Analysis and influence on hygrothermal comfort and ventilation in educational centres in the Basque Country.

DOCTORAL THESIS
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SUMMARY

Spanish

En las últimas décadas múltiples investigaciones han evaluado el confort alcanzado en el interior de edificios midiendo diferentes condiciones ambientales. Estas condiciones se denomina calidad ambiental interior, en inglés Indoor Environmental Quality (IEQ), la cual agrupa el confort térmico, la calidad del aire interior, la iluminación y el confort acústico. Y pese a que la ventilación no es un factor que determina la IEQ, tiene un impacto directo en las condiciones que alcanzan la IAQ y el confort térmico.

Investigaciones previas sobre IEQ se centran principalmente en oficinas y edificios residenciales, con menos estudios en centros educativos. Los colegios son espacios especialmente vulnerables debido a la edad de sus ocupantes, que se encuentran en pleno desarrollo y donde una mala IEQ puede afectar su salud y rendimiento académico. Además, la densidad de ocupación en los colegios es mayor que en otros tipos de edificios, como las oficinas.

Por lo tanto, es fundamental garantizar una adecuada IEQ en estos centros. Los parámetros más estudiados en investigaciones previas son el confort térmico y la ventilación. Existen múltiples modelos que definen el confort térmico, modelo adaptativo o balance energético. Asimismo, es importante asegurar una ventilación adecuada en el interior, utilizando diferentes métodos para evaluarla, la percepción de los ocupantes, la concentración de gases o ratios de ventilación. En cuanto a la medición de estos modelos, se pueden utilizar diferentes metodologías, como encuestas, monitorización o simulaciones.

Tras revisar la literatura relevante de los últimos años, se ha analizado qué se ha investigado, cómo se ha medido y qué características constructivas se consideran relevantes para alcanzar el confort. Se ha identificado la influencia del clima, la relación ventana-fachada (WWR), área de ventana respecto a la superficie del aula (DF), transmitancia térmica de los cerramientos, orientación, planta, sistemas de sombreado, instalaciones de climatización, tipología del aula, el sistema de ventilación y la edad de los ocupantes. Se han identificado múltiples argumentos y debates sobre la influencia de estos factores en el confort térmico y la percepción de los ocupantes.

Además de las características constructivas, también se ha investigado el comportamiento y la capacidad de adaptación de los ocupantes, así como el contexto en el que se han realizado las mediciones. En el caso de esta investigación, se llevó a cabo durante la pandemia de COVID-19, lo que implicó la implementación de ciertos protocolos de ventilación y cambios en el comportamiento de los ocupantes.

Una vez realizado este análisis de la literatura previa, surgieron nuevas preguntas y debates. El objetivo principal de esta tesis es responder a estas preguntas en el contexto de los centros educativos en el País Vasco:

¿Cómo son los centros educativos en el País Vasco? ¿Qué características constructivas y de funcionamiento los hacen únicos?

¿Qué nivel de confort higrotérmico y ventilación se está alcanzando en estos centros? ¿Se encuentra dentro de los límites establecidos?

¿Qué características tienen un impacto en el confort alcanzado? ¿En qué medida influyen? En particular, se busca investigar si el sistema de ventilación influye en el confort en las aulas, dado el debate existente en la literatura previa.

Para lograr este objetivo principal, se plantean siete objetivos parciales. En primer lugar, la selección de los casos de estudio en función de las características, necesidades y limitaciones de los centros educativos en el País Vasco, prestando especial atención al sistema de ventilación. En segundo lugar, la caracterización de los casos de estudio, analizando las características identificadas como relevantes para el confort térmico y la ventilación. En tercer lugar, la aplicación de un protocolo de monitorización en los tres casos de estudio, considerando las diferentes fases de ocupación y teniendo en cuenta las limitaciones del uso de cada aula. En cuarto lugar, la aplicación de este protocolo en las aulas seleccionadas en cada caso de estudio, obteniendo las condiciones ambientales durante las diferentes fases de ocupación. En quinto lugar, se establecer un único criterio de confort higrotérmico y ventilación para todas las aulas durante los periodos ocupados. En sexto lugar, analizar las condiciones alcanzadas en cada aula e identificar fortalezas y vulnerabilidades comparando el confort en cada una. Por último, cuantificar el impacto de las características significativas en el confort térmico mediante diferentes pruebas estadísticas.

Para lograr estos objetivos, se ha desarrollado una metodología dividida en tres fases, que se ha aplicado en tres casos de estudio.

En la primera fase, se han caracterizado los tres casos de estudio seleccionados, teniendo en cuenta las características identificadas en la literatura previa como relevantes para el confort higrotérmico y la ventilación en las aulas, a nivel de edificio, aula y comportamiento de los ocupantes. Esto ha permitido obtener una diversidad de características en las aulas, facilitando el análisis del impacto de diferentes características en el confort.

En la segunda fase, se ha diseñado un protocolo de monitorización de los casos de estudio. El protocolo ha tenido en cuenta las diferentes fases de ocupación y las limitaciones del uso de las aulas. Aplicando este protocolo en las aulas seleccionadas de cada caso de estudio, registrando las condiciones ambientales durante las diferentes fases de ocupación.

En la tercera fase, se ha establecido un criterio único de confort y ventilación para todas las aulas durante los periodos ocupados. Analizando las condiciones ambientales alcanzadas en cada aula durante las diferentes fases de ocupación comparando el nivel de confort en cada una e identificando las fortalezas y vulnerabilidades. Además, se ha realizado un análisis estadístico para cuantificar el impacto de las características significativas en el confort térmico.

Una vez analizados los principales resultados obtenidos tras la aplicación de la metodología en los tres casos de estudio, se han comparado con los resultados obtenidos en investigaciones previas. Estos resultados se han agrupado según los diferentes argumentos y debates identificados en la literatura previa.

En primer lugar, en cuanto al confort alcanzado en comparación con investigaciones anteriores, se han obtenido condiciones ambientales similares a las de otros estudios en términos de temperatura y humedad relativa. Sin embargo, se han logrado mejores valores de concentración de CO_2 que en otros estudios. En general, se observa un mayor confort en verano que en invierno para todas las aulas.

Es importante tener en cuenta que el criterio seleccionado para evaluar el confort presenta múltiples limitaciones, ya que cada norma o estándar tiene diferentes criterios que afectan la interpretación de los resultados obtenidos en la monitorización. Por lo tanto, se ha analizado la variación que supondría aplicar otros estándares a este caso de estudio, como el Reglamento de Instalaciones Térmicas en los Edificios (RITE), modelos no adaptativos de la UNE-EN 16798 o las recomendaciones de protocolo COVID del Gobierno Vasco. Se observa que, al aplicar estos estándares alternativos, el nivel de confort alcanzado se reduce drásticamente, especialmente en términos de temperatura y concentración de CO_2.

En cuanto al análisis de las características que influyen en el confort, se ha determinado que ninguna de ellas ha tenido una influencia estadísticamente significativa en verano. Sin embargo, durante el invierno, la temperatura ha sido el factor más influido. Cabe destacar que la concentración de CO_2 no ha sido afectada por el sistema de ventilación, encontrándose únicamente una relación estadísticamente significativa en la planta entre la que se ubica el aula y la concentración de CO_2.

En segundo lugar, se ha evaluado el impacto del sistema de ventilación en el confort. En la literatura previa, se han identificado limitaciones y fortalezas tanto para los sistemas de ventilación mecánica como para la ventilación natural. Los sistemas de ventilación mecánica presentan un alto consumo energético y pueden generar disconfort localizado, pero ofrecen una mayor eficiencia energética y un mayor control de las condiciones ambientales. Por otro lado, la ventilación natural depende de las condiciones ambientales exteriores y no permite un control preciso de las condiciones interiores, pero aprovecha los recursos existentes, reduciendo el consumo energético y tiene un mayor rango de aceptación del confort. Aunque múltiples investigaciones han demostrado que la ventilación mecánica mejora las condiciones ambientales y el confort en las aulas, no ha sido el caso en este estudio. Otros autores también han argumentado que la ventilación natural es suficiente en este clima y que también se puede lograr un buen confort en los centros educativos. En caso de detectar ciertas vulnerabilidades o períodos en los que no se pueda garantizar el confort, se recomienda optar por un sistema híbrido con control bajo demanda como apoyo a la ventilación natural, ya que este sistema logra el mejor equilibrio entre consumo energético y confort.

Además se ha observado el impacto y la mejora que tiene ventilar durante los descansos en las condiciones ambientales interiores, reduciendo la elevada concentración de CO_2 que puede producirse durante los períodos de ocupación, logrando un mejor confort térmico.

Finalmente, se ha evaluado el impacto que tiene la adaptación de los ocupantes y el contexto en el que se realizan las mediciones. Durante el período de monitorización, el protocolo COVID ha influido en el cambio del comportamiento habitual de los ocupantes. Especialmente durante el invierno, donde el comportamiento habitual es priorizar el confort térmico en lugar de la ventilación, este protocolo insta a priorizar la ventilación por encima del confort térmico. En cada centro educativo estudiado, el protocolo COVID aplicado ha sido más o menos exigente según el sistema de ventilación presente, lo que ha influido en los valores de confort alcanzados. Se ha observado que no se ha sacrificado el confort térmico para obtener una mejor ventilación, y se ha detectado que aquellas aulas que han priorizado el confort térmico durante el invierno suelen tener un peor equilibrio en el confort alcanzado en comparación con aquellas que sí han seguido el protocolo COVID. En comparación con los protocolos COVID de otros países, las recomendaciones del gobierno vasco han sido más exigentes.

Otro factor analizado ha sido la capacidad de adaptación de los ocupantes, la cual también influye en el confort. Investigaciones previas han detectado una discrepancia en la percepción del confort térmico entre las edades de los estudiantes y el profesorado. En aquellas aulas donde los ocupantes tienen una mayor capacidad para cambiar las condiciones de su entorno, se alcanza un mayor confort. En este contexto, otro factor influyente en la capacidad de adaptación de los ocupantes es la monitorización en vivo. Investigaciones anteriores han demostrado que cuando los ocupantes pueden visualizar las condiciones ambientales en el interior mediante la monitorización, tienden a realizar más cambios en su entorno para lograr una mejor ventilación y confort térmico.

Las principales conclusiones obtenidas a lo largo de esta investigación se han agrupado en cuatro temas principales, que se han tratado a lo largo del desarrollo de esta tesis.

En primer lugar, en cuanto al confort, se ha observado que, en promedio, se alcanza un mayor confort en verano que en invierno. En general, se logra un buen nivel de confort, excepto en los gimnasios durante el invierno, donde se registran temperaturas muy bajas. También se ha identificado un ligero sobrecalentamiento en algunas aulas durante el invierno y en otras durante el verano. La humedad relativa no ha sido una limitación importante para alcanzar el confort higrotérmico. Sin embargo, al comparar los resultados con otros estándares o normas, se observan grandes limitaciones para lograr el confort.

En segundo lugar, se ha evaluado la influencia de las características constructivas en el confort. Se ha determinado que las características constructivas solo han tenido una influencia estadísticamente significativa en invierno, mientras que en verano no se ha encontrado ninguna. Esto indica que el confort alcanzado en verano en todas las aulas es generalizado y que el diseño de los centros educativos, influenciado por el clima, permite alcanzar este nivel de confort.

En tercer lugar, se ha observado que el sistema de ventilación no ha tenido un impacto estadísticamente significativo en el confort. Esto contradice con algunas investigaciones anteriores que han demostrado mejoras en el confort higrotérmico y la ventilación en las aulas al introducir sistemas de ventilación mecánica a aulas que ventilaban de manera natural. En este estudio, se ha logrado un buen confort independientemente del sistema de ventilación utilizado.

Teniendo en cuenta las oportunidades y limitaciones de la ventilación natural, se concluye que es suficiente para este clima para alcanzar el confort, siempre y cuando se preste atención a la ventilación durante los descansos y la ventilación nocturna. Cuando solo se utilice la ventilación natural y no se pueda lograr el confort deseado, se recomienda optar por sistemas híbridos con control bajo demanda como apoyo a la ventilación natural.

Por último, se ha aplicado el modelo de confort adaptativo, que tiene en cuenta la capacidad de los ocupantes para alcanzar el confort. Es relevante dar la oportunidad a los ocupantes de adaptar su entorno para lograr un mejor confort, mediante ventanas de fácil apertura y un control descentralizado.

Con estas conclusiones, se sugiere la implementación de sistemas de monitorización y visualización en vivo para que los ocupantes puedan tomar decisiones informadas y lograr un mayor confort en las aulas.

Finalmente, se han identificado varias limitaciones que afectan la interpretación de los resultados. Muchas de estas limitaciones se presentan como oportunidades para futuras investigaciones, ya que permitan continuar esta investigación y ampliar las preguntas y nuevas hipótesis surgidas durante su desarrollo.

English

Multiple research studies have evaluated indoor comfort in the last decades by measuring different environmental conditions. These conditions are called Indoor Environmental Quality (IEQ), which groups together thermal comfort, indoor air quality, lighting and acoustic comfort. Although ventilation does not determine IEQ, it directly impacts the conditions that achieve IAQ and thermal comfort.

IEQ research has focused mainly on offices and residential buildings, with less research on schools. Schools are particularly vulnerable due to the age of their occupants, who are still in development age and where poor IEQ can affect their health and academic performance. In addition, occupancy density in schools is higher than in other building types, such as offices.

It is, therefore, essential to ensure adequate IEQ in these centres. The parameters most studied in previous research are thermal comfort and ventilation. Multiple models define thermal comfort, the adaptive model or the heat balance. It is also significant to ensure adequate indoor ventilation, using different methods to assess ventilation, occupant perception, gas concentration, or ventilation ratios. As for the measurement of these models, different methodologies can be used, such as surveys, monitoring or simulations.

After reviewing the relevant literature of recent years, what has been researched, how it has been measured, and what building features are considered relevant to achieving comfort have been analysed. Identifying the influence of climate, window-to-wall ratio (WWR), window area and classroom surface area (DF), thermal transmittance of envelopes, orientation, floor plan, shading systems, air conditioning installations, classroom typology, the ventilation system and the age of the occupants. Multiple arguments and debates have been acknowledged on the influence of these factors on thermal comfort and occupant perception.

In addition to the construction characteristics, the behaviour and adaptive capacity of the occupants have also been investigated, as well as the context in which the measurements were taken. This research was carried out during the COVID-19 pandemic, which involved the implementation of specific ventilation protocols and changes in occupant behaviour.

Once this analysis of previous literature had been carried out, new questions and debates arose. The main objective of this thesis is to answer these questions in the context of schools in the Basque Country:

What are the educational centres in the Basque Country like, and what are their construction and operation characteristics that make them unique?

What hygrothermal comfort and ventilation level is achieved in these centres, and is it within the established limits?

Which features impact the comfort achieved, and to what extent do they influence it? In particular, given the debate in previous literature, seeking to investigate whether the ventilation system influences classroom comfort.

In order to achieve this main objective, seven partial objectives are proposed. Firstly, the case studies were selected according to the characteristics, needs, and limitations of the educational centres in the Basque Country, paying particular attention to the ventilation system. Secondly, the characterisation of the case studies, analysing the characteristics identified as relevant for thermal comfort and ventilation. Thirdly, a monitoring protocol was applied in the three case studies, considering the different occupancy phases and the limitations of using each classroom. Fourthly, this protocol will be applied in the selected classrooms in each case study, obtaining the environmental conditions during the different occupancy phases. Fifthly, to establish a single criterion of hygrothermal comfort and ventilation for all classrooms during the occupied periods. Sixth, analyse the conditions achieved in each classroom and identify strengths and vulnerabilities by comparing the comfort in each. Finally, quantify the impact of significant features on thermal comfort using different statistical tests.

A three-phase methodology has been developed and applied to three case studies to achieve these objectives.

In the first phase, the three selected case studies were characterised, considering the characteristics identified in previous literature as relevant for hygrothermal comfort and ventilation in classrooms, at the level of building, classroom and occupant behaviour. This selection allowed a diversity of classroom characteristics to be obtained, facilitating the analysis of the impact of different characteristics on comfort.

In the second phase, a protocol for monitoring the case studies was designed. The protocol considered the different phases of occupation and the limitations of using the classrooms. This protocol was applied in the selected classrooms of each case study, recording the environmental conditions during the different phases of occupation.

In the third phase, a single comfort and ventilation criterion was established for all classrooms during the occupied periods. The level of comfort in each classroom was compared by analysing the conditions achieved in each classroom during the different occupation phases and identifying strengths and vulnerabilities. In addition, a statistical analysis was carried out to quantify the impact of significant features on thermal comfort.

Once the main results obtained after applying the methodology in the three case studies have been analysed, they have been compared with those obtained in previous research. These results have been grouped according to the different arguments and debates in the previous literature.

Firstly, in terms of the comfort achieved compared to previous research, similar environmental conditions have been obtained in terms of temperature and relative humidity as in other studies. However, better values of CO_2 concentration have been achieved than in other studies. In general, a higher comfort is observed in summer than in winter for all classrooms.

Significantly, the criterion selected to evaluate comfort has multiple limitations, as each standard has different criteria that affect the interpretation of the results obtained in the monitoring. Therefore, was analysed the variation of applying other standards to this case study, such as Regulation on Thermal Installations in Buildings (RTIB), non-adaptive models of UNE-EN 16798 or the COVID protocol recommendations of the Basque Government. It is observed that, when applying these alternative standards, the comfort level achieved is drastically reduced, especially in terms of temperature and CO_2 concentration.

In terms of the analysis of the characteristics influencing comfort, it was determined that none of them had a statistically significant influence in summer. However, during the winter, temperature was the most influential factor. It should be noted that the concentration of CO_2 was not affected by the ventilation system, with a statistically significant relationship being found only between the floor on which the classroom is located and the concentration of CO_2.

Secondly, the impact of the ventilation system on comfort has been assessed. In previous literature, limitations and strengths have been identified for mechanical and natural ventilation systems. Mechanical ventilation systems have high energy consumption and can generate localised discomfort but offer higher energy efficiency and greater control of ambient conditions. On the other hand, natural ventilation relies on outdoor environmental conditions and does not allow precise control of indoor conditions, but it uses existing resources, reduces energy consumption, and has a broader range of acceptance of comfort. Although multiple research has shown that mechanical ventilation improves environmental conditions and comfort in classrooms, this was not the case in this study. Other authors have also argued that natural ventilation is sufficient in this climate and that good comfort can be achieved in schools. In case of detecting vulnerabilities or periods where comfort cannot be guaranteed, opting for a hybrid system with on-demand control to support natural ventilation is recommended, as this system achieves the best balance between energy consumption and comfort.

The impact and improvement of ventilation during breaks in indoor environmental conditions has also been observed, reducing the high concentration of CO_2 that can occur during periods of occupancy and achieving better thermal comfort.

Finally, the impact of occupant adaptation and the context in which the measurements are taken have been assessed. During the monitoring period, the COVID protocol has influenced the occupants' usual behaviour change. Especially during winter, where the usual behaviour is to prioritise thermal comfort over ventilation, this protocol urges prioritising ventilation over thermal comfort. The COVID protocol was more or less demanding in each school studied, depending on the ventilation system, influencing the comfort values achieved. It has been observed that thermal comfort has not been sacrificed to obtain better ventilation, and it has been detected that those classrooms that have prioritised thermal comfort during the winter tend to have a worse balance in the comfort achieved compared to those that have followed the COVID protocol. The Basque government's recommendations have been more demanding than other countries' COVID protocols.

In addition, the adaptability of the occupants has also been found to influence comfort. A discrepancy in thermal comfort perception was found between the ages of students and teachers. In classrooms where the occupants have a more remarkable ability to change the conditions of their environment, greater comfort is achieved. In this context, live monitoring is another factor influencing the adaptability of occupants. Previous research has shown that when occupants can visualise indoor environmental conditions through monitoring, they tend to make more environmental changes to achieve better ventilation and thermal comfort.

The main conclusions drawn throughout this research have been grouped into four main themes, which have been addressed throughout the development of this thesis.

Firstly, it has been observed that, on average, more comfort is achieved in summer than in winter. Generally, a good comfort level is achieved, except in the gymnasiums during the winter, where very low temperatures are recorded. Slight overheating has also been identified in some classrooms during the winter and others during the summer. Relative humidity was not a significant constraint in achieving hygrothermal comfort. However, when comparing the results with other standards or norms, significant limitations exist in achieving comfort.

Secondly, the influence of construction characteristics on comfort was evaluated. It was found that the construction features only had a statistically significant influence in winter, while none was found in summer; this indicates that the comfort achieved in summer in all classrooms is generalised and that the design of the schools, influenced by the climate, allows this level of comfort to be achieved.

Thirdly, it was observed that the ventilation system did not have a statistically significant impact on comfort; this contradicts previous research that had shown improvements in hygrothermal comfort and ventilation in classrooms when mechanical ventilation systems were introduced to naturally ventilated classrooms. This study achieved good comfort regardless of the ventilation system used.

Considering the opportunities and limitations of natural ventilation, it is concluded that it is sufficient for this climate to achieve comfort, provided that attention is paid to ventilation during breaks and night ventilation. When only natural ventilation is used, and the desired comfort cannot be achieved, it is recommended to opt for hybrid systems with on-demand control to support natural ventilation.

Finally, the adaptive comfort model, which considers the occupants' ability to achieve comfort, has been applied. It is essential to allow occupants to adapt their environment to achieve better comfort through easy-to-open windows and decentralised control.

With these findings, it is suggested that live monitoring and visualisation systems be implemented to enable occupants to make informed decisions and achieve greater comfort in classrooms.

Finally, several limitations have been identified that affect the interpretation of the results. Many of these limitations are presented as opportunities for future research, as they would allow for the continuation of this research and the extension of the questions and new hypotheses that emerged during its development.

NOMENCLATURE

BC	Basque Country
ICBSE	Chartered Institution of Building Services
Cor	Correlation
DF	Daylight Factor
RH	Relative Humidity
HVAC	Heating, Ventilating and Air Conditioning
IAQ	Indoor Air Quality / Indoor Air Quality
IEQ	Indoor Environmental Quality
NV	Natural Ventilation
MC	Mechanical Cooling
MV	Mechanical Ventilation
OD	Occupation Density
PMV	Predictive Mean Vote
PPD	Predicted Percentage Of Dissatisfied
SBS	Sick Building Syndrome
T	Temperature
TBC	Technical Building Code
RTIB	Regulation on Thermal Installations in Buildings
WWR	Window-to-Wall Ratio
WHO	World Health Organization

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1 INTRODUCTION

In recent years, there has been a significant increase in the amount of time we spend indoors compared to outdoors, reaching more than 80% of the time spent indoors [1], [2]. In the case of children, schools are the second place where they spend the most time after their homes [2].

In addition, schools are vulnerable spaces mainly because of two factors: first, because of the low age of their occupants, who are still at a developmental age. Second, because of school occupancy, not only do they have longer hours of occupation, but also the occupancy density is higher [2], especially in the classrooms, which is higher than in other buildings such as offices.

Being schools more vulnerable spaces is important to ensure proper Indoor Environmental Quality (IEQ), which has an impact on the health of the occupants [3] and the performance of both students and teachers [4]–[7].

IEQ consists of the combination of factors inside the building that guarantee comfort conditions [8]. These factors are grouped into thermal comfort, indoor air quality, acoustic comfort and visual comfort.

Within the extensive literature that has analysed IEQ in educational centres, there are two critical aspects on which most studies have focused: thermal comfort and ventilation; both impact people’s perception and health and are easy to measure.

Over the last decade, multiple literature reviews have been published focusing on thermal comfort and ventilation in educational centres [2], [4], [9]–[11]. These reviews analyse previous research's objectives and most relevant aspects, such as what comfort is achieved and perceived.

Both standards and some of the literature that focuses on schools establish a relationship between the ventilation system and thermal comfort, not only in the perceived comfort of the occupants but also in the difference in ranges considered comfortable.

In this context, there is a debate on improving comfort conditions depending on the ventilation system. While some achieve better results with mechanical ventilation systems than with natural ventilation [12], [13], some have found that mechanical ventilation systems are more efficient than natural ventilation. Other studies with natural ventilation achieve better results than those with mechanical ventilation [2] or good enough conditions that insertion of mechanical systems is not necessary [14], [15].

Apart from the ventilation system, different construction features have been identified in the literature as impacting comfort. Some examples are the orientation [2], [11], the surface area of the windows [16], [17] or shading systems [18], among many other characteristics analysed.

Taking up these discrepancies and influences found in previous research, which impact thermal comfort and ventilation in schools, this thesis focuses on the context of the Basque Country. The aim is to analyse what hygrothermal comfort and ventilation are achieved in multiple educational centres and to evaluate which factors impact this comfort.

In order to achieve this objective, a methodology based on three phases is used to characterise, monitor and evaluate the hygrothermal comfort and ventilation in three case studies located in Vitoria-Gasteiz during two monitoring campaigns. After applying the methodology, the results are analysed, and the relevant statistical analyses are applied, detecting possible strengths and vulnerabilities in the classrooms.

This thesis analyses what conditions are being met and what factors influence the achievement of this comfort. Contextualizing in the Basque Country, the debate generated in previous literature, what factors must be considered to achieve better comfort in schools, and the current detection of possible vulnerabilities.

The development of this thesis consists of six chapters in addition to the necessary annexes to achieve the main objective of this thesis, which is to analyse the hygrothermal comfort and ventilation in educational centres in the Basque Country, summarised in Figure 1-1.

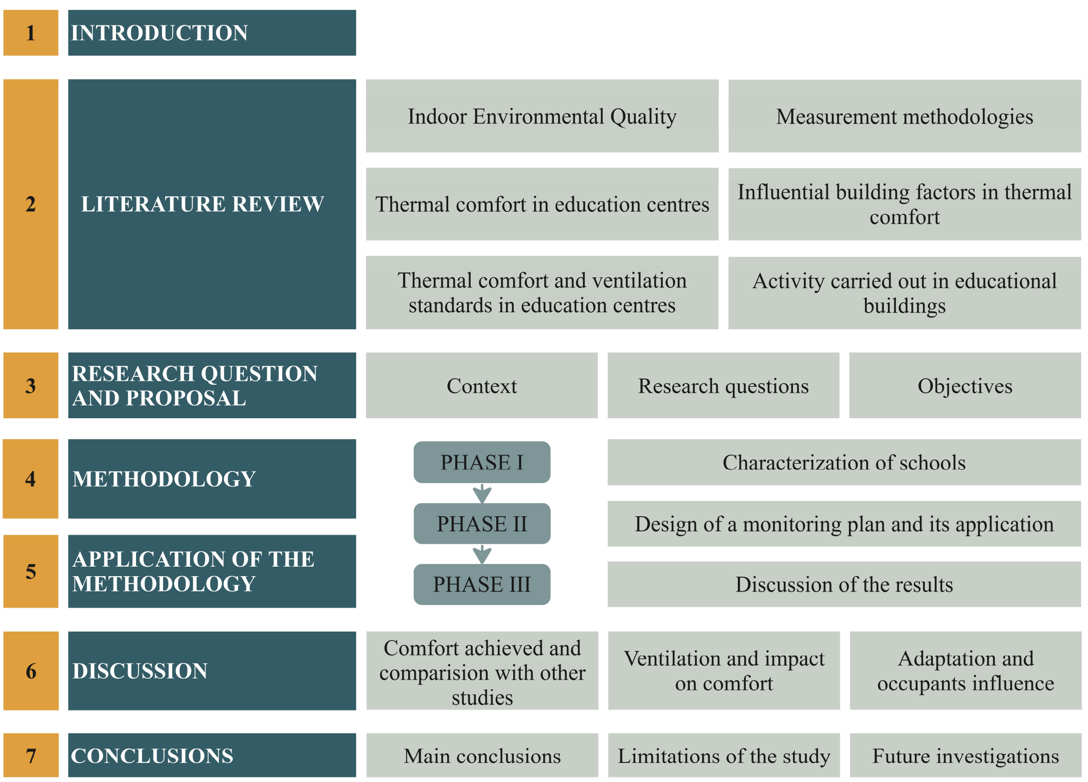


Figure 1-1. Structure followed in the thesis

First, the most significant previous literature has been analysed, contextualising the most influential concepts and standards that limit thermal comfort and ventilation. It has been selected the most relevant reviews and analysed recent research studies on thermal comfort and ventilation in educational centres.

Second, after analysing the literature, research questions and objectives that will give shape and context to the development of the thesis have been proposed.

Third, a methodology divided into three phases has been proposed, which responds to the previously stated objectives based on the characterisation, monitoring and analysis of these results in different statistical forms.

Fourth, after selecting the three case studies in the Basque Country, where this methodology is applied, the main results of this research have been obtained.

Fifth, the main arguments developed in this thesis have been compared with previous research, and the most relevant results have been discussed.

Finally, after comparing and interpreting the results, these arguments have reached the main conclusions. The different limitations detected in the development of the investigation are also presented. Similarly, the questions that have been arising as future research are presented, which complement the current research and the hypotheses put forward, and their answers give rise to the continuation of this research in the future.

2 LITERATURE REVIEW

Analysing previous literature, it has been found that there are multiple investigations to assess thermal comfort in educational centres. These investigations have used different methods and measured different factors. In order to have a broader view before setting out the objectives of the thesis, an analysis of the literature is made. It is divided into three parts (Figure 2-1). First, is defined what thermal comfort is and which models or standards limit and define it. Second, the most commonly used methodologies for assessing thermal comfort are presented. Finally, those factors that, according to the previous literature, have an impact on thermal comfort will be introduced and evaluated their impact.

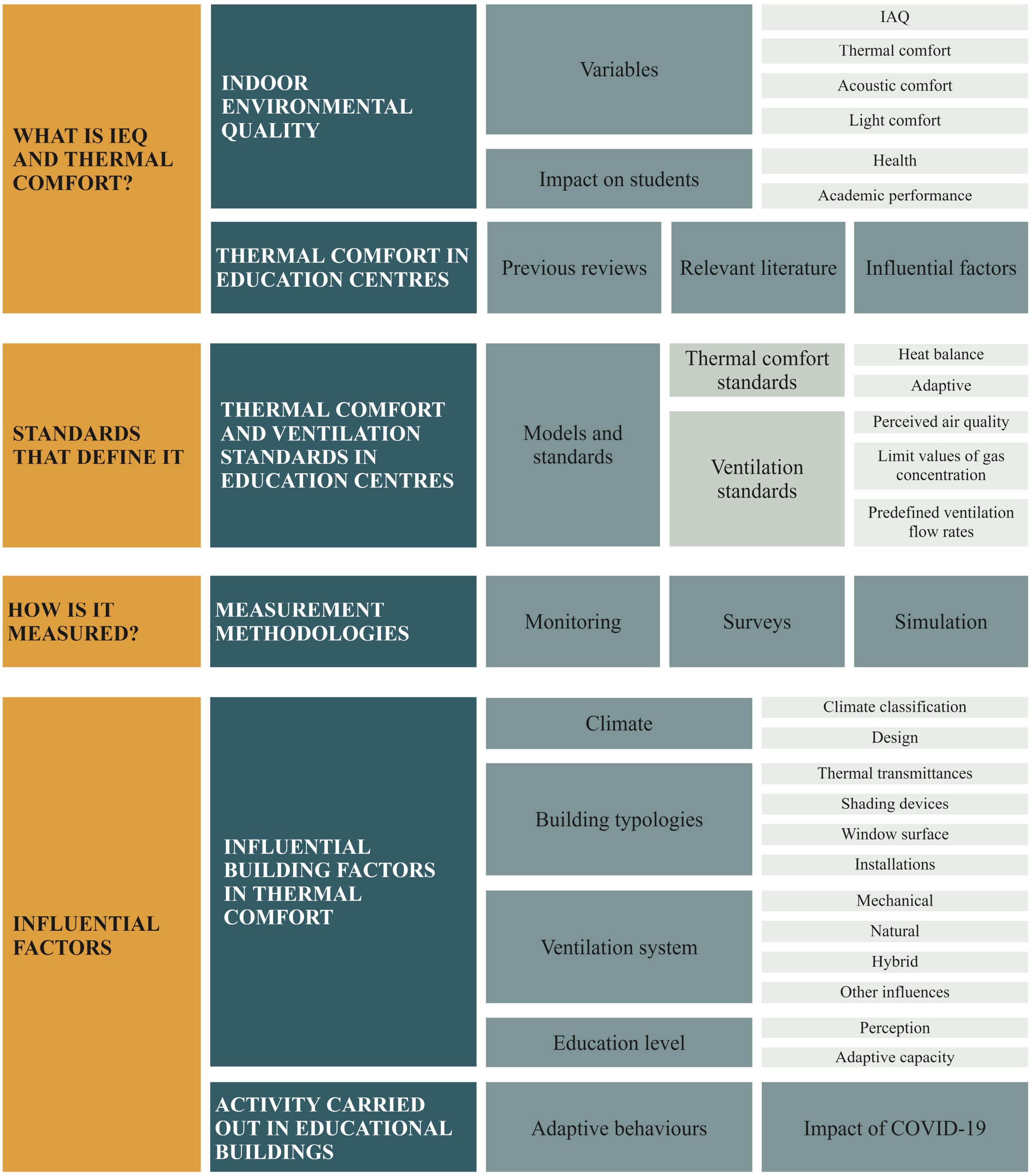


Figure 2-1, Literature review outline

2.1 INDOOR ENVIRONMENTAL QUALITY

In the last decades, multiple models have been created to evaluate the comfort of indoor environments. This indoor environment, called Indoor Environmental Quality (IEQ), involves multiple types of comfort.

These environmental conditions also significantly impact the energy consumption of the building, so how comfort conditions are ensured and achieved will influence not only the comfort of the occupants but also the performance of the building [8].

The IEQ depends on multiple variables, including temperature, relative humidity, air velocity, occupancy, noise, pollutant concentration or lighting. All these variables can be grouped into four broad categories [8]: thermal comfort, indoor air quality (IAQ), lighting comfort and acoustic comfort (Figure 2-2). One of the crosscutting factors that directly affects thermal comfort and IAQ is ventilation. Through indoor air renewal, ventilation must ensure adequate air quality while maintaining comfortable indoor temperatures and conditions.

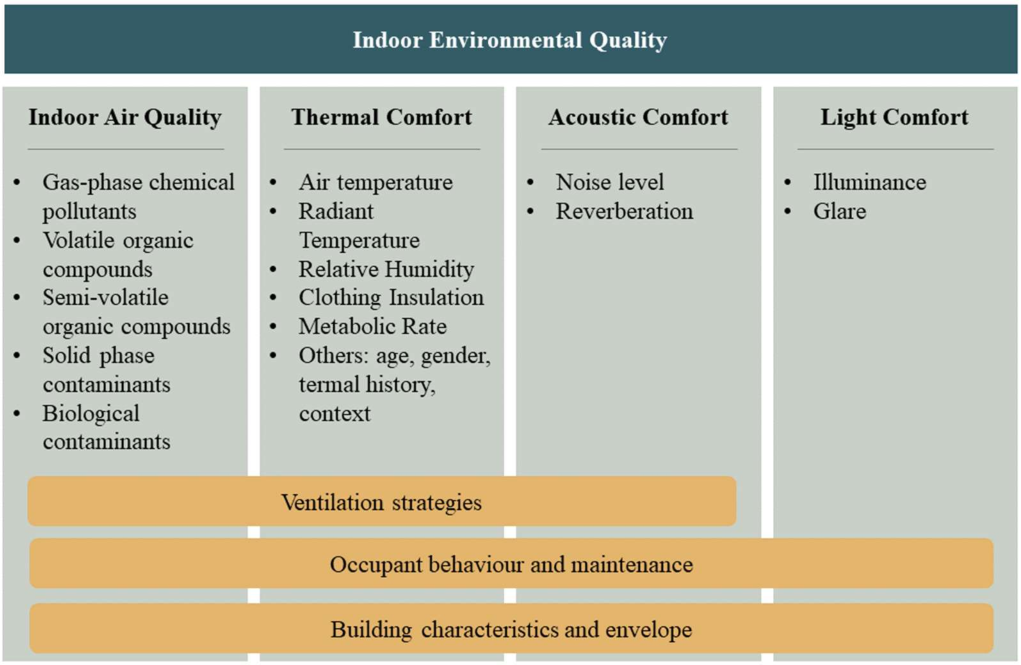


Figure 2-2. Indoor Environmental Quality parameters

Several studies have used CO_2 concentration to indicate good ventilation based on concentrations set by different standards. In addition, some articles have used this indicator to measure indoor air quality [19]–[21]. As reviewed in previous literature [22], this indicator can be considered insufficient and over-simplifying as most pollutants cannot be predicted based on CO_2 concentration, which is emitted mainly indoors, and most contaminants are emitted outdoors. Indirectly, the efficiency and the way of achieving IAQ and thermal comfort will be influenced by the implemented ventilation system and may affect acoustic comfort.

This contradiction is reflected in the Wells-Riley equation [23], which shows that good air quality and adequate ventilation are more important than not having too high CO_2 concentration [4].

Analysing previous research studying IEQ, it is found that more research has been carried out in offices or homes than in educational centres [9]. However, in recent years, the number of studies carried out in schools has grown exponentially.

