1016/j.buildenv.2013.06.012).

- [26] I. Sarbu and C. Pacurar. “Experimental and numerical research to assess indoor environment quality and school-work performance in university classrooms”. In: *Building and Environment* 93 (Nov. 1, 2015), pp. 141–154. doi: [10.1016/j.buildenv.2015.06.022](https://doi.org/10.1016/j.buildenv.2015.06.022).
- [27] S. Ahrentzen, J. Erickson, and E. Fonseca. “Thermal and health outcomes of energy efficiency retrofits of homes of older adults”. In: *Indoor Air* 26.4 (Aug. 2016), pp. 582–593. doi: [10.1111/ina.12239](https://doi.org/10.1111/ina.12239).
- [28] K. Van Den Wymelenberg and M. Inanici. “Evaluating a New Suite of Luminance-Based Design Metrics for Predicting Human Visual Comfort in Offices with Daylight”. In: *LEUKOS* 12.3 (July 2, 2016). Publisher: Taylor & Francis .eprint: <https://doi.org/10.1080/15502724.2015.1062392>, pp. 113–138. doi: [10.1080/15502724.2015.1062392](https://doi.org/10.1080/15502724.2015.1062392).
- [29] E. Shen, J. Hu, and M. Patel. “Energy and visual comfort analysis of lighting and daylight control strategies”. In: *Building and Environment* 78 (Aug. 1, 2014), pp. 155–170. doi: [10.1016/j.buildenv.2014.04.028](https://doi.org/10.1016/j.buildenv.2014.04.028).
- [30] I. Konstantzos, S. A. Sadeghi, M. Kim, J. Xiong, and A. Tzempelikos. “The effect of lighting environment on task performance in buildings – A review”. In: *Energy and Buildings* 226 (Nov. 1, 2020), p. 110394. doi: [10.1016/j.enbuild.2020.110394](https://doi.org/10.1016/j.enbuild.2020.110394).
- [31] A. Çakir. “Human Factors in Lighting”. In: *Behaviour & Information Technology* 33.10 (Oct. 3, 2014). Publisher: Taylor & Francis .eprint: <https://doi.org/10.1080/0144929X.2014.949422>, pp. 1111–1113. doi: [10.1080/0144929X.2014.949422](https://doi.org/10.1080/0144929X.2014.949422).
- [32] K. C. H. J. Smolders and Y. A. W. de Kort. “Bright light and mental fatigue: Effects on alertness, vitality, performance and physiological arousal”. In: *Journal of Environmental Psychology*. Light, lighting, and human behaviour 39 (Sept. 1, 2014), pp. 77–91. doi: [10.1016/j.jenvp.2013.12.010](https://doi.org/10.1016/j.jenvp.2013.12.010).
- [33] S. Kang, D. Ou, and C. M. Mak. “The impact of indoor environmental quality on work productivity in university open-plan research offices”. In: *Building and Environment* 124 (Nov. 1, 2017), pp. 78–89. doi: [10.1016/j.buildenv.2017.07.003](https://doi.org/10.1016/j.buildenv.2017.07.003).
- [34] H. Dehghan, M. T. Bastami, and B. Mahaki. “Evaluating combined effect of noise and heat on blood pressure changes among males in climatic chamber”. In: *J Educ Health Promot* 6 (May 5, 2017), p. 39. doi: [10.4103/jehp.jehp_107_15](https://doi.org/10.4103/jehp.jehp_107_15).
- [35] W. Yang and H. J. Moon. “Cross-modal effects of noise and thermal conditions on indoor environmental perception and speech recognition”. In: *Applied Acoustics* 141 (Dec. 1, 2018), pp. 1–8. doi: [10.1016/j.apacoust.2018.06.019](https://doi.org/10.1016/j.apacoust.2018.06.019).
- [36] A. Standard. “Standard 55-2004”. In: *Thermal environmental conditions for human occupancy* 3 (2004).

- [37] H. Wu, Y. Wu, X. Sun, and J. Liu. “Combined effects of acoustic, thermal, and illumination on human perception and performance: A review”. In: *Building and Environment* 169 (Feb. 1, 2020), p. 106593. doi: [10.1016/j.buildenv.2019.106593](https://doi.org/10.1016/j.buildenv.2019.106593).
- [38] W. Yang, H. J. Moon, and M.-J. Kim. “Combined effects of short-term noise exposure and hygrothermal conditions on indoor environmental perceptions”. In: *Indoor and Built Environment* 27.8 (Oct. 1, 2018). Publisher: SAGE Publications Ltd STM, pp. 1119–1133. doi: [10.1177/1420326X17703774](https://doi.org/10.1177/1420326X17703774).
