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# Evaluating the Feasibility of Hybrid Ventilation in Educational Spaces: A Simulation Study in the Basque Country Climate

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***Abstract* – This paper delves into the examination of indoor comfort in classroom environments and its interplay with ventilation on human wellbeing in scenarios of varying indoor carbon dioxide concentrations. The assessment of these parameters was done according to the provisions outlined in the Spanish national Regulation of Thermal Installations in Buildings (RITE). This study also compares various ventilation strategies, namely natural, mechanical and hybrid ventilation, commenting the pros and cons of each method in the climate of the Basque Country, Spain. To do so, a classroom in the School of Architecture in the Basque Country was modelled in thermal simulation software. Simulations were carried out for full days in 10-minute intervals using Design Builder and considered three different exterior scenarios (a cold day, temperate day, and a warm one) and three different ventilation systems (natural, mechanical with simple flux, and hybrid). Two additional scenarios where added for control, one with no ventilation at all and another with a partial, constant, natural ventilation, like was done during the COVID-19 pandemic. Thus, the natural ventilation option was evaluated under four conditions (windows always closed, windows constantly open 15 %, COVID-19 mode, and windows operated by thermal sensation of the user). The mechanical system evaluated consisted of a constant flux ventilation for IDA 2 IAQ with an air flux of 12.5 L/s per person. The modelled hybrid system consisted in a combination of simple flux mechanical ventilation and open windows and doors under some particular conditions. An occupancy rate of 50 % of the theoretical maximum occupancy of the classroom and a scheduled heating operation were considered. This article presents the $CO_2$ concentration, energetic balance and thermal comfort results obtained in the simulation and compares between the different scenarios. The results showed that the hybrid ventilation system was able to effectively control indoor air quality, providing a healthy and comfortable environment for occupants. The hybrid system demonstrated improved energy efficiency compared to the natural ventilation system, while maintaining an acceptable indoor air quality. Overall, the results of this study highlight the importance of considering hybrid ventilation in educational spaces in the northern Basque Country climate. The study provides valuable insights for building design and operation, especially for renovation of existing schools and educational facilities that lack any means of mechanical ventilation, showing some of the potential for hybrid ventilation to improve indoor air quality and energy efficiency.**

***Keywords* – Energy efficiency; Indoor Air Quality (IAQ); hybrid ventilation; mixed-mode buildings; thermal comfort; schools.**

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# 1. INTRODUCTION

The provision of a comfortable and conducive learning environment for students in classrooms and office workers has always been crucial for achieving good work performance and results. Maintaining an operative temperature within the range of 21–25 ºC has traditionally been associated with optimal comfort and better performance [1], [2], as the body feels at ease and can concentrate better.

In addition, one of the factors that has been overlooked in practice (although extensively studied in research) but significantly affects student performance is the concentration of $CO_2$ particles in the classroom. These particles are emitted by the students' breathing and electronic devices in the room. When their concentration exceeds 800 ppm in indoor areas, many people experience discomfort, headaches, fatigue, and general apathy, with children being more vulnerable due to their higher metabolic activity [3], [4]. This situation adversely affects both teachers and students, regardless of the temperature of the classroom. Proper ventilation is critical to reduce $CO_2$ concentration in internal spaces but can be sometimes opposite to energy efficiency [5].

Furthermore, high concentrations of particles not only affect performance but also facilitate the transmission of viruses [6]. The COVID-19 pandemic has exemplified this, as continuous indoor ventilation has been necessary to mitigate contagions [7]–[10], but this has impacted energy consumption and is especially clear in educational buildings [11] Therefore, this project aims to analyse the impact of ventilation on air quality and thermal comfort in classrooms and indoor environments. It investigates different ventilation methods and their characteristics to determine the most appropriate method for optimizing air quality and minimizing energy consumption through simulations.

The study is conducted using three characteristic days: a cold, temperate, and hot day. The temperate one coincides with the teaching period or school year, is given special attention. Using the CBE Clima Tool software [12], a graph representing the outdoor climate and comfort is obtained. Figs. 8, 9 and 10 in the Annex display the climatic characteristics of Bilbao throughout the year, which is representative of the typical climate of the Basque coast.

# 2. METHODOLOGY

To obtain and compare results, each ventilation method has several conditions. Natural ventilation evaluates the performance of indoor comfort by opening and closing windows, mechanical ventilation in relation to the power used and hybrid ventilation both to achieve a better result.

## *2.1. Description of the Case Study*

The study focuses on the School of Architecture of the UPV/EHU. The chosen classroom serves as a reference also in other study centres, since it maintains the regulations for classroom design governed by the Basque Country manual (see Fig. 1).