Schools are considered more vulnerable spaces due to different factors, such as the age of their occupants, who are still at a developmental age and are more vulnerable to different factors that might affect their growth [4].

Secondly, there is a relationship between thermal comfort and IAQ and the academic performance of their students [4], [5]. In the study by Kelly and Dear [3], it has been identified how the improvement of IAQ directly impacts the decrease of respiratory symptoms, class absenteeism, and students' short and long-term academic performance.

In previous investigations, a relation has been recognised between the rise of CO_2 concentration and harmful health effects. When CO_2 exceeds 1000 ppm, a relationship with low ventilation rates is established [24].

Low ventilation rates, low relative humidity, and elevated temperatures have been proven to impact the students' learning performance [6], [7]. Moreover, it has been proved that IAQ worsens when temperature increments and is not guaranteed enough ventilation [25].

Other studies have related thermal comfort to student performance, concluding that students prefer cooler temperatures than adults and perform better in cooler temperatures [26], [27].

Also concerning insufficient ventilation, the study conducted by Shendell et al. [28] concluded that when the concentration of CO_2 in classrooms increased by 100 ppm, school absenteeism increased by 10-20%.

School occupancy density, the number of students per square metre, in these spaces, especially in classrooms, is 3 to 4 times higher than in offices [2]. Because of this, ventilation plays a crucial role in maintaining optimal indoor conditions. Also, related to occupation, school hours are very long, and the second indoor place where children spend most of their time after home [2].

Failure to ensure proper indoor environmental conditions has an impact on people's health, and in the case of schools, it has an impact on teaching. The health problems caused by poor IEQ can be divided into two categories, as presented in the study carried out by Mendes et al. [29]. Firstly, the Sick Building Syndrome is a symptom that arises during exposure and is related to the building itself.

Secondly, Building-Related Illnesses include diseases and symptoms also caused by exposure to the environmental conditions of the building, but in this case, they can affect people after they have left the building.

The sum of these factors reflects the impact on the development of the youngest, one of the most vulnerable groups in our society. It is a crucial objective to guarantee comfort conditions that help their development. For this reason, many previous research studies have focused on studying thermal comfort in schools using objective and subjective methods.

2.2 THERMAL COMFORT IN EDUCATION CENTRES

Considering the importance and role that IEQ plays in educational centres, a characterisation of the most relevant literature on thermal comfort in schools in recent years has been carried out. This characterisation allows a clearer idea of which factors are the most relevant and proposes a methodology that achieves the main objectives of this thesis.

Thermal comfort is that condition of mind which expresses satisfaction with the thermal environment [30]. This condition is influenced by multiple factors that impact the assurance and achievement of thermal comfort.

Multiple recent literature reviews analyse previous research on thermal comfort in schools. In 2016, Zomorodian et al. [9] reviewed the previous literature on thermal comfort in classrooms and related issues over the last decades to achieve a holistic view of this topic, reaching extensive conclusions on the constructive influences on thermal comfort and the relationship between this with the perception of its occupants. Subsequently, in 2019, Singh et al. [2] published a review on thermal comfort in classrooms over the last five decades to analyse the gaps found in the literature. In this last review, they reached conclusions on comfort as a function of air-conditioned systems and proposed adaptive comfort equations. In 2023, Jastaneyah et al. published their review on thermal comfort and ventilation in educational buildings [10], combining architecture and nanotechnology, to combine the two to reduce energy consumption.

These literature reviews serve as a starting point for this revision. They bring what conclusions have been reached and what gaps exist in the literature. Hence, this literature review evaluates the thermal comfort achieved in different previous studies in education centres, considering what parameters had an impact and other relevant factors, such as the perception they can have on their occupants. In order to achieve this objective, this section aims to have a broader view of those fundamental concepts that influence thermal comfort and how other studies have related the impact of different features on thermal comfort.

For this purpose, a search was carried out in the Scopus database. This search focused on scientific publications in high-impact journals after 2016 was made with the keywords "*thermal comfort*" and "*school*". This search was last updated on 20 February 2023, with more than 330 results available. First, by reading the title and abstract, a first selection was made, and those studies considered to be of no interest concerning the objective of this section were discarded, either because they deviated from the chosen topic or did not analyse thermal comfort quantitatively. Subsequently, of those considered to be of interest, a total of 31 articles considered to be of greater relevance were selected [16], [18], [26], [27], [31]–[57]. They were analysed in more detail in '10.1 ANNEX 1: Compilation of previous literature'.

The selected articles are categorized based on different criteria, see Table 2-1 includes the year of study, country, climate, season, thermal comfort approach, used methodology, education centre typology, number of centres studied, ventilation type, construction characteristics considered and monitored parameters. The following sections will define and develop the characteristics analysed.

Table 2-1. Characteristics analysed of the relevant literature.

Study relevant information											
DOI	Year	Country	Climate	Weather classification	Season	Education level	Number of schools	Number of classrooms (total)	Ventilation system	Characteristics analysed	Methodology

Comfort			**Monitored parameters**							**Other**	
DOI	Comfort model	Standard	Air temperature	Relative Humidity	Globe temperature	Air velocity	CO_2	Solar radiation	Outdoor	Analysis typology	Improvement strategies

2.3 THERMAL COMFORT AND VENTILATION STANDARDS IN EDUCATION CENTRES

Multiple models define thermal comfort, varying from what parameters are considered influential, their scope of application, and the occupants' adaptability to achieve thermal comfort, resulting in different limits and ranges that define thermal comfort for each case.

This section develops which models exist and which standards limit thermal comfort and methods to limit ventilation values. It has been selected those applied in the previous literature and developed according to which parameters the range that will limit the comfort is measured or limited.

2.3.1 Thermal comfort standards

This section first presents which thermal comfort models exist and which factors influence the determination of thermal comfort, followed by the standards that allow calculating or limiting these thermal comfort values based on the previously defined models.

2.3.1.1 Thermal comfort models

Thermal comfort models can be classified into rational models, those based on heat balance equations, and adaptive models. The rational models are based on the model developed by Fanger [58], which, using energy balance equations and empirical methods developed on adults in climate chambers, introduced the concepts of the predictive mean vote (PMV) and predicted percentage of dissatisfied (PPD). Based on mathematical models, the PMV and PPD indices aim to predict the degree of dissatisfaction and temperature comfort of the occupants of a climate-controlled space. According to Fanger, the factors influencing thermal comfort are air temperature, mean radiant temperature, air velocity, air humidity, air pressure, metabolic rate and clothing.

Although PMV and PPD are highly popular indexes, previous research on thermal comfort in case studies has found a disparity between the values obtained by these indices for predicting comfort and the thermal sensations recorded by occupants in everyday circumstances [59].

In general, this is due to the higher adaptive capacity of occupants than would be predicted by the PMV and PPD indices. The most significant discrepancy between these two factors has been found mainly when outdoor temperatures are high and indoor temperatures increase, as in practice, PMV predicts that occupants will feel warmer than they experience [60].

As a result of this discrepancy, adaptive models emerged. These models are based on people's ability to acclimatise to different environmental conditions, mainly influenced by outdoor temperature throughout the year.

In turn, these adaptive methods, unlike heat balance models, do not require knowledge of the clothing conditions (clos) or metabolic activity (mets) to which occupants are subjected in order to calculate thermal comfort levels [59].

Based on field work analysing adaptation influenced by outdoor temperature, multiple standards have introduced this variable into the equation that calculates comfort temperature [10]. For this purpose, different standards set different outdoor temperature limits (both minimum and maximum). Compared to static models, the comfort range achieved in these models is more extensive, which corresponds to energy savings [4]. Also, previous research highlights the importance of considering adaptive models from the design phase for their occupants to achieve thermal comfort [8].

Analysing previous literature, there is research that only uses heat balance methods based on PMV and PPD [16], [18], [27], [31], [40], [42]–[44], [48], [50], [55], [57] others use adaptive models where the influence of the outdoor temperature is taken into account in achieving indoor comfort [32], [34], [45] and others where both methods are used simultaneously [33], [35]–[39], [41], [46], [47], [49], [51]–[54], [56], [61]. An increase in the use of adaptive models has been observed in recent years [9].

Considering the multiple factors that influence the definition of thermal comfort, which parameters have been the most monitored for calculating thermal comfort in the previous literature have been analysed. For this purpose, studies in educational centres with monitoring as part of their methodology have been selected.

The most measured parameters in these investigations have been the operative temperature in 28 articles [16], [18], [26], [27], [31], [33]–[36], [38]–[54], [56], [57], 20 have measured relative humidity [18], [27], [33], [35], [36], [38], [40]–[42], [44]–[48], [50]–[54], [56], [57], 16 air velocity [27], [33], [35], [36], [40], [41], [44]–[47], [50], [52]–[54], [56], [57], 15 globe temperature [27], [33], [36], [38], [39], [41], [42], [44]–[46], [50], [52]–[54], [57] 11 outside temperature [26], [33], [38], [41], [45], [46], [49]–[51], [53], [54] 9 CO_2 concentration [31], [33], [34], [42], [47], [49]–[51], [53] and 2 solar radiation [16], [53].

2.3.1.2 Standards defining thermal comfort

Considering the existing thermal comfort models, this section summarises the most commonly used standards in the literature for limiting thermal comfort. In Figure 2-3, they are classified based on the model they use and the different distinctions they make based on the ventilation system.

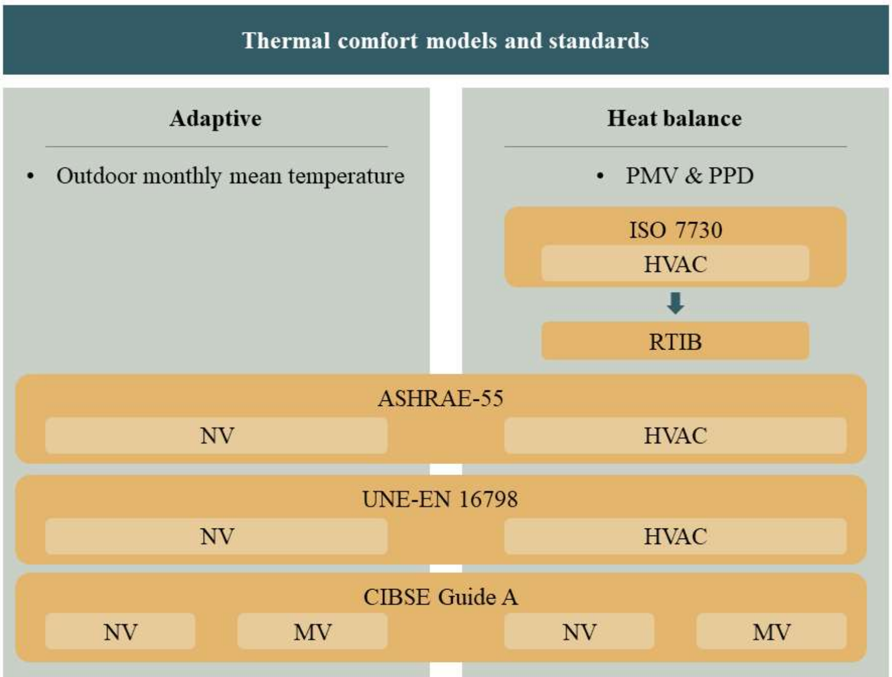


Figure 2-3. Diagram of thermal comfort models

First, the international standard UNE-EN-ISO 7730 [62], which comfort is given by the heat balance method, establishes comfort ranges based on PMV and PPD, influenced by the factors previously defined by Fanger [58] (air temperature, mean radiant temperature, air velocity, humidity, metabolic rate and clothing). This thermal sensation measured by PMV and through which the PPD is obtained provides data on thermal discomfort by predicting the percentage of people feeling either too cold or too hot. This discomfort can be caused by radiant temperature asymmetry, draughts or vertical air temperature difference.

This standard was designed considering air-conditioned areas or chambers that could be controlled mechanically and establishing the welfare limits using the PMV and PPD indices. The only reference to the adaptability of occupants that this standard makes is through clothing (this parameter, measured in clos, directly affects the PMV index).

Since it uses PMV and PPD values to set comfort limits, it assigns a maximum percentage of the dissatisfied and average expected votes for each category, summarised in Table 2-2 below, where category IV is only present in UNE-EN 16798 [63]. All other criteria are the same as UNE-EN ISO 7730 [62].

Table 2-2. Thermal environment categories PMV and PPD.

Category	PPD (%)	PMV
I	< 6	- 0.2 < PMV < + 0.2
II	< 10	- 0.5 < PMV < + 0.5
III	< 15	- 0.7 < PMV < + 0.7
IV	< 25	- 1.0 < PMV < + 1.0

In this international standard, the relative humidity for the temperature limits has been 60% in summer and 40% in winter. When temperature and activity are moderate (<26 °C and < 2 met), the influence of relative humidity is quite limited, having a modest impact on heat sensation. As the UNE-EN-ISO 7730 standard itself states, a 10% increase in relative humidity increases the equivalent heat sensation at operative temperature by 0.3 °C.

Other standards like the proposed by the United States, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) at the ASHRAE 55 standard [30] apply mainly to offices but can be extrapolated to other buildings of similar activity. In this standard, a distinction is also made between naturally air-conditioned spaces, limiting comfort based on outdoor temperature when the monthly outdoor average is between 10 °C and 33.5 °C. This limiting comfort operative temperature for naturally ventilated spaces is calculated through Equation 2-1, where Tc is the operative temperature (°C) and To is the monthly average outdoor temperature (°C).

$$Tc \leq 0.31\text{-}To+21.3$$
$$Tc \geq 0.31\text{-}To+14.3$$

Equation 2-1. Thermal comfort for naturally ventilated spaces by ASHRAE 55

For mechanically ventilated spaces, comfort is calculated through Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD), operative temperature ranges, relative humidity and dew point temperature, establishing a limit of PPD < 10 and PMV ±0.5. It establishes a maximum humidity ratio at 0,021, corresponding to the standard water vapour pressure of 1.910 kPa for a dew-point temperature of 16.8°C, with no minimum humidity limit. However, it clarifies that there are no limits on relative humidity or airspeed for naturally ventilated cases.

In this standard, the range of acceptable operative temperatures is considered 80% of acceptability by occupants. This percentage is obtained by considering a 10% dissatisfaction of general comfort obtained through the PMV and PPD indexes (Category II in Table 2-2). Another 10% were dissatisfied with possible partial thermal discomfort (which affects only some parts of the body). In those environments or application areas where more demanding thermal comfort conditions are required, the percentage limiting the range of satisfactory operative temperatures for occupants increases from 80% to 90%. These percentages and temperature limits have been based on adaptive models obtained through multiple studies conducted mainly in offices.

In the United Kingdom, the CIBSE standards are applied. In the case of limiting environmental comfort, it is limited by the CIBSE Guide A standard [59]. This standard establishes a general guideline recommending winter and summer temperature ranges, ventilation ratios, infiltration, lighting and noise levels for different building typologies.

This standard differentiates between mechanically and naturally ventilated buildings when limiting indoor operative temperature. In the case of mechanically ventilated buildings, it is limited by a range limited by a PMV ±0.25. If the PMV could be increased to ±0.5 (keeping PPD at <10%), the acceptable operative temperature range can be increased by 1 °C, both minimum and maximum. For the calculation of the limiting operative temperature, it sets a relative humidity of 50%. It limits the relative humidity between 40% and 70% for both cases.

Maintaining these criteria for mechanically ventilated buildings establishes a comfort temperature range between 19 °C and 21 °C for winter and between 21 °C and 23 °C for summer (Table 2-3 and Table 2-4). It is not so restrictive for naturally ventilated spaces and only limits the maximum temperature during summer to avoid overheating, establishing that the operative temperatures in naturally ventilated spaces must be below 25 °C. At the same time, for the calculation of overheating, it increases the operative temperature to 28 °C as long as less than 1% of the occupied hours are maintained.

When the adaptive approach is applied to limiting thermal comfort, these temperature ranges are limited by Equation 2-2 for free-running operated buildings and Equation 2-3 for heated or cooled-operated buildings.

$$Tc \leq 0.33 \cdot To + 20.8$$
$$Tc \geq 0.33 \cdot To + 16.8$$

Equation 2-2. Temperature limits for naturally ventilated units according to CIBSE Guide A

$$Tc \leq 0.09 \cdot To + 24.6$$
$$Tc \geq 0.09 \cdot To + 20.6$$

Equation 2-3. Temperature limits for mechanically ventilated according to CIBSE Guide A

On another level, the standard UNE-EN 16798 [63] uses adaptive models establishing different groups for assessing environmental comfort (categories I to IV from more to less restrictive) according to how restrictive it is to achieve comfort. The most commonly used is category II (medium) as the expected level of design and operation, although the more restrictive level (category I) should be used for those spaces occupied by more vulnerable groups due to their more restrictive conditions. This standard differentiates between buildings with mechanical cooling systems and naturally ventilated buildings to achieve thermal comfort. The standard is applied where the activity carried out by its occupants is mainly sedentary.

Also, they are considered naturally ventilated buildings where the occupants have access to window operation and a certain freedom to choose their clothing; hence, they have a certain freedom to change their clothing's thermal insulation and thermal conditions.

For those without mechanical cooling systems, the indoor temperature limits are a function of the outdoor temperature, being limited to outdoor values between 10 °C and 30 °C to calculate the minimum and maximum indoor limits of thermal comfort, especially during the intermediate seasons, spring and autumn, which are less vulnerable than summer and winter where peak maximum and minimum temperatures are achieved.

Since indoor comfort limits used by the adaptive method can only be achieved by natural means through outdoor temperature, the standard established that during winter, the limits to use as indoor comfort would be the same as those presented for mechanically cooled (MC) buildings.

In Figure 2-4, different adaptive standards show how the indoor comfort temperature changes depending on the outdoor mean temperature. Different groups within each standard based on how strict comfort should be considered. The graph shows UNE-EN 16798, ASHRAE-55 and CIBSE Guide A for natural ventilation, where it can be observed how CIBSE is the most restrictive one (without categories) and considers the highest indoor comfort temperatures for cold and hot outside temperatures. Even UNE-EN 16798 and ASHRAE have similar minimum limits; for their maximums, UNE-EN 16798 is less restrictive.

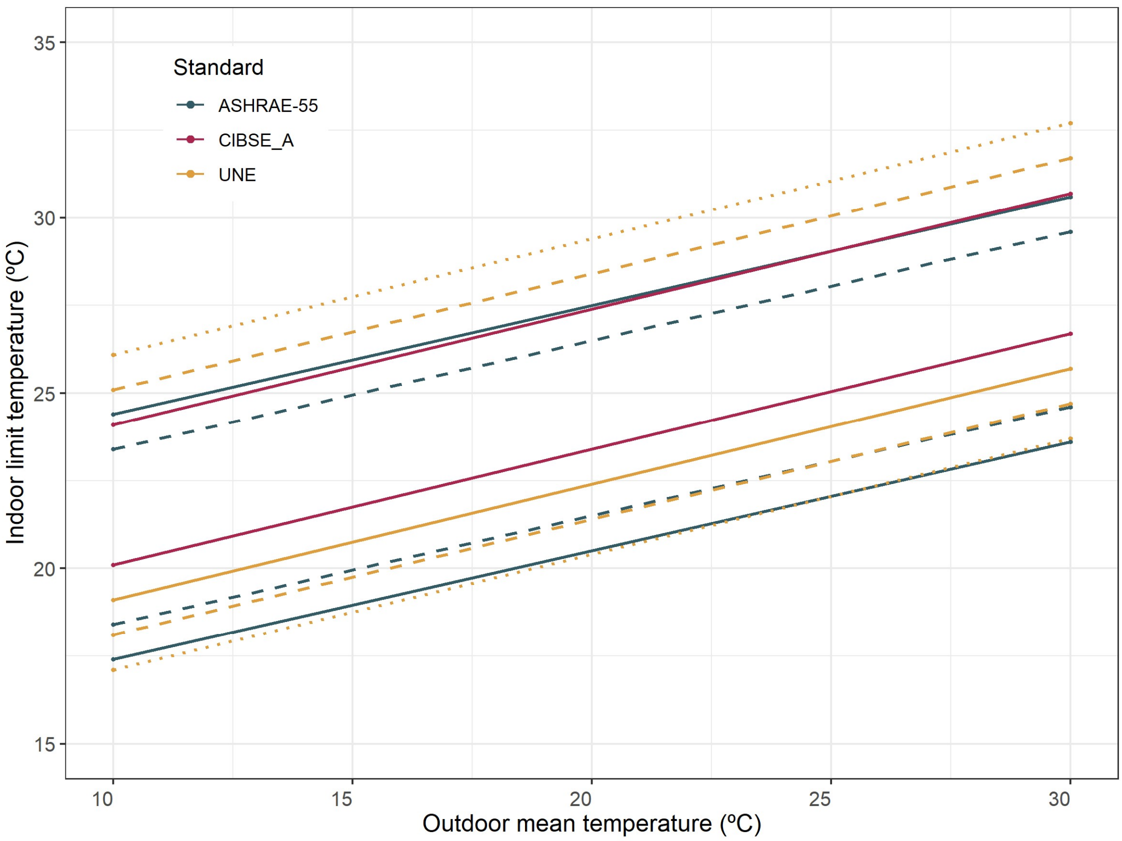


Figure 2-4. Indoor temperature limits for different adaptive standards

At the same time, the same standard differentiates for those buildings that do have an HVAC system. For these, it establishes different indoor temperature limits, based on PPD-PMV criteria in EN ISO 7730 standard in different categories (table B.1 - UNE-EN 16798-1). These have been obtained through surveys and previous findings, so each category establishes a single limit temperature value that allows the installations to be sized to achieve these values.

Table 2-3 shows, together with other standards, the ranges for the operative temperature during winter. Table 2-4 shows the ranges for the operative temperature during summer. These ranges are limited according to how restrictive it is to achieve comfort in three categories.

Concerning relative humidity, this standard only specifies criteria for sizing in special buildings such as museums or health centres, where humidification and de-humidification processes will occur, establishing limits for category II of a maximum of 60% relative humidity and a minimum of 25%. For the rest of the calculations in the standard, an average of 50% relative humidity has been indicated.

In Spain, the nationally applicable Regulation on Thermal Installations in Buildings (RTIB) [64] establishes temperature and relative humidity limits based on the UNE-EN ISO 7730 standard [62]. This temperature and relative humidity calculation is based on the metabolic activity, degree of clothing and estimated percentage of dissatisfaction (PPD) of the occupants. For calculating the facilities, optimal temperatures are considered above 21 °C in winter and below 25 °C in summer. When the values of metabolic activity, degree of clothing, air velocity, or PPD vary, they shall be calculated in the same way as in UNE-EN ISO 7730. As for relative humidity, unlike UNE-EN ISO 7730, it establishes recommended limits between 40% and 60%.

Table 2-3. Operative temperature comfort (Tc) limits for different standards during winter.

Standard	**Winter comfort**			
	Cat I	**Cat II**	**Cat III**	**Cat IV**
UNE-EN 16798:2020 (without MC)	Tc ≥ 0.33·To + 18.8 - 3	Tc ≥ 0.33·To + 18.8 - 4	Tc ≥ 0.33·To + 18.8 - 5	
UNE-EN 16798:2020 (with MC)	>21.0	>20.0	>19.0	>18.0
ASHRAE 55-2013 (NV)	Tc ≥ 0.31·To+15.3	Tc ≥ 0.31·To+14.3		
UNE-EN ISO 7730:2005 RTIB	22.0 ± 1.0	22.0 ± 2.0	22.0 ± 3.0	
CIBSE Guide A (NV)	Tc ≥ 0.33·To+16.8			
CIBSE Guide A (heated/cooled)	Tc ≥ 0.09·To+20.6			
CIBSE Guide A (no adaptive model)	19 ≥ Tc ≥ 21			

Table 2-4. Operative temperature comfort (Tc) limits for different standards during summer

Standard	Summer comfort			
	Cat I	**Cat II**	**Cat III**	**Cat IV**
UNE-EN 16798:2020 (without MC)	Tc ≤ 0.33·To + 18.8 + 2	Tc ≤ 0.33·To + 18.8 + 3	Tc ≤ 0.33·To + 18.8 + 4	
UNE-EN 16798:2020 (with MC)	<25.5	<26.0	<27.0	<28.0
ASHRAE 55-2013 (NV)	Tc ≤ 0.31·To+20.3	Tc ≤ 0.31·To+21.3		
UNE-EN ISO 7730-2005 RTIB	24.5 ± 1.0	24.5 ± 1.5	24.5 ± 2.5	
CIBSE Guide A (NV)	Tc ≤ 0.33·To+20.8			
CIBSE Guide A (heated/cooled)	Tc ≤ 0.09·To+24.6			
CIBSE Guide A (NV no adapative model)	Tc ≤ 25			
CIBSE Guide A (MV no adapative model)	21 ≤ Tc ≤ 23			

In the literature review developed by Zomorodian et al. [9] on thermal comfort in educational buildings, one conclusion reached is the disparity between the thermal comfort defined by different standards (UNE-EN ISO 7730, ASHRAE 55, CIBSE Guide A or EN15251, replaced by UNE-EN 16798) and the thermal neutrality achieved in different studies for the same climatic zone. Therefore, the authors suggest that the analysis for calculating thermal neutrality in students should be done in smaller areas, taking micro-climatic factors into account.

2.3.2 Ventilation standards

In addition to those parameters defined by Fanger that define thermal comfort, analysed in the previous section, one parameter most frequently measured in studies on thermal comfort has been the concentration of CO_2 due to the influence that ventilation has on thermal comfort [9].

Ventilation is the process of providing fresh air to indoor spaces. Correct ventilation must ensure the removal or reduction of harmful pollutants from the indoor space. Therefore, ventilation can also passively cool a naturally ventilated space or distribute the thermally conditioned air to a space [59].

The relationship between ventilation and thermal comfort will influence the thermal comfort conditions and the occupants' perception of the quality of the ventilation and the ventilation system. Previous research shows an elevated thermal comfort range for occupants in naturally ventilated schools than mechanically ventilated ones [65].

The CO_2 concentration in classrooms is a key indicator for assessing the quality of ventilation. Ventilation rates, classroom volume, number of occupants, activities carried out, and occupancy in these spaces influence CO_2 concentration [66]–[68]. Breathing by occupants is the leading emitter of CO_2 in indoor spaces. In outdoor spaces, the most influential in cities is emitted by road traffic [69].

Considering this, in the following sections, the different standards have been grouped by different methods, which define how comfort is achieved by defining an adequate range of ventilation and air quality. The standards presented below, in Figure 2-5, differentiate the limit values for achieving correct ventilation into four groups (I-IV) according to how restrictive it is to achieve these conditions, with thermal comfort standards being group I the most restrictive.

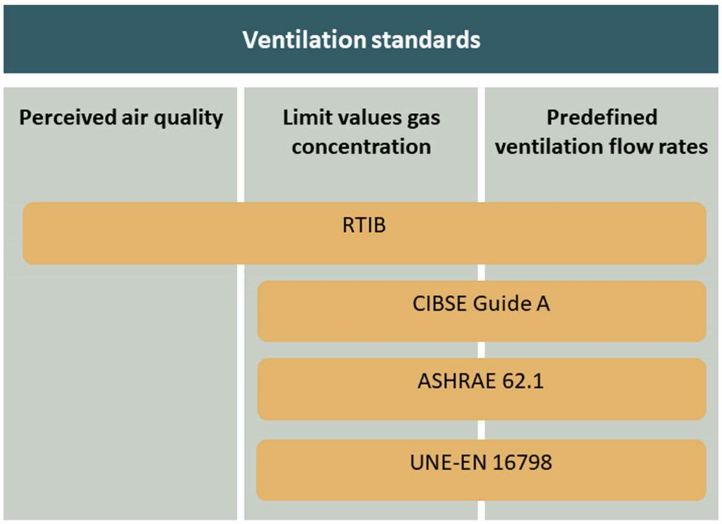


Figure 2-5. Ventilation standards by the methodology used

Different standards previously presented for thermal comfort, such as RTIB [64] or CIBSE Guide A [59], are based on UNE-EN 13779 [70] when it comes to limiting correct ventilation. This UNE-EN 13779 standard was superseded in 2018 by the current UNE-EN 16798 standard. Despite this, even in its updates after 2018, the RTIB standard continues to use the methods defined in UNE-EN 1377. Different methods are being defined by different standard to measure or limit ventilation values.

2.3.2.1 Method 1: based on perceived air quality

RTIB is the only standard that defines indoor air quality limits based on occupant perception. This perception is based on the one defined in CR 1752 [71] according to decipols (dp).

The decipol and olf are concepts created by Fanger [64]. The olf is based on the average odour emitted by an adult seated and takes an average of 0.7 showers daily. The decipol is defined as the air quality of the space where 1 olf is emitted and is being ventilated at a rate of 10 L/s with fresh air. Therefore, the RTIB limits according to the perceived air quality by decipols for the four categories, as shown below in Table 2-5.

Table 2-5. Limitations for perceived air quality

Standard	Olfactive method (dp)			
	Cat I	Cat II	Cat III	Cat IV
RTIB	0.8	1.2	2.0	3.0

Although UNE-EN 16798 also groups it as perceived air quality, its limits are predefined by flow rates per surface area or the number of people, presented in the section '2.3.2.3 Method 3: based on predefined ventilation flow rates'.

2.3.2.2 Method 2: using limit values of gas concentration.

Another method used in the standards to ensure proper ventilation is to use CO_2 concentration to indicate air changes. This calculation can be done by four different methods based on the fully mixed mass balance model [72].

Firstly, steady-state or accumulation methods can be limited when applied in classrooms because steady-state CO_2 concentration may not be reached due to multiple causes, such as changes in occupancy or physical activity before or during the classroom occupation to be measured. Nevertheless, this method has been used in previous literature, such as the investigation carried out by Ding et al. [49] in secondary schools in the Netherlands.

Secondly, decay methods are used during unoccupied periods. These transient mass balance methods can provide equivalent results. However, the ventilation levels calculated for these periods are not representative of occupied periods or as a function of the operation of HVAC systems, if any. In the schools examined, most heating, ventilation and air conditioning systems were switched off immediately after the students left. Therefore, the ventilation rates determined at the end of the school day are likely to be of less interest for many types of building investigations.

Third, accumulation methods, without occupancy measurements, and CO_2 concentration trends must be carefully examined to determine whether the steady-state or accumulation method can be used and to determine an appropriate time window for analysis. It is used in investigations such as the one by Miranda et al. at a university in Spain [50].

Finally, transient mass balance methods, if occupancy measurements can be obtained, ventilation rates determined by transient mass balance methods will provide the most accurate and robust results.

Considering these calculation methods, the standards most commonly used in the previous literature set a single CO_2 concentration value indoors depending on the external CO_2 concentration for the four assigned categories, summarised in Table 2-6. Considering a constant value of CO_2 emissions by the occupants.

The standard UNE-EN 16798 [63] limits the concentration of CO_2 in indoor spaces according to the outdoor concentration, which can oscillate between 350 ppm and 500 ppm, assuming a standard CO_2 emission of 20 l/(h/person). This limit is between 550 ppm and 1350 ppm over the outdoor mean concentration.

In ASHRAE 62.1 [73], based on a steady-state CO_2 concentration, the indoor CO_2 concentration was limited to less than 700 ppm above the outdoor concentration.

As specified above, the RTIB and CIBSE guide A standards are based on the now cancelled UNE-EN 13779 [70], which, when applied to non-residential buildings, limited the CO_2 concentration for each assigned category above the outdoor CO_2 concentration, ranging a concentration from 350 ppm to 1200 ppm over outdoor concentration.

The WHO guide [74] also limits indoor concentration limits for pollutants that significantly impact health, such as carbon monoxide, benzene or formaldehyde. No reference to CO_2 concentration is made in this guideline.

Table 2-6. Limitations of CO_2 concentration as a tracer gas over exterior CO_2 mean concentration

Standard	CO_2 concentration max (ppm)			
	Cat I	Cat II	Cat III	Cat IV
UNE-EN 16798	550	800	1350	1350
EN 13779 (RTIB and CIBSE Guide A)	350	500	800	1200
ASHRAE 62.1	700 ppm			

2.3.2.3 Method 3: based on predefined ventilation flow rates

Another method established in the standards is setting minimum ventilation values according to ventilation ratios, surface area, or occupancy. These values, assigned for the four categories defined in the different standards, are presented below in Table 2-7. This table shows that all the standards presented, UNE-EN 16798 [63], EN 13779 [70] and ASHRAE 62.1 [73], have different limits to ensure minimum air flow rate, limiting the flow rate (l/s) according to the number of people (l/s/person) and surface area ($l/(s·m^2)$).

In the case of schools, since their occupancy density is higher than that of other building typologies, ventilation based on the number of people (l/s/person) will be more restrictive than that based on floor area ($l/s·m^2$).

Table 2-7. Limitations on predefined ventilation flow rates

Standard	Ventilation (l/s/person) (l/(s·m^2))							
	Category I		Category II		Category III		Category IV	
UNE-EN 16798	10	2.0	7	1.4	4	0.8	2.5	0.55
EN 13779 (RTIB and CIBSE Guide A)	20	NA	12.5	0.83	8	0.55	5	0.28
ASHRAE 62.1	10	1.5	5	0.9	3.8	0.6	2.5	0.3

2.4 MEASUREMENT METHODOLOGIES

There are multiple methods for measuring the thermal comfort in which the occupants of an indoor space find themselves. These methods can be classified into two groups [75]. First, objective methods are those that use quantitative data based on measurements. Second, subjective methods that use qualitative data based on occupants' perceptions.

Regarding the study of thermal comfort in educational centres, the most commonly used methods are monitoring [31], [47]–[50] and surveys [43], generally carried out simultaneously [16], [27], [33], [35], [36], [38]–[42], [44]–[46], [51]–[54], [56], [57], [61]. This combination of monitored data and occupant perception provides information on the occupant comfort level for different environmental conditions, allowing to know which parameters influence the occupants' perception [76]. Another method used to study thermal comfort in educational centres is simulation [32], [34], [37], [55], and in some cases, the simulation is accompanied by monitoring [18].

2.4.1.1 Monitoring

In objective methods, the results are obtained from quantifiable data, not perceptions [75]. The most commonly used in this group is monitoring, which measures those variables and indicators considered relevant for each study. Depending on the different characteristics of the space to be monitored, the monitoring strategies proposed will be very different.

Monitoring is the most widely used method in previous literature to measure thermal comfort and other IEQ parameters. Depending on the purpose of the monitoring, a different monitoring campaign will be chosen, defined by the measurement period, duration and location.

Thermal comfort monitoring can help to understand the evolution of thermal comfort during the measurement period and the many parameters that influence it. These monitoring campaigns can last from weeks to years and allow a comparison of seasonal behaviour, i.e. the influence of outdoor environmental conditions and the support of heating or cooling systems.

Long-term monitoring, in which the main objective is to analyse the evolution during periods of occupancy and unoccupancy and to obtain sufficient values to estimate behaviour over a desired period. Short-term monitoring is most commonly used when accompanied by surveys to determine the thermal sensation and environmental conditions that occupants prefer. It can last from spot measurements up to a few days.

When designing a monitoring plan, other technical characteristics of the sensors, such as connectivity, data storage system, accuracy and whether calibration is required, must also be considered.

Specific sensors broadcast live measurements obtained online through auxiliary systems, like systems based on the Internet of Things. Others store the monitoring data on an internal card, becoming a limitation when working with the data and interpreting them simultaneously with the monitoring, being especially vulnerable during long monitoring periods. The memory capacity of the card used will also have an influence. Another limitation of the sensors is the possible disturbance they can cause, as some emit noise and can disturb or interrupt teaching.

Another key defining characteristic of sensors is their accuracy, which will allow more detailed data to be obtained and will vary according to their tolerance and sensitivity. Another characteristic is the need to calibrate the sensors; this will influence whether the sensor comes pre-calibrated from the factory or needs to be calibrated by the purchasers.

Depending on these characteristics will significantly influence the price of the sensors [77]. Currently, there is a wide range and choice of sensors. This wide choice, reflected in the price of some sensors, even if some have poorer technical performance, has made them more affordable and a more widely used tool in a more significant number of studies [78]; this factor must be taken into account when designing improvement or implementation strategies that are replicable and accessible.

When choosing a monitoring strategy, multiple construction characteristics and the space to measure must be considered, such as the. A key factor is the location of the sensors; standards such as UNE-EN ISO 7726 [79] recommend their placement at approximately 1.1 m height, simulating the breathing height of the students. It is also recommended that the sensors be placed away from windows, doors, and people to prevent their breathing from altering the monitoring results and to avoid direct sunlight and excessive moisture exposure.

The season of the year in which it is monitored also influences this. Evaluating previous literature monitored periods, most focus on the most vulnerable season, winter [16], [48], [50], [51], [53], and summer [26], [33], [34], [39], [47], [54], while others measure in autumn [27], [35], [52] or spring and autumn [18], [41], which are less vulnerable seasons, or all academic year [31], [36], [42], [43], [46], [49], [55]. In hot climates, where the climatic seasons are differentiated between the dry season and rainy season, some articles have only monitored during the dry season [32], [37], [40] while others have studied during both periods [38], [45], [56], [57].