- [39] C. Buratti, E. Belloni, F. Merli, and P. Ricciardi. “A new index combining thermal, acoustic, and visual comfort of moderate environments in temperate climates”. In: *Building and Environment* 139 (July 1, 2018), pp. 27–37. doi: [10.1016/j.buildenv.2018.04.038](https://doi.org/10.1016/j.buildenv.2018.04.038).
- [40] W. Yang and H. J. Moon. “Combined effects of acoustic, thermal, and illumination conditions on the comfort of discrete senses and overall indoor environment”. In: *Building and Environment* 148 (Jan. 15, 2019), pp. 623–633. doi: [10.1016/j.buildenv.2018.11.040](https://doi.org/10.1016/j.buildenv.2018.11.040).
- [41] S. Torresin, G. Pernigotto, F. Cappelletti, and A. Gasparella. “Combined effects of environmental factors on human perception and objective performance: A review of experimental laboratory works”. In: *Indoor Air* 28.4 (2018). eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1111/ina.12457>, pp. 525–538. doi: [10.1111/ina.12457](https://doi.org/10.1111/ina.12457).
- [42] A. Asif, M. Zeeshan, and M. Jahanzaib. “Indoor temperature, relative humidity and CO2 levels assessment in academic buildings with different heating, ventilation and air-conditioning systems”. In: *Building and Environment* 133 (Apr. 2018), pp. 83–90. doi: [10.1016/j.buildenv.2018.01.042](https://doi.org/10.1016/j.buildenv.2018.01.042).
- [43] G. Bekö, J. Toftum, and G. Clausen. “Modeling ventilation rates in bedrooms based on building characteristics and occupant behavior”. In: *Building and Environment* 46.11 (Nov. 1, 2011), pp. 2230–2237. doi: [10.1016/j.buildenv.2011.05.002](https://doi.org/10.1016/j.buildenv.2011.05.002).
- [44] E. Delzendeh, S. Wu, A. Lee, and Y. Zhou. “The impact of occupants’ behaviours on building energy analysis: A research review”. In: *Renewable and Sustainable Energy Reviews* 80 (Dec. 1, 2017), pp. 1061–1071. doi: [10.1016/j.rser.2017.05.264](https://doi.org/10.1016/j.rser.2017.05.264).
- [45] R. Andersen, V. Fabi, J. Toftum, S. P. Corgnati, and B. W. Olesen. “Window opening behaviour modelled from measurements in Danish dwellings”. In: *Building and Environment* 69 (Nov. 1, 2013), pp. 101–113. doi: [10.1016/j.buildenv.2013.07.005](https://doi.org/10.1016/j.buildenv.2013.07.005).
- [46] N. Jain, E. Burman, C. Robertson, S. Stamp, C. Shrubsole, F. Aletta, E. Barrett, T. Oberman, J. Kang, P. Raynham, D. Mumovic, and M. Davies. “Building performance evaluation: Balancing energy and indoor environ-

- mental quality in a UK school building”. In: *Building Services Engineering Research and Technology* 41.3 (May 2020), pp. 343–360. doi: [10.1177/0143624419897397](https://doi.org/10.1177/0143624419897397).
- [47] *Guidelines on Building Regulations 2010*. Red. by E. J. d. P. Hansen. SBI Guidelines. Hørsholm: SBI forlag, Aug. 2012. ISBN: 978-87-92739-05-6.
- [48] d. N. C. Comite’Europe’ en. “Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics”. In: *EN 15251* (2007). Publisher: CEN.
- [49] J. Gao, P. Wargocki, and Y. Wang. “Ventilation system type, classroom environmental quality and pupils’ perceptions and symptoms”. In: *Building and Environment* 75 (May 1, 2014), pp. 46–57. doi: [10.1016/j.buildenv.2014.01.015](https://doi.org/10.1016/j.buildenv.2014.01.015).
- [50] A. Heebøll, P. Wargocki, and J. Toftum. “Window and door opening behavior, carbon dioxide concentration, temperature, and energy use during the heating season in classrooms with different ventilation retrofits—ASHRAE RP1624”. In: *Science and Technology for the Built Environment* 24.6 (July 3, 2018), pp. 626–637. doi: [10.1080/23744731.2018.1432938](https://doi.org/10.1080/23744731.2018.1432938).