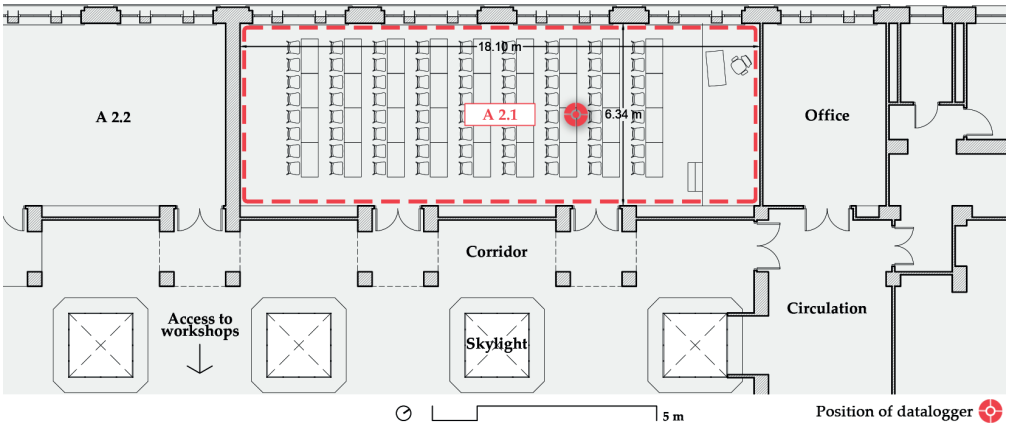



Fig. 1. Floorplan of the simulated classroom. In another study, the classroom has been monitored, with the temperature, R.H. and $CO_2$ sensor located in the indicated place as in [11].

The analysed classroom has been monitored in different periods of time. This has made it possible to observe the poor air quality in some periods. The results of these monitoring are available at [13]. The classroom has a maximum capacity of 72 students. In the COVID period a limit of 50 % occupancy was set. The maximum occupancy of the classrooms is only reached during specific periods such as exams. For this study, an occupancy of 36 students has therefore been considered. The following figure shows the simulated classroom, very similar to other classrooms in the building (see Fig. 2).

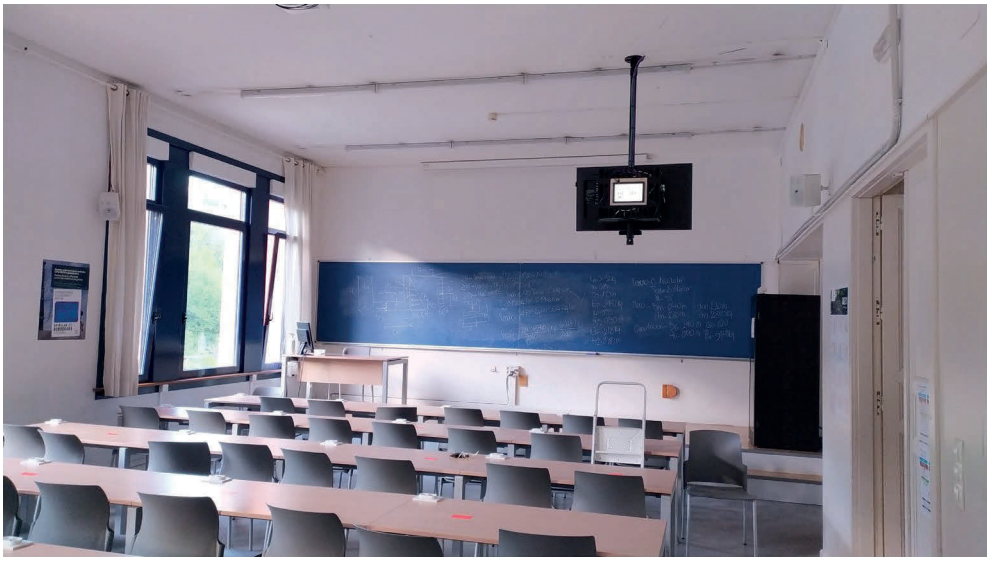


Fig. 2. Image of the simulated classroom.

The Design Builder software was used to carry out the study. Design Builder uses the EnergyPlus simulation engine, with a three-dimensional model generator. It allows a detailed evaluation of the different ventilation systems in the building to assess their impact on indoor

comfort. It calculates the energy consumption and $CO_2$ emissions of the building, for specific HVAC systems and for the use of luminaires and other equipment, as well as evaluating the thermal behaviour of a given configuration. It is worth mentioning that the program also has drawbacks when it comes to reflecting the results. As it is a simulation, there are values that are implemented directly without progress, such as the heat produced by people entering the classroom. The model is divided into two zones, the first one simulating the classroom and the second one simulating an unoccupied interior space (see Fig. 3).