Regarding the monitoring strategy, other parameters such as period, amount of sensors, and the number of measurement points have to be taken into account, the results of which will significantly influence the interpretation of the results. In general, it has been found that most studies use only one sensor per classroom [66], [72], [80]–[84] and in some cases even five sensors per classroom [21]. The most commonly used measurement duration is at least one week [80], [85]–[87], compared to other articles where they monitor much longer continuous periods, such as all academic year [83].

2.4.1.2 Surveys

Subjective methods are the simplest to apply [75] but often the most complex and limited. Surveys provide broad knowledge and have the lowest cost [88]. At the same time, it is the method with the most significant limitations due to its high involvement, difficulty in reaching many respondents, and the time required. This complexity in surveys is also reflected in the diversity of opinions on the same environmental conditions, which makes it challenging to analyse the results if only this method is used.

In the case of questionnaires in schools, a significant limitation has been the simplification so the students can understand it, especially for young students, limiting the scope of the questionnaires [89].

Several studies have measured the thermal perception of occupants through surveys, in some cases differentiating between students and teachers [39], [54], [90]. Through these surveys, results have been obtained on the degree of satisfaction with the temperature at which they are and the desire to change the thermal conditions inside. Other studies use the surveys to propose specific improvement strategies for occupants to achieve greater thermal comfort, such as fans, air conditioning systems or shading systems [16].

The impact of thermal comfort on academic performance has also been measured and evaluated through surveys [91]. A limitation pointed out by previous articles focusing on academic performance has been the lack of standardised methods of measuring it [11]. The authors note that standardised methods for measuring thermal comfort exist, but they do not allow them to compare their results on student performance with those of other studies.

2.4.1.3 Simulation

In previous research on measuring thermal comfort in schools, some used simulation software as part of their methodology. The most commonly used programs in the literature have been the Energy Plus simulation Tool [32], [37], [55], Integrated Environment Solutions (IES) Virtual Environment [34] and Design Builder [18].

Those investigations that use simulation as part of their methodology to measure thermal comfort represent a small percentage because simulation is a more widely used tool to analyse the energy performance of buildings [92].

Using simulation methods has several advantages over other methods, such as predicting or studying different strategies in the same model, evaluating possible improvement strategies, or knowing in more detail the situation in different parts that would be very difficult and limited to measure based on the number of measurements or Computational Fluid Dynamics simulation. Another advantage is that they do not have to interrupt teaching and are not limited to the accessibility of the centres because of their distance or the time needed to visit multiple centres.

With the current trend of digitalisation processes in construction, simulation and digital modelling support are essential. These methods allow for predicting and reflecting the behaviour of buildings, establishing improvements in case studies through comfort indicators [93].

2.5 INFLUENTIAL BUILDING FACTORS IN THERMAL COMFORT

According to previous literature, multiple characteristics influence the comfort of its occupants [4]. This section focuses on those characteristics related to design and construction that have been considered relevant to thermal comfort, analysing which ones have been measured in previous studies and how they impact thermal comfort; this will be key to proposing a methodology for this thesis.

This section is grouped into four sections corresponding to different characteristics (Figure 2-6): climate, building typology, ventilation system, and educational level.

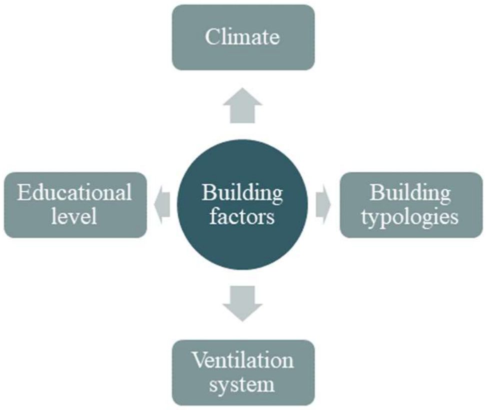


Figure 2-6. Influential building factors analysed

2.5.1 Climate

The location of the building has a significant impact, as the climatic conditions and seasons will influence the design of the building [94].

One of the most applied climate classifications is Köppen-Geiger's [95] (Figure 2-7). This classification considers variables to classify the climates: mean annual precipitation, mean annual temperature, the temperature of the hottest month, the temperature of the coldest month, number of months where the temperature is above 10 °C, precipitation of the driest month, precipitation of the driest month in summer, precipitation of the driest month in winter, precipitation of the wettest month in summer and precipitation of the wettest month in winter.

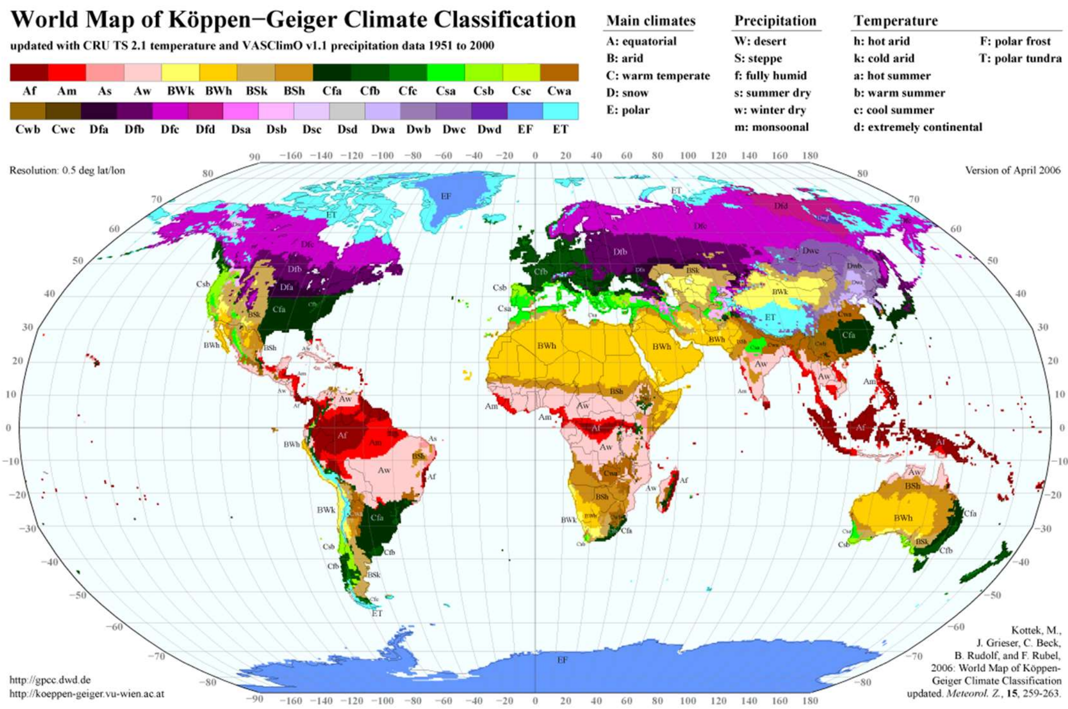


Figure 2-7. Köppen-Geiger climate classification world map. Source [96]

This climate classification is grouped into five categories: A (tropical or equatorial), B (arid), C (temperate), D (continental or snow), and E (polar). There are different sub-categories based on the previously defined variables.

Analysing previous research on thermal comfort in schools, in which climate was their case studies located (see Figure 2-8). The majority of studies have been found to take place in temperate climates (C) [18], [26], [31], [32], [34], [37], [39], [41], [43], [46], [48]–[50], [52], [54], [55] followed equally by tropical climates (A) [37], [38], [40], [44], [56], [57] and arid climates (B) [16], [27], [33], [35], [45], [53], and finally those carried out in continental climates (D) [36], [42], [43], [47], [51]. No studies were found in polar climates.

This finding of a higher number of articles in temperate climates differs from the result obtained in the review by Chatzidiakou et al. [4], where more research was found in hot climates, followed by temperate and finally cold climates.

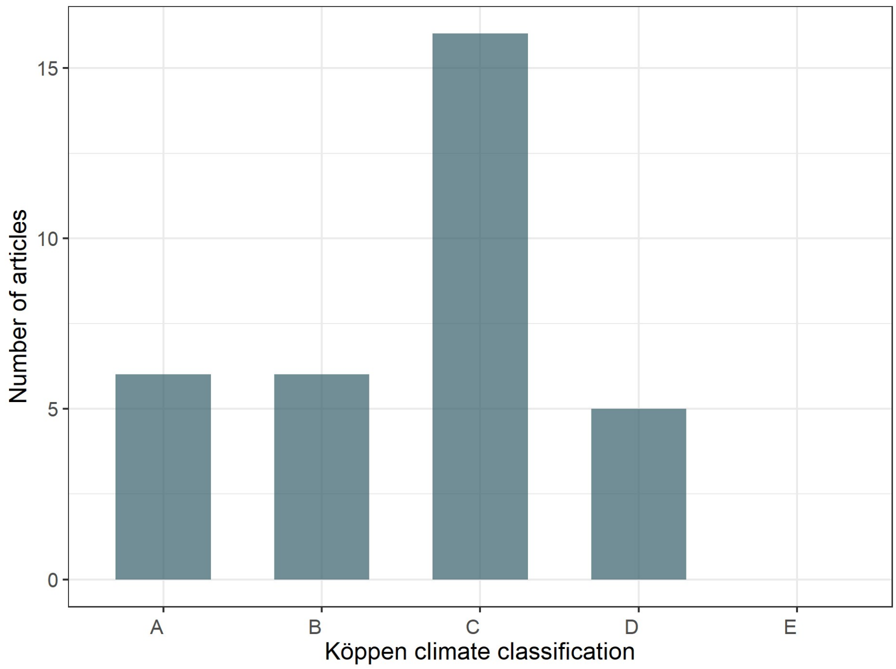


Figure 2-8 Climate classification for analysed articles

One of the conclusions commonly reached in studies in hot climates is the disparity between the comfort felt by occupants and the comfort limited by different standards. Multiple studies have evaluated this disparity and concluded that globally used standards such as ASHRAE-55 or even local thermal comfort standards are not appropriate for these climates [40], [41], [45].

Other studies, carried out in semi-arid climates, Bsk in Köppen-Geiger classification, with very low average temperatures, where the annual average is below 18 °C, have also found a disparity between the comfort perceived by students and the comfort limited by different standards due to cultural and occupant adaptation factors. In the study conducted by Jiang et al. [53] in rural China with a Bsk climate, it was found that students leave their jackets on inside the classrooms, which, when the clos are increased, significantly reduces the temperature they consider thermal comfort. This difference resulted in a range of comfort reported by students between 13 °C and 18 °C compared to the 21 °C to 24 °C range set by the ASHRAE-55 standard.

In other studies conducted in the same climate (Bsk) but in other countries with a different adaptation culture, such as the one by Yang et al. in the sub-Arctic area of Sweden [42], the comfort achieved is very different. In this study, overheating in classrooms during the winter has even occurred. In order to adapt to the thermal conditions indoors, students even adapt by taking off their socks, so a reduction in clos. Analysing these two studies as an example, the significant influence that culture has on the adaptation measures chosen by the students and the school when it comes to guaranteeing thermal comfort conditions can be seen.

Beyond adaptation to the current climate and the impact of climatic conditions on the architectural design phase and the capacity of occupants to adapt, the current trend of climate crisis raises other design questions. New approaches to the resilience of buildings currently constructed are emerging. The capacity of occupants to adapt to the increase in outdoor temperatures influencing indoor thermal comfort has to be considered [43].

2.5.2 Building typologies

The construction of the building itself will significantly influence the comfort conditions and the energy performance of the building. In previous literature reviews [10], those construction characteristics that should be considered for the impact on thermal comfort and ventilation in buildings are Window to Wall Ratio (WWR), layout, dimensions, building's thermal envelope properties and external shading. This review already highlights that very few researchers have considered these characteristics in their analysis, as they have focused their studies on numerical simulation methods and experiments.

Other studies which analyse the impact of construction on thermal comfort conclude that building construction features, such as the thermal properties of the building envelope, have a significant influence on thermal comfort [8], [18], [37]–[39], [57].

Another characteristic of the building that also has an influence is the year of construction, as this will influence the design of the building in terms of regulations and minimum requirements. The year of construction will vary from the materials and thermal transmittance of the building envelope to the ventilation system or infiltration of the building.

In Spanish regulations, these limit values for thermal transmittance for each type of envelope are limited by the Technical Building Code (TBC) from 2006, in the Basic Document on Energy

Saving (DB-HE) [97]. For the coldest climate, it limits the transmittance in roofs to 0.46 $W/m^2 \cdot K$, in façades 0.74 $W/m^2 \cdot K$ and openings to 3.1 $W/m^2 \cdot K$. In 2013, the TBC DB-HE [98] decreased its requirements, resulting in maximum transmittance for the coldest climate in roofs of 0.35 $W/m^2 \cdot K$, 0.55 $W/m^2 \cdot K$ for façades and 2.5 $W/m^2 \cdot K$ for openings. Furthermore, since 2019, TBC DB-HE [99],[100], in the coldest climate, limits roofs to 0.33 W/m^2 K, façades 0.37 $W/m^2 \cdot K$ and openings 1.8 $W/m^2 \cdot K$. Before the TBC, in the Basic Building Standard (NBE-CT-79 [101]), these values were much higher, limiting transmittance in roofs to 0.7 $W/m^2 \cdot K$ and 1.2 $W/m^2 \cdot K$ for façades and without any limitation for openings. As for the ventilation system, since its publication in the Regulation on Thermal Installations in Buildings (RTIB) in 2007 [102], ventilation in buildings is required to be ensured by mechanical or hybrid means. In addition to the age of the building, the condition and maintenance of the building [94] influence the quality and perception of future occupants.

Constructive properties have been analysed in macro studies such as SINPHONIE [94], where comfort and air quality were studied in a total of 122 European schools. These schools were mainly built with brick and concrete; only 16% had insulated facades, and 18% had insulated roofs. Most of the insulated schools were located in the northernmost parts of Europe compared to schools in central or southern Europe; this shows that in these areas, the main objective is to avoid the penetration of cold indoors and not the possible overheating that may be produced.

The classroom location to be monitored will also have an influence, mainly its orientation [2], [11] that will impact thermal and lighting comfort, and the proximity of its facades to major roads or other elements will influence acoustic comfort and IAQ [103].

Regarding openings, many studies have concluded the influence of their size using the WWR indicator, which is the ratio between the façade surface and the surface of the opening in that façade. This indicator is especially relevant in hot climates because of its impact on overheating. Some studies limit the size of openings based on the façade area, recommending that the WWR should not exceed 20% in any orientation in hot climates to ensure the correct thermal performance of the building [16].

In addition, this opening dimension can also be defined by the ratio between the room and the light transmittance capacity, i.e. the capacity of the façade to transmit natural light from the outside, called daylight factor (DF), which considers the physical properties of the glass. This ratio is recommended to be higher than 2%. When only the ratio of the room to the glazed area is considered, some standards currently require a ratio of 10% and recommend 15% for future constructions [104], [105]. The study by Becker et al. [17] recommended a bigger ratio than 13% for northern and 10% for southern orientations. Based on Turkish national regulations, some studies recommend an opening corresponding to 25% [55].

A key element related to the design of openings is shading systems, which significantly prevent overheating, especially in hot countries [16]. Studies such as the one by Kükrer et al. [18] have studied the impact of different shading elements on thermal comfort and energy consumption, especially on south-facing façades. It was found that the implementation of movable shading systems increases thermal comfort in south-facing areas by 45% by reducing solar gains by 23% and cooling energy savings by 8.5%; this achieves a total energy saving of 30% in south-facing rooms during the summer months.

Other installations, apart from the ventilation system, influence thermal comfort. Previous research has found a difference in the level of thermal comfort achieved by students in classrooms according to different heating systems [9], [106] or air conditioning systems [9], [26], [107]. Both have an impact not only on the comfort achieved but also on the behaviour of the occupants in achieving this comfort.

Indirectly, the typology of the classroom to be studied also influences, for example, whether it is a conventional classroom, a corridor space, a gymnasium or other spaces commonly found in schools. Typologies will influence not only the metabolic rate and clothing of its occupants [2] but also the design of that space, varying in volume and surface area, which will mainly influence temperature and air renewal levels.

Another building feature of schools that also impacts the comfort and behaviour of its occupants is the outdoor space, especially the schoolyard itself [108]. Its design will influence the outdoors, such as greenery, shaded areas, choice of materials, equipment and adult supervision [109].

2.5.3 Ventilation system

Ventilation is one of the most critical features influencing indoor environmental conditions, along with the permeability of the building, which, with the current trend in building design, is becoming more airtight, making them more energy efficient and reducing operating costs [110]. If this airtightness is high and proper ventilation is not ensured, certain pollutants that originate indoors increase their concentration and impact people's health [3].

In turn, ventilation systems must ensure minimum levels of air renewal, as this is the parameter that will have the most significant influence on the energy performance of the building and will have an impact on the health of its occupants [72].

The literature has classified the ventilation systems into different typologies: natural ventilation [27], [31], [33]–[36], [38]–[41], [44]–[48], [50]–[53], [56], [57] which represents the majority of educational buildings in Europe [94] mechanical ventilation [18], [42], [43] and hybrid ventilation [37]. The rest of the studies analysed have carried out their research in multiple buildings with different ventilation systems between them [16], [26], [32], [49], [54], [55], but in all of them there are case studies with natural ventilation. These ventilation systems are described based on the definitions by the standard UNE-EN 16798-3 [111] and previous research [112].

2.5.3.1 Mechanical ventilation system

When air renewal occurs through electromechanical systems, the space is considered to be mechanically ventilated. Mechanical ventilation can be grouped into three sub-categories:

First, supply-only ventilation systems, where the air is mechanically drawn in through fans and combined with passive air extraction systems to ensure fresh air inside the building. This air is mechanically "pushed" into the building, thus creating a positive pressure difference concerning the outside.

Second, extract-only ventilation systems, in which air is extracted from a room by an assisted fan that transfers the air to the outside employing devices located in the building envelope. In residential buildings, they are generally found in bathrooms or kitchens and regulate the airflow if controlled by timers or switchers. This type of system creates a negative pressure difference between the interior and the exterior. This system has certain advantages in humid or highly polluted rooms.

Third, two-directional ventilation systems or "dilution ventilation". These systems, which ventilate with assisted volumetric flow in two directions, supply and exhaust, are usually thermally treated. In recent years, they are commonly used in office spaces and residential buildings with HVAC systems. These systems are efficient but have a high energy consumption.

2.5.3.2 Natural ventilation system

In naturally ventilated buildings, this air renewal is produced exclusively by the action of the wind and the difference in temperature between inside and outside, which produces a pressure difference. This system requires minimum maintenance of the building conditions and does not involve directly any energy consumption. On the other hand, as the air entering the building cannot be thermally treated, it impacts the environmental and thermal conditions inside the building, indoor temperatures and ventilation depending on the outdoor environmental conditions.

Another limitation in naturally ventilated buildings is external noise, which can be limited when occupants open windows to avoid noise pollution; this is especially significant in schools close to busy or noisy roads [36], [113].

2.5.3.3 Hybrid ventilation system

Depending on environmental conditions, hybrid or mixed systems rely on natural and mechanical ventilation. This type of ventilation can happen by three different methods:

First, supplementary mechanical ventilation is used when the required ventilation values cannot be achieved by natural means alone. For this purpose, a fan is often used to support air extraction.

Second, complementary, when mechanical and natural ventilation work simultaneously to achieve the required ventilation in the building.

Third, alternate, when both systems are incorporated separately in the building. It will use mechanical or natural ventilation depending on the climatic conditions and the ventilation required to achieve indoor comfort.

This approach maximises comfort and avoids the high costs incurred by using heated mechanical systems all year round. However, integrating both systems requires a good design that considers different details to achieve comfort that can considerably reduce energy consumption when only mechanical ventilation is used.

2.5.3.4 Other influences of the ventilation system

After classifying different ventilation systems in the previous standards and literature, a debate exists concerning the best ventilation system that reaches the best indoor results. This debate concerns the limitations each system presents and the opportunities each case study presents.

Multiple studies have found that despite the significant difference between naturally and mechanically ventilated schools, naturally ventilated schools still provide optimal ventilation conditions in temperate climates. They achieve ventilation ratios above the minimum recommended by the standard [80].

At the same time, some operations improve ventilation in schools. In naturally ventilated buildings, in research such as that carried out by Gallego Sánchez-Torija et al. [31], it has been found that taking advantage of breaks in classrooms to ventilate naturally can guarantee and may be a sufficient measure to ensure the correct indoor air quality in classrooms. The limitation found in this research is that, in many cases, this ventilation is not carried out adequately.

Related to this limitation in naturally ventilated centres, the study by Miranda et al. [50] concluded that the CO_2 concentration should be measured in classrooms to know the most critical and vulnerable moments. At these times, it is recommended to ventilate by fully opening the windows to achieve the highest possible ventilation when the outside temperature is above 12 °C, as it has been established that this does not compromise thermal comfort in classrooms.

Night cooling is another passive strategy recommended in the literature [34]; it has been indicated for buildings with high thermal inertia and when day and night temperatures fluctuate considerably during "cooling" periods. Helping to use thermal storage in the building better to achieve indoor comfort temperatures during the occupied period often coincides with the hottest hours.

In other reviews or studies, it was found that, on average, schools with mechanical ventilation systems reached lower CO_2 concentration and better thermal comfort than in naturally ventilated schools [12], [13], [31], [114].

At the same time, in those centres where natural ventilation has been proven not to reach enough renovations, mechanical ventilation systems have been introduced; as a result, not only has ventilation improved but also thermal comfort [12], [13]. In this aspect, the different approaches used by the researchers and the opportunities taken by the case studies show the impact different ventilation systems can have on the results.

2.5.4 Educational level

The type of educational building impacts not only its design but also thermal comfort, depending on the age of its occupants, as their behaviour, occupation, thermal perception, and activity will be very different. Most studies have been carried out in elementary schools [16], [26], [27], [31], [33]–[36], [38], [39], [41], [42], [46], [48], [51], [53]–[56] high schools [26], [27], [31], [32], [35], [40]–[47], [49], [52], [53], [56], [57], universities [18], [50] or kindergarten [31].

There is also a difference in the perception of thermal comfort among occupants of schools [59] by their age, both between different ages of students [26], [90], [115] and between adults and students [39], [54], [90]. This different perception by age is caused by older people having lower metabolisms, which is compensated for by their lower evaporative loss. As studied in previous research analysed by CIBSE [59], the preferred thermal environment at the same activity and clothing level is not that different between young and adults.

Another factor that may influence the perception of comfort is gender [59], as women have a slightly lower metabolism rate than men. However, it has been demonstrated that the preferred thermal environment is almost the same at the same activity and clothing level. Sometimes, women's preference for higher temperatures is caused by the difference in the thermal insulation of their clothing [116].

The difference in perceived comfort between adults and students has been studied in several studies [26], [36], [39], [54]. A common conclusion is that children prefer lower temperatures than adults to consider themselves comfortable, voting for a neutral thermal sensation. The temperature difference calculated in the study by Korsavi and Montazami [36] is 1.9 °K lower in non-heating periods and 2.8 °K in heating periods. In the study by Nam et al. [117], the temperature preference difference between the primary students and their teachers is 0.5 °K lower in summer and 3.3 °K in winter.

Similarly, in the study by Montazami et al. [39] analysing thermal comfort in naturally ventilated schools during unheated periods, the comfort of primary school students compared to adults was 3°K less. In the study by Kim and Dear [26], this value is reduced to 2°K less for primary school students than adults and remains at 3°K less for secondary school students than adults.

Concerning the comfort perceived by students, it has been found that infants are more tolerant of temperature changes during non-heating periods than during heating periods [36].

The adaptive capacity of students has also been observed as a function of the outside temperature. Primary school students were the least affected by these temperature changes. As Singh et al. state in their study [2] reinforced by previous literature, this is due to the ability to make clothing decisions, as primary school students are still dependent on adults, while secondary school students have a more limited scope to adapt. Some studies also point to the obligation to wear a uniform, which significantly limits the ability to adapt clothing to temperatures.

2.6 ACTIVITY CARRIED OUT IN EDUCATIONAL BUILDINGS

2.6.1 Adaptive behaviours

According to adaptive models, if a change produces discomfort, people react in ways that bring them back to comfort. According to research conducted by Singh et al. [2], the different types of adaptation are grouped into three categories (Figure 2-9).

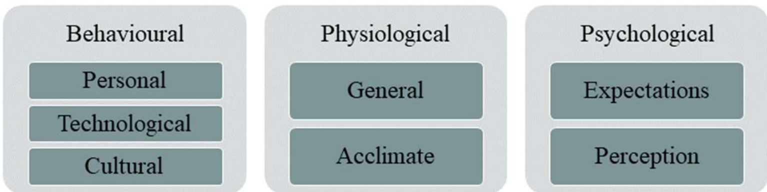


Figure 2-9. Classification of adaptation methods

First is behavioural, which groups together those actions that occupants take that impact body mass and heat flux. These actions can be classified as personal, technological, or cultural. It is considered personal when individuals can change their clothing insulation or activity level to adapt to their thermal environment [14], [117]. Technological when an instrument rather than the individual carries out this change. Culture is based on those systems used growing up. For example, in tropical climates, buildings are more ventilated and perceived to achieve better thermal comfort with natural ventilation than mechanical ventilation [118], [119].

Second is physiological adaptation, which is caused by prolonged exposure to, for example, the impact of the climate. These adaptations can be either general or acclimatised based on the duration of exposure to the adaptation [120].

Finally, psychological adaptation, where socio-economic and socio-cultural experiences influence occupants. These experiences influence expectations and perceptions, understood as how the occupants change their thermal perception based on their expectations of the thermal environment [120].

To ensure this option of controlling thermal comfort, the occupants must have the control tools to adjust the thermal comfort to their needs. These adaptation tools can be, for example, the operation of fans and the opening of windows during summer or the temperature control in winter. Individual control is much more effective than achieving comfort when controlled in groups [59].

There are previous theses, such as the one developed by Korsavi at Coventry University, where he analyses adaptive behaviours and strategies to improve IEQ in eight schools in the UK, reaching as one of his main conclusions that students are not being guaranteed sufficient opportunities to practice adaptive behaviours to their environmental conditions [1].

It is especially relevant to ensure the possibility for students to adapt, as the temperature at which they feel comfortable differs from that of the teachers. Nevertheless, today, in schools, the control to change the environmental conditions is carried out mainly by the teachers and not the students. This disparity between perception and control limits students' ability to achieve thermal comfort, with only individual measures such as changing their clothing insulation [1], [42].

The operation and design of windows also help achieve different aspects of comfort, visual, thermal, and air quality, which impacts energy consumption. This design makes it more accessible to the occupants with subdivided windows. As previously mentioned, night cooling ventilation during warm periods helps to reduce the operative temperatures for the following day during occupancy, so the design of windows to ensure night cooling ventilation, such as windows of different sizes, also plays an important role [1].

2.6.2 Impact of COVID-19

Occupancy in educational establishments and their timetable have a direct impact on the concentration of CO_2 produced naturally while the occupants are breathing [66]. It also influences the frequency of breaks, allowing for more classroom ventilation. When considering occupancy in educational centres, it is necessary to consider the timetable of classes and possible extracurricular activities in the building.

Ventilation patterns and occupancy in classrooms have been greatly influenced by COVID-19 [121], as most schools have implemented a "COVID protocol" intending to improve ventilation [122], [123]. Because of the COVID-19 pandemic, information and concern about IAQ and ventilation have increased, especially those related to schools, since it has influenced classrooms because of their high occupancy density and the vulnerability of their occupants. Because of its vulnerability, classroom attendance was affected by the lockdown that most countries were subjected to due to the pandemic.

Therefore, when it became necessary to return to the classroom, multiple recommendations, guidelines, and regulations were created to establish a protocol for returning to the classroom [122]–[126]. The common goal of these resources is to ensure proper classroom ventilation using available methods. The guide by Harvard [121] explains how to measure and quantify ventilation using different methodologies and improve ventilation rates using different resources by those means available. In addition, the World Health Organization (WHO) [123] made some considerations focused on teachers and policy-makers on how to return to the classrooms as safely as possible; these considered from community to school level, classroom and individual level, all intended to keep it as safe as possible by distancing, masks, ventilation and other measures proposed.

A common denominator has been monitoring CO_2 inside classrooms with a clear protocol for action based on this concentration, prioritising this ventilation, by those means available naturally or mechanically, over other parameters such as thermal comfort. Some guides were made in Spain to establish recommendations to achieve this objective.

The *Consejo Superior de Investigaciones Científicas* (CSIC) presented its guide [124], intended to serve as a tool explaining strategies and solutions to determine whether the ventilation achieved in the classroom is adequate. It recommends measuring CO_2 and favouring natural ventilation by opening doors and windows, prioritising ventilation over thermal or acoustic comfort. This guide is based on the guide created by Harvard University for the same purpose [122] and on previous measurement work on ventilation and infiltration in Spain.

The *Aireamos* project [125] was born from multiple research institutes and universities collaborating to find CO_2 levels in schools. This initiative presents the usefulness of ventilation in educational centres to reduce the risk of COVID-19 contagion through the air using CO_2 as an indicator. As observed in previous literature, this indicator is easy, quick and accessible to measure. This project presents measurement guides and information on multiple sensors available on the market to facilitate the choice of schools. It also provides different resources for calculation and ventilation strategies to reduce the viral load.

A guide was also produced by the Basque Country's government to reduce COVID-19 emissions and exposure [126]. For this purpose, two strategies were proposed; the first focused on reducing the possible emission of COVID-19 by reducing classroom occupancy and high-intensity activities, as well as requiring face masks. The other strategy, focused on reducing exposure, apart from the previously mentioned mask and maintaining distance, calls for more ventilation of indoor spaces. To this end, it suggests air renewal rates between 5 and 6 ACH for an occupancy density between 4 and 5 m^2/person. Considering it adequate when CO_2 concentrations stay below 700 ppm, proposing a maximum of 800 – 1000 ppm that should not be exceeded.

3 RESEARCH QUESTION AND PROPOSAL

3.1 CONTEXT

The literature review has developed definitions of thermal comfort and the influence of ventilation on thermal comfort. Both concepts have been analysed from their more theoretical aspect, expanding on the different methods and indicators defined for their measurement and influence on occupants in educational centres. These definitions and analyses have been obtained from the different standards that establish limits or ranges to be considered acceptable. The objective of these thermal comfort limits is that the occupants are in a state of thermal well-being. An analysis has also been carried out of construction characteristics and activities carried out in educational centres that previous literature has considered to be influential on comfort.

As previously presented, much literature identifies educational centres as vulnerable spaces. Firstly, due to their construction characteristics, they have a high density of occupants [2]. Secondly, due to the age of their occupants [4], because of their age, as they are still in their developmental years, they are more vulnerable to environmental conditions, since when at a younger age, they are less able to adapt to these conditions to achieve thermal comfort or take active measures.

The literature review has presented the relationship between comfort achieved in different climates and case studies; on this topic, a debate is generated between investigations. A discussion generated in the literature is the influence of climate on the adaptability of its occupants and perception of comfort, especially in more extreme climates, where in the case of very hot climates [40]–[42], [53], how adaptability and the discrepancy between the thermal limits of comfort set by different standards and that perceived by the occupants, both for very hot climates [40], [41] and very cold climates [42], [53].

Gaps have also arisen in the influence of different characteristics on comfort [10], as many previous researchers focused their studies on the numerical comfort results and not so much on the characteristics of the case study analysed.

The most debated feature in terms of its influence on thermal comfort is the ventilation system, as the current trend is towards the use of mechanical (or hybrid) systems.

Previous research has been found to argue that the insertion of such mechanical systems is not necessary, especially in more temperate climates, where it is ensured that thermal comfort and ventilation conditions are achieved by natural means alone [80], [110]. Meanwhile, in other research, the argument and conclusions are the opposite, with better conditions in mechanically ventilated centres [12], [13], [24].

Understanding the current situation in schools concerning thermal comfort and the influence of ventilation is one of the main objectives from which many questions arise. Focusing on the Basque Country (BC), case studies will be selected in this geographical context, and an attempt will be made to answer the questions that arise following the outline in Figure 3-1.

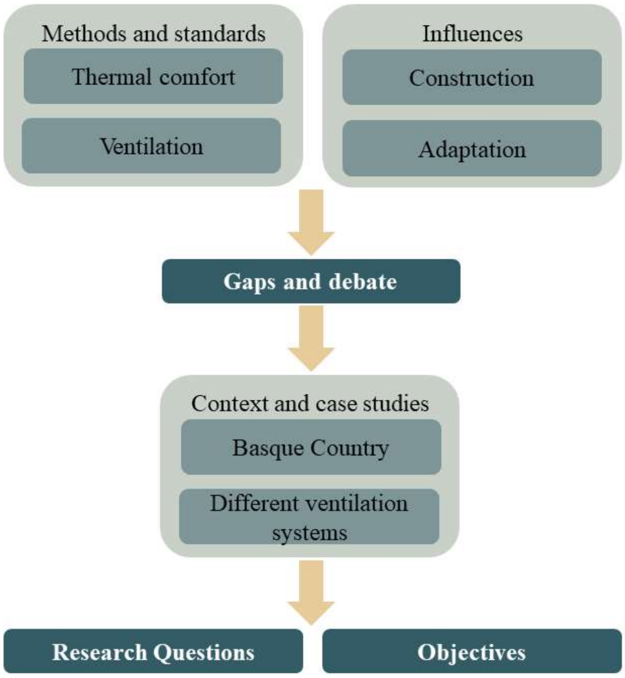


Figure 3-1. Proposed graphical abstract

3.2 RESEARCH QUESTIONS

Understanding the debate and gaps raised in the literature review, multiple questions are raised in the BC context. This thesis aims to answer these questions and respond to the debates generated in the literature in the context of the BC, focusing on what conditions and influences currently affect thermal comfort and ventilation in classrooms and, at the same time, to understand the factors that influence and improve indoor conditions in the future.

- What are the centres in the BC like? Based on selected case studies and the characteristics identified as influential in the literature review, what characteristics are different in the centres and their functioning?
- What comfort is being achieved in schools? In particular, what hygrothermal comfort and ventilation levels are being achieved during the different occupancy phases of the schools? Do these values achieve the recommended regulated values?

- What construction and activity characteristics influence the achievement of this comfort? If they do, how much are they influencing it? Especially given the debate generated in the literature review, does the ventilation system have an influence? Are mechanical ventilation systems in classrooms necessary to achieve greater hygrothermal comfort and better ventilation?

3.3 OBJECTIVES

The answer to the previous questions defines this thesis's framework and content. Its answer reaches the main objective of this thesis, which is the current situation of hygrothermal comfort and ventilation in the educational centres of the Basque Country and which characteristics influence it.

In order to achieve this main objective, multiple sub-objectives have been developed that aim to answer the research questions previously posed by characterising, measuring, analysing and discussing the data obtained in the selected schools (Figure 3-2). Resolving these partial objectives will result in developing a phased methodology that will respond to each objective.

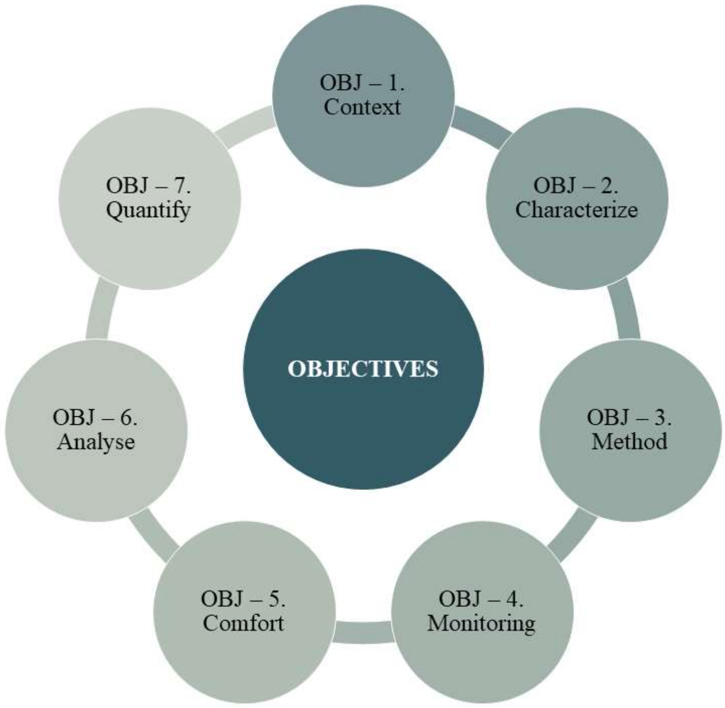


Figure 3-2. Partial objectives of the thesis.

- OBJ-1 Context. In order to select educational centres that are representative of the BC, the first objective is to classify the educational centres of the Basque Country according to their properties, needs, requirements and limitations that influence thermal comfort as previously analysed in the literature review, taking in special consideration the ventilation system.

- OBJ-2 Characterise. Once the case studies have been selected, analyse and characterise the selected educational centres. To identify the main parameters that influence thermal comfort and ventilation in educational centres, as well as which parameters to measure, it has been studied through the analysis of the extensive previous literature on this subject, reflecting which are the most influential parameters, both constructive and behavioural. After this classification, a selection of those case studies that are considered representative has been made. With this partial objective, it is intended to achieve a complete characterisation of the case study schools according to the characteristics considered influential and representative according to the literature review that impacts comfort.