- [51] J. Rosbach, E. Krop, M. Vonk, J. van Ginkel, C. Meliefste, S. de Wind, U. Gehring, and B. Brunekreef. “Classroom ventilation and indoor air quality—results from the FRESH intervention study”. In: *Indoor Air* 26.4 (2016). eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1111/ina.12231>, pp. 538–545. doi: [10.1111/ina.12231](https://doi.org/10.1111/ina.12231).
- [52] L. Stabile, M. Dell’Isola, A. Frattolillo, A. Massimo, and A. Russi. “Effect of natural ventilation and manual airing on indoor air quality in naturally ventilated Italian classrooms”. In: *Building and Environment* 98 (Mar. 1, 2016), pp. 180–189. doi: [10.1016/j.buildenv.2016.01.009](https://doi.org/10.1016/j.buildenv.2016.01.009).
- [53] D. Zhang and P. M. Bluysen. “Energy consumption, self-reported teachers’ actions and children’s perceived indoor environmental quality of nine primary school buildings in the Netherlands”. In: *Energy and Buildings* 235 (Mar. 15, 2021), p. 110735. doi: [10.1016/j.enbuild.2021.110735](https://doi.org/10.1016/j.enbuild.2021.110735).
- [54] R. M. Almeida and V. P. de Freitas. “Indoor environmental quality of classrooms in Southern European climate”. In: *Energy and Buildings* 81 (Oct. 2014), pp. 127–140. doi: [10.1016/j.enbuild.2014.06.020](https://doi.org/10.1016/j.enbuild.2014.06.020).
- [55] M. Zinzi, S. Agnoli, G. Battistini, and G. Bernabini. “Deep energy retrofit of the T. M. Plauto School in Italy—A five years experience”. In: *Energy and Buildings* 126 (Aug. 15, 2016), pp. 239–251. doi: [10.1016/j.enbuild.2016.05.030](https://doi.org/10.1016/j.enbuild.2016.05.030).
- [56] P. Mocová and J. Mohelníková. “Indoor Climate Performance in a Renovated School Building”. In: *Energies* 14.10 (May 14, 2021), p. 2827. doi: [10.3390/en14102827](https://doi.org/10.3390/en14102827).

- [57] S. E. Zaeh, K. Koehler, M. N. Eakin, C. Wohn, I. Diibor, T. Eckmann, T. D. Wu, D. Clemons-Erby, C. E. Gummerson, T. Green, M. Wood, E. Majd, M. L. Stein, A. Rule, M. F. Davis, and M. C. McCormack. “Indoor Air Quality Prior to and Following School Building Renovation in a Mid-Atlantic School District”. In: *International Journal of Environmental Research and Public Health* 18.22 (Jan. 2021). Number: 22 Publisher: Multidisciplinary Digital Publishing Institute, p. 12149. doi: [10.3390/ijerph182212149](https://doi.org/10.3390/ijerph182212149).
- [58] L. Pérez-Lombard, J. Ortiz, and C. Pout. “A review on buildings energy consumption information”. In: *Energy and Buildings* 40.3 (Jan. 1, 2008), pp. 394–398. doi: [10.1016/j.enbuild.2007.03.007](https://doi.org/10.1016/j.enbuild.2007.03.007).
- [59] E. ISO. “52016-1; Energy Performance of Buildings—Energy Needs for Heating and Cooling, Internal Temperatures and Sensible and Latent Heat Loads—Part 1: Calculation Procedures”. In: *International Organization for Standardization: Geneva, Switzerland* (2017).
- [60] M. C. Peel, B. L. Finlayson, and T. A. McMahon. “Updated world map of the Köppen-Geiger climate classification”. In: *Hydrology and Earth System Sciences* 11.5 (Oct. 11, 2007). Publisher: Copernicus GmbH, pp. 1633–1644. doi: [10.5194/hess-11-1633-2007](https://doi.org/10.5194/hess-11-1633-2007).
- [61] T. Colinart, M. Bendouma, and P. Glouannec. “Building renovation with prefabricated ventilated façade element: A case study”. In: *Energy and Buildings* 186 (Mar. 2019), pp. 221–229. doi: [10.1016/j.enbuild.2019.01.033](https://doi.org/10.1016/j.enbuild.2019.01.033).
- [62] I. 7726. “Ergonomics of the Thermal Environment—Instruments for Measuring Physical Quantities (ISO 7726: 1998)”. In: (1998).