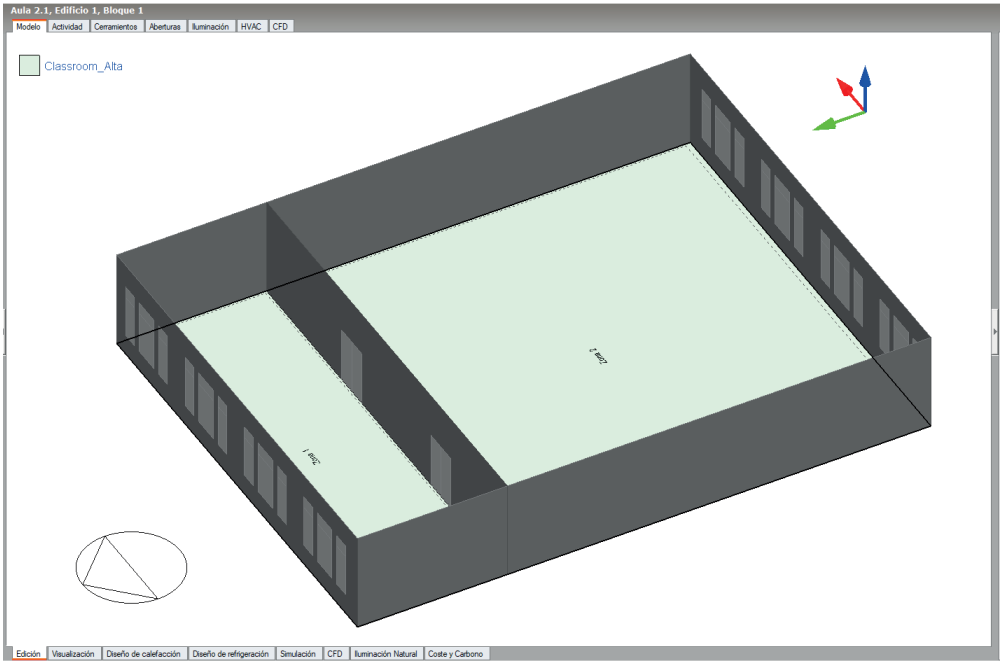



Fig. 3. Design Builder model.

In the software used, it is possible to manage variables such as occupancy, pollutant generation, environmental control and other parameters that will affect the interior conditions of the classroom. Classroom occupancy plays a key role due to the indoor gains and $CO_2$ emissions that occur in relation to this parameter. The occupancy schedule has been established for school hours from 8:30 to 14:00 and from 15:00 to 20:00, which is very common in study centres.

Three different simulation days have been chosen to represent different annual seasons: winter, spring and summer. The environmental control establishes the power set points for heating, cooling and ventilation. The hours established for these are from 8:30 to 20:00, which are the opening hours for the building choses as case study.

### *2.2. Ventilation Methods at Play*

Four cases of natural ventilation [14]–[16] are analysed: always-open windows, temperature-dependent windows, continuously closed windows and ventilation in COVID period (Table 1).

TABLE 1. DESCRIPTION OF THE VENTILATION METHODS ANALYSED

| | | | |
|---|---|---|---|
| Natural | Open windows | A percentage of window opening is established and the windows are kept open during periods of classroom occupancy | OPEN |
| | Temperature set point based | Temperature is set at 24 ºC, when the indoor air reaches this temperature, the windows are opened to allow outside air to enter | SET TEMP |
| | Closed | The windows remain closed continuously without allowing the admission of outside air | CLOSED |
| | COVID-19 | In order to renew the air inside the space and reduce the possibility of transmission, windows are programmed to be opened every hour for 10 minutes | COVID |
| Mechanical | | Mechanical ventilation is regulated at different power levels [17], [18]. Generally, when the mechanical ventilation is active, windows are not opened. An air renewal rate of 12.5 l/s per person is established in compliance with RITE | MECHANICAL |
| Hybrid | | A scenario with hybrid ventilation is recreated [19], [20]. For this, use is made of the two previous methods. The opening of the natural ventilation is maintained at 24 ºC and, in this case, the mechanical ventilation is set so that the $CO_2$ concentration does not exceed 900 ppm | HYBRID |

### *2.3. Indoor Air Quality Parameters Standards*

This study focuses on Indoor Air Quality based on three main factors, air temperature, relative humidity and $CO_2$ levels. The limit values are those regulated by the "Reglamento de Instalaciones Térmicas en los Edificios" RITE [21], the current standard in Spain for the design of educational spaces. This regulation establishes the set values for designing thermal installations in buildings In Spain, the RITE, in its 2009 update, set the air temperature of educational spaces between 23–25 ºC (summer) and between 21–23 ºC (winter) and a relative humidity of 45–60 % (summer) and 40–50 % (winter).

This study also considers the ideal temperature criteria defined by the National Institute of Occupational Safety and Health – INSHT [22]. In order to achieve a temperature with less than a 10 % margin of dissatisfaction, INSHT recommends temperatures of 23–26 °C (summer) and between 20–24 °C (winter). The relative humidity of the air should be between 30 % and 70 %.

Finally, the regulation establishes maximum $CO_2$ levels of 900 ppm for building spaces. The analysis of these three parameters will allow us to establish the IAQ differences between each ventilation system analysed (see Table 2).