- OBJ-3 Method. According to the literature review, monitoring is the most commonly used method for analysing thermal comfort and ventilation, followed by surveys and simulations. In some investigations, different methods have been used simultaneously. Therefore, in this thesis, monitoring has been applied to measure and obtain real data on environmental conditions in the different selected classrooms. The aim of this method is, first, to apply a single monitoring protocol, which allows to know the environmental situation in the selected schools continuously, taking into account the different schedules of occupation and characteristics that make each classroom unique. Second, this analysis focuses on real data and not based on perceptions. Third, given the limitations of the case studies, this monitoring protocol will be replicable in future case studies.

- OBJ-4 Monitoring. After fulfilling the previous objective, the monitoring protocol designed will be applied in the multiple classrooms of the selected schools. This monitoring aims to discover what is happening and what environmental conditions are recorded in the case studies. The different phases of occupation that characterise the schools will be relevant in this analysis.

- OBJ-5 Comfort. Establish a single comfort criterion for all classrooms. After analysing the current regulations that limit thermal comfort and ventilation in the literature review, a single criterion will be chosen. This comfort criterion will be defined by different limits, ranges and percentages of time that will be considered acceptable as comfort. Considering these limits, different indicators will be created, which will allow to quantify the comfort achieved in each classroom for each environmental parameter measured individually and jointly.

- OBJ-6 Analyse. Analysis of the comfort conditions reached in each classroom. Having achieved the previous objective of establishing comfort criteria and indicators, the comfort analysis aims to determine what favourable and vulnerable situations occur in each classroom. To achieve this objective, the data obtained from the monitoring and indicators will be used to compare the comfort achieved in the different classrooms. This objective aims to understand the situation achieved in each indicator and the relationships or influences between the different parameters measured. It allows to know if the correct environmental conditions and healthy spaces are being guaranteed in the educational centres.

- OBJ-7 Quantify. Analyse and quantify the influence of different characteristics on thermal comfort and ventilation. To identify those characteristics considered as relevant in the literature review. The objective is to pay special attention to the ventilation system since it has been debated in previous research, as reflected in the research questions. This objective is especially relevant since knowing which characteristics positively or negatively influence the design of educational centres in the future will allow us to design them to achieve better comfort. As the comfort analysis will be carried out with the same monitoring protocol, this objective aims to develop conclusions on the influence of different properties using different statistical methods.

4 METHODOLOGY

According to the previous objectives, this chapter sets out a methodology for assessing the hygrothermal comfort achieved in educational centres and the relationship between comfort and the main influential characteristics. For this purpose, a methodology is proposed that analyses the current situation of educational centres in the Basque Country (BC) from the point of view of hygrothermal comfort and ventilation, divided into three phases (Figure 4-1).

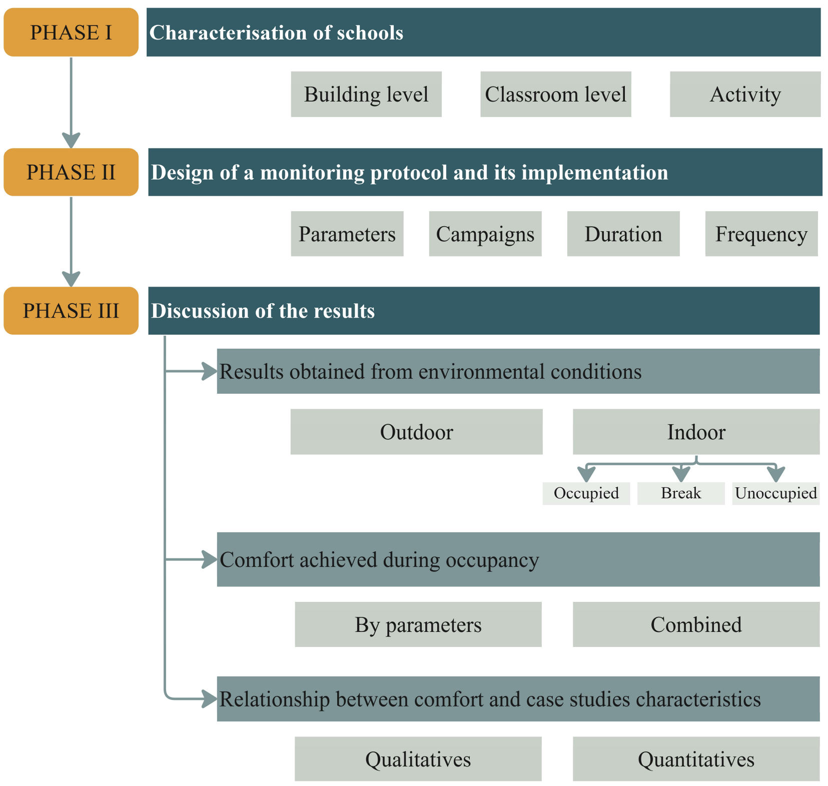


Figure 4-1. Methodology outline

In the first phase, three case studies have been selected based on the activity's constructive and relevant properties, which impact hygrothermal comfort. These three case studies, considered representative, have been characterised according to those characteristics identified in previous literature that have a relevant impact on the classroom's environmental conditions and comfort.

In the second phase, a unique monitoring protocol has been proposed for the selected centres, which can be replicated in future case studies. This measurement protocol makes it possible to obtain real quantitative values of the level of hygrothermal comfort and ventilation in the classrooms continuously during different phases of occupation.

Finally, in the third phase, the interpretation of comfort to be used is defined, and which standards, previously defined in the literature review, have influenced this term. The impact of the different characteristics analysed in the case studies on comfort will also be analysed in this discussion of the results.

4.1 PHASE I: CHARACTERISATION OF SCHOOLS

As analysed in the literature review, different characteristics of educational centres that influence the hygrothermal comfort of their occupants have been identified. This section groups and highlights the characteristics of the selected case studies (Figure 4-2).

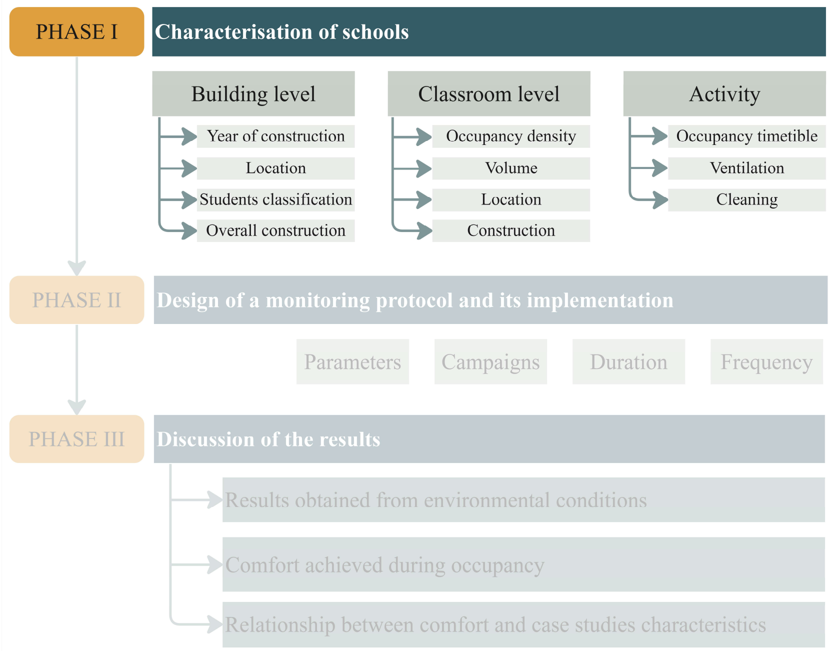


Figure 4-2. Methodology phase I outline

The field of study of this thesis focuses on the Basque Country (BC). Therefore, a characterisation of all BC educational centres was first carried out to select the case studies. This characterisation is developed according to objective OBJ- 1, which states that it is necessary to know the context before selecting the case studies.

The characterisation has been developed in the '10.2 ANNEX 2: Characterisation of schools in the Basque Country' where, with the information provided by the Department of Education of the Basque Government, all schools have been characterised according to the information accessible through their respective cadastres [127]–[129]. Those characteristics set as influential in the decision-making process of the case study and those details that were accessible and interpreted this information have been defined. With this collection and interpretation of information, the decision and criteria followed for selecting the case studies have been made.

This characterisation has helped identify the educational centres' qualities and establish a basis for choosing the three case studies that will be the object of study of this thesis. In the analysis based on the year of construction, it has been observed that most educational centres are old and have not been renovated for the most part. It is therefore deduced that the indoor environmental conditions will be deficient concerning those more modern centres, where there are more significant construction requirements and the implementation of mechanical ventilation systems that guarantee them. In turn, these more modern centres, considered to have a mechanical or hybrid ventilation system as required by the Regulation on Thermal Installations in Buildings (RTIB) after its publication in 2007, are not very representative of the total number of educational centres in the BC, with 65 centres built after 2007 out of the 1142 centres (5.69%). Of the 1142 centres listed in the Basque Government's database, three centres, which respond to different criteria, have been selected.

The year of construction was particularly relevant when choosing the case study centres, as this date influences the different construction standards required in each period. For this study, the required maximum transmittances and the ventilation system incorporated in the buildings were particularly relevant.

As this thesis aims to analyse both hygrothermal comfort and classroom ventilation, it has been considered relevant to analyse more recently built schools. It is considered that the environmental conditions achieved indoors are closer to comfort as since 2006, there have been more restrictive transmittance requirements, and therefore, better thermal comfort will be achieved.

As analysed in '10.2 ANNEX 2: Characterisation of schools in the Basque Country', most centres are outdated and have not been renovated, so conditions close to comfort are expected not to be guaranteed, especially in the colder months. As can be seen from the literature with case studies in similar climates, it is not possible to guarantee comfort conditions, especially in the colder months [8]. It is considered that in these centres, it is necessary to carry out renovations to achieve minimum thermal transmittance conditions that facilitate the achievement of comfort.

Following the criterion of selecting more modern schools, their transmittances are lower and more similar, thus allowing for a better comparison of the results obtained and a better analysis of the influence of the ventilation system in particular and the influence of many other construction characteristics.

Therefore, three schools with different ventilation systems were chosen using this criterion. Among these schools, the impact of multiple construction characteristics on the comfort achieved in each classroom was analysed. With this analysis, observing the different limitations and opportunities generated by each ventilation system has also been possible.

These centres have been chosen in the same city, Vitoria-Gasteiz (north of Spain). Despite the limitation of not selecting centres from different provinces and not being from the most numerous province such as Bizkaia, it is located in the most abundant climatic typology of the BC according to the Köppen-Geiger classification Cfb (humid temperate climate with mild summer) [95].

Once the three case studies had been chosen, an interview was conducted with the centre to detect possible vulnerabilities and learn critical information about each centre. These interviews provided key information about their behaviour and the limitations caused by COVID-19, for example, implementing a COVID plan in each centre and how they have altered their ventilation behaviour or access to classrooms. Some of the schools also expressed the presence of different pathologies, such as infiltration leaks or problems caused by the maintenance of the facilities.

This interview has also served as a support for the selection of the classrooms that have been chosen as case studies. Firstly, because of the collaboration and active participation of the teaching staff, as well as their constructive characteristics, to obtain greater representativeness of classroom typologies to study the impact of different characteristics.

Subsequently, following objective OBJ-2, each centre was characterised according to the most relevant characteristics identified in previous literature. Table 4-1 lists those properties that will be analysed in the three case studies. These properties have been divided into three groups according to their scale, first at the building level, second at the classroom level and third at the activities carried out in each classroom.

Table 4-1. Characterisation of case studies

Building level	Year	Year of construction		
		Year of renovation		
	Location	City	City name	
			Population	
			Population density	
			Climate	
		Situation	Location in the city	
			Proximity sources	
	Students	Classification		
		Age group		
		Number of students		
	Construction	Number of floors		
		Orientations		
		Installations	Ventilation system	Natural
				Hybrid
				Mechanical
			Heating system	Centralized
				Active during monitoring
				Operation system
			Cooling system	
		General conditions		
Classroom level	Classroom selected			
	Occupancy (average)			
	Volume	Classroom volume (m^3)		
		Classroom surface (m^2)		
		Classroom occupancy density (m^2 /student)		
		Volume occupancy density (m^3 /student)		
	Location within the school	Floor		
		Orientations		
	Solar Protection	Typology		
		Operation		
	Construction	Window area (m^2)		
		Window opening capacity (m^2)		
		Window to Wall Ratio (WWR) (%)		
		Daylight Factor (DF) (%)		
Activity	Occupancy	Building occupancy hours		
		Classes timetable		
		Timetable of other extracurricular activities in the school		
	Cleaning	Frequency of cleaning		
	Ventilation	Ventilation protocol	During occupancy	
			Overnight	
			Ventilation frequency recording	

At the building level, the year of construction has been considered relevant due to the construction requirements set by different technical standards, and in case the centre has been renovated, the year of renovation. Its location, not only in which city, but also the city's characteristics, i.e. its population density, green areas, and the climate in which it is located, because of its influence not only directly on comfort but also on the design of the building. The school's location within the city and proximity to external agents that produce acoustic and environmental pollution are also characterised. The school's age range, level of education and number of students, which will limit the occupancy densities and levels of activity throughout the centre, are considered relevant. Finally, aspects related to the construction of the building, such as the number of floors, orientation, and facilities that compose it, considering its typology and operating hours (ventilation, heating, cooling), construction materials and its state of conservation.

At the classroom level, the first step was to identify the classroom to be studied and its average occupancy. Then, its surface area and volume were measured, obtaining information such as occupancy density. Regarding the location of the classroom within the school, its orientation and the floor on which it is located were considered key. Finally, a characteristic identified in the literature as very influential on hygrothermal comfort and ventilation is the window's surface area; obtaining relevant data such as the opening capacity of these and their relationship with the façade, window-to-wall ratio (WWR), and the relationship between the window's surface area and the classroom's surface area, daylight factor (DF). Related to the design of the openings is the shading system that accompanies it, analysing its typology and time of use.

In terms of the activity carried out, three factors were considered: the timetable for occupancy of the building and classrooms, the frequency of cleaning in the classrooms and, finally, the ventilation protocols and the involvement of the teaching staff when it comes to ventilation. This last section aims to determine whether the centre had any minimum requirements for classroom ventilation during classes or breaks.

These characteristics have been analysed and compared in section '5.1.1 Constructive properties', where their relationship with hygrothermal comfort and ventilation has subsequently been quantified in section '5.3.3 Relation between comfort and constructive '.

4.2 PHASE II: DESIGN OF A MONITORING PROTOCOL AND ITS IMPLEMENTATION

Once the constructive properties of the building, the classrooms and the activity carried out in the educational centres have been analysed, in this second phase of the methodology, a measurement strategy has been designed, which, following OBJ-3, has established monitoring as the measurement method. This monitoring protocol can be applied to any Basque Country (BC) educational centre and has been implemented in the three selected case studies (Figure 4-3).

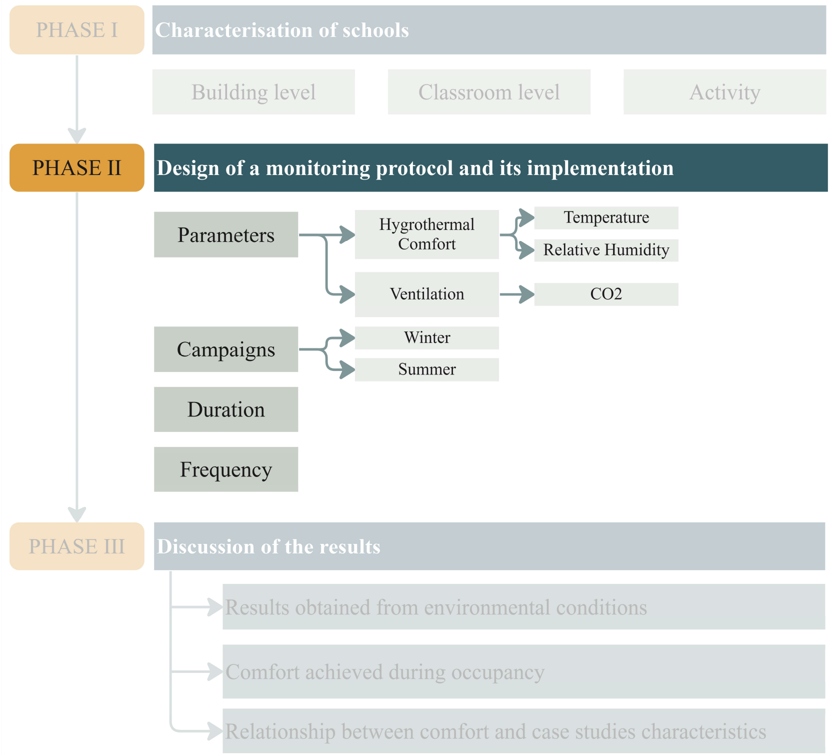


Figure 4-3. Methodology phase II outline

Considering the results in 10.2 ANNEX 2: Characterisation of schools in the Basque Country, the chosen case studies have different ventilation systems and are very common construction typologies in BC. With the monitoring protocol proposed, real data will be obtained that allows, on the one hand, the environmental conditions and comfort achieved in the classrooms to be evaluated and, on the other, the influence of the characteristics analysed on comfort to be studied.

This monitoring plan consisted of two campaigns at the most vulnerable times during the school term for this climate. The first campaign during winter (10 January to 28 January) on returning from the school holidays coincided with the coldest days of the year. The second pre-summer campaign (24 May to 11 June) is just weeks before the end of the school year, with the hottest days outdoors coinciding with the school calendar. For simplification, these two campaigns will henceforth be referred to as winter and summer, respectively. Each campaign monitored each school continuously for one week, simultaneously monitoring the different classrooms selected in each building, following objective OBJ-4.

This thesis aims to determine hygrothermal comfort and the impact of different ventilation systems on achieving comfortable conditions. Following those indicators used in previous literature and limited by the standards that refer to hygrothermal comfort and ventilation limits, temperature and relative humidity have been measured to obtain information on hygrothermal comfort and CO_2 concentration as an indicator of the ventilation level.

One sensor per classroom was used for monitoring. RTR-576 sensors have been used [130], which are non-dispersive infrared (NDIR) sensors with internal storage and online data transmission. These sensors measure CO_2, temperature and relative humidity with a range of 0 to 9999 ppm, 0 to 55 °C and 10 to 95%, respectively and with an accuracy of ± 50 ppm, ± 0.5 °C and ± 1%, respectively. Monitoring these three parameters makes it possible to obtain the hygrothermal comfort (temperature and relative humidity) and classroom ventilation (CO_2) conditions.

The sensor's location, being only one per classroom, is highly vulnerable to the interpretation of the results. For this reason, all the recommendations of previous literature and standards have been followed to choose their location in each classroom. The sensors were placed at approximately 1m height, as recommended by the UNE-EN ISO 7726 standard [79], emulating the height at which students breathe. They were also placed at a distance from where the students and teachers sit to prevent them from breathing on top of the sensors, as this would mainly alter the results obtained for CO_2 concentration. For this reason, a minimum distance of 1 m from the students' and teachers' seats has also been established, and the sensor has also been placed to avoid possible draughts and direct solar radiation through the windows.

The measurement frequency selected was 2 minutes. This frequency was chosen mainly to have information during the break periods between classes because, in one of the case studies, they only have breaks of up to 15 minutes, so if a more common frequency were chosen, such as 5 minutes, only two measurements would be obtained, considering this number insufficient information to develop in the results section. Therefore, a higher frequency was chosen, with measurements every 2 minutes.

Table 4-2 summarises the chosen monitoring protocol, applied in all case study schools, to compare the results obtained and be easily replicable in future research.

Table 4-2. Monitoring protocol summary

Number of case studies	3	educational centres
Number of classrooms per case study	3	classrooms
Number of sensors per classroom	1	temperature, relative humidity and CO_2
Number of monitoring campaigns	2	winter and summer
Duration of each campaign	1	week
Frequency of measurement	2	minutes

4.3 PHASE III: DISCUSSION OF THE RESULTS

This section explains how the results obtained in the monitoring will be analysed and how the comfort achieved is defined through the monitored parameters and the standards that limit it (Figure 4-4).

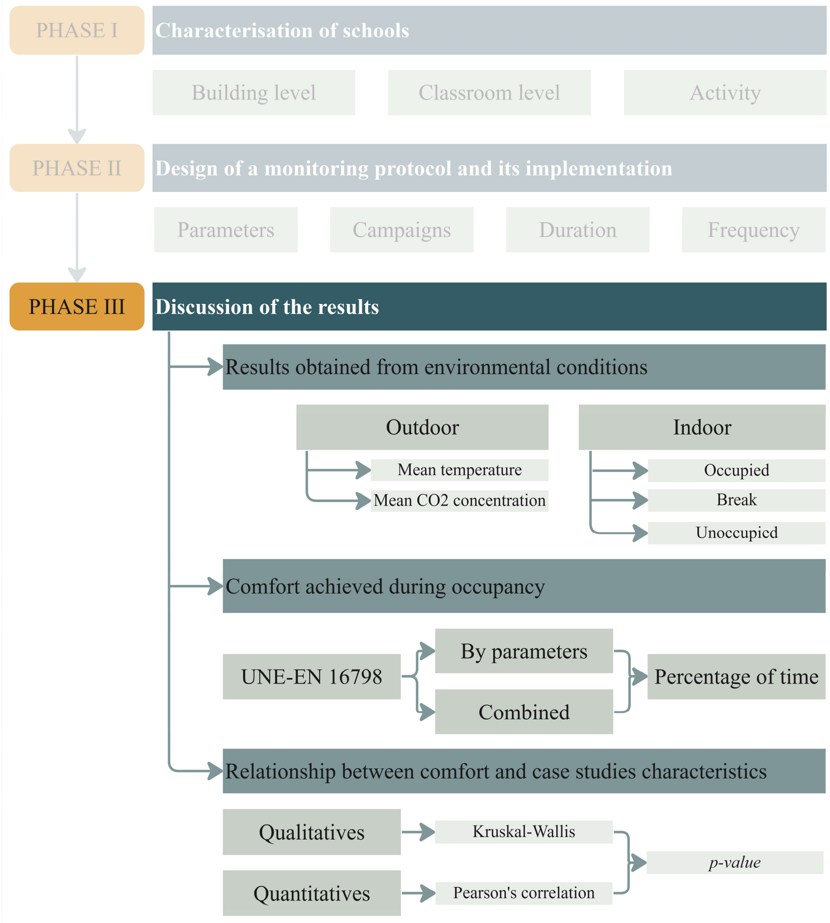


Figure 4-4. Methodology phase III outline

This analysis of the monitored data aims to gain a better insight into the current situation regarding hygrothermal comfort and ventilation and the schools' needs and requirements, allowing further analysis of the impact of different features on achieving comfort in classrooms following objective OBJ-5.

Throughout the analysis, occupancy in the measured classrooms has been differentiated into three categories. First, when the classrooms are occupied, when there are classes and students are in the classrooms. Second, during break periods between occupied periods, those break periods between classes lasting more than 5 minutes where the classroom is occasionally empty due to classes not being held in the classroom, such as physical education or music, and therefore temporarily empty; or break or lunchtime, while the school is still busy and occupied. Finally, classrooms are considered unoccupied when classes end at the end of the day according to each timetable until the following day when classes resume or during the weekend, when they may be occupied by cleaning staff.

Considering the different occupancies in classrooms is especially relevant in the analysis of CO_2 concentration, as it serves as an indicator of classroom occupancy since the occupants are the leading emitter, producing it naturally during respiration.

The results obtained from the monitoring have been analysed in three different parts. First, the results were analysed directly for the three measured parameters indoors, analysing the conditions achieved indoors, and an analysis of what happens according to the types of occupancy previously described has been carried out (OBJ-5). In the second part, only the data from occupied classrooms were selected to analyse the comfort situation (OBJ-6). Finally, this comfort level in each classroom was compared with the previously selected characteristics to analyse the influence and impact they may have (OBJ-7).

4.3.1 Results obtained from environmental conditions

With the data obtained from the monitoring, following the OBJ-4 objective, a first analysis was carried out for the three average parameters (temperature, relative humidity, and CO_2). These provide information on classroom hygrothermal comfort and ventilation levels (OBJ-5).

First, it is necessary to know the outdoor environmental conditions since using adaptive models will limit classroom comfort ranges. Secondly, the conditions inside the classrooms will be analysed, differentiating by type of occupancy, occupied, resting or unoccupied.

4.3.1.1 Outdoor environmental conditions

Following adaptive comfort models, outdoor environmental conditions have been considered. Due to the technical limitations of the sensors used in this research, measuring the same period outdoors as indoors was not possible.

For this reason, the outdoor temperature and relative humidity data for this research were obtained from the open-access public administration database [131]. Different weather stations, which measure continuously, are located in different parts of the city. The station closest to the three case studies was used in this case.

Analysing the average monthly outdoor temperatures has helped to detect the most vulnerable months, observing the months with the lowest temperatures and those with the highest. Once these most vulnerable months had been observed and compared with the school calendar, selecting the two measurement campaigns with the most vulnerable temperatures for the three centres was possible, as they were monitored continuously.

To obtain the outdoor CO_2 concentration, the same RTR-576 sensors were used. Due to technical limitations and unfavourable outdoor environmental conditions, it was only possible to carry out this outdoor monitoring on some days at the same time as the monitoring campaigns (maximum of three consecutive days). Hence, the data extracted from these results is the average CO_2 concentration, which is the basis for the UNE-EN16798 standard for limiting CO_2 concentration indoors.

In gathering information on temperature, relative humidity, and CO_2 for the limits set by the UNE-EN 16798 standard, only the average outdoor temperature and the average outdoor concentration of CO_2 have been considered. Having obtained this starting point, which has been used to calculate the time in comfort, this section will obtain the average monthly outdoor temperature for the months analysed in both monitoring campaigns and the average CO_2 concentration for each school.

4.3.1.2 Indoor environmental conditions

Classroom monitoring was carried out continuously for one week in each centre. For this reason, knowing the occupation schedules in the classrooms was essential. This section aims to know the actual situation of the classrooms throughout the different phases of occupation, i.e. what environmental conditions occur inside them and what ranges are reached.

This analysis was carried out based on occupancy, when classrooms are occupied by teachers and students, during break times between classes, or when classrooms are unoccupied at the end of classes.

For this purpose, the three parameters measured (temperature, relative humidity and CO_2 concentration) in each classroom for each season have been analysed. This analysis uses medians, minimums, maximums and ranges during the winter and summer for those classrooms monitored in both seasons.

The results are represented and analysed using quadrants, where the actual distribution of the parameters measured in each case can be observed, making it possible to know which is the most vulnerable time when the most unfavourable times for achieving comfort occur, such as the highest concentration of CO_2 or temperature values outside the comfort range, both higher and lower values, as well as relative humidity.

4.3.2 Comfort achieved during occupancy

Once the values obtained from the monitoring have been analysed in the previous sections, this section aims to establish comfort limits for these values, allowing the analyses and comparison in which comfort is reached in each classroom.

For this reason, this part of the methodology sets out how comfort will be analysed, choosing the analysis period only when the classrooms are occupied since it is mainly relevant to know the comfort situation of the occupants.

The adaptive model and the limits set by the UNE-EN 16798 standard have been followed to evaluate this comfort. Within this standard, there are different ranges of requirements as analysed in previous literature; category II has been chosen in this analysis, as it is the most commonly applied.

A single comfort criterion has been considered for the three schools, following the OBJ-5 objective, even though they have different ventilation systems. The standard distinguishes between different ways of measuring the hygrothermal comfort limits depending on the air-conditioning system, being for mechanically cooled buildings using temperature limits set for the prior sizing of the installations and for those buildings without a mechanical ventilation system or mechanical cooling, using equations which limit the minimum and maximum comfort temperatures indoors depending on the average monthly outdoor temperature.

Therefore, a single criterion limiting comfort has been chosen, as the adaptive model is the current trend [2], allowing to compare the results between different classrooms under the same criterion. Considering these comfort limits, this methodology section has been divided into two parts.

First, to achieve objective OBJ-6, each parameter measured in each classroom was analysed individually, measuring the percentage of time spent in comfort during the occupied periods of each campaign.

Secondly, the percentage of time that each classroom remains in comfort has been measured when the three parameters measured are simultaneously in comfort (simultaneous comfort) when hygrothermal comfort and ventilation levels established by the UNE-EN 16798 standard are simultaneously achieved for the three parameters monitored, making it possible to obtain a single indicator that makes it easier to compare the results obtained in each classroom.

For hygrothermal comfort, temperature and relative humidity were measured. The temperature is limited by the standard UNE-EN 16798 [63] defined in Figure B.1 and calculated using equation B.1 of the same standard. These limits are calculated based on the average monthly outdoor temperatures between 10 °C and 30 °C. Then, in Equation 4-1, the calculations for the thermal comfort limits are presented, where T_{sup} (°C) is the upper-temperature limit, T_{inf} (°C) is the lower temperature limit, and T_{me} (°C) is the average monthly outdoor temperature. When the outdoor monthly averages exceed the marked limits (10 °C and 30 °C), T_{me} is replaced in the equation by 10 °C or 30 °C as appropriate.

$$T_{sup} = 0.33 \cdot T_{me} + 18.8 + 3$$
$$T_{inf} = 0.33 \cdot T_{me} + 18.8 - 4$$

Equation 4-1. Comfort limits operative temperature

According to UNE-EN 16798 [63], the limits for relative humidity are only specified in section B.3.3, presenting different ranges for the sizing of humidification and dehumidification installations in buildings that require it due to their singular use. These relative humidity ranges have been considered for this research as ranges that limit comfort, being limited between 25 and 60% for category II.

The CO_2 concentration has been used to indicate classroom occupancy and to allow a more detailed differentiation between occupied and unoccupied classrooms. It has also been used to assess the level of ventilation in classrooms. Its concentration is limited in the standard by three different methods, as defined in the literature review. The method chosen is the second method of the UNE-EN 16798 standard. [63] where good ventilation is defined as a function of the indoor CO_2 concentration. A maximum difference from the average outdoor concentration limits this indoor CO_2 concentration. In the case of the chosen category II, a maximum concentration of 800 ppm compared to the average outdoor concentration. This limitation is defined by considering a CO_2 emission standard of 20l/(h/person).

The results in this section have been analysed using the percentage of time spent in comfort, comparing between classrooms and centres. In previous standards, such as ASHRAE-55 for its comfort equations, it is limited to an 80% favourable vote. In other cases, the acceptance rate is 90% when there is a higher requirement for thermal comfort. The acceptance percentage of 80% has been derived based on a 10% overall dissatisfaction (PMV and PPD indices) and an additional 10% for possible local thermal discomfort.

Therefore, 80% could be an indicator to follow in this section as a sufficient percentage of time in comfort. Subsequently, the rest of the time that does not remain in comfort will be evaluated as to whether the classrooms are above or below each limit marked accordingly.

4.3.3 Relationship between comfort and case studies characteristics

In this last part of phase III of the methodology, following objective OBJ-7, the analysis to be carried out to calculate the possible relationship between the different characteristics of the educational centres considered relevant and the comfort achieved in each classroom studied is proposed. This part will make it possible to find out how different characteristics influence the achievement of comfort through the different parameters measured in the educational centres of the BC. This influence will make it possible to improve the future design and quality of educational centres, know which construction characteristics are most influential in achieving comfort, and detect possible vulnerabilities.

After characterising the schools and analysing the hygrothermal comfort and ventilation achieved in the classrooms measured in the previous sections, this part of the methodology quantifies the relationship between this characterisation and comfort.

Previously, the literature review has pointed out characteristics that impact school comfort. These were analysed in the first phase of the methodology, choosing the most significant. Those that were different in the different schools and classrooms selected which made it possible to quantify their impact and the variance they could cause.

For this purpose, ten characteristics (Figure 4-5) have been selected and grouped according to their nature, whether they are qualitative or quantitative properties. First, the qualitative properties analysed have been the measurement campaign (season in which they were measured), the ventilation system, the heating system, orientation, the floor number and the type of classroom. Second, quantitative properties have been analysed, such as occupancy density, volume, Window to Wall ratio (WWR), and Daylight Factor (DF).

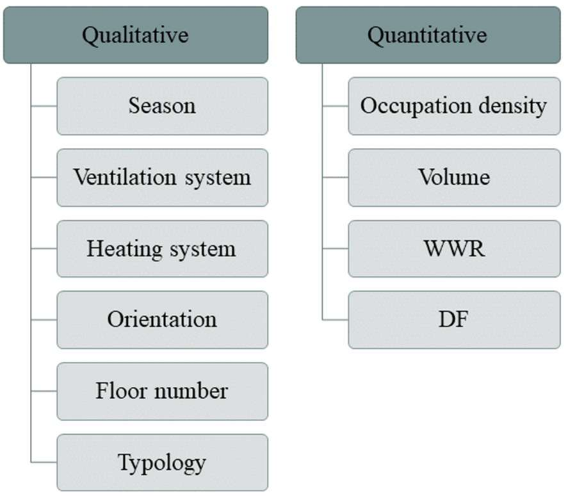


Figure 4-5. Analysed characteristics in phase III by their nature

These selected quantitative and qualitative characteristics have been statistically compared with the percentage of time that each classroom is in comfort. This percentage of comfort has been carried out on the one hand with the simultaneous comfort, when the three parameters are simultaneously in comfort, and on the other hand with each parameter individually, with the results achieved in the previous section of the methodology. This indicator is very sensitive in the most vulnerable cases. Therefore, knowing how it can impact the different comforts is also relevant.

Considering the limitations of the previously proposed indicators, the possible relationship between the characteristics and the different comforts analysed has been calculated and analysed. This analysis will make it possible to detect the impact of these characteristics on comfort and quantify if they do have an impact.

Due to the nature of the data, the Kruskal-Wallis test was performed for the qualitative characteristics [132]. This test compares the distribution and median of two or more groups to determine their differences, thus establishing the hypothesis that this characteristic influences the results obtained. This test has been used because, being a non-parametric test, a normal data distribution is unnecessary. The results obtained from this test will be interpreted using this null hypothesis and with *p-values* that consider whether the relationship obtained is statistically significant.

The results obtained from the Kruskal-Wallis test only indicate whether at least one group obtains medians different from the rest. Nevertheless, to identify which groups obtained this difference, the Dunn posthoc test was used [132], which allows to know the differences between all the groups that are part of the analysed characteristic. This test is applied with the Bonferroni adjustment in case of multiple comparisons.

The quantitative data have been analysed, and their possible relationship with comfort has been calculated using Pearson's correlation coefficient [133], which measures the linear relationship between two quantitative variables. Following Cohen's classification [134], a weak correlation with values between ±0.1 and ±0.3, a moderate correlation with values between ±0.3 and ±0.5 and a high correlation with values higher than ±0.5, with a maximum value of ±1.0, have been considered for both positive and negative relationships.

The relationship was considered statistically significant in both tests when the obtained *p-value* < 0.05. Therefore, the process followed is determining whether the relationship is statistically significant. Subsequently, with the Kruskal-Wallis test according to the degrees of freedom and chi-squared (X^2), the relationship was established, and if this relationship exists, the Dunn test was used to calculate which group does not fulfil the hypothesis. Subsequently, the same process was carried out for the quantitative characteristics, firstly, to determine if the relationship is statistically significant and secondly, to determine the existing relationship according to the ranges indicated by Cohen.

Both tests have been applied to the different measured comforts, first calculated for the previously calculated simultaneous comfort indicator and then to the comforts for each measured parameter. Before these calculations, the influence of the measurement campaign on each comfort achieved was analysed, as it was considered that since the two seasons are the most vulnerable, it is relevant to know the impact that the characteristics analysed have on both campaigns.

5 APPLICATION OF THE METHODOLOGY IN THREE CASE STUDIES

The proposed methodology has been applied in three case studies. This chapter follows the previously described three phases. Each of these phases has a clear objective.

In the first phase, the selected educational centres have been characterised to identify the construction and activity characteristics carried out in these centres to identify those characteristics that define them as unique.

In the second phase, the chosen monitoring protocol is applied in the three centres. It identifies the limitations and barriers encountered in its application.

Finally, in the third phase, the results obtained in the monitoring are analysed, with the aim not only of finding out what environmental and comfort conditions are being provided in each classroom but also of quantifying and detecting possible influences and relationships between their construction and activity characteristics and the comfort achieved.

5.1 PHASE I: CHARACTERISATION OF SCHOOLS

The objective of this first phase is to characterise the case studies. To achieve this objective (OBJ-2), this phase has been divided into two chapters. First, the constructive characteristics at both school and classroom levels are characterised. Secondly, those that refer to the activity in these centres are analysed.

All these data from the first phase were obtained by different means, firstly through interviews with each centre, where it was possible to find out about the activity, timetables carried out in these centres and the different problems they face. Within construction deficiencies, problems of infiltration and high noise from ventilation installations were identified. These interviews were also used to select the classrooms to be measured, mainly by seeking the collaboration of a participative teaching staff.