- [63] S. Chen, M. D. Levine, H. Li, P. Yowargana, and L. Xie. “Measured air tightness performance of residential buildings in North China and its influence on district space heating energy use”. In: *Energy and Buildings* 51 (Aug. 1, 2012), pp. 157–164. doi: [10.1016/j.enbuild.2012.05.004](https://doi.org/10.1016/j.enbuild.2012.05.004).
- [64] J. Lee, J. Kim, D. Song, J. Kim, and C. Jang. “Impact of external insulation and internal thermal density upon energy consumption of buildings in a temperate climate with four distinct seasons”. In: *Renewable and Sustainable Energy Reviews* 75 (Aug. 1, 2017), pp. 1081–1088. doi: [10.1016/j.rser.2016.11.087](https://doi.org/10.1016/j.rser.2016.11.087).
- [65] A. Reilly and O. Kinnane. “The impact of thermal mass on building energy consumption”. In: *Applied Energy* 198 (July 15, 2017), pp. 108–121. doi: [10.1016/j.apenergy.2017.04.024](https://doi.org/10.1016/j.apenergy.2017.04.024).
- [66] S. Somasundaram, A. Chong, Z. Wei, and S. R. Thangavelu. “Energy saving potential of low-e coating based retrofit double glazing for tropical climate”. In: *Energy and Buildings* 206 (Jan. 1, 2020), p. 109570. doi: [10.1016/j.enbuild.2019.109570](https://doi.org/10.1016/j.enbuild.2019.109570).

- [67] V. Pungercar, Q. Zhan, Y. Xiao, F. Musso, A. Dinkel, and T. Pflug. “A new retrofitting strategy for the improvement of indoor environment quality and energy efficiency in residential buildings in temperate climate using prefabricated elements”. In: *Energy and Buildings* 241 (June 2021), p. 110951. doi: [10.1016/j.enbuild.2021.110951](https://doi.org/10.1016/j.enbuild.2021.110951).
- [68] K. Kuusk, T. Kalamees, S. Link, S. Ilomets, and A. Mikola. “CASE-STUDY ANALYSIS OF CONCRETE LARGE-PANEL APARTMENT BUILDING AT PRE- AND POST LOW-BUDGET ENERGY-RENOVATION”. In: *JOURNAL OF CIVIL ENGINEERING AND MANAGEMENT* 23.1 (July 1, 2016), pp. 67–75. doi: [10.3846/13923730.2014.975741](https://doi.org/10.3846/13923730.2014.975741).
- [69] V. Földváry, G. Bekö, S. Langer, K. Arrhenius, and D. Petráš. “Effect of energy renovation on indoor air quality in multifamily residential buildings in Slovakia”. In: *Building and Environment* 122 (Sept. 2017), pp. 363–372. doi: [10.1016/j.buildenv.2017.06.009](https://doi.org/10.1016/j.buildenv.2017.06.009).
- [70] M. G. Bjørneboe, S. Svendsen, and A. Heller. “Evaluation of the renovation of a Danish single-family house based on measurements”. In: *Energy and Buildings* 150 (Sept. 2017), pp. 189–199. doi: [10.1016/j.enbuild.2017.04.050](https://doi.org/10.1016/j.enbuild.2017.04.050).
- [71] M. Gil-Baez, Á. B. Padura, and M. M. Huelva. “Passive actions in the building envelope to enhance sustainability of schools in a Mediterranean climate”. In: *Energy* 167 (Jan. 15, 2019), pp. 144–158. doi: [10.1016/j.energy.2018.10.094](https://doi.org/10.1016/j.energy.2018.10.094).
- [72] M. E. Liébana-Durán, B. Serrano-Lanzarote, and L. Ortega-Madrigal. “Identification of Cost-Optimal Measures for Energy Renovation of Thermal Envelopes in Different Types of Public School Buildings in the City of Valencia”. In: *Applied Sciences* 11.11 (Jan. 2021). Number: 11 Publisher: Multidisciplinary Digital Publishing Institute, p. 5108. doi: [10.3390/app11115108](https://doi.org/10.3390/app11115108).
- [73] K. B. Wittchen and S. Aggerholm. “Calculation of building heating demand in EPIQR”. In: *Energy and Buildings* 31.2 (Feb. 2000), pp. 137–141. doi: [10.1016/S0378-7788\(99\)00027-4](https://doi.org/10.1016/S0378-7788(99)00027-4).
- [74] P. Wargocki and N. a. F. Da Silva. “Use of visual CO2 feedback as a retrofit solution for improving classroom air quality”. In: *Indoor Air* 25.1 (2015). eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1111/ina.12119>, pp. 105–114. doi: [10.1111/ina.12119](https://doi.org/10.1111/ina.12119).