TABLE 2. SUMMARY OF THE COMFORT ASSESSMENT CRITERIA OF THE SELECTED SPANISH NATIONAL STANDARDS

| **Standard** | **Operative Temperature, ºC** | **Relative humidity, %** | **$CO_2$, ppm** |
|---|---|---|---|
| RITE – Winter | 21–23 | 40–50 | 900 |
| RITE – Summer | 23–25 | 45–60 | 900 |
| INSHT – Winter | 20–24 | 30–70 | 900 |
| INSHT – Summer | 23–26 | 30–70 | 900 |

# 3. RESULTS

## *3.1. Analysis of Ventilation Systems*

First, the differences in the various natural ventilations in a tempered climate are analysed. This climate has been chosen as it gives the best insight into the performance of the four simulations (see Table 3).

TABLE 3. MEAN VALUES OF TEMPERATURE, RELATIVE HUMIDITY AND $CO_2$ FOR THE FOUR NATURAL VENTILATION CASES ANALYSED ON THE WARM REFERENCE DAY

| | **$CO_2$, ppm** | | | **Operative temperature, ºC** | | | **RH, %** | | |
|---|---|---|---|---|---|---|---|---|---|
| Natural Vent. | Average | Max | Min | Average | Max | Min | Average | Max | Min |
| Open | 509 | 621 | 400 | 19.2 | 21.3 | 17.4 | 44 | 49 | 42 |
| Close | 1229 | 2261 | 400 | 24.1 | 27.5 | 20.6 | 47 | 67 | 33 |
| COVID | 729 | 1242 | 400 | 22.2 | 25.6 | 19.0 | 41 | 47 | 37 |
| Temperature | 714 | 1471 | 400 | 22.3 | 24.2 | 19.5 | 40 | 48 | 36 |

The most remarkable row is the one with closed windows. It represents the values that a classroom can reach if there is no ventilation beyond the infiltrations that may exist. The maximum values of $CO_2$ and temperature reach 2261 ppm and 27.5 degrees, affecting the health and comfort of the occupants of the classroom if the circumstances arise, due to the high concentration of $CO_2$ particles and the high temperature reached in the classroom.

Keeping the windows open improves indoor $CO_2$ conditions, but sacrifices indoor temperature and consequently comfort.

In the latter two cases, having a regulated window opening results in a more balanced temperature and ppm concentration. The maximum $CO_2$ values exceed 900 ppm, but the average maintains adequate numbers. The following analysis compares the different climates for a window opening as a function of temperature (see Table 4).

TABLE 4. AVERAGE VALUES OF TEMPERATURE, RELATIVE HUMIDITY AND $CO_2$ OF THE TEMPERATURE DEPENDENT CASE ANALYSED ON THE REFERENCE DAYS

| | **$CO_2$, ppm** | | | **Operative temperature, ºC** | | | **RH, %** | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average | Max | Min | Average | Max | Min | Average | Max | Min |
| Cold | 1091 | 2228 | 400 | 20,0 | 23.2 | 16.4 | 35 | 49 | 27 |
| Warm | 714 | 1471 | 400 | 22,3 | 24.2 | 19.5 | 40 | 48 | 36 |
| Hot | 1079 | 2299 | 400 | 26,3 | 29.1 | 23.9 | 70 | 88 | 58 |

This table shows the limitations of natural ventilation. The opening of windows is established at 24 ºC and above. In a cold climate (winter) there is practically no opening of the windows in order not to lose heat from inside the classroom. Consequently, the $CO_2$ concentration values increase and are harmful to the health of the members of the space.

With the temperate climate (spring) the situation improves. It is more common to reach the window opening temperature, so there is a greater renewal of air in the interior space.

In hot weather (summer) a similar scenario occurs as in cold weather. Due to the high temperatures outside, the program interprets that it must close the windows to prevent heat from entering, again increasing the concentration of $CO_2$ particles.

From analysing natural ventilation, we move on to hybrid ventilation. For these simulations, a constant flow of mechanical ventilation has been established and supported by natural ventilation in order to reduce the sizing of the mechanical equipment (see Table 5).

TABLE 5. AVERAGE VALUES OF TEMPERATURE, RELATIVE HUMIDITY AND $CO_2$ OF THE HYBRID VENTILATION CASE ANALYSED ON THE REFERENCES DAYS

| | **$CO_2$, ppm** | | | **Operative temperature, ºC** | | | **RH, %** | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average | Max | Min | Average | Max | Min | Average | Max | Min |
| Cold | 775 | 1174 | 400 | 17.9 | 20.7 | 15.1 | 33 | 38 | 30 |
| Warm | 688 | 1167 | 400 | 21.7 | 24.1 | 19.1 | 41 | 45 | 38 |
| Hot | 729 | 1158 | 400 | 26.0 | 28.6 | 23.8 | 64 | 72 | 58 |

Compared to the previous table, it can be seen that the concentrations of $CO_2$ particles do not reach problematic situations thanks to mechanical ventilation. The difference is especially noticeable in cold and warm climates, where the average is 1100 ppm and the maximum is 2300 ppm, and the average is 750 ppm and the maximum is 1100 ppm. One of the aspects that has been analysed is the comparative energy consumption between the three ventilations (Table 6).

TABLE 6. COMPARATIVE ENERGY CONSUMPTION BETWEEN THE THREE VENTILATIONS ANALYSED ON THE TEMPERATE REFERENCE DAY

| | **ACH** | | | **$CO_2$ concentration, ppm** | | | **Operative temperature, ºC** | | | **Ventilation losses, Wh** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Av | Max | Min | Av | Max | Min | Av | Max | Min | Av | Max | Min |
| Natural-temperature w/ setpoint | 0 | 0 | 0 | 715 | 1471 | 400 | 22.0 | 24.1 | 18.8 | 0 | 0 | 0 |
| Hybrid | 0.99 | 1.00 | 0.97 | 686 | 1167 | 400 | 21.5 | 24.3 | 18.3 | 1308 | 1683 | 962 |
| Mechanical | 2:96 | 2.98 | 2.92 | 693 | 801 | 415 | 21.2 | 23.5 | 19.5 | 3275 | 4080 | 2125 |

In Table 6, the ventilation losses column for the automated natural ventilation with temperature set point showed 0 Wh. This is because the simulated indoor temperature on a temperate day did not exceed the 24 ºC temperature set point, thus the windows did not open.

Hybrid ventilation was established in such a way that it requires half the average energy of mechanical ventilation. Hybrid ventilation relies on natural ventilation and therefore achieves approximate $CO_2$ particle and temperature values while saving energy. It is worth mentioning that the maximum required energy values are also reduced in hybrid ventilation, resulting in smaller and less expensive equipment.

### *3.2. The influence of climate*

This subsection briefly analyses the influence of the outdoor climate of the selected reference days in the $CO_2$ concentration and comfort of a reference classroom.

First, we have the temperate climate that occurs approximately in the months of October, November, March and April. Four graphs have been generated to better visualize the results in this climate: temperature $CO_2$ evolution graph, comfort graph (temperature and relative humidity), $CO_2$ evolution and Temperature and $CO_2$ graph. For example, the following graph shows the evolution of the temperature in the analysed classroom on the warm reference day (see Fig. 4).

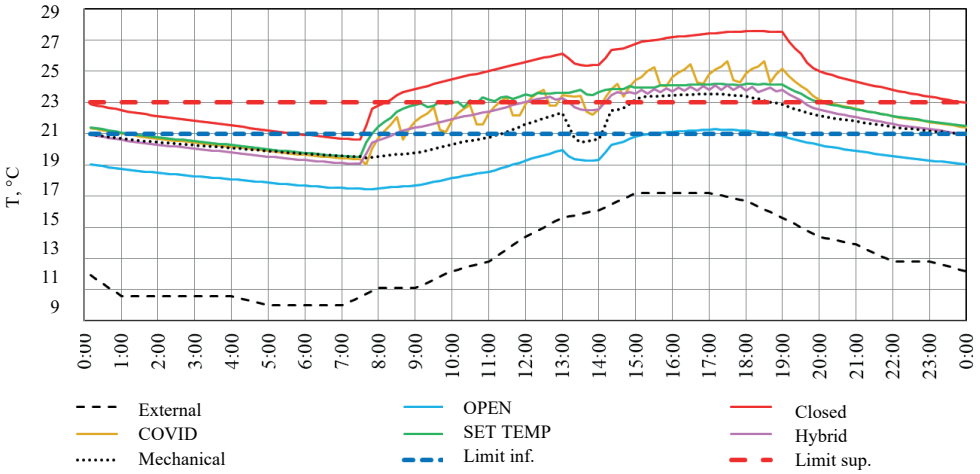



Fig. 4. Temperature evolution graph on the warm reference day.

The following graph shows the temperature and humidity pairs within the two comfort limits analysed, INSHT and RITE (see Fig. 5).

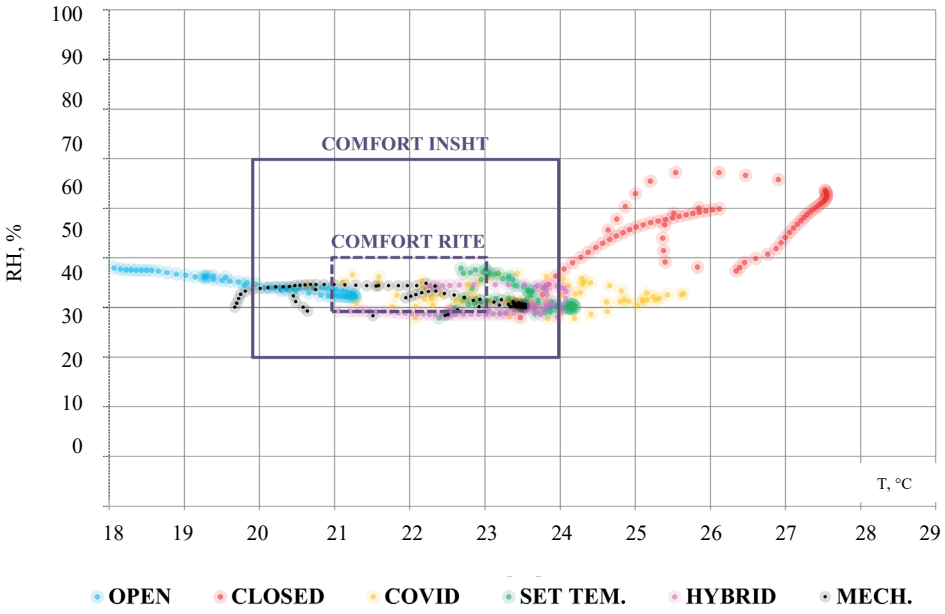



Fig. 5. Comfort graph according to RITE and INSHT limits for Temperature and Relative Humidity pairs. Only occupied hours are plotted.

As for the temperature (see Fig. 4, Fig. 5), in this case almost all systems are able to stay within comfort. The closed window system generates too high temperatures. The window temperature control system works adequately, dissipating heat at times when occupancy produces excess heat.

To complete the IAQ analysis, the $CO_2$ evolution in a school day and the Temperature and $CO_2$ pairs are shown in Fig. 6 and Fig. 7.

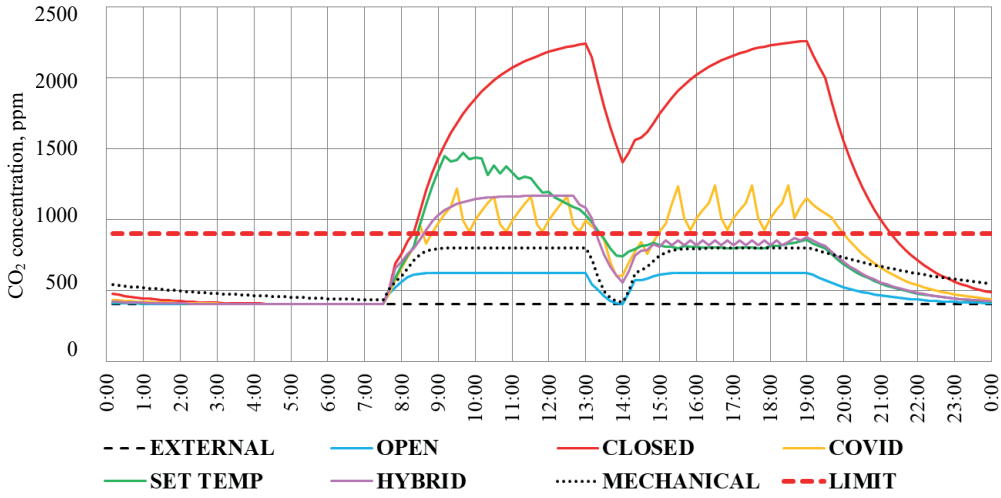



Fig. 6. Evolution of $CO_2$ concentration (ppm) on a temperate day.

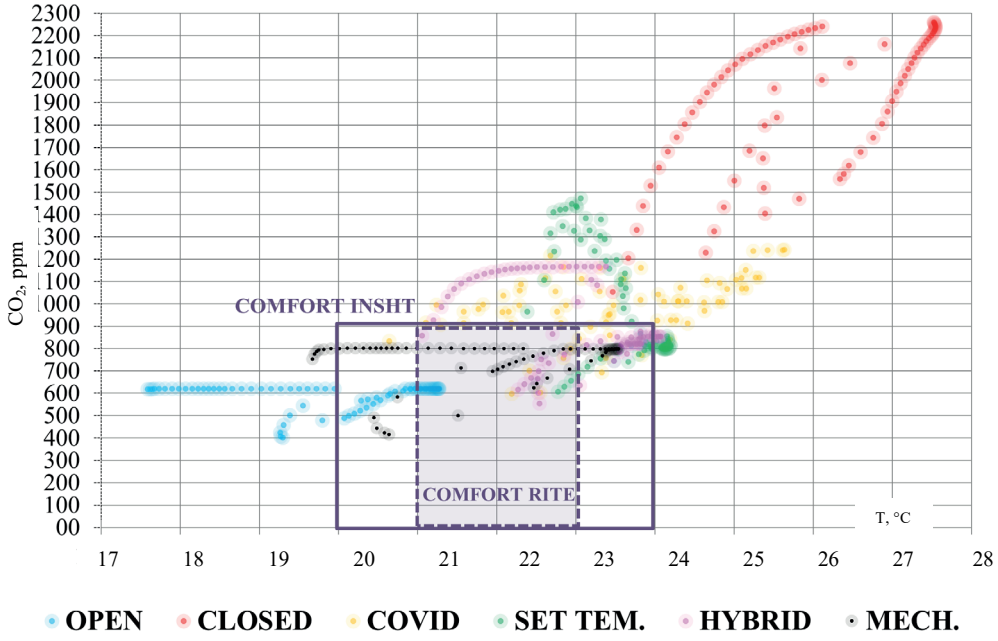



Fig. 7. $CO_2$ (ppm) and temperature (ºC) graph on a temperate day (occupied hours only).

In terms of $CO_2$ concentration (Fig. 6 and Fig. 7), the permanent open window and mechanical ventilation systems maintain adequate $CO_2$ levels below the 900-ppm threshold. The temperature-controlled and hybrid systems function properly once the classroom reaches the temperature set point (24 °C). Indoor temperature, outdoor temperature and $CO_2$. This is

a very common day profile in the climatic zone of the Basque Coast, so it is the one that could showcase the most benefits in terms of energy savings and environmental comfort. If the heating schedule were advanced or the temperature set point reduced, natural ventilation would come in earlier.

Next, in the cold climate all simulated systems have difficulty maintaining temperature inside the comfortable range except for the closed window system and the temperature window control system. Regarding $CO_2$ measurements, the permanently open window systems and the mechanical ventilation are maintained with adequate $CO_2$ levels below the normative of 900 ppm. It is observed that maintaining a high temperature leads to poor air quality, and good $CO_2$ levels lead to very low temperatures. A hybrid system in this case would serve to lower the temperature with high occupancies while mechanical ventilation takes over the rest of the time. Days with this temperature profile are rare in the Basque Coast climate zone.

Finally, in hot weather, in relation to temperature, all systems were unable to maintain comfort in the simulation. The closed window scenario resulted in excessive heat. The window temperature control system does not achieve optimal results either, and it seems that the best alternative is to keep the windows most of the time. A system with intelligent window opening would allow free-cooling during night-time, which together with the high inertia of the building of the case study (representative of common construction practice in the same period in Spain) would improve indoor comfort. Regarding $CO_2$ concentration, the scenarios that considered permanently open windows and mechanical ventilation were able to maintain adequate $CO_2$ levels below the 900 ppm threshold. Opening periods can be considered depending on the outside temperature. This is a fairly uncommon daytime profile in the climatic zone of the Basque Coast and normally not inside the school year, so it may not be a priority scenario for the design of a hybrid ventilation system.

## 4. CONCLUSION

The analysis performed in section 3 shed light into the intricacies of scheduling window opening in the way that would be required to maintain comfort levels inside the classrooms. Some additional factors make the complexity greater than the one analysed in this study, such as variable occupancy and the range of window openings (window opening is not discrete, but somehow a continuum). In addition, the analysis lets us draw the following insights and conclusions:

- An average occupancy of classrooms has been supposed for simulation, but in university spaces, the variability of occupancy can be much higher than in primary or secondary education where attendance is compulsory. This variability in occupancy entails highly variable internal occupancy loads. It is common for low occupancy to produce discomfort due to excess cold in a classroom and for high occupancy to generate the opposite effect; and, consequently, force users to open the windows, with the associated loss of energy.
- The COVID-19 epidemic has raised awareness of the need to maintain adequate IAQ. Rising energy prices have also led to a significant reduction in heating hours in order to reduce costs. At this point in time, leaving window operation entirely to users may not be the same strategy.
- Retrofitting schools and faculties with mechanical ventilation systems may be economically or architecturally unfeasible in many cases, and further development of intelligent window opening control systems can help improve the indoor environment

in university spaces, with potentially lower implementation and operation costs than mechanical ventilation systems.

– Hybrid systems (combining window opening and mechanical ventilation systems) can help make mechanical systems less costly (reduction in peak ventilation flux for mechanical ventilation systems). They can also reduce window opening time when it is not interesting from an energy efficiency standpoint and allow for some heat-recovery, combining benefits of both mechanical and natural ventilation.
– A large part of the tertiary education school term or school year corresponds to days with temperatures in the range analysed as temperate. Hybrid systems show the highest potential benefits precisely in these temperate periods of the year.

Overall, this study highlights the importance of considering different ventilation options in educational spaces to ensure a healthy and comfortable environment for occupants. The results can be useful for building designers, engineers, and facility managers in selecting the most appropriate ventilation system for new construction or retrofitting existing buildings.

The hybrid ventilation system, which combined mechanical ventilation with natural ventilation through open windows and doors, proved to be an effective way to control indoor air quality and maintain thermal comfort, as a compromise between fully natural or mechanical ventilation. It was able to improve IAQ while providing an acceptable thermal environment for occupants while reducing energy loss.

Future research could investigate hybrid ventilation performance in various types of buildings, occupancy levels, and user behaviour's impact on ventilation systems' effectiveness. Evaluating hybrid ventilation's long-term maintenance and energy consumption can help identify barriers to widespread implementation. Furthermore, examining renewable energy sources' incorporation, such as solar power or pre-heating [23], [24], into hybrid ventilation systems can improve energy efficiency and environmental sustainability while providing comfortable indoor environments. These studies could refine and optimize hybrid ventilation, facilitate its wider adoption in buildings, and help building owners and facility managers make informed decisions.

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## ANNEX

The reference climates used were those obtained for the city of Bilbao from the EPW climate file downloaded at the repository of free climate data for building performance simulation (https://climate.onebuilding.org/).

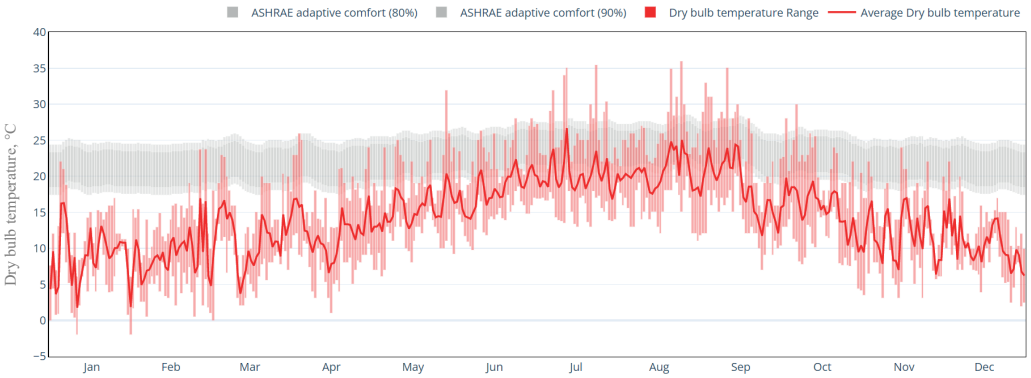



Fig. 8. Daily chart Temperature and Humidity evolution graph.

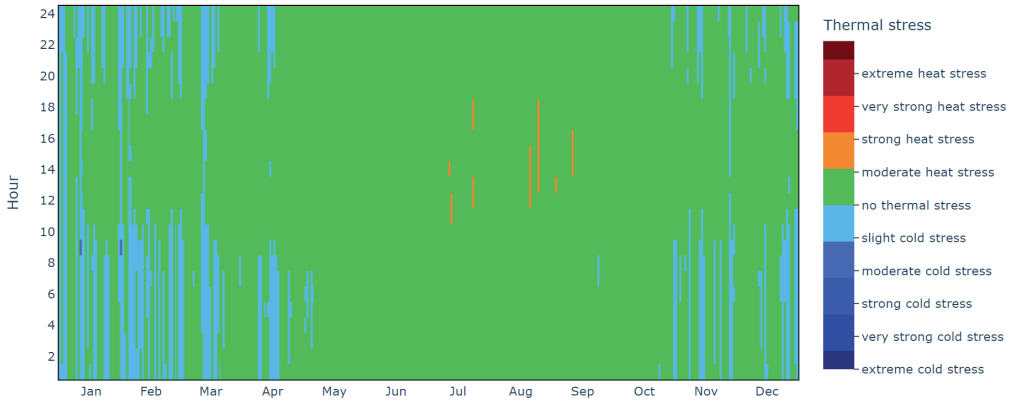



Fig. 9. Outdoor comfort with no wind and no direct solar radiation. Year-round thermal stress. The green area indicates adequate comfort that there is no thermal stress.

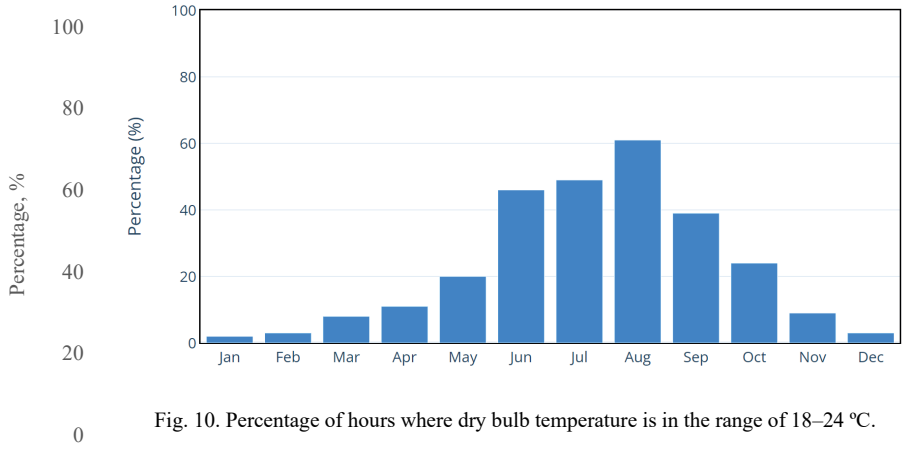



Fig. 10. Percentage of hours where dry bulb temperature is in the range of 18–24 ºC.