After the interviews, the different constructive characteristics were analysed, as developed in Table 4-1, which can be found in full in '10.3 ANNEX 3: Characterisation of case studies'.Although it is a methodology that can later be applied to other case studies, a limitation found in this research has been the non-collaboration of the architectural studies, so that different characteristics that can be identified as relevant could not be obtained, such as the detailed construction of the envelope and their transmittances or the design of the ventilation installations, mainly. To cope with this limitation, the required information was obtained by visual observation during the visits to the case studies.

5.1.1 Constructive properties

Three educational centres have been selected for this study, all located in the city of Vitoria-Gasteiz, in the north of Spain. It is a medium-large city with approximately 250,000 inhabitants; it has large areas reserved for parks (33% of its surface area). According to the Köppen-Geiger classification [95], it has a temperate oceanic climate with mild summer (Cfb).

The three selected schools are located in different parts of the city Figure 5-1. The first school (S1) is located in the north of the city in the neighbourhood of Ibaiondo, close to busy roads, while the next school (S2) is located in the neighbourhood of Mariturri, on the outskirts of the city, and the last school (S3) is located in Zabalgana, very close to the city's green belt [135].

Figure 5-1. Case studies location in Vitoria-Gasteiz

As shown in Figure 5-2, S1 is an elementary and pre-elementary school for ages 3 to 12 years, S2 is an elementary and pre-elementary school for ages 2 to 12 years, and S3 is a secondary school for ages 12 to 18.

Figure 5-2. Case studies, from left to right, S1, S2 and S3

In terms of year of construction, S1 was built in 2006, S2 in 2016 and S3 in 2018. All three are relatively new compared to the rest of the schools built in the Basque Region, which was analysed in '10.2 ANNEX 2: Characterisation of schools in the Basque Country', which is why they are generally in an excellent state of maintenance. This date of construction has also influenced the installations required by the building regulations of each period, as reflected in Table 5-3, in the next section, '5.1.2 Activity', which summarises the characteristics of each classroom in terms of its natural and mechanical ventilation system and its operation.

The year of construction also reflects the minimum construction requirements and its thermal construction properties. In each period, reflected by the update of construction standards in the Spanish Technical Building Code (TBC), maximum thermal transmittances are required for each type of enclosure. Therefore, the three selected centres have higher thermal performance compared to the majority of schools built, as most were built in the 1970s.

Without detailed construction data for the three centres, the TBC limit transmittances have been considered. Thus, the transmittances achieved in S1 are at least 0.74 $W/m^2{\cdot}K$ in the façade and 3.1 $W/m^2{\cdot}K$ in the windows. In S2 and S3, there is a transmittance of 0.55 $W/m^2{\cdot}K$ in the façade and 2.5 $W/m^2{\cdot}K$ in the windows.

Considering their installations, the school S1 has no mechanical ventilation system, only the gymnasium, which has a double flow heat with a recovery system and centralised control for its management, which is active during school hours. School S2 has a semi-centralised mechanical ventilation system, which is controlled by the management but has multiple units, usually covering four classrooms in each unit. This system has a double-flow system with heat recovery. The S3 school, which is the most up-to-date, has a centralised mechanical ventilation system with double flow and heat recovery. The only limitation of this system is that due to its noise, the teachers and staff complained about it and in consequence, its power operation remains reduced to 50%.

In each centre, three different classrooms have been chosen. For school S1, an elementary classroom, a pre-elementary classroom, and the gymnasium have been chosen, the same for school S2. For the secondary school S3, a secondary, a technology, and a baccalaureate classrooms have been chosen. The criterion for choosing the classrooms is to select classrooms with different characteristics that subsequently calculate the impact of these different characteristics on the comfort achieved in the classroom.

As for other installations in the three case studies, none have a cooling system. All have centralised heating, controlled by the administration, not the centre's management. Their heating systems are by hot water radiators in all three centres, except in the pre-elementary classrooms in S1 and S2. These two classrooms have underfloor heating, and the gymnasiums have no heating system, only by previously treated supply air. In both schools (S1 and S2), there is a kitchen that only heats the food, so there is no combustion process, and in school S3, there is no kitchen.

For solar protection, in the S1 centre, the gymnasiums have fixed horizontal aluminium louvres for the south-facing window as solar protection. At the same time, the rest of the classrooms in the school have automated blinds that automatically close at night, individually and centrally controlled. The same happens for the elementary classrooms in S2, which have automated blinds in all classrooms, the gymnasium has no sun protection at all, and the pre-elementary classroom has only a horizontal overhang that forms part of the upper floor balcony, which acts in this case as sun protection. In the secondary school, S3, as in the other schools, has automated blinds that are lowered at night for all classrooms. At the same time, in the technology classroom, some of the windows that are facing north have a perforated metal panel that covers the glazing, which acts as a solar protection.

Below, Table 5-1 defines the orientation, floor plan, volume, surface area, window-to-wall ratio (WWR), and daylight factor (DF) for each monitored classroom. For this reason, different classroom characteristics, such as orientation, floor plan, volume, and surface area, have been selected in each centre. Both volume and surface will affect the occupancy density in each classroom.

The orientation and the floor plan in which each classroom is located have been chosen with the typological variety offered by each centre. Concerning volume and surface area, the classrooms in all the centres have similar surface areas and volumes, but in all the centres, a classroom with a bigger size than the rest has been chosen (as can be seen in Table 5-1). Therefore, in S1 and S2, the gymnasiums were chosen; in S3, as it does not have a gymnasium, the technology classroom was chosen.

Table 5-1 shows that all WWR values are higher than 30%, with the S1 gymnasium standing out at 78% and the S2 gymnasium at 47%, compared with the literature review recommendation for warm countries of a maximum of 20%.

In this analysis, not having sufficient information on the characteristics and properties of the openings, only the ratio between the surface area of the opening and the surface area of the classroom has been established. Therefore, by redefining the DF and comparing the values obtained in Table 5-1 for each classroom, all exceed the recommended values of at least 10%. Although two classrooms do not reach the 15% recommended for future designs, the primary classroom of school S1 has 13%, and the pre-elementary classroom of school S2 has 15%.

Table 5-1. Characterization of the studied classrooms

SCHOOL	CLASSROOM TYPOLOGY	ORIENTATION	FLOOR NUMBER	VOLUME (m^3)	SURFACE (m^2)	WWR (%)	DF (%)
S1	Gymnasium	South	Ground floor	1945.4	327.8	78	34
S1	Elementary classroom	North	Second floor	164.4	52.7	32	13
S1	Pre-elementary classroom	South	Ground floor	161.4	54.7	39	16
S2	Gymnasium	South	Ground floor	1060.2	202.6	47	25
S2	Elementary classroom	West	Second floor	149.4	48.9	38	20
S2	Pre-elementary classroom	South	Ground floor	170.3	56.8	48	15
S3	High school classroom	West	First floor	138.4	48.8	40	18
S3	Technology classroom	North and East	First floor	289.0	106.5	31	17
S3	Baccalaureate classroom	West	Second floor	138.4	48.8	40	18

The occupancy density in each centre and each classroom is very different (Table 5-2), especially in centre S3, which, being the newest centre, has a lower number of students enrolled, reflected in a lower occupancy density than the rest. Likewise, the direct relationship with the surface area of each classroom is also observed, especially in the largest classrooms of each centre, the gymnasiums and technology classroom.

Table 5-2. Occupancy density in each classroom

School	Classroom	Occupation density (student/m^2)
S1	Gymnasium	0.08
S1	Elementary classroom	0.47
S1	Pre-elementary classroom	0.26
S2	Gymnasium	0.12
S2	Elementary classroom	0.51
S2	Pre-elementary classroom	0.28
S3	High school classroom	0.41
S3	Technology classroom	0.19
S3	Baccalaureate classroom	0.31

5.1.2 Activity

Regarding the activity carried out in each classroom, the timetable varies from classroom to classroom. As the monitoring was carried out during COVID-19, no extracurricular activities were conducted in any school. COVID-19 influenced the protocols taken in the schools that were influenced by the measures imposed by the regional government [126]. These measures enforced outdoor activity and ventilation as much as possible by cross ventilation, taking advantage of breaks between classrooms and measuring CO_2 concentration to acknowledge the effectivity of the measures.

These measures, known as the COVID protocol in the centres, directly impact classroom environmental conditions. Therefore, when interpreting the monitored results obtained, the occupants' behaviour will be considered as this protocol has limited them.

Related to the ventilation systems and the construction of the buildings, the ability of its users to achieve comfort is limited, as reflected in Table 5-3. As mentioned in the previous section, each centre has different mechanical ventilation systems. In addition, all schools have natural ventilation in most of their classrooms, but to a limited extent.

Table 5-3. Natural ventilation (NV) and mechanical ventilation (MV) operation

School	**Classroom**	**NV**	**Window opening**		**Door opening**	**MV**	**Schedule**	**Control**
S1	Gymnasium	No				Yes	8:30h-17:30h	Centralized
S1	Elementary classroom	Yes	Sliding	Ensure all time	No	No		
S1	Pre-elementary classroom	Yes	Tilted	Ensure all time	Yes	No		
S2	Gymnasium	No				Yes	8:30h-17:30h	Centralized
S2	Elementary classroom	Yes	Tilt-turn	Ensure all time	No	Yes	8:30h-17:30h	Centralized
S2	Pre-elementary classroom	Yes	Casement	When considered	Yes	Yes	8:30h-17:30h	Centralized
S3	High school classroom	Yes	Tilt-turn	When considered	No	Yes	7:30h-15:30h	Centralized
S3	Technology classroom	Yes	Tilt-turn	When considered	No	Yes	7:30h-15:30h	Centralized
S3	Baccalaureate classroom	Yes	Tilt-turn	When considered	No	Yes	7:30h-15:30h	Centralized

School S1 has the most significant application with their COVID protocol to ventilate due to the lack of a mechanical ventilation system. In the elementary classrooms on the first and second floors, the sliding windows had to be kept open at least 5 cm at all times, taking advantage of the breaks to open them completely. In these classrooms, the doors were kept closed during lessons because of the noise, but during breaks, they were occasionally entirely opened at the teachers' discretion. In the pre-elementary classrooms on the ground floor, there is a small tilted window on the façade, which was always kept open when the classrooms were occupied, and a door connected outside, which was opened when the teacher considered it necessary. In this case, the door to the internal corridor was always kept open, allowing for better cross-ventilation. Finally, in the gymnasium, natural ventilation can only be achieved by infiltration through the windows as these cannot be opened, ventilating only by its mechanical ventilation system.

In school S2, despite having mechanical ventilation in all the classrooms, it was suggested to the teachers to keep the windows open while teaching took place. Therefore, in the primary classrooms on the first and second floors, at least the tilt-and-turn windows were always kept in a tilted position and occasionally, depending on the teacher, fully opened during breaks or when weather permitted it. The doors to the inner corridor were only opened occasionally during breaks. In the pre-elementary classrooms on the ground floor, there is only one door on the façade, as the window is fixed and cannot be opened. This door was only opened for student access from the outside and when weather permitted it. The door leading to the interior corridor was always open.

In school S3, with mechanical ventilation in the entire centre, teachers were encouraged to open the tilt-and-turn windows at their discretion. In addition, in this school, the ability to open tilt-and-turn windows is limited by key access, so only teachers can open them. Therefore, at the teachers' discretion, classroom windows were opened occasionally. At the same time, the doors are always locked. Occasionally, during lessons, they are kept open but, at the same time, are permanently closed during breaks for security reasons.

In all schools, cleaning is done daily at the end of classes, and all schools have implemented within their COVID protocol that windows are to be kept fully open while cleaning. All centres keep windows, doors, and blinds closed at night for security reasons, preventing passive ventilation and passive cooling at night.

COVID-19 and the protocols used in the three centres have significantly impacted the means of ensuring ventilation and the perception and knowledge of the teaching staff and students. The sensitivity of the teaching staff to this issue is significant, as they are responsible for ventilating and, if accessible, changing indoor comfort conditions.

For example, in the primary classroom in school, S1, the teacher wanted to involve his students in the monitoring that was being carried out as part of this thesis. So, they took a reading of the monitored data (Figure 5-3), which was also explained in class, and measures were taken to improve their conditions.

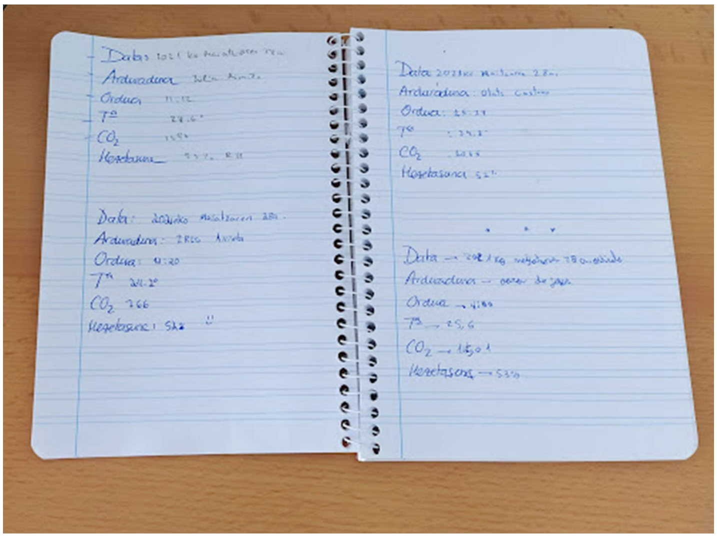


Figure 5-3. Reading of the monitored data by students in the elementary classroom in S1

The S3 school had a COVID delegate to ensure correct classroom conditions. To achieve this goal, the COVID delegate had a portable sensor that measured the point concentration of CO_2 at the time (Figure 5-4). For this purpose, he measured the CO_2 concentration in different classrooms throughout the morning. The concentration was considered high when it exceeded the 700 ppm set by the Basque government's COVID guideline recommendation [126]. When this concentration was high at the time of measurement, teachers were urged to open the windows and the door to increase ventilation in the classroom, thus reducing the CO_2 concentration.

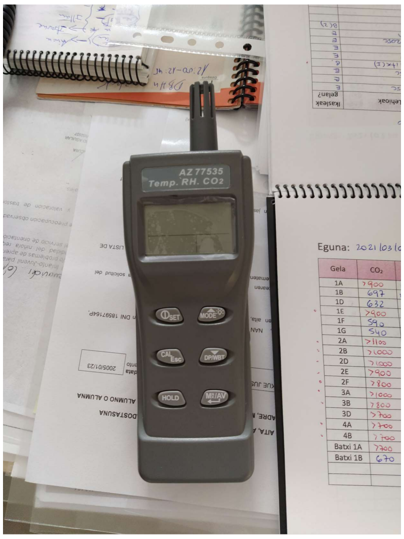
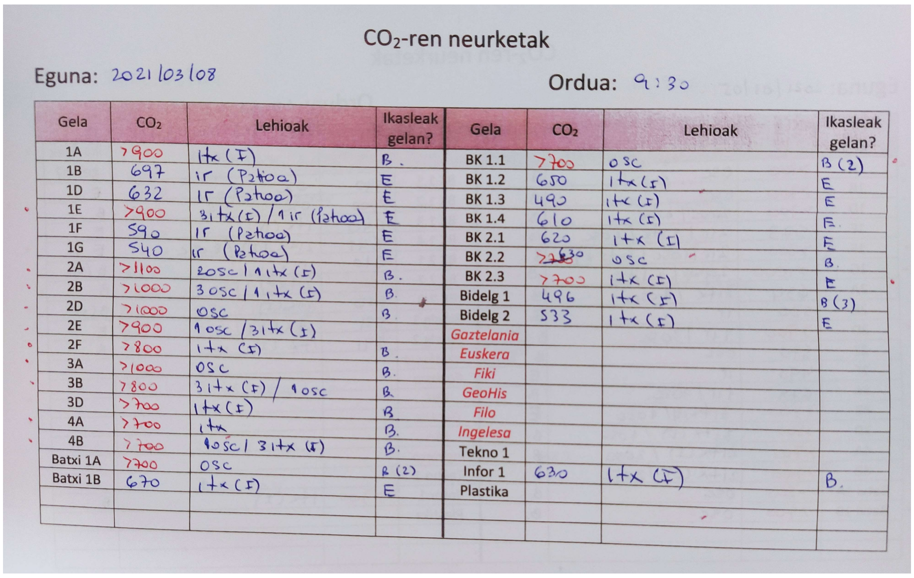


Figure 5-4. Portable CO_2 sensor used in S3 by COVID responsible

Although the classrooms had a mechanical ventilation system activated during all hours of occupancy, as shown in Figure 5-5, CO_2 often exceeded 700 ppm after several hours of teaching in the morning.



CO_2-ren neurketak

Eguna: 2021/03/08 Ordua: 9:30

Gela	CO_2	Lehioak	Ikasleak gelan?	Gela	CO_2	Lehioak	Ikasleak gelan?
1A	>900	1tx (I)	B.	BK 1.1	>700	osc	B (2)
1B	697	1r (Patioa)	E	BK 1.2	650	1tx (I)	E
1D	632	1r (Patioa)	E	BK 1.3	490	1tx (I)	E
1E	>900	3 1tx (I) / 1 ir (Patioa)	E	BK 1.4	610	1tx (I)	E
1F	590	1r (Patioa)	E	BK 2.1	620	1tx (I)	E
1G	540	ir (Patioa)	E	BK 2.2	>630	osc	B.
2A	>1100	2osc / 1 1tx (I)	B.	BK 2.3	>700	1tx (I)	E
2B	>1000	3osc / 1 1tx (I)	B.	Bidelg 1	496	1tx (I)	B (3)
2D	>1000	osc	B.	Bidelg 2	533	1tx (I)	E
2E	>900	1osc / 3 1tx (I)		Gaztelania			
2F	>800	1tx (I)	B.	Euskera			
3A	>1000	osc	B.	Fiki			
3B	>800	3 1tx (I) / 1osc	B.	GeoHis			
3D	>700	1tx (I)	B.	Filo			
4A	>700	1tx	B.	Ingelesa			
4B	>700	1osc / 3 1tx (I)	B.	Tekno 1			
Batxi 1A	>700	osc	B (2)	Infor 1	630	1tx (I)	B.
Batxi 1B	670	1tx (I)	E	Plastika			

Figure 5-5. Monitored data by COVID responsible in different classrooms in S3.

Classroom occupancy is the primary source of CO_2, and the selected schools have different occupancy schedules depending on their typology. S1 and S2 are primary schools, so there is teaching in the morning and afternoon except on Wednesdays when there is only teaching in the morning, with a break of approximately half an hour for snacks and a break of approximately two hours for lunch.

In S1, classes start at 9:15 and finish at 17:00, with a difference of more or less 5 minutes for each class so that not all students enter and leave at the same time as part of their COVID protocol. The same protocol of different access and exit times happen in S2, but with a timetable from 9:00 to 16:30. In S3, which is a secondary and baccalaureate school, teaching is concentrated only in the mornings and midday, from 8:15 to 14.15, never in the afternoon. They do not have the same daily timetable and have 15-minute breaks every two classes.

5.2 PHASE II: DESIGN OF A MONITORING PLAN AND ITS APPLICATION

When applying the proposed methodology in the selected case studies, two monitoring campaigns have been carried out during the most vulnerable periods, the first during the coldest weeks of the school year from 10 to 28 January.The second campaign was carried out during the hottest weeks of the school year before the summer holidays, from 24 May to 11 June, from now on summer. The monitoring was conducted continuously for one week in each school, simultaneously in the different classrooms and with a monitoring frequency of 2 minutes. This monitoring plan follows the above-described objective OBJ-3.

While in the winter campaign, three classrooms were monitored due to technical limitations, during the summer campaign, only two classrooms per school could be measured for shorter periods outside. Table 5-4 shows the codes to refer to each monitored classroom and the periods when they were monitored during both campaigns.

Table 5-4. Monitoring period and code of the studied classrooms

School	Classroom	Code	Monitoring period	
			Winter	Summer
S1	Gymnasium	S1U01	10 January - 14 January	24 May - 28 May
S1	Elementary classroom	S1U02	10 January - 14 January	24 May - 28 May
S1	Pre-elementary classroom	S1U03	10 January - 14 January	NA
S2	Gymnasium	S2U01	17 January - 21 January	31 May - 4 June
S2	Elementary classroom	S2U02	17 January - 21 January	31 May - 4 June
S2	Pre-elementary classroom	S2U03	17 January - 21 January	NA
S3	High school classroom	S3U01	24 January - 28 January	7 June - 11 June
S3	Technology classroom	S3U02	24 January - 28 January	7 June - 11 June
S3	Baccalaureate classroom	S3U03	24 January - 28 January	NA

When choosing the location of the sensors in the classrooms, although it was tried to place them as similarly as possible, as each classroom has unique characteristics, it was taken into account the limitations and possibilities of each of them to choose the location, responding to the characteristics of each classroom taking into account the limitations previously mentioned, avoiding possible drafts, direct solar radiation or avoiding the alteration of results due to proximity to students (Figure 5-6). For this reason, the sensors have always been placed on top of desks or auxiliary furniture, simulating the height of the students, except for pre-elementary classrooms and gymnasiums. In the pre-elementary classrooms, they were placed higher to prevent them from reaching the sensor. Furthermore, the sensors were placed in a more protected position on the gymnasium's perimeter due to electrical connection limitations and to avoid possible impacts.

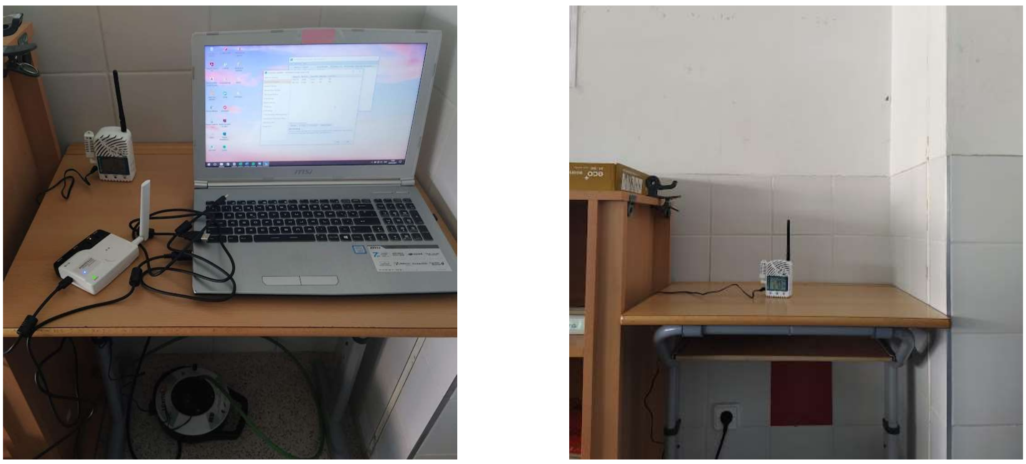


Figure 5-6. Installation and programming of the sensor in classroom S1U01

For monitoring, RTR-576 [130] sensors have been used, which are nondispersive infrared (NDIR) sensors with internal storage and online data transmission, which measure CO_2, temperature and relative humidity with a range of 0 to 9999ppm, 0 to 55 °C and 10 to 95% respectively and with an accuracy of ±50 ppm, ±0.5 °C and ±1% respectively.

The sensors used have multiple operating options (

Figure 5-7). These sensors can stream live monitoring results on their web-based platform, T&D WebStorage Service [136] or store the results on the internal memory card in the sensor.

Due to the lack of free internet access in the educational centres, the data has been stored on the internal card. To avoid possible confusion or errors every time the sensor's location has been changed, the stored data have been downloaded using the RTR500BW program itself [137].

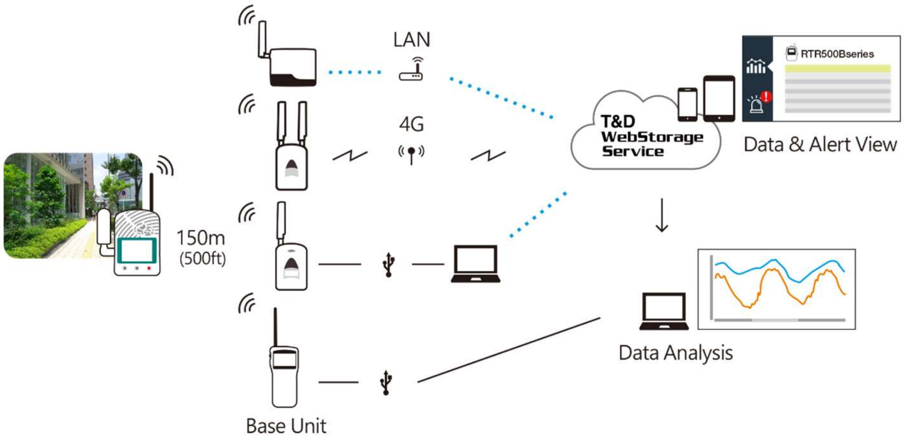


Figure 5-7. Schematic diagram of sensor operation [130]

5.3 PHASE III: DISCUSSION OF THE OBTAINED RESULTS

Once the characterisation of the schools (Phase I) and the monitoring plan that has been applied in these schools (Phase II) have been established, the objective of Phase III is to know what hygrothermal comfort and ventilation are being achieved in the selected schools and the influence that different characteristics have on this comfort. Following this thesis's objectives OBJ-4, OBJ-5, OBJ-6, and OBJ-7, this third phase is divided into three parts, with partial objectives that help achieve the stated objective.

As shown in Figure 5-8, the indoor and outdoor environmental conditions obtained in the three case studies during the different occupancy phases are analysed in the first part. In the second part, the results obtained during the occupied periods are analysed according to the UNE-EN 16798 standard, which establishes different limits and ranges to consider comfort. Finally, in the third part, the comfort achieved is compared with the different characteristics of each case study.

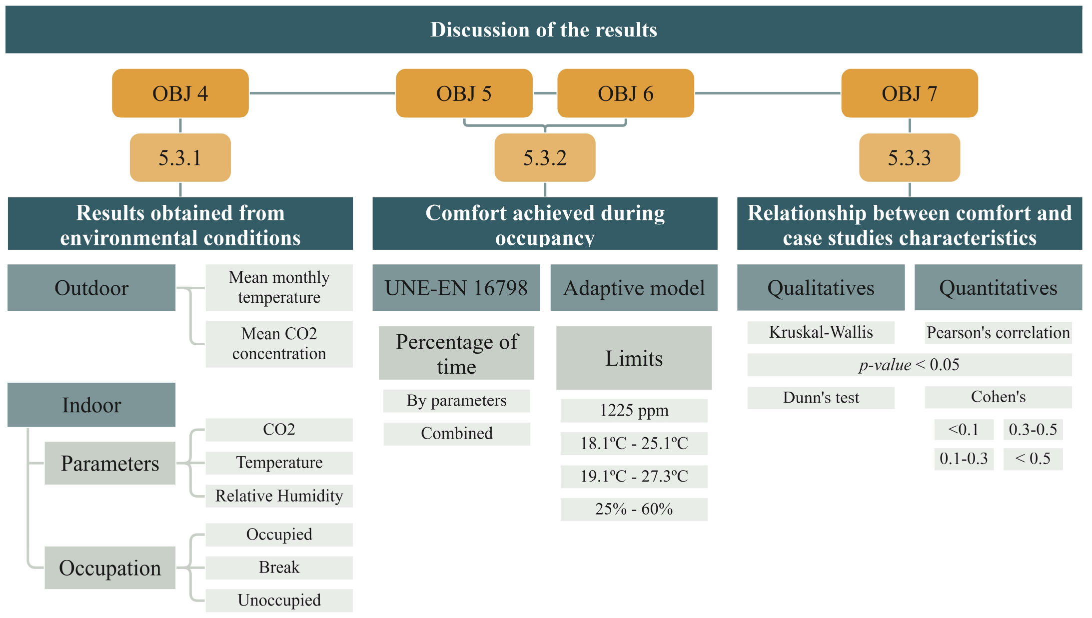


Figure 5-8. Application of the methodology phase III outline

5.3.1 Environmental conditions obtained

This first section analyses the outdoor and indoor environmental conditions in the three case studies following OBJ-4. First, outdoors, the type of climate of Vitoria-Gasteiz has been analysed. Then, the three parameters chosen as indicators for comfort, temperature and relative humidity for hygrothermal comfort and CO_2 concentration for ventilation levels were analysed and will be considered when studying indoor environmental conditions.

The environmental conditions achieved in the three case studies have been analysed in the second part. The results obtained for the same three parameters that serve as indicators of hygrothermal comfort and ventilation in the measured classrooms, CO_2 concentration, temperature and relative humidity, are compared. In this section, the analysis has been separated according to the occupancy in the different classrooms.

5.3.1.1 Outdoor environmental conditions

Outdoor climate strongly influences the design of centres [94]. The three schools selected are located in the city of Vitoria-Gasteiz. According to the Köppen-Geiger classification [95], Vitoria-Gasteiz is in a Cfb climate. This climate, known as western coastal maritime (oceanic), is characterised by cold or mild winters with average temperatures between -3 °C and 18 °C and cool summers with an average temperature above 10 °C in the warm months. Precipitation is well distributed throughout the year [138].

This section analyses the outdoor indicators used in the UNE-EN 16798 standard to limit indoor comfort. For this purpose, this section analyses the outdoor results for temperature, relative humidity and CO_2 concentration, although only the outdoor temperature and CO_2 concentration values will limit the indoor comfort values.

The average monthly outdoor temperature was the first criterion for outdoor environmental conditions. This data not only allows us to calculate the limit range for the indoor temperature but also to know the evolution of outdoor temperatures. These temperatures were analysed to select the two monitoring campaigns during the school calendar, choosing those where the maximum and minimum averages were recorded.

As mentioned above, monitoring was done for short periods outside each centre. The same sensors have been used indoors for temperature and relative humidity. The open-access data of the public administration in its Open Data Euskadi data catalogue has been used [131]. This open-access data contains hourly information on temperature, relative humidity and outdoor irradiance.

With these two sources of real data, the administration's open access data was used to analyse the average monthly temperature and relative humidity for the whole calendar year in which the monitoring was carried out. The CO_2 concentration outside was obtained from the monitoring data, as it was possible to measure it immediately outside each building during the winter campaign.

Table 5-5 summarises the average monthly outdoor temperature and relative humidity. Data from the public administration for the weather station near the city centre on Gasteiz Avenue was used.

Table 5-5. Mean outdoor temperature and relative humidity

Month	Mean temperature (°C)	Mean relative humidity (%)
January	5.31	74.53
February	7.42	72.93
March	8.72	67.64
April	9.84	64.88
May	13.18	66.82
June	16.73	72.59
July	18.14	70.62
August	18.17	72.61
September	17.92	73.23
October	13.17	71.80
November	7.26	81.01
December	6.75	85.01

Analysing the temperature results obtained for the selection of the monitoring campaigns, it was found that the coldest month is January, which is why the first measurement campaign began in January after the Christmas school holidays. Although the months with the highest average outdoor temperatures are July and August, as there is no teaching in these months, and in

September, classes have different timetables and start late in the month, June was chosen. At the same time, classes finish in mid-June, so the last week in May had to be monitored.

Once these two monitoring campaigns have been selected for the following section, using the equations presented in the UNE-EN 16798 standard, these monthly outdoor temperatures will limit the indoor comfort temperature. For January, it is 5.31 °C, for May 13.18 °C and 16.73 °C for June.

Relative humidity provides information not only on outdoor environmental conditions but also on its influence on the occupants' perception of comfort. However, the indoor comfort limit is not limited by the data obtained outdoors. The values obtained in Table 5-5 show how the average varies progressively each month, with the maximum average relative humidity in December (85%) and the minimum in April (65%).

To analyse the outdoor CO_2 concentration, the same RTR-576 were used, although for shorter periods, due to the technical limitations of the sensors. These sensors were located in the immediate exterior of each school

Figure 5-9. At school S1, in the covered bicycle parking area next to the main entrance to the building. In school S2, on the library balcony on the first floor. In school S3, on the shutters of the still disused classrooms of the school.

Figure 5-9 Exterior of the case studies, from left to right, S1, S2 and S3

Once the monitoring results at each centre had been obtained, the oscillation of the CO_2 values was first analysed, obtaining the hourly average for each centre. Subsequently, the average outdoor CO_2 concentration was analysed for each case study as necessary data to limit the comfort of the indoor concentration.

Figure 5-10 analyses the hourly average outdoor CO_2 concentration for each case study over 24 hours. In all schools, it can be seen that as activity increases during school hours, the outdoor CO_2 concentration also increases.

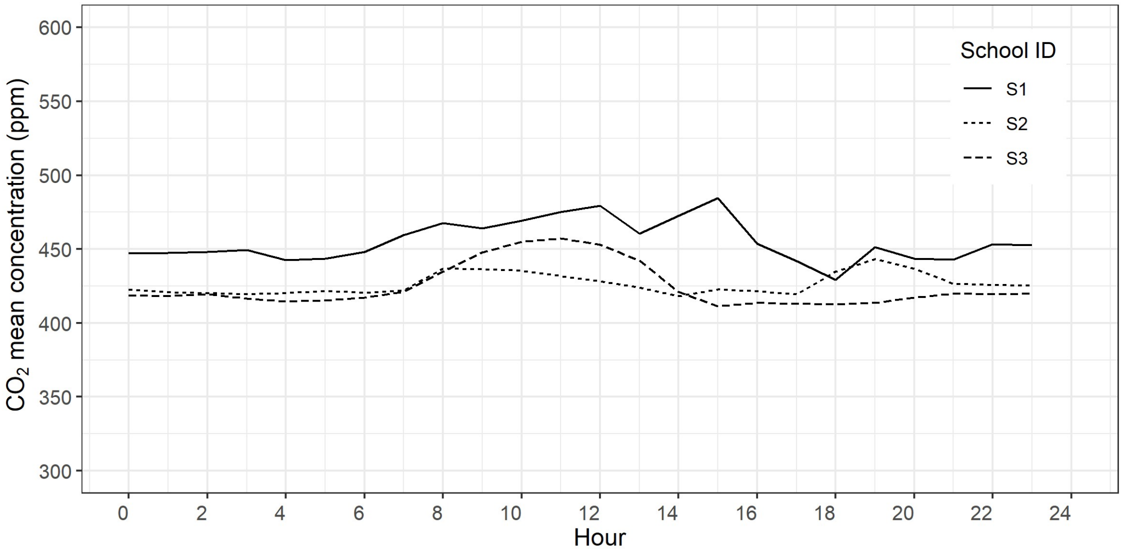


Figure 5-10. Outdoor CO_2 mean hourly concentration in each school measured

Analysing the outside concentration in each school, Figure 5-11 shows the different percentiles for each case study from which the mean concentration has been extracted in Table 5-6.

The most significant variance in CO_2 concentration is observed at school S1, with a mean of 456.35 ppm, reaching a maximum value of 591 ppm and a minimum of 411 ppm; followed by school S3, which has the lowest average of the three schools with an average concentration of 425.85 ppm, but with values reaching a maximum of 553 ppm and a minimum of 394 ppm. Finally, school S2 has an average of 426.87 ppm with a minimum of 407 ppm and a maximum of 500 ppm.

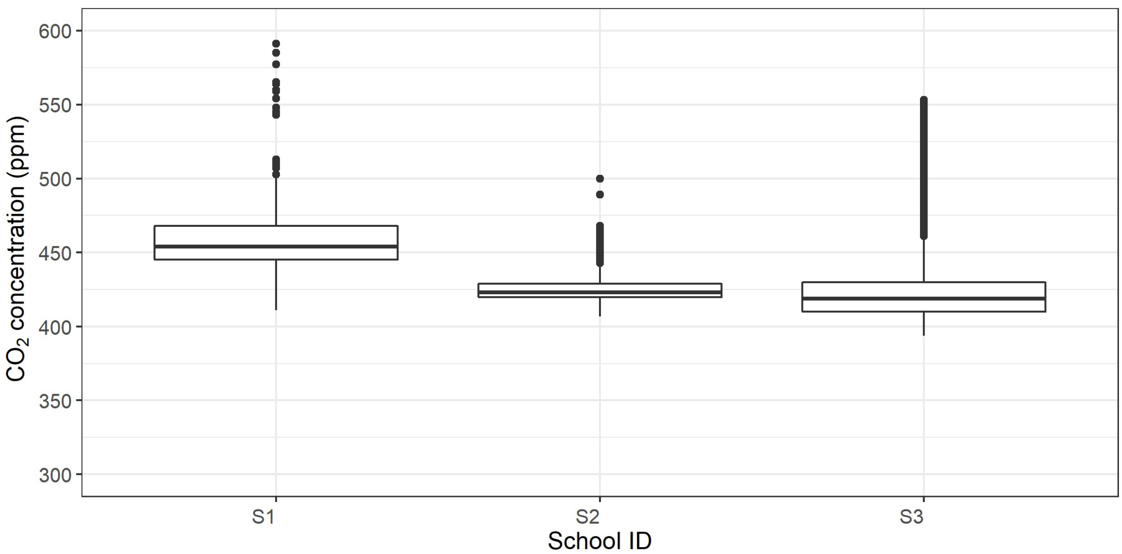


Figure 5-11. Outdoor CO_2 concentration distribution per location

As this section aims to obtain the average CO_2 concentration outdoors, the results obtained for each case study are shown in Table 5-6. The criterion chosen was to use the same limit for all sites. As the outdoor measurement in each centre has been short, less than a week, the most restrictive average has been used, i.e., the lowest of the three centres, which will limit indoor CO_2 concentration comfort criteria.

In this case, it has been with the lowest CO_2 mean concentration. The S3 school, with an average of 425.85 ppm, an average of 425 ppm will be considered for further calculations.

Table 5-6. CO_2 outdoor mean concentration values

	S1	S2	S3
Mean concentration	456.35	426.87	425.85

5.3.1.2 Indoor environmental conditions

The monitoring campaigns were carried out continuously for one week in each centre. This way, temperature, relative humidity, and CO_2 concentration data were obtained during each centre's different occupation and disoccupation periods.

This section aims to determine each classroom's environmental conditions according to occupancy. Although only comfort during occupied periods will be analysed later, the influence of rest and unoccupied times is relevant, as previous literature has shown [31], where using correct strategies allows for ventilation and passive control of indoor temperature.

In the development of this section, the type of occupation in the classroom has been analysed, so it has been divided into three parts: firstly, when the classrooms are occupied. Secondly, when they are on break and thirdly, when they are unoccupied, in each occupancy stage, the three measured parameters have been represented by the quartiles reached in each campaign. Representing the absolute minimum at 0%, the median at 50% and the absolute maximum at 100%, where the 25% and 75% percentiles of the points measured are also key in some sections.

5.3.1.2.1 Occupied periods

The following is an analysis of the results obtained during the periods spent in the classrooms. Figure 5-12 graphs the CO_2 concentration for each classroom for the two monitoring campaigns. Generally, outstanding results are obtained in all monitored classrooms. As reflected in previous literature, the season in which it is measured indirectly affects the behaviour of the users, so concentrations during the winter are higher as occupants tend to ventilate less to achieve thermal comfort.

At the same time, there is no significant observation relevant to comparing the ventilation systems of each school. S1 has natural ventilation (except for the gymnasium, which has mechanical ventilation), while S2 and S3 have mechanical ventilation. In S3, CO_2 concentration is slightly higher, especially during the winter, compared to the other two schools.

The medians for all classrooms are within the limit established by UNE-EN 16798, the lowest median being recorded in S1U01 in summer with 531 ppm and in winter with 530 ppm. The highest medians are recorded in summer by S1U02 with 737 ppm and in winter by S2U02 with 1079 ppm.

Analysing the maximum values that are reached during winter, classroom S3U03 is the one that reaches the highest concentration with an absolute maximum of 3362 ppm, and during summer, classroom S1U02 has a maximum of 3808 ppm. Although both are absolute maximum values, they do not represent a trend. Since analysing the 75% percentile in both classrooms, in winter for classroom S3U03, it is 1199 ppm, and in summer in classroom S1U02, it is 1071 ppm, so in both classrooms, during these most unfavourable periods for each of them at least 75% of the time they are in comfort.

During winter, the classrooms in the S3 centre have the highest variance, with a maximum difference between their absolute maximum and minimum of 2936 ppm for classroom S3U03. In turn, in the S1 centre, the variance is much lower, reaching its minimum in the gymnasium of this centre (S1U01) with a maximum variance of only 399 ppm.

During summer, school S1 has the most significant difference between its maximum and minimum, reaching its maximum in S1U02 with a variance of 3411 ppm. However, the gymnasium of this school is still the classroom with the lowest variance, with a difference of 397 ppm between its maximum and minimum, followed by S2U01 with a difference of only 406 ppm.

In contrast, classroom S2U02 reaches an absolute maximum of 2234 ppm during winter, and its 75% is at 1324 ppm, above the UNE-EN 16798 limit, making it the classroom with the highest CO_2 concentration during winter.

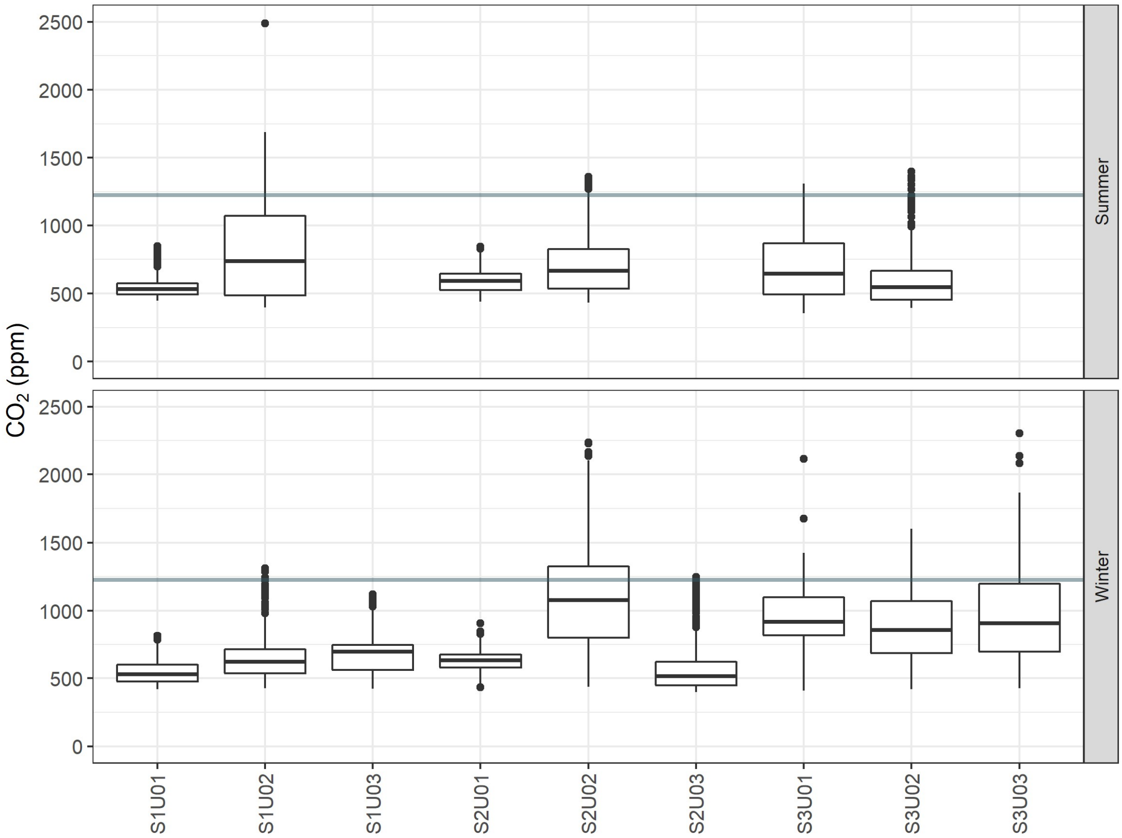


Figure 5-12. CO_2 concentration during occupied periods

Analysing values of hygrothermal comfort during the occupied periods, the results obtained from temperature monitoring (Figure 5-13) and relative humidity (Figure 5-14) in each classroom will be analysed first.

Analysing the temperatures reached in both winter and summer for the different classrooms monitored, the following temperatures are observed, grouped by percentiles for each measurement campaign (Figure 5-13). The maximum and minimum temperature limits according to UNE-EN 16798 have been plotted. These limits depend on the average monthly outdoor temperature in winter; from 10 to 28 January, the lower limit temperature is 18.1 °C, and the upper limit is 25.1 °C. As the monitoring in the warmest period was carried out from 24 May to 11 June, there are two different limits, the lower limit for May being 19.1 °C and the upper limit 26.1 °C in yellow; and for June 20.3 °C and 27.3 °C respectively in blue.

In winter, the two gymnasiums measured in schools S1 and S2 (S1U01 and S2U01) reach temperatures well below the comfort temperatures set by the UNE-EN 16798 limits. In the case of gymnasium S1U01, both in winter and summer, it is the classroom with the lowest temperatures in all percentiles, reaching in winter an absolute minimum of 14.4 °C and an absolute maximum of 17.2 °C and summer an absolute minimum of 18.8 °C and an absolute maximum of 23.7 °C, being the winter values especially vulnerable.

Analysing the median temperatures obtained during winter, the classroom S1U02 stands out. In contrast, during the winter, it maintains a median temperature of 23.1 °C, an abnormally high temperature considering that it is naturally ventilated and the average monthly outside temperature for January was 5.3 °C.

Comparing the median summer temperatures, the two classrooms measured in the S2 centre reach the highest temperatures, with medians reaching 24.9 °C in S2U01 and 25.1 °C in S2U02.

Comparing the maximum temperatures in winter, the S2U03 classroom stands out, reaching an absolute maximum temperature of 26.8 °C (but 75% is at 22 °C), followed by S1U02 with an absolute maximum of 25.6 °C (and 75% at 24 °C). In other words, although the absolute maximum is recorded in S2U03, higher temperatures are found in S1U02. Summer maximums are reached in the S2 centre, with an absolute maximum in S2U01 at 27.7 °C (with 75% at 25.6 °C) and for S2U02 at 27.3 °C (obtaining 75% at 25.7 °C).

Analysing this trend in maximum temperatures, schools S1 and S2 are the ones that, on average, reach the highest temperatures, although they are still within the comfort limits set by UNE-EN 16798 so that overheating is not reached in any classroom during the summer, but only occasionally during the winter (S1U02 and S2U03).

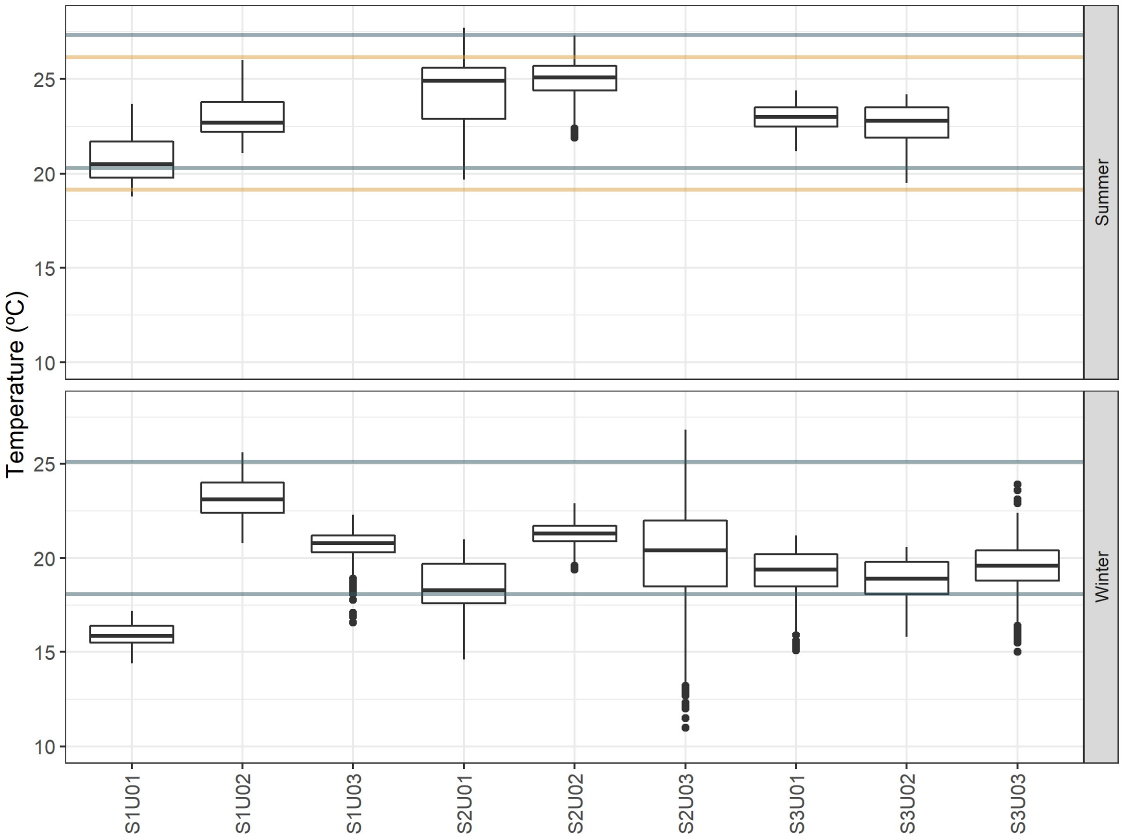


Figure 5-13 Temperature during occupied periods

Analysing the relative humidity data in Figure 5-14 shows the values obtained from monitoring relative humidity (%) by quartiles in each classroom during the occupied period. The limits considered in the UNE-EN 16798 standard have also been plotted, with a minimum relative humidity of 25% and a maximum of 60%.

The results obtained in school S1 stand out, where the variance is much higher than in the rest of the schools in both seasons. In winter, this variance is much higher compared to the rest of the classrooms, while in summer, although it is still higher, the difference is less significant. Analysing the values obtained, in summer, the centre with the highest relative humidity is S3U02, with a median of 52% and an absolute maximum of 63%, i.e. slightly exceeding the limit of 60%.

On the other hand, S1 is the centre with the highest relative humidity measured in the three classrooms during the winter. The highest relative humidity is reached in the gymnasium S1U01, with a median of 46% and a maximum of 68%, with a maximum of 75% at 62%, which means that at least 25% of the occupied time, this classroom exceeds the limits set by the UNE-EN 16798. The lowest relative humidity is reached in summer in classroom S1U02, with an absolute minimum of 31% and a median of 43%.

During winter, very similar values are obtained, with S1U02 recording an absolute minimum of 18% and a median of 25%, i.e. at least half of the time in this classroom, a relative humidity lower than the limit set by the UNE-EN 16798 standard (25%) is recorded. S2U03 reaches an absolute minimum of 18% and a median of 26%, i.e. values very similar to S1U02 and with a high percentage of the time with a relative humidity below the limit set by the UNE-EN 16798 standard.

In all three schools, the relative humidity is higher during the summer season, falling better within the range limited by the standard than during winter. The relative humidity is lower in winter than in summer, which may be mainly due to the use of hot water radiators as heating systems, which reduce the relative humidity level indoors.

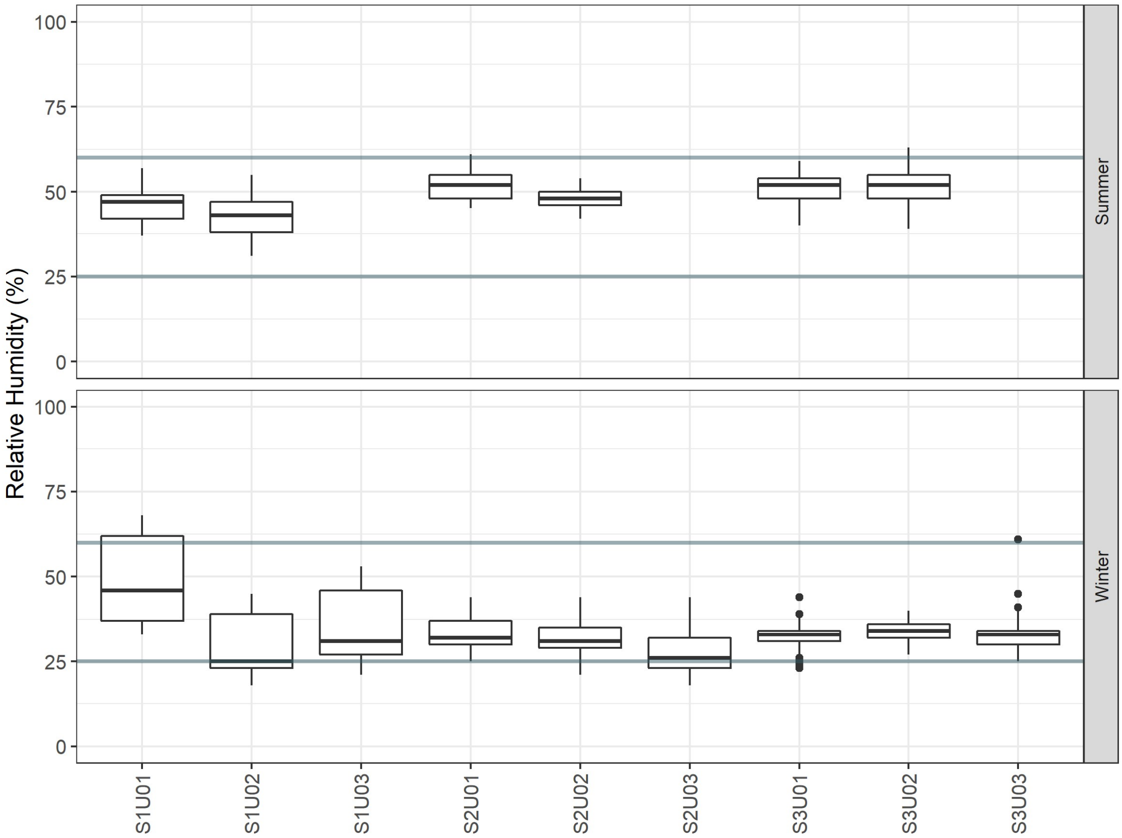


Figure 5-14. Relative humidity during occupied periods

5.3.1.2.2 Break periods

This section analyses the results obtained from monitoring during break periods. A break is considered when students are not in the classroom, but the school is still busy. In other words, when students are at break time for more than 5 minutes or have other classes taught in other classrooms. These break times are key to improving indoor environmental conditions in classrooms as they do not interfere with the discomfort caused by different measures, such as very cold or strong currents, but have a significant positive impact, such as reducing the concentration of CO_2 or avoiding overheating.

Analysing the CO_2 concentration shown in Figure 5-15 as expected in the absence of occupied classrooms, the concentrations obtained are lower than those recorded during occupied classrooms, as described in the previous section.

Comparing the medians obtained, they all obtain values within the comfort limits. However, one classroom with the highest median, S2U02, obtains a lower median in winter (630 ppm) than in summer (677 ppm).

The absolute maximums are reached in winter by S3U01 with 3098 ppm, although the 75% percentile is 978.75 ppm. In summer, the maximum is recorded in classroom S1U02 with 1416 ppm, although again, the 75% percentile is at 817 ppm, and S3U01 has an absolute maximum of 1217 ppm and 75% at 897.75 ppm. That is to say that the absolute maximum values do not represent a high trend but are point values recorded and do not represent a high percentage above the values limited by UNE-EN 16798.

The high values reached in CO_2 concentrations during breaks reflect, on the one hand, that in those classrooms with mechanical ventilation, it is difficult to evacuate the old indoor air and introduce fresh air by mechanical means, and it can be considered that they are not ventilating sufficiently. Also, in those classrooms that are naturally ventilated (S1U02 and S1U03), they obtain lower averages in winter than in summer, so they ventilate faster in winter than in summer, which may be since in winter, there is a more significant difference between the indoor and outdoor temperature than in summer.

Significant mean values were obtained in all classrooms during the break period. It makes no sense to analyse the variance since, at their absolute minimums, they can be considered to have reached a steady state with the environment, equalling the outdoor CO_2 concentration values outside.

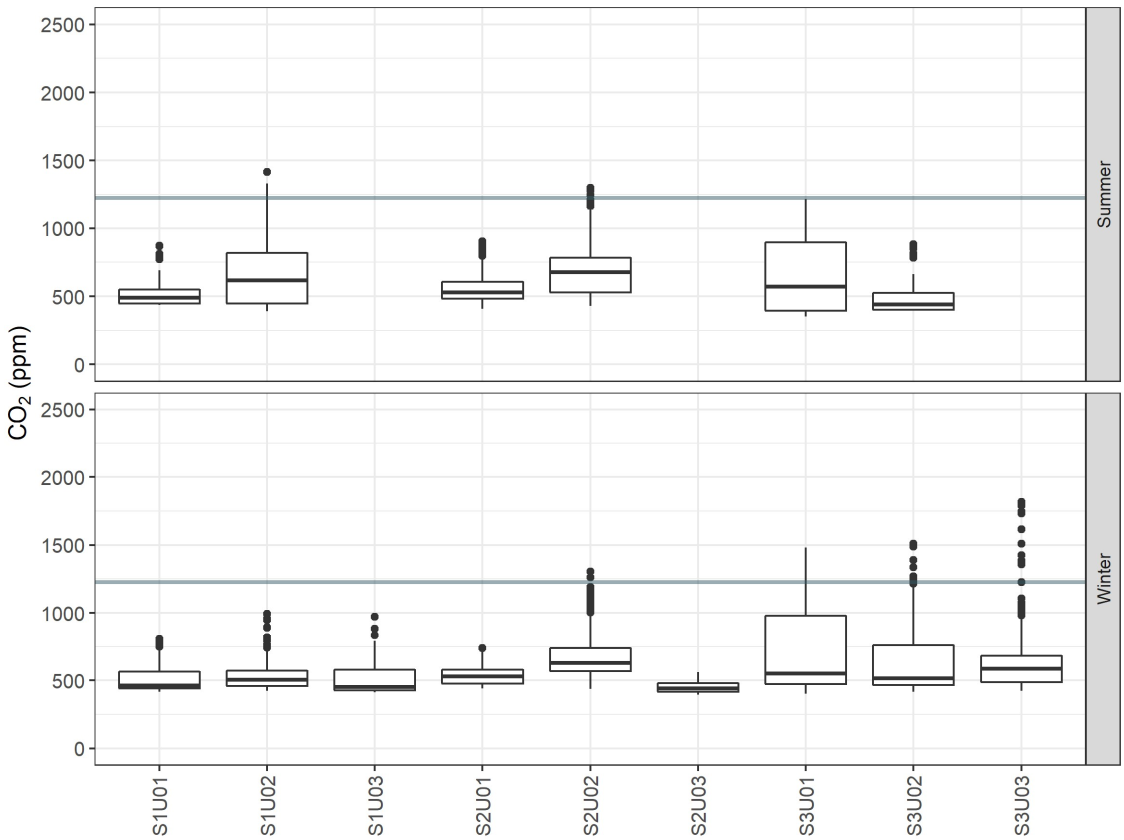


Figure 5-15. CO_2 concentration during break periods

Analysing the temperature reached during break time, Figure 5-16 shows that during the occupied period, the gymnasium in S1U01 is the classroom with the lowest temperature in winter and summer. In winter, it records an absolute minimum of 14.5 °C and an absolute maximum of 17.2 °C with a median temperature of 15.4 °C. In summer, these temperatures range from 18.9 °C to 23.8 °C with a median temperature of 21.8 °C.

Unlike when the classrooms are occupied, in this case, the absolute minimum in winter is recorded in classroom S2U03 instead of the gymnasium. The absolute minimum recorded in S2U03 is 11.9 °C, followed by S3U01 with an absolute minimum temperature of 12.5 °C. Analysing the 25% percentile in both classrooms, they are at 18.1 °C and 16.38 °C, respectively, higher values than those recorded for the 25% percentile in the gymnasium S1U01 with 15 °C.

What stands out in the results obtained during winter are the high temperatures reached in classroom S1U02. Although the heating consumption data was not accessible, it can be deduced that a very high consumption is being reached to maintain such a high temperature.

The second classroom in winter with the highest absolute maximum is S2U01, which reaches 24.6 °C, also reaching the absolute minimum, so the variation in this classroom is the highest. Comparing the averages, the second classroom with the highest median is S2U02 at 21.1 °C, with the second lowest temperature at 19.8 °C.

S2 is the centre with the highest temperatures measured in summer in the two classrooms. While the absolute maximum and 75% are reached in S2U01 with 27.6 °C and 25.7 °C, respectively, this same classroom and S2U02 reach the highest median (24.7 °C). In the case of classroom S2U02, it reaches the highest absolute minimum and 25% percentile (21 °C and 23.7 °C respectively).

These values in S2 reflect the possible vulnerability of overheating in the classrooms of this school. If, even during the breaks, such high temperatures are obtained, the classrooms cannot take advantage of this break to lower their temperatures and achieve better comfort in the following hours of occupation. On the other hand, winter shows an occupancy impact on temperatures, significantly lower during breaks than during occupancy periods. Therefore, outside temperatures impact indoor comfort, as during breaks, some teachers ventilate differently during summer and winter, preventing better indoor comfort.

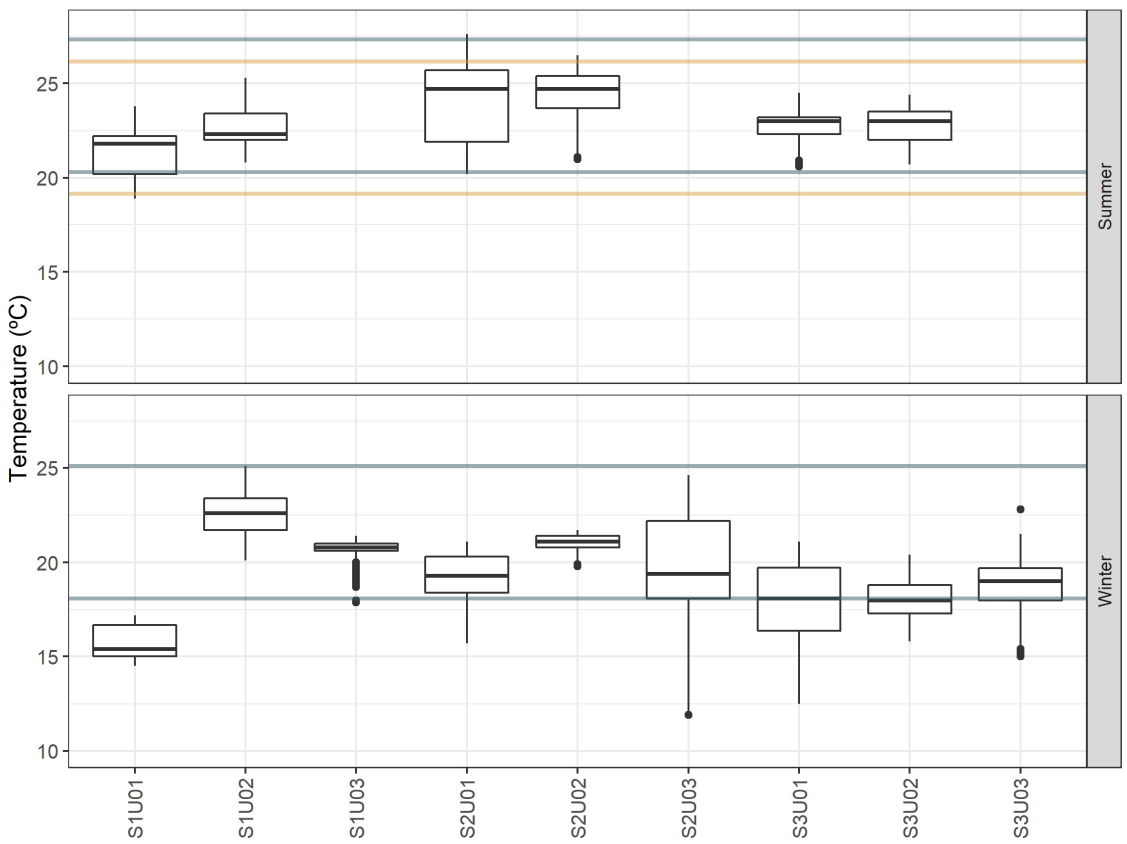


Figure 5-16. Temperature during break periods

Analysing relative humidity during breaks in Figure 5-17, relative humidities are still lower in winter than in summer. The values are similar to those recorded during the occupied periods, although slightly lower in winter and slightly higher in summer.

The S1 centre continues to be the centre with the most significant variation in relative humidity in its three monitored classrooms. In winter, S1U01 is the classroom with the highest relative humidity, followed by S1U03, with absolute maximums of 67% and 51%, respectively. The absolute minimums are around 20% relative humidity in classrooms S1U02, S2U02 and S2U03. However, unlike the other parameters, the 25% percentile is found at a relative humidity of 22% for classrooms S1U02 and S2U03, from which it can be interpreted that there is a tendency for these minimum values to be close to 20%.

Analysing the medians obtained for the relative humidity in the different classrooms, the highest median value is obtained in classroom S1U01 with a median relative humidity of 37%. The classroom with the lowest median relative humidity is S2U03, with 24%. This last value is below the recommended value of the UNE-EN 16798 standard (25%), which means that at least 50% of the time, it is below the limits established by this standard.

During the summer campaign, the classroom with the lowest relative humidity was classroom S1U02. These minimum values were obtained in all percentiles compared to the rest of the classrooms monitored in summer. The absolute minimum relative humidity was 34%, and the absolute maximum was 53%, with a median of 44%. In turn, the highest relative humidity in this campaign was reached in classroom S3U01, with an absolute maximum of 61% and a median of 54%.

In other words, although there is a tendency for low relative humidity in this centre, especially in winter, in summer, it is still the classroom with the lowest relative humidity, obtaining values within the limits set by UNE-EN 16798. Considering this standard's comfort range, better relative humidity is obtained indoors in summer than in winter. Generally, there is no significant difference in the values obtained during occupation.

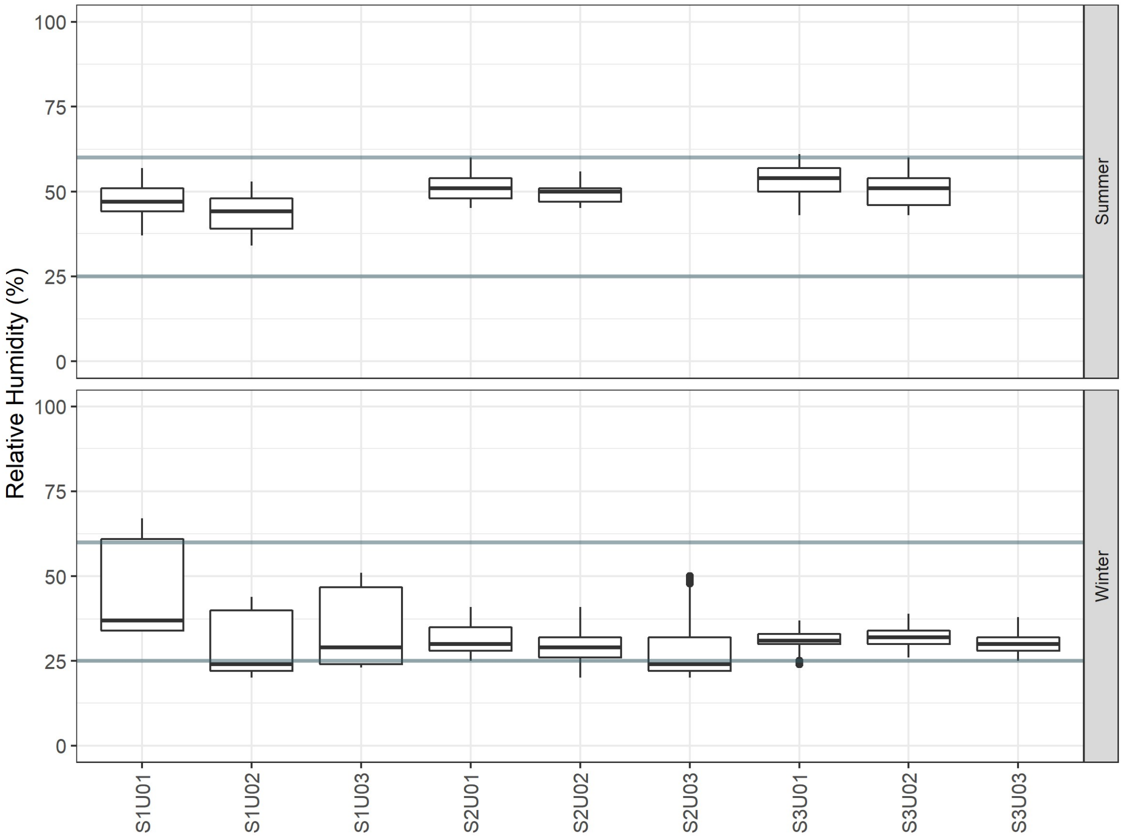


Figure 5-17. Relative Humidity during break periods

5.3.1.2.3 Unoccupied periods

This section analyses the environmental conditions in classrooms during unoccupied periods. The centre is considered unoccupied when teaching finishes at the end of classes and weekends. Although during weekdays within these hours, there is occasional occupation by cleaning staff, who clean in the afternoons when teaching is finished in all the centre classrooms.

Figure 5-18 represents the CO_2 concentration during unoccupied periods. It can be seen that the steady state is reached in all classrooms, as all percentiles are overlapping. Likewise, the maximum values represent specific moments and are not a trend in all the classrooms; this is due, as mentioned above, to the occasional occupation by cleaning staff, which increases the concentration of CO_2 in the interior, or when the classes end at the end of the day, the time it can take for this concentration to reduce.

As the peaks are represented by specific moments and not by trends, it is more interesting to analyse the 75% percentile. For this percentile, the maximum was obtained in winter in classroom S2U01 with 583 ppm. This percentile is more than 100 ppm higher than the rest of the classrooms. This percentile shows how, once the classes have finished, the difficulty this classroom has in reducing the CO_2 concentration is achieved very gradually compared to the rest of the classrooms.

During the summer, all classrooms have overlapping percentiles. The maximum is reached in S2U02 with a 75% percentile of 455 ppm and in S1U01 with 450 ppm. These values are almost identical to the absolute minimums reached in each classroom (a difference of less than 50 ppm between values). From these values, it can be interpreted that the steady state is reached quickly in the classrooms during the summer in the unoccupied periods.

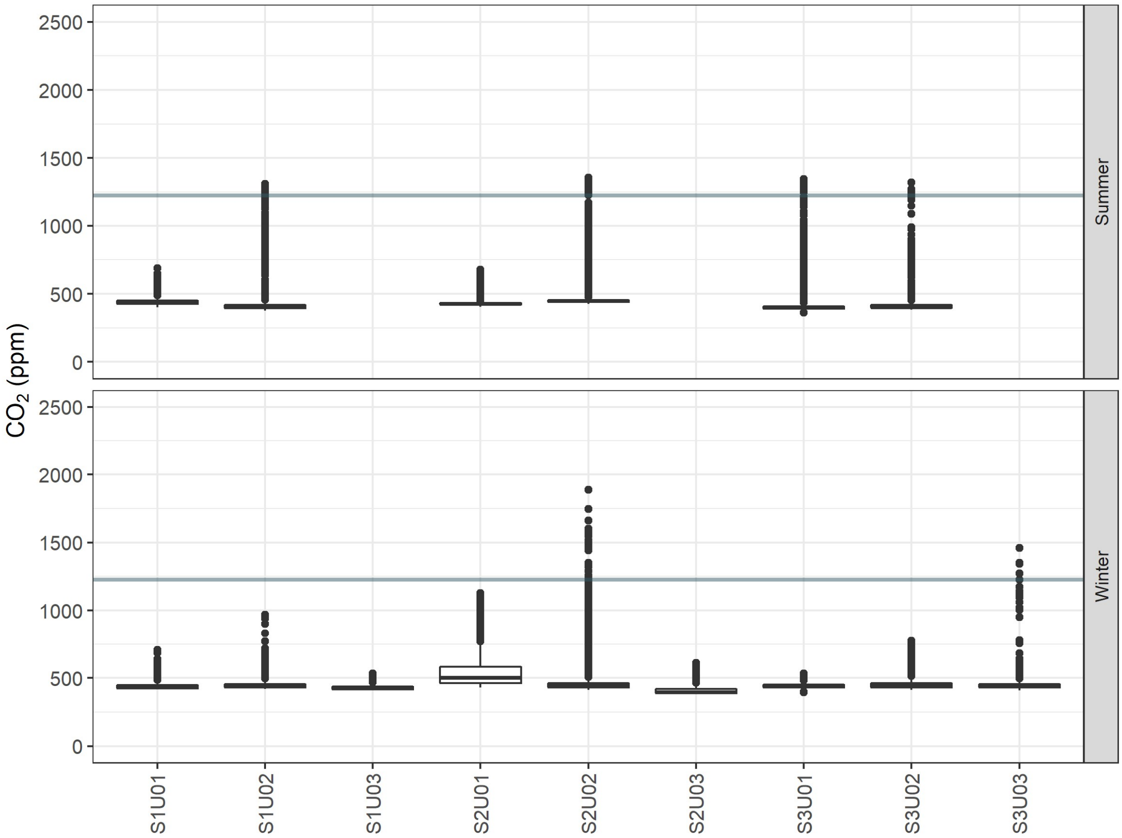


Figure 5-18. CO_2 concentration during unoccupied periods

Analysing the temperature reached by the classrooms during unoccupied periods (Figure 5-19), the thermal inertia in the three schools can be observed. Particularly during the summer, very high temperatures are reached, even though the unoccupied period is the coldest time outdoors. In school S2, the highest temperatures are reached during this period, with S2U02 being the classroom with the highest minimum temperatures, registering an absolute minimum temperature of 23.3 °C and an absolute maximum of 26.6 °C with a median temperature of 24.9 °C. In the same centre, classroom S2U01 recorded the highest absolute maximum of the whole centre, reaching 27 °C.

In contrast to these values, gymnasium S1U01 is the classroom where the lowest temperatures continue to be recorded in all percentiles for both seasons, as during the occupied period. These minimum temperatures are lower than those reached during the occupied periods, with the median in winter decreasing from 19.6 °C when the classrooms are occupied to 17.5 °C when they are unoccupied, and the same for the maximum temperatures, which decreases from 22.3 °C to 21.1 °C. In summer, no significant variation is observed between the temperatures when the centre is occupied and when it is unoccupied.

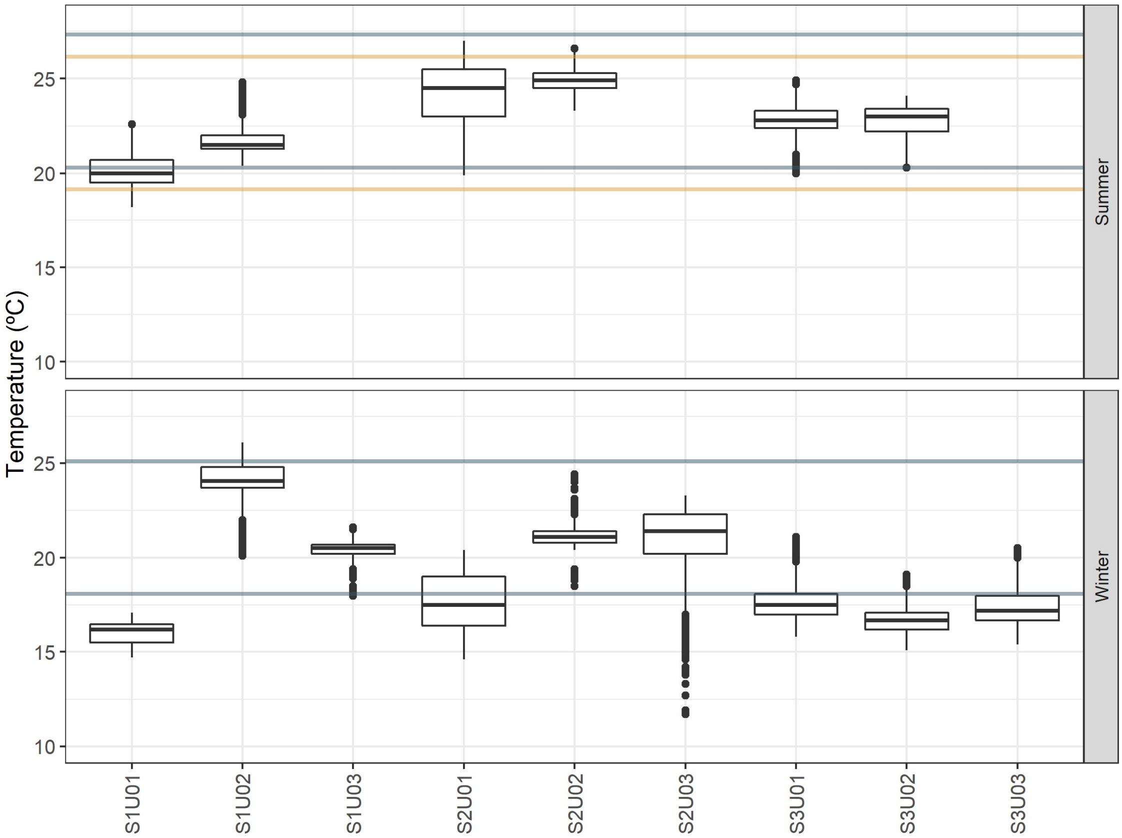


Figure 5-19. Temperature during unoccupied periods

Analysing the relative humidity during the unoccupied period (Figure 5-20), no significant difference is observed with the values previously analysed during the occupied periods.

The only striking value is the change in classroom S2U01, which, during occupied periods, is one of the classrooms with the highest relative humidity during the summer, but when unoccupied, it is the one with the lowest relative humidity.

The rest of the classrooms follow a similar behaviour, with S3U01 and S3U02 registering the maximum in summer and S1U02 the classroom with the highest relative humidity in winter.

Analysing the minimums, in summer, S1U02 reaches the minimum relative humidity of 31%, and in the winter classroom, S2U03 has a minimum relative humidity of 18%.

As with the temperature, the absolute maximum and minimum, as shown in Figure 5-20, are the same. These are specific moments and do not represent a trend, except S1 in winter and S3U01 during summer.

The 75% percentiles are all within the limits established by UNE-EN 16798. On the other hand, in the 25% percentile during the winter, many classrooms have lower relative humidities than the UNE 25% standard, being S1U02, S1U03, and S2U03 in winter.

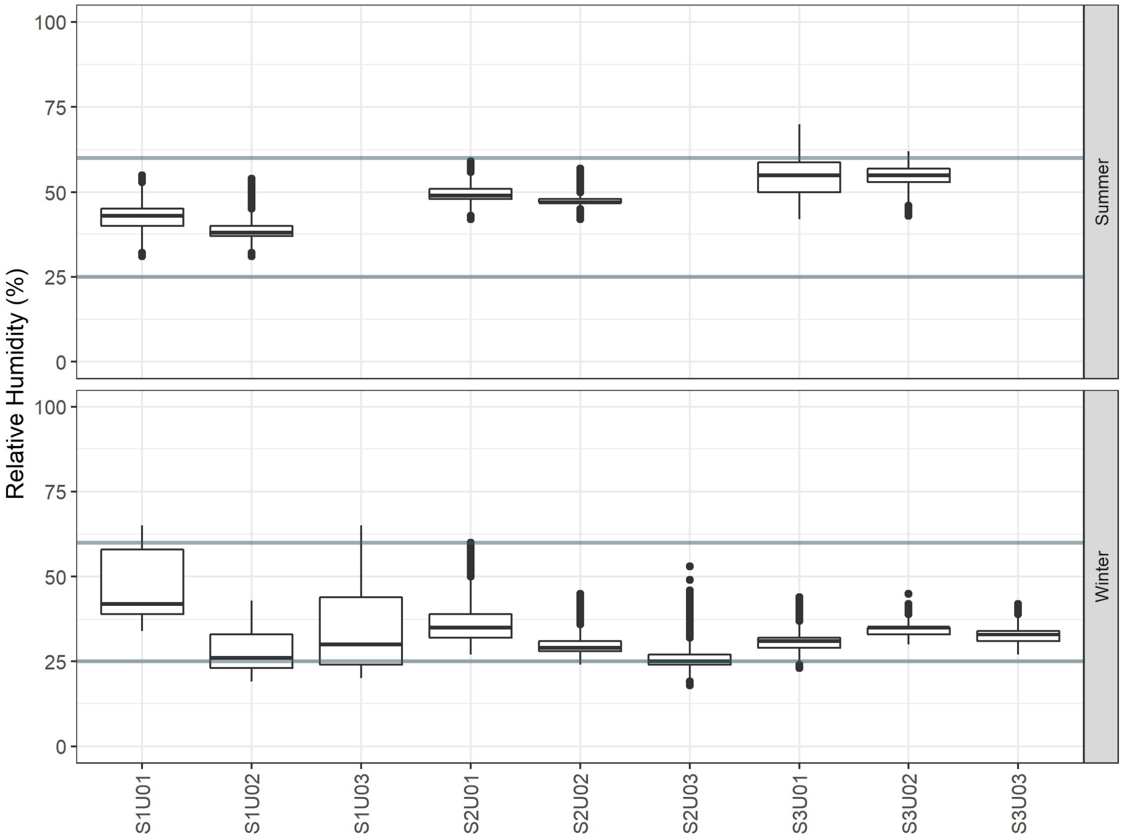


Figure 5-20. Relative Humidity during unoccupied periods

5.3.2 Thermal comfort achieved during classroom occupation

The aim of this section (OBJ-5 and OBJ-6) is to analyse the comfort achieved by the occupants of the school when they stay in the classrooms. It is essential to guarantee correct comfort conditions not only because of the impact this has on the perception of comfort and the health of its occupants but also because of the impact it can have on teaching [5].

In order to analyse this comfort, the limits set by the UNE-EN 16798 standard have been used. As the literature review describes, this standard uses different models to establish this comfort. In this study, the adaptive model has been applied.

For this purpose, the limits set by this standard are described below for the different parameters measured indoors: air temperature, relative humidity and CO_2 concentration. Applying the equations presented in the methodology Equation 4-1, the limits presented in Table 5-7 have been obtained.

The monthly average outdoor temperature determines the indoor temperature limits. As presented in section '5.3.1.1. Outdoor environmental conditions' outdoor temperature during the monitored months of January, May and June have been 5.31 °C, 13.18 °C and 16.73 °C, respectively. The standard states that for these equations, if the outdoor monthly averages are lower than 10 °C or higher than 30 °C, these temperatures will be used as limits in the equation. Therefore, in this case, during January, as the monthly average is lower than 10°, these 10° are used to calculate the limit.

Therefore, applying the equation Equation 4-1, the limits obtained for the temperature are those presented in Table 5-7. For January, it limits between 18.1 °C and 25.1 °C; for May, 19.1 °C and 26.1 °C; and for June, 20.3 °C and 27.3 °C.

The relative humidity is not limited by values obtained from outside. Therefore, according to what is described in the UNE-EN 16798 in section *B.3.3 Recommended criteria for the sizing of humidification and dehumidification*, the lower relative humidity limit is considered 25% and 60% for the maximum.

The average outdoor CO_2 concentration limits the indoor CO_2 concentration. This level of CO_2 concentration is used as an indicator of the levels of ventilation and fresh air introduced into the classrooms, particularly when the occupancy schedule is known.

As shown in Table 5-6, the outdoor averages obtained were 456.35 ppm in school S1, 426.87 ppm in school S2 and 425.85 ppm in school S3. The mean obtained at school S3 was chosen as the most restrictive value. Considering this, a maximum limit value of 1225 ppm is obtained for the indoor concentration study, and the same limit value will be used for all three schools.

Table 5-7. Thermal comfort and ventilation limits applied in the case study

		Lower limit	Upper limit
Temperature (°C)	**January**	18.1	25.1
	May	19.1	26.1
	June	20.3	27.3
Relative humidity (%)		25	60
CO_2 (ppm)		-	1225

To describe the comfort achieved, the indicator used was the percentage of time during occupancy that this parameter remained within the limits indicated for each classroom in each campaign. In order to find out what comfort is being achieved, this chapter has been divided into two parts. Firstly, the comfort achieved during occupied periods has been analysed for each of the three parameters measured according to the limits previously described in the UNE-EN 16798 standard. Next, the time remained when the three parameters were simultaneously in comfort was analysed.

Subsequently, where necessary, the time spent in a classroom in discomfort has been analysed to see whether it is above or below the limits previously presented in Table 5-7. Comfort was analysed as a function of the percentage of time during occupancy within the limits set. It has been used as acceptable when this percentage of time is above 80 %, as used by the ASHBRAE-55 standard to establish its comfort limits.

5.3.2.1 Individual comfort per parameter

Overall, Figure 5-21, Figure 5-22 and Figure 5-23 show the percentage of time in comfort for each of the parameters analysed. Using CO_2 concentration as an indicator of ventilation levels and temperature and relative humidity as hygrothermal comfort.

Analysing the CO_2 concentration Figure 5-21, multiple classrooms are in comfort 100% of the time in the first two classrooms, the gymnasium S1U01 during winter and summer, the primary classroom S1U02 in winter and the pre-elementary classroom S1U03 also in winter.

The worst ventilation comfort results are obtained in classroom S2U02 during winter, where only 66% of the time is in comfort, followed by classroom S3U03 also during winter with 76% of the time in comfort, then S1U02 during summer with 84% and S3U02 during winter with 90%.

Surprisingly, S1, the oldest school without any ventilation system in any classroom except the gyms, gives the best results for both winter and summer. However, the general situation of the three schools regarding CO_2 concentration is quite favourable, with all of them being in comfort for more than 80% of the occupied time, except for those previously mentioned.

Comparing the CO_2 concentration averages obtained and the percentage of time spent in comfort, better comfort has been achieved in summer than in winter. The average in both seasons is very high, reaching in winter 91% while in summer 96%.

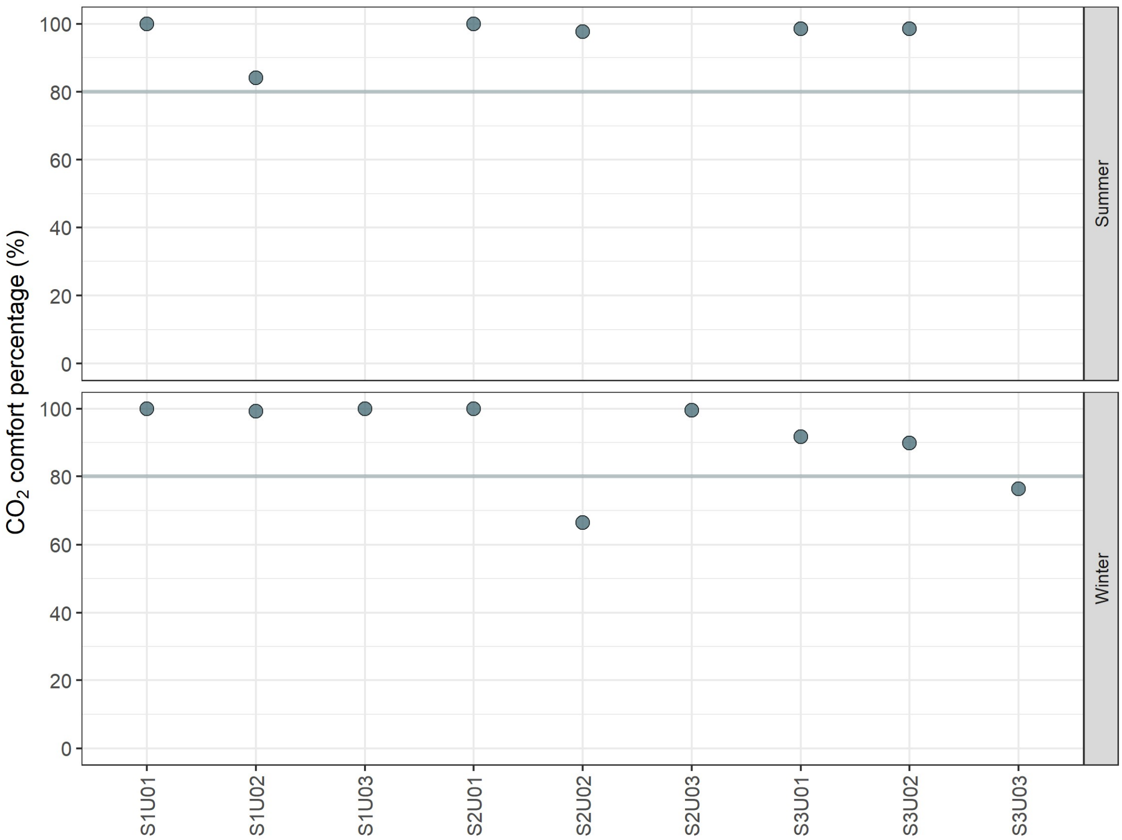


Figure 5-21. Percentage of time CO_2 is in comfort

Regarding hygrothermal comfort, temperature (Figure 5-22) and relative humidity (Figure 5-23) values are lower than the comfort percentages achieved by CO_2. In summer, better temperature and humidity results are generally achieved. The two monitored gymnasiums have temperatures far from comfort, especially S1U01 in winter, where thermal comfort is never reached and S2U01, which was only reached 59% of the time. It should be noted that both gymnasiums have a much larger volume, a large glazed surface and no heating system.

Excluding the gymnasiums, during winter, the classrooms with the worst temperatures are S3U02 with comfort 75% of the time and S2U03 with 78% of the time. The rest of the classrooms during winter have the comfort of more than 83% of the time, reaching the best thermal comfort in winter in classroom S2U02 at 100% of the time in comfort, followed by S1U03 with 99% and S1U02 with 95%.

The comfort results obtained in summer are very different from those recorded in winter. In this case, gymnasium S1U01 reaches comfort 96% of the time (compared to 0% in winter). The classrooms that reach the worst temperatures in summer are the school S2 in the gymnasium S2U01, reaching only 79%, followed by classroom S2U02 with 90%. The most comfortable classrooms are S1U02 and S3U01, with thermal comfort 100% of the time occupied. On average, comfort has been achieved 76% of the time in winter and 94% in summer, so more thermal comfort is achieved in summer than in winter.

Analysing the situation of the classrooms when they are not in comfort, it is observed that the behaviour is not expected. During winter, two classrooms occasionally overheat, S1U02 (3% of the time) and S2U03 (less than 1%). The rest of the classrooms that are not comfortable 100% of the time have temperatures below those considered comfortable. First of all, both gymnasiums stand out: classroom S1U01, which is in discomfort 100% of the time, followed by classroom S2U01, which has temperatures 41% below comfort. The other classrooms that remain in discomfort for the longest time during the occupied periods, and which are in this situation for more than 20% of the time analysed, are the S3U02 classroom with 25% and S2U03 with 22%.

During the summer, no classrooms are at uncomfortable temperatures for more than 20% of the period analysed. One classroom reaches overheating, classroom S2U02, 10% of the time. In turn, classroom S2U01 reaches overheating 15% of the time but at the same time obtains temperatures below comfort 7% of the time. Lastly, classroom S3U02 reaches temperatures below comfort 4% of the time analysed.

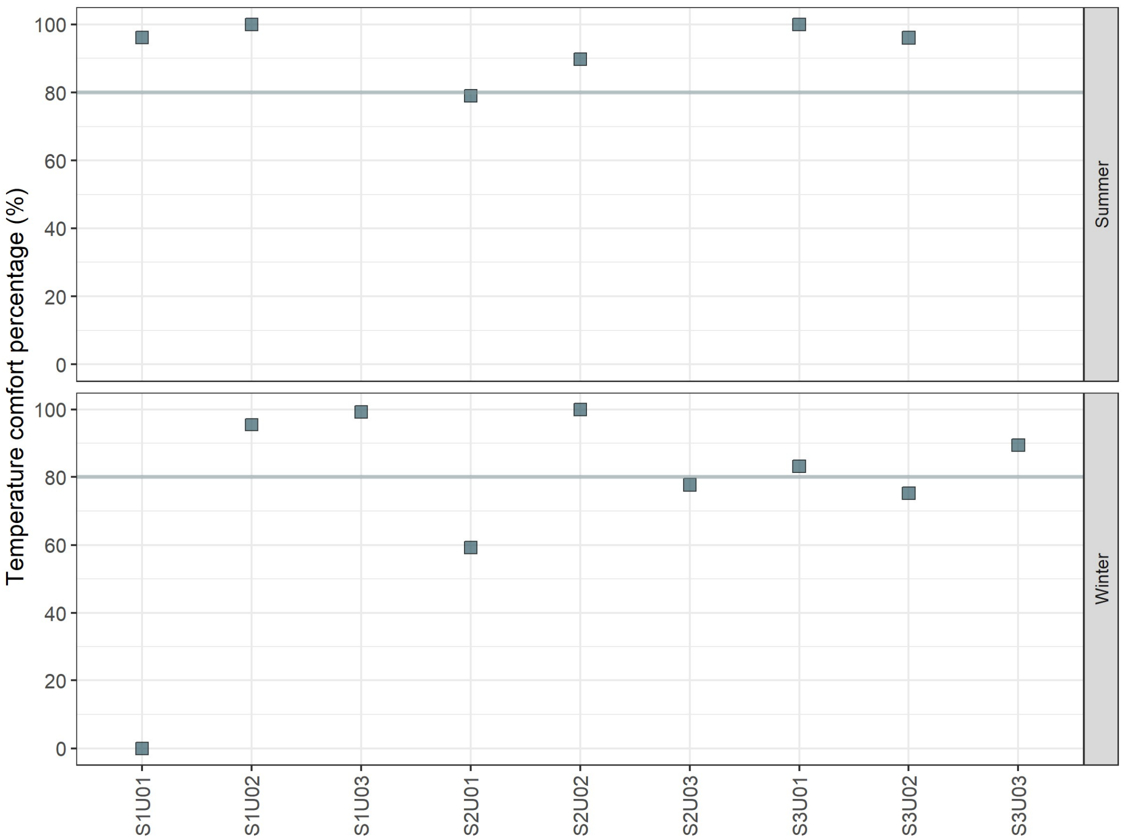


Figure 5-22. Percentage of time temperature is in comfort

Looking at the comfort results obtained for the relative humidity (Figure 5-23), two distinct groups can be observed: those that reach relative humidities within the limits set by the UNE-EN 16798 standard almost 100% of the time and those that are around 60% of the time in comfort.

All the classrooms measured in summer are around this group close to 100%. In winter, three classrooms spend approximately 60% of the time in comfort. S2U03 classroom reaches a minimum comfort only 63% of the time, followed by the S1U02 classroom with 64% and finally, the S1U01 gymnasium with 66%, coinciding with what was previously analysed, when during winter, the minimum relative humidities were not reached.

On average, comfort was achieved 87% of the time in winter and 99% in summer. Despite what was observed in the previous section, both values are very positive. The classrooms that do not reach almost 100% relative humidity are due to low relative humidity inside the monitored classrooms.

In the summer, only two classrooms occasionally exceed the comfort limit: classroom S2U01 by 1% and classroom S3U02 by 3% of the time. During winter, the relative humidity limits established as comfort are exceeded with higher and lower values. Higher relative humidities were obtained in classroom S1U01 34% of the time and in classroom S3U03 less than 1% of the time. Relative humidities below the comfort values were achieved in classroom S2U03 37% of the time, followed by classroom S1U02 36% of the time. Three other classrooms reached lower relative humidities, but none reached the limit of 20% of the time analysed, with S1U03 reaching these relative humidities 4% of the time, S2U02 2% and S3U01 1%.

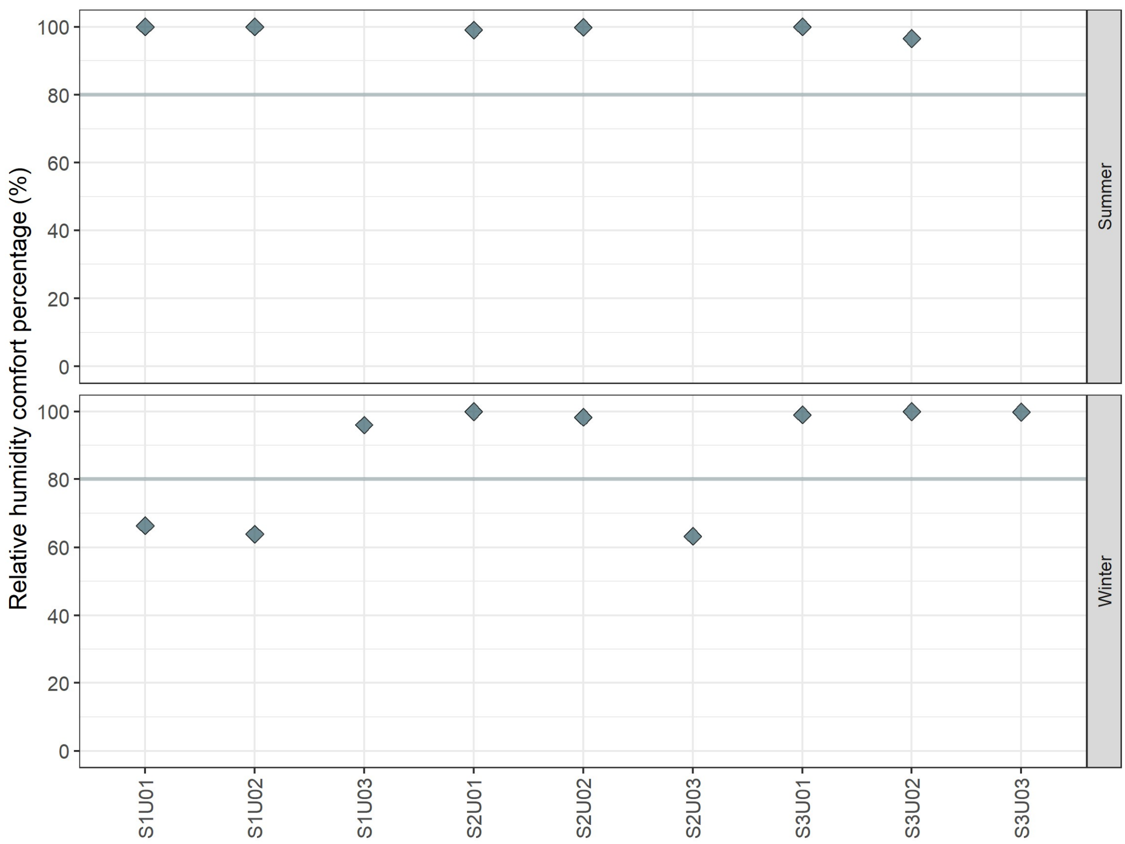


Figure 5-23. Percentage of time relative humidity is in comfort

5.3.2.2 Simultaneous comfort

In the analysis carried out, this simultaneous comfort indicator has been created, in which comfort is considered to exist inside the classrooms when the three parameters measured are simultaneously within the comfort limits previously analysed. As in the previous comfort analysis, it has only been considered when the classrooms are occupied. The creation of this indicator facilitates the analysis by being able to compare a single value between the different classrooms. It will also make it possible to compare these values with those obtained in other studies.

Figure 5-24 shows superimposed, in yellow, the percentage of time in comfort simultaneously for each classroom for the two measurement campaigns. In blue is the percentage of time in comfort for each parameter presented in previous sections.

This calculation shows how sensitive this indicator is to the different parameters measured. Especially in winter in the S1U01 gymnasium, the temperature never reaches comfort. Even though the CO_2 is in the comfort range 100% of the time, it will never reach all three parameters simultaneously.

Analysing the percentage of time in comfort achieved in all classrooms, it can be seen that better simultaneous comfort is achieved in summer, with an average of 90% in all classrooms, compared to 59% in winter.

In summer, school S2 is the school with the worst results, limited mainly by the lower percentage of comfort obtained by the temperature, with classroom S2U01 obtaining a simultaneous comfort of 79% and classroom S2U02 87%, although in school S1 classroom S1U02 achieves a simultaneous comfort of 84%. The rest of the classrooms obtain simultaneous comfort values of over 94%, achieving outstanding comfort values in summer.

Once again, temperature is the parameter with the most limited total comfort in winter. As mentioned, the classroom with the worst values in winter is the gymnasium S1U01, which never reaches thermal comfort, so it never reaches simultaneous comfort, even though it has 100% of the time the CO_2 in comfort.

Contrary to this situation is the S2U02 classroom during winter, where the temperature is 100% of the time in comfort, but it reaches worse ventilation values, with the CO_2 concentration being 66% of the time in comfort. Therefore, in this classroom, priority was given to maintaining thermal comfort rather than ventilation, contrary to what was proposed in the COVID protocol in the centres during the period measured.

Following S2U02, the classroom with the worst values is S2U03. In this classroom, a simultaneous comfort of 44% is achieved, mainly limited by relative humidity and temperature. In the third position is classroom S1U02, with a simultaneous winter comfort of 59%, although this time is limited only by relative humidity. In the fourth position, classroom S2U01 had a comfort of 59%, limited by relative humidity and temperature.

Observing the simultaneous comfort values obtained, it can be seen that in the naturally ventilated classrooms, greater comfort has been achieved even on the coldest days, reflecting the capacity and opportunity in these classrooms to adapt to the comfort conditions. However, only one classroom achieves simultaneous comfort of over 80% during winter, classroom S1U03. All classrooms exceed 80% of the time over simultaneous comfort in summer, except classroom S2U01 (79% of simultaneous comfort).

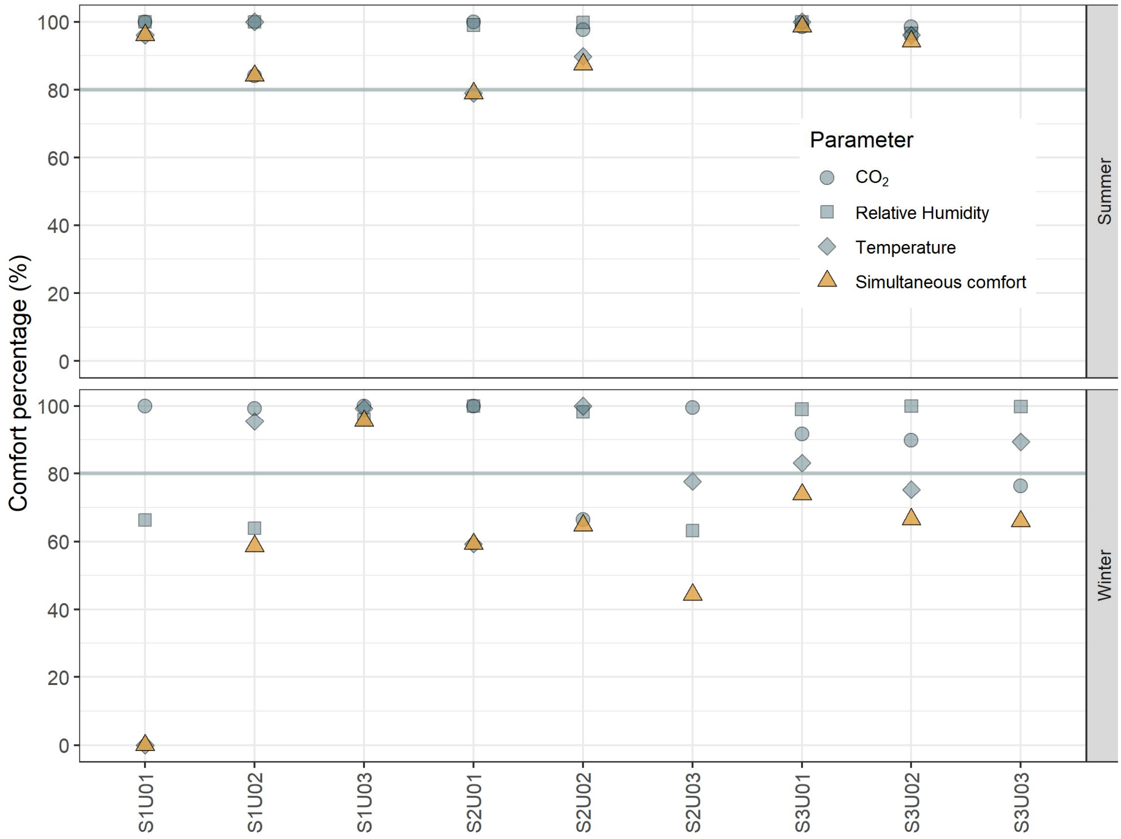


Figure 5-24. Comfort percentage per classroom

5.3.3 Relation between comfort and constructive characteristics

Following what was presented in the methodology, this section aims to determine which characteristics influence achieving comfort in the classrooms (OBJ-7). The comfort calculated in the previous section has been considered. It is considered relevant to perform these calculations not only with the simultaneous comfort indicator when the three measured parameters are simultaneously in comfort but also with the impact these characteristics have on the different measured comforts.

In those classrooms where the worst comfort values have been achieved, it is relevant to analyse and measure the influence of different features on the different calculated comforts. For example, if they influence only the hygrothermal comfort but not the ventilation. For this purpose, knowing how it influences each case has been considered relevant.

Different calculation methods were then applied according to the nature of the characteristics analysed. The Kruskal-Wallis test [132] was used for qualitative characteristics, and Pearson's correlation test [133] was used for quantitative characteristics. In both tests, the first was the *p-value*, indicating whether the calculated relationship is statistically significant when this value is less than 0.05.

Because they were considered influential, the characteristics selected for these tests were grouped according to their nature, qualitative or quantitative. The qualitative characteristics analysed were the ventilation system, heating system, orientation, floor on which it is located and type of classroom. The quantitative characteristics selected were occupancy density, volume, Window to Wall ratio and Daylight Factor.

For the qualitative characteristics, the Kruskal-Wallis test has been applied, which, depending on the degrees of freedom of each characteristic analysed, is compared with the chi-squared value (X^2) obtained, which indicates the relationship. This test aims to indicate whether the medians of the groups measured are significantly different to reject the null hypothesis.

If the null hypothesis is rejected, the comfort values obtained have indeed been influenced by the characteristics analysed. It can then be concluded that the difference between groups for the same characteristic is significant.

If the result of applying this test is statistically significant and the null hypothesis is rejected, Dunn's test is subsequently applied [132]. This test indicates within the group that makes up each characteristic compared to which one has a relationship with the data analysed.

Subsequently, for the quantitative data, the linear correlation test was applied to compare two quantitative values, indicating, on the one hand, whether the relationship is statistically significant or not (*p-value*). Then, this relationship is quantified, obtaining, as a result, how strong this relationship is and, depending on the sign obtained, positive or negative, whether the relationship is direct or indirect.

Consequently, depending on the value obtained for this ratio, as described in the methodology according to the range according to Cohen's classification, it is considered when it is less than 0.1, between 0.1 and 0.3, between 0.3 and 0.5 or greater than 0.5, it will indicate a null, weak, moderate or high correlation respectively, both in positive and negative values.

Applying these tests to the comforts achieved in each classroom has resulted in the data presented in Figure 5-26 for the qualitative characteristics and those presented in Figure 5-28 for the quantitative characteristics.

5.3.3.1 Influence of the measurement campaign on the comfort achieved

In this section, it was considered relevant to analyse the possible influence of the monitoring campaign on the comforts achieved before analysing the influence of the different qualitative and quantitative characteristics.

The calculation of the influence of the campaign will determine whether the difference between the achieved comforts is statistically significant and whether the further analysis will be carried out together or separately for each campaign.

This analysis is considered relevant since in the previous sections, where the results obtained in monitoring the classrooms are analysed and commented on, different behaviours and comforts achieved have already been detected. This difference is observed both in some classrooms and in the different measurement campaigns carried out.

It is also relevant that because some of the classrooms could not be measured during both campaigns, there is not a large enough sample to generalise the results obtained in classrooms with similar characteristics to other classrooms.

Then, Figure 5-25 shows the *p-value* obtained by applying the Kruskal-Wallis test between the comforts achieved for each monitoring campaign. The only statistically significant value of the results obtained was for simultaneous comfort. In other words, for simultaneous comfort, statistically significant differences in comfort values were obtained between winter and summer.

With these values, it can be affirmed that better simultaneous comfort is obtained in summer than in winter, with an average comfort of 59% and 90%, respectively. Although different values are obtained in each classroom, no statistically significant value has been obtained for the rest of the comforts previously analysed. Considering these results, it is relevant to analyse the rest of the sections, differentiating between the two campaigns because the simultaneous comfort is statistically significant.

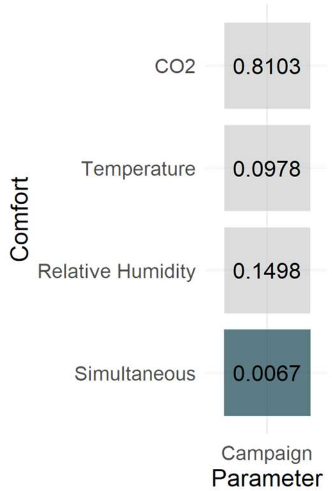


Figure 5-25. Campaign impact on different comforts (p-value).

5.3.3.2 Relationship between comfort and qualitative characteristics

Analysing the *p-values* obtained in Figure 5-26 for the qualitative characteristics, the lack of any statistically significant relationship between the comfort achieved and the selected characteristics stands out. The only relationship obtained was the floor on which the classroom is located with the CO_2 values during winter ($p = 0.0424$).

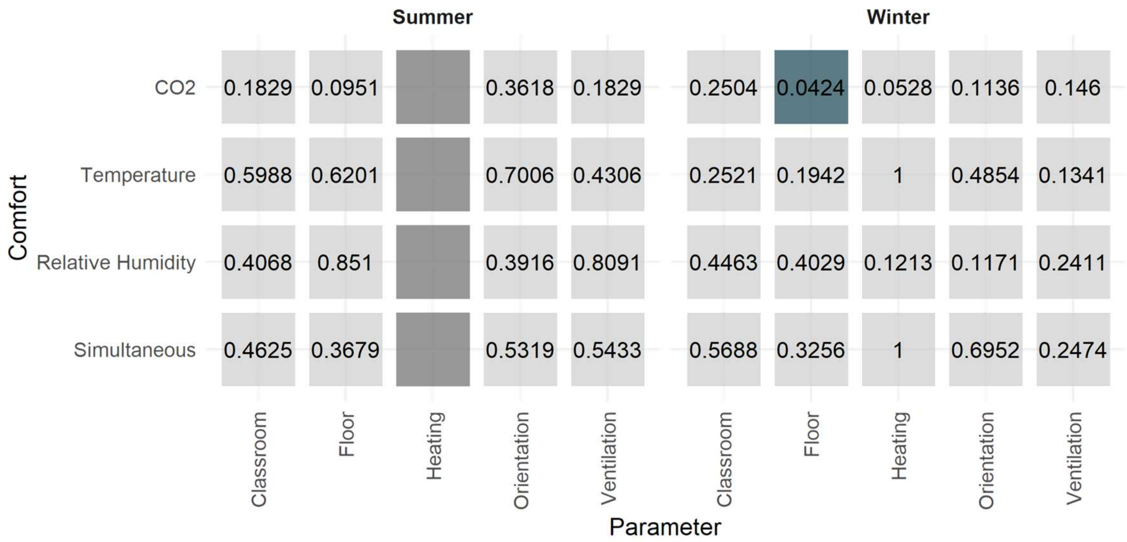


Figure 5-26. Qualitative data impact on comfort for each campaign (p-value).

When a *p-value* = 1 is reached, there is an absolute certainty that this hypothesis is fulfilled; this means that there is no influence of the heating system on the temperature comfort, nor is there a simultaneous comfort influence of the heating system on the temperature comfort.

In Dunn's post-hoc test [132] pairwise test with Bonferroni adjustment represented by the adjusted *p-value* (p_{adj}), only a significant difference was found in winter between the ground and second floor ($p_{adj} = 0.05$), while in summer, no statistically significant difference was observed. Figure 5-27 graphically shows the CO_2 concentration reached in the classrooms during the winter campaign as a function of the floor on which they are located.

It can be seen that even though there are different types of classrooms, those located on the ground floor (children's or gymnasium) have a lower variance than the classrooms located on the upper floors, whose characteristics are more similar to each other.

Therefore, there is no significant difference between the first and second floors ($p_{adj} = 1.0000$) or between the ground floor and the first floor ($p_{adj} = 0.2588$). However, there is a statistically significant difference between the ground and second floors.

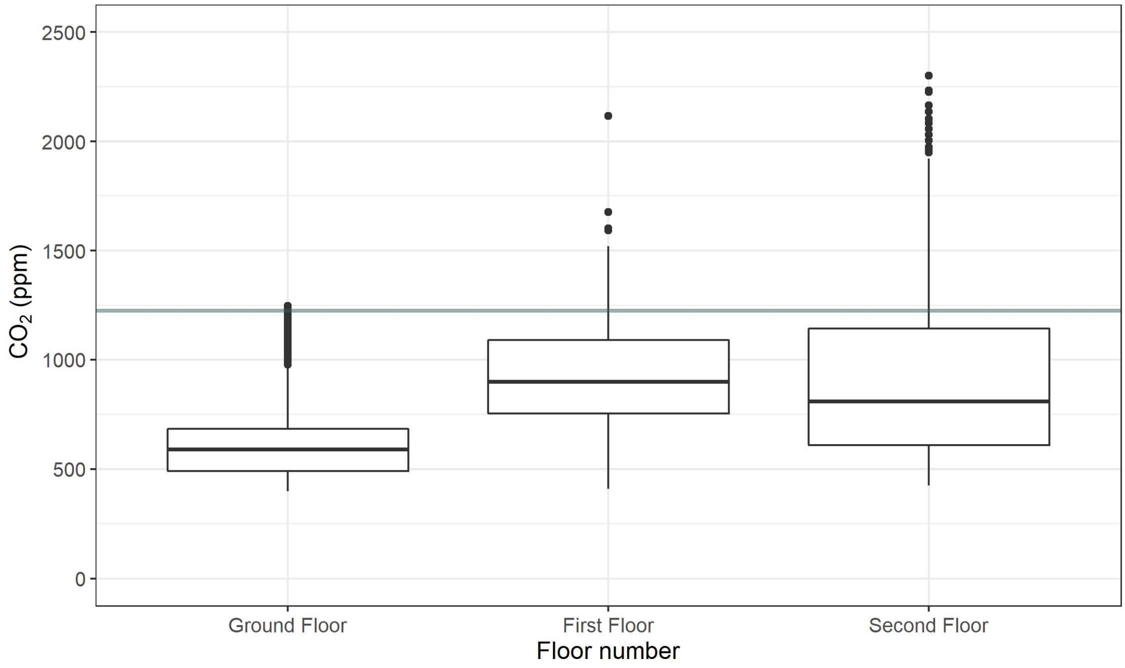


Figure 5-27. CO_2 concentration by floor level in winter

5.3.3.3 Relationship between comfort and quantitative characteristics

Figure 5-28 shows the results obtained for the quantitative characteristics. First, the *p-value* was obtained, which is considered a statistically significant relationship in the case of being less than 0.05. Subsequently, the value of the relationship between each characteristic and type of comfort was calculated for each monitoring campaign.

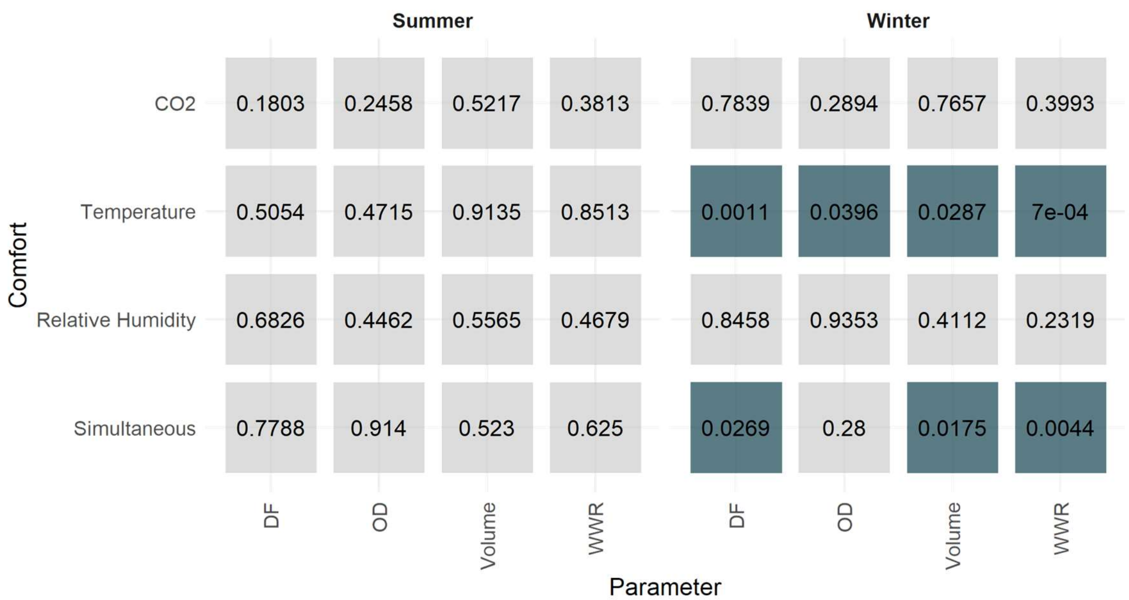


Figure 5-28. Quantitative data impact on comfort for each campaign (p-value).

As can be seen, very different values have been obtained concerning the test carried out on the qualitative characteristics. In this case, it can be seen that multiple characteristics do have a significant influence on comfort. Volume (p = 0.0175), Window to Wall Ratio (WWR) (p = 0.0044), and Daylight Factor (DF) (p = 0.0269) influence simultaneous comfort in winter. Similarly, winter temperature comfort is influenced by occupancy density (OD) (p = 0.0396), volume (p = 0.0287), WWR (p = 0.0007) and DF (p = 0.0011). Meanwhile, no other characteristic significantly influences comfort during summer for both simultaneous comfort and temperature. No other statistically significant relationship was found for the rest of the comforts in the different campaigns monitored.

Figure 5-29. Correlation test between comfort and quantitative data

The values obtained in the linear correlation test show strong relationships with some characteristics (Figure 5-29). In those characteristics considered significant ($p < 0.05$), the correlation (cor) values for these characteristics were high in all of them, obtaining cor ≥ ± 0.6902. Establishing a cor = - 0.7597 for the volume, simultaneous comfort in winter, and a cor = - 0.8423 for WWR and cor = - 0.7256 for DF. Again, the winter comfort temperature is related to the OD of cor = 0.6902, for volume cor = - 0.720, WWR cor = 0.9093 and DF cor = - 0.8950.

This similarity in the values achieved for thermal and simultaneous comfort reflects the significant influence that temperature has on the achievement of comfort in classrooms and the influence these construction features have on it.

Apart from those already described as statistically significant, high relationships (when the correlation is higher than 0.5) have also been obtained for CO_2 concentrations in summer, finding a negative correlation with an OD of cor = - 0.5619 and for DF cor = 0.6297.

In other words, the higher the occupancy density increases, the worse the CO_2 comfort is, following what has been analysed in previous literature. The second value, the daylight factor, is influenced by the size of the window to the surface area of the classroom in order to achieve comfort; the higher this ratio, the larger the opening to the classroom size, and the greater the CO_2 comfort.

From these results, it is significant that the occupancy density, being people the leading CO_2 emitter indoors, has not reached a statistically significant relationship, i.e. not all values obey this hypothesis (*p-values* much higher than 0.05), and when evaluating the correlation, a lower relationship is obtained between occupancy density and CO_2 comfort in winter (cor = - 0.3975) than in summer (cor = - 0.5619).

From these values, it can be interpreted that the higher the occupancy density, the lower the CO_2 comfort and, therefore, the higher the CO_2 concentration. The fact that the correlation is higher in summer means that occupancy density has a more significant influence on comfort than in winter.

Analysing the relationship between comfort and WWR, it is noteworthy that WWR has not obtained a relationship as strong as that obtained by DF. Even so, a moderate correlation was obtained, cor = 0.44. Therefore, the surface area of the classroom has more influence than the surface area of the opening to the façade when it comes to achieving better ventilation values.

Analysing the rest of the characteristics, although none of them is statistically significant, some moderate correlations (between ± 0.3 and ± 0.5) and some weak (between ± 0.1 and ± 0.3) have been obtained.

A moderate relationship was obtained between simultaneous comfort in winter with occupancy density (cor = 0.4047) and in summer with volume (cor = 0.3300). In summer, a weak correlation is also achieved to WWR (cor = 0.2555) and DF (cor = 0.1486). A moderate positive correlation with OD (cor = 0.3691) and a negative correlation with DF (cor = - 0.3432) is observed for the comfort achieved by temperature during summer.

There is no high correlation in the comfort achieved by relative humidity, but multiple moderate correlations were obtained. Negative correlations were obtained with volume (cor = - 0.3136) and WWR (cor = - 0.4434) during winter. Nevertheless, contrary to these values, these relationships have been positive during summer, obtaining moderate positive relationships to volume (cor = 0.3051) and WWR (cor = 0.3719). A moderate positive correlation was also found in summer with OD (cor = 0.3888) and a weak correlation with DF (cor = 0.2149).

Finally, with CO_2 comfort concentration, a weak to moderate correlation with all characteristics has been obtained in both measurement campaigns. In winter, there is a moderate correlation with OD (cor = - 0.3975) and WWR (cor = 0.3212) and a weak correlation with volume (cor = - 0.1163) and DF (cor = 0.1071). During summer, a moderate correlation was reached between volume (0.3310) and WWR (cor = 0.4411).

Firstly, the relationship between volume and CO_2 comfort in summer is negative, but in winter, it is positive. Therefore, the volume influences the CO_2 concentration and ventilation. From these values, it can be deduced that ventilation is different between summer and winter, with lower CO_2 values being obtained in summer and worse in winter, so that the renovations, according to their volume in summer, are being ventilated more in the larger ones and in winter in the smaller ones. However, weak correlation values have been obtained for both cases.

Secondly, the influence that WWR has during summer on CO_2 comfort. Being higher in summer than in winter, the larger the area of the opening, the lower the concentration of CO_2, so the size of the opening has a direct impact on the level of ventilation in the classrooms. The size of the opening is also important because of its ability to transmit natural light and ventilate the entire classroom.

In previous sections, Figure 5-24 shows the percentage of time each classroom spends in comfort. The gymnasium's vulnerability to reaching thermal comfort can be observed since these comfort conditions are not reached in S1 during the winter season and reach low values in S2. This vulnerability is caused by multiple characteristics, such as their large volume, orientation, and lack of a heating system. Therefore, excluding these classrooms in the analysis, the thermal comfort during winter increases by 13.10% on average, going from an average comfort of 76% to 89%.

No statistical relationship was found for the other characteristics analysed, *with p-values* too far apart to be considered significant and correlations of less than 0.1. For example, this poor statistical relationship between different construction properties can be seen when comparing the two pre-elementary classrooms (S1U03 and S2U03). These classrooms have very similar characteristics and other differences, such as the ventilation system and the opening of windows. As the comfort being achieved in them is very different, the influence of some of these characteristics is not considered significant.

6 OVERALL DISCUSSION

Previously, a phased methodology was developed with the final objective of characterising, measuring and analysing the comfort in different educational centres and the influence that different characteristics have on this comfort. Subsequently, this methodology was applied in three schools in Vitoria-Gasteiz.

The previous section presented the results obtained through applying the methodology in detail. In this chapter, the main arguments will be developed through these results obtained, comparing them with those achieved in previous research. This section aims to detect possible vulnerabilities and strengths regarding the comfort achieved and its influences, analysing whether they are similar to those achieved by previous similar studies.

For the development of this discussion, the main results per argument have been grouped into three sections (Figure 6-1). First, the comfort achieved is related to the three measured parameters. Second, on classroom ventilation, focusing on the different systems and strategies used to improve this ventilation and their impact on comfort. Third, the behaviour and adaptation of the occupants and how this affects the results obtained.

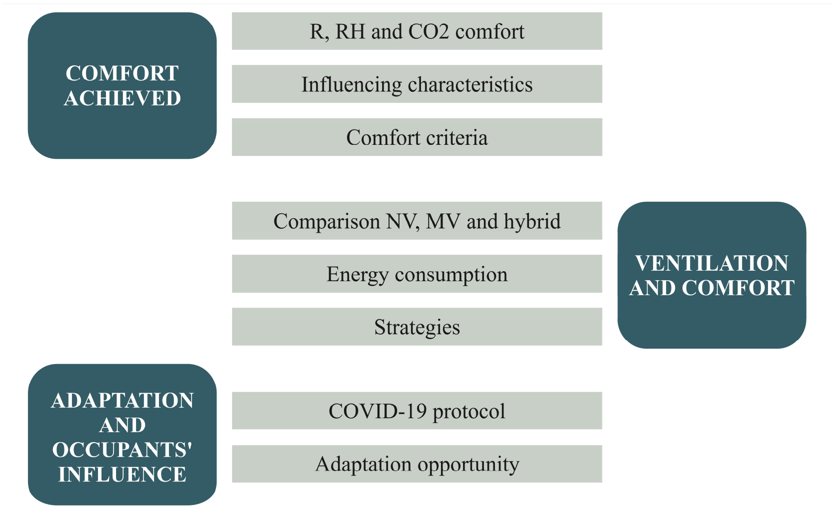


Figure 6-1 Discussion topics by main arguments

6.1 COMFORT ACHIEVED AND COMPARISON WITH OTHER STUDIES

This analysis has been carried out in three sub-sections. After applying the methodology, the first sub-section compares the comfort obtained in this thesis with the comfort obtained in other research. Second, the impact of different parameters on comfort is compared. Third, the influence of the chosen comfort criterion is calculated and analysed, comparing the results obtained with other standards or recommendations.

6.1.1 Hygrothermal comfort and ventilation achieved in classrooms

Previously, in the analysis of the results obtained in section '5.3.2 Thermal comfort achieved during classroom occupation', the classrooms obtained very high comfort values. Centres S1 and S2 have the highest medians within the comfort limits. As seen in Table 6-1, the comfort averages achieved in the three centres for each monitoring campaign have been grouped, with generally high percentages of time in comfort being obtained.

Table 6-1. Mean comfort percentage for each parameter and season

	Winter (%)	Summer (%)
Temperature	75.50	93.50
Relative Humidity	87.41	99.24
CO_2	91.46	96.49
Simultaneous	84.79	96.41

The classrooms were most comfortable in summer for all the parameters measured. In winter, CO_2 concentration was the parameter with the highest comfort time (91.46%); in summer, relative humidity was the parameter with the highest comfort time (99.24%).

Analysing the results obtained for the simultaneous comfort indicator, the vulnerability of this indicator can be observed. Its value is strongly influenced by those parameters that achieve the worst results throughout the monitoring, the temperature being the lowest indicator in both measured campaigns. At the same time, it is not affected by those parameters that obtain outstanding values. In most cases, although the temperature is outside the comfort limits, affecting the simultaneous comfort indicator, the CO_2 concentration is 100% of the time in comfort.

6.1.1.1 Temperature achieved compared to other studies.

In the SINPHONIE study [94] carried out in more than 300 schools across Europe, the temperature was monitored, among multiple factors, reaching a mean of 20°C, median of 21°C, minimum of 8°C and maximum of 30°C. Similar temperatures were obtained in this study's results.

It was found that S1 during winter, due to its gym (S1U01), where temperatures never achieve comfort level, is the school with the lowest average comfort. However, this school (S1) has the best comfort over 98% of occupied time during summer.

Except for S1 during winter, on average, all schools achieve good comfort over 80% of the time, with similar mean temperatures between 19 °C and 20 °C in winter. However, a broader range was observed in summer, with mean temperatures from 21.77 °C to 24.70 °C.

Table 6-2. Mean temperature and comfort percentage per school campaign

	Winter		Summer	
	Temperature (°C)	**Comfort (%)**	**Temperature (°C)**	**Comfort (%)**
S1	19.98	64.92	21.77	98.06
S2	19.96	79.00	24.70	84.40
S3	19.25	82.60	22.77	98.04

In this study, analysing the temperatures obtained outside the comfort limits, it is worth highlighting when overheating occurs. During winter, classrooms S1U02 and S2U03 are 3% and 1% of the time, respectively, above the established limits during the occupied periods. Although these percentages are very low, it is noteworthy that these same classrooms never overheat during the summer. On the other hand, classrooms S2U02 and S2U01 suffer from overheating in summer, 10% and 15%, respectively, achieving S2 an average of 24.7 °C during summer. At the same time, during the summer season, the other two classrooms experience temperatures below what is considered comfortable. Classroom S3U02 is occupied 4% of the time with temperatures below comfort, and classroom S2U01 for 7%, which also experiences overheating during the same period.

If, instead of the UNE-EN 16798 standard, a different one had been applied, which only sets a lower limit for winter and an upper limit for summer, it could not be established if overheating occurred in winter or cold temperatures indoors during summer. This same phenomenon happens in other studies with colder climates. as is monitored in some classrooms in this study [42].

Extensive literature has been found that studies overheating in schools during the warm season [139]–[143], overheating in climates where it has not been a concern until now but is beginning to occur [7], as well as preventing overheating that may be caused by global warming [43], [140], [144], [145]. It is estimated that in naturally ventilated classrooms during school occupancy hours, by 2050, more than 50% would be under overheating conditions, and by 2090 this would increase to 70%. This increase in outdoor temperatures and the design of new, more airtight and highly insulated schools may also lead to overheating indoors [146], [147].

In previous research, under the 3SqAir project [148] of the Interreg Sudoe programme, one of the six case studies was the Donostia Superior Technical Architecture School of the University of the Basque Country. In this project, thermal comfort, IAQ and noise level were monitored. Regarding thermal comfort, during the hottest period, overheating was detected in the classroom with mechanical ventilation, with better thermal comfort and ventilation values being obtained in the classroom with natural ventilation. On the other hand, during winter, higher CO_2 concentrations were reached in the naturally ventilated classroom due to the priority given to thermal comfort. These results are similar to those in other studies [139]–[143].

6.1.1.2 Relative humidity achieved compared to other studies

In the SINPHONIE study [94], in more than 300 European schools, a mean relative humidity of 43%, a median of 42%, a minimum of 6%, and a maximum of 98% were obtained, recording a wider relative humidity range. Analysing only mean and median values are similar to those obtained in this thesis.

Similar to the temperatures, except for S1 in winter, on average, all schools achieve comforts over the indicator 80%, in this case, over 87%. On average, the lowest relative humidity was achieved in winter in S2 at close to 30% and the highest in S3 during summer at over 51%.

Table 6-3. Mean relative humidity and comfort percentage per school campaign

	Winter		Summer	
	RH (%)	**Comfort (%)**	**RH (%)**	**Comfort (%)**
S1	38.39	75.41	44.66	100.00
S2	30.74	87.18	49.35	99.45
S3	32.53	99.64	51.21	98.28

In this study, the variation of the relative humidity in classroom S2U01, in both seasons when it is occupied and unoccupied, stands out. Significantly, during winter, the maximum relative humidity increases up to 16% from occupied (maximum 44%) to unoccupied (maximum 60%). In summer, there is not a big difference between the values monitored during occupied and unoccupied periods.

Therefore, during winter in this gymnasium, there is an impact of occupancy on its relative humidity values, while neither in winter nor in the gymnasium of the other school is there such a difference in relative humidity values.

6.1.1.3 CO_2 concentration achieved compared to other studies

In the monitored schools, the average CO_2 concentration and percentage of comfort during the occupied periods, presented in Table 6-4, were obtained.

Table 6-4. Mean CO_2 concentration and comfort percentage per school per campaign

	Winter		Summer	
	CO_2 (ppm)	**Comfort (%)**	**CO_2 (ppm)**	**Comfort (%)**
S1	621.23	99.77	664.81	92.08
S2	754.64	88.68	657.16	98.85
S3	937.82	85.94	644.21	98.56

The three schools have obtained optimal average CO_2 concentrations, highlighting the high average concentrations reached in winter in S2 and S3, reflected in the time in comfort. Analysing this percentage, school S1 achieves greater comfort than S2 and S3 in winter but lower during summer. Nevertheless, all the educational centres achieve comfort higher than the acceptable 80%.

School S3, on average, during winter, despite being the most recently constructed and mechanically ventilated, has the highest mean CO_2 concentration (937 ppm) and the lowest percentage of comfort (almost 86%) during winter. During summer, on average, all schools are comfortable over 92% of the time, which can be considered as great comfort is achieved.

In contrast, in other research, such as that carried out by Hama et al. [24], naturally ventilated classrooms obtained higher concentrations of CO_2 than mechanically ventilated classrooms. The authors obtained mean concentrations of 861 ppm for the naturally ventilated and 796 ppm for the mechanically ventilated ones. However, the best result, i.e. the lowest CO_2 concentrations, is obtained in the hybrid ventilated classrooms with an average of 731 ppm [13], [67].

Similar results have been achieved in research carried out by Santamouris et al. [12], where CO_2 concentration was measured in 27 naturally ventilated schools in Greece (median 1070 ppm) and reviewed in 182 naturally ventilated (1420 ppm) and 220 mechanically ventilated (910 ppm) schools in more than 127 countries. Looking at the peak concentrations obtained, the authors obtained concentrations over 1500 ppm, 47% in naturally ventilated and 15% in mechanically ventilated schools, and over 2000 ppm, 18% in naturally ventilated and 5% in mechanically ventilated schools.

Comparing these results, schools with natural ventilation in other studies have obtained much higher CO_2 concentrations than in this study. Also, schools with mechanical ventilation during winter obtained similar values to those in this study, but they were much lower during summer.

Another influential factor is the evolution of the CO_2 concentration during the day and the week. The research carried out by Bain-Reguis et al. [13] found that in classrooms, the CO_2 concentration increased during the day (higher concentration during the afternoon) and also during the week. In this study, the concentrations are generally higher in the afternoon, but no increase was observed during the week, with the occupancy time of each classroom being more influential than the week day.

6.1.2 Comfort criteria

The methodology applied has been monitoring, from which real data is obtained. Nevertheless, when it comes to interpreting the data and considering when the occupants are in comfort, the criteria to be chosen have an impact. Considering which standard or recommendation to choose as comfort will influence the results.

This section aims to determine how other comfort criteria influence the obtained monitoring. How demanding are the chosen criteria, the influence on the indicator used, and the percentage of time in comfort during the occupied period.

As developed in the methodology, the criterion chosen for comfort in this research has been the UNE-EN 16798 standard [63] under the adaptive model, applying a single comfort criterion in the three case studies.

6.1.2.1 Temperature comfort limits

Throughout this thesis, the adaptive model presented in the UNE-EN 16798 standard has been used as a criterion for defining comfort. This standard bases the limits of the indoor comfort temperature on the outdoor temperature obtained in Vitoria-Gasteiz during the monitored period (Equation 4-1). The comfort limits for January were 25.1 °C and 18.1 °C, for May 26.1 °C and 19.1 °C and for June 27.3 °C and 20.3 °C.

Compared to previous research, in the literature review by Singh et al. [2] where 89 articles on thermal comfort in educational centres were analysed, and in those where the adaptive model was used, a range of comfort temperatures was obtained for universities in winter from 22 °C to 23.5 °C and in the summer months from 27.3 °C to 30.7 °C. Being relatively higher temperatures than those obtained for these case studies. In turn, the review by Chatzidiakou et al. [4] concluded that school comfort temperatures ranged in winter between 19 °C and 21 °C and in summer between 22 °C and 27 °C, more similar to this study.

According to the WHO, the minimum recommended thermal comfort is 18 °C [149]. This value is derived from a health perspective and considers the impact on energy consumption to achieve high indoor temperatures during the cold season.

In other studies in Spain, the Regulation on thermal installations in buildings (RTIB) was applied as an indicator of environmental comfort conditions. As in the research carried out by Campano et al. [46] in schools and institutes in Andalusia (Spain) and the research carried out by Gallego Sánchez-Torija et al. [31] in schools in Madrid (Spain).

The RTIB, which applies to new buildings or renovations with HVAC installations, bases its comfort limits on the ISO 7730 standard using the PMV and PPD calculation method, establishing an activity of 1.2 met and clothing 0.5 clo in summer and 1 clo in winter, obtaining temperature limits for summer between 23 °C and 25 °C and winter between 21 °C and 23 °C.

These RTIB values are designed for buildings with climatic installations that ensure these temperatures. The lower limit set for winter is very high compared to the one used in this research with UNE-EN 16798; this can be seen in Figure 6-2, which represents the different comfort temperature ranges for different standards.

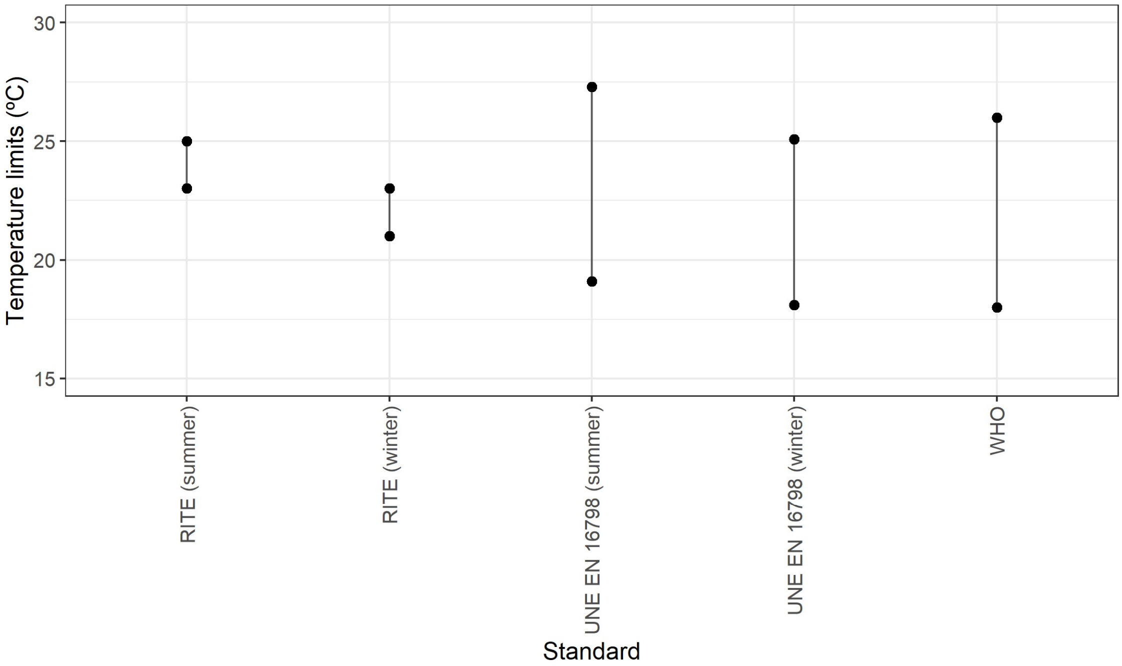


Figure 6-2. Temperature limits for different standards

If the comfort calculation in this research had been carried out with the RTIB criteria, the percentage of time in comfort would have changed significantly (see Figure 6-3). For these case studies, the average comfort in winter would be 23% and in summer 33%, far from the 75% in winter and 94% currently achieved. These results demonstrate that achieving comfort values with such strict limits and far from adaptive behaviour is challenging.

As was presented in the literature review, where the limits set by different standards most commonly used in previous research were presented, and observing the results obtained by different reviews and articles, a significant disparity is observed between temperature limits considered comfort. This difference between the limits influences the interpretation of the results obtained.

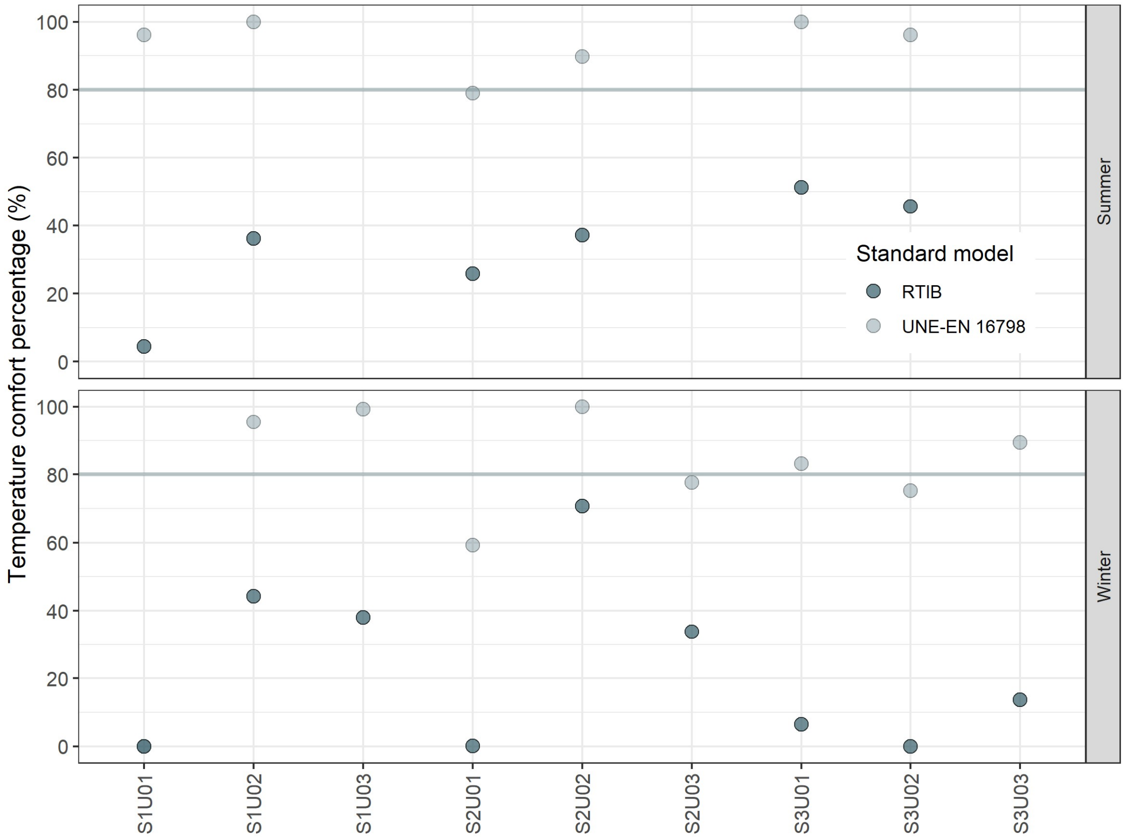


Figure 6-3 Temperature comfort percentage for RTIB and UNE-EN 16798 standard

6.1.2.2 Relative humidity comfort limits

This study uses the limits for relative humidity as the indicator in the UNE-EN 16798 standard. This standard only refers to buildings that require humidification and dehumidification systems when they fall outside the range of 25% and 60% relative humidity.

The results obtained in these schools during the winter show that the classrooms that have not reached the comfort level in relative humidity have been due to not reaching the minimum value of 25%. This relative humidity limit varies widely with other standards (Figure 6-4). For example, ASHRAE-55 [30] does not consider a minimum relative humidity limit, so in this study, the percentage of time in relative humidity in comfort would increase considerably in those cases where it has been considered more vulnerable. Furthermore, the ASHRAE-55 standard specifies a maximum humidity ratio of 0.012 for a dew-point temperature of 16.8 °C.

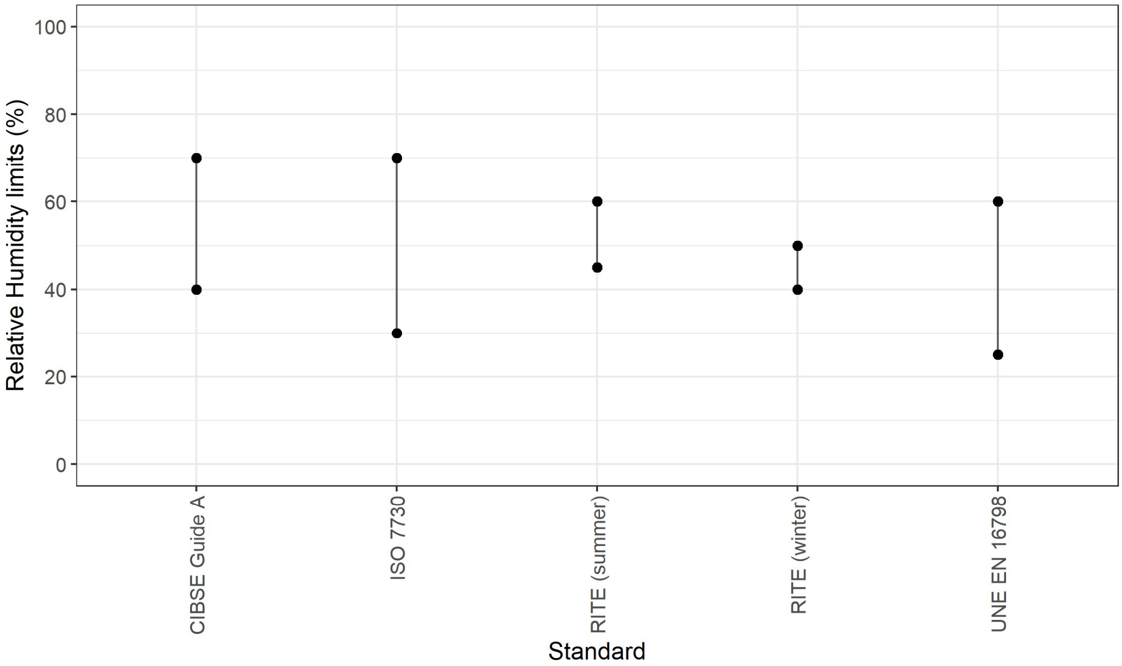


Figure 6-4. Relative Humidity limits for different standards

Alternatively, in ISO 7730 [62], the recommended relative humidity is between 30% and 70%. In the case of the CIBSE guide A standard [59], the limits are similar, between 40% and 70%. In both cases, as the lower limit is higher than in UNE-EN 16798, this study's classrooms with lower relative humidities would achieve worse comfort under this criterion.

The RTIB(2013) [150] in Spain establishes limit values for relative humidity depending on the season, between 45% and 60% in summer and 40% and 50% in winter. These are strict values and very tight ranges compared to other standards. If these limits were applied in this study, the average comfort in winter would be 11% and in summer 76% compared to the current average values of 87% in winter and 99% in summer. The comfort obtained during winter would be reduced by up to 70%, the limit set by RTIB being very restrictive.

6.1.2.3 Comfort limits for CO_2 concentration

Applying the UNE-EN 16798 standard, the indoor CO_2 concentration is obtained as a function of the average outdoor concentration obtained. The school with the lowest average outdoor CO_2 concentration has been used in this case.

Using the same criteria for all three schools, a more restrictive limit has been obtained (1225 ppm) compared to if it had been applied to each school based on the average outdoor concentration.

Although S1 is also the school with the highest outdoor concentration, it has the lowest indoor concentration, so this indicator change would not have influenced it. The schools inside had an average concentration during occupation of 761.9 ppm in winter and 656.2 ppm in summer (and medians of 675 ppm and 576 ppm, respectively). The result was 91.46% of the time in comfort in winter and 96.49% of the time in comfort in summer.

As seen in chapter '5.3.2.1 Individual comfort per parameter', the classrooms during both monitoring campaigns have reached comfort values for CO_2 concentration above 84%, except during winter in classrooms S2U02 (66%) and S3U03 (76%). These are considered very high comfort values.

A COVID protocol was active during the monitoring at the three centres. During this period, the Basque Government (BG) presented a plan that stipulated that CO_2 concentrations should not exceed 700 ppm [126]. By applying this limit of 700 ppm, the comfort time would be reduced to 68% in winter and 48% in summer (see Figure 6-5).

With these results, in contrast to the UNE-EN 16798 standard, where a higher percentage of comfort was obtained in summer than in winter, with this stricter limit, the obtained percentage of comfort is higher in winter than in summer. The limitation generated with such a low comfort limit (700 ppm) is that it does not show the actual evolution of the concentration over the monitored time