- [75] R. M. Almeida, V. P. de Freitas, and J. M. Delgado. *School Buildings Rehabilitation: Indoor Environmental Quality and Enclosure Optimization*. SpringerBriefs in Applied Sciences and Technology. Cham: Springer International Publishing, 2015. ISBN: 978-3-319-15358-2 978-3-319-15359-9. doi: [10.1007/978-3-319-15359-9](https://doi.org/10.1007/978-3-319-15359-9).

- [76] A. française de normalisation. *Norme française: NF EN 15251*. ISSN: 0335-3931. La Plaine-Saint-Denis, France: Afnor éd., 2007. 46 pp.
- [77] R. E. Stumm. “Revisiting the 1,000 ppm CO₂ Limit.” In: *ASHRAE Journal* 64.6 (2022).
- [78] A. Kassambara. *rstatix: Pipe-Friendly Framework for Basic Statistical Tests*. Version 0.7.2. Feb. 1, 2023.
- [79] W. J. Fisk. “The ventilation problem in schools: literature review”. In: *Indoor Air* 27.6 (2017), pp. 1039–1051. doi: [10.1111/ina.12403](https://doi.org/10.1111/ina.12403).
- [80] R. Maddalena, M. J. Mendell, K. Eliseeva, W. R. Chan, D. P. Sullivan, M. Russell, U. Satish, and W. J. Fisk. “Effects of ventilation rate per person and per floor area on perceived air quality, sick building syndrome symptoms, and decision-making”. In: *Indoor Air* 25.4 (2015). eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1111/ina.12149>, pp. 362–370. doi: [10.1111/ina.12149](https://doi.org/10.1111/ina.12149).
- [81] D. A. Coley and A. Beisteiner. “Carbon Dioxide Levels and Ventilation Rates in Schools”. In: *International Journal of Ventilation* 1.1 (June 2002), pp. 45–52. doi: [10.1080/14733315.2002.11683621](https://doi.org/10.1080/14733315.2002.11683621).
- [82] S. Liu, R. Li, R. J. Wild, C. Warneke, J. A. de Gouw, S. S. Brown, S. L. Miller, J. C. Luongo, J. L. Jimenez, and P. J. Ziemann. “Contribution of human-related sources to indoor volatile organic compounds in a university classroom”. In: *Indoor Air* 26.6 (2016). eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1111/ina.12272>, pp. 925–938. doi: [10.1111/ina.12272](https://doi.org/10.1111/ina.12272).
- [83] P. Wargocki and D. P. Wyon. “Ten questions concerning thermal and indoor air quality effects on the performance of office work and schoolwork”. In: *Building and Environment* 112 (Feb. 2017), pp. 359–366. doi: [10.1016/j.buildenv.2016.11.020](https://doi.org/10.1016/j.buildenv.2016.11.020).
- [84] U. Satish, M. J. Mendell, K. Shekhar, T. Hotchi, D. Sullivan, S. Streufert, and W. J. Fisk. “Is CO₂ an Indoor Pollutant? Direct Effects of Low-to-Moderate CO₂ Concentrations on Human Decision-Making Performance”. In: *Environmental Health Perspectives* 120.12 (Dec. 2012). Publisher: Environmental Health Perspectives, pp. 1671–1677. doi: [10.1289/ehp.1104789](https://doi.org/10.1289/ehp.1104789).
- [85] O. Ramalho, C. Mandin, J. Ribéron, and G. Wyart. “Air Stiffness and Air Exchange Rate in French Schools and Day-Care Centres”. In: *International Journal of Ventilation* 12.2 (Sept. 1, 2013). Publisher: Taylor & Francis eprint: <https://doi.org/10.1080/14733315.2013.11684013>, pp. 175–180. doi: [10.1080/14733315.2013.11684013](https://doi.org/10.1080/14733315.2013.11684013).
- [86] M. Santamouris, A. Synnefa, M. Assimakopoulos, I. Livada, K. Pavlou, M. Papaglastra, N. Gaitani, D. Kolokotsa, and V. Assimakopoulos. “Experimental investigation of the air flow and indoor carbon dioxide concentration in classrooms with intermittent natural ventilation”. In: *Energy and Buildings* 40.10 (Jan. 1, 2008), pp. 1833–1843. doi: [10.1016/j.enbuild.2008.04.002](https://doi.org/10.1016/j.enbuild.2008.04.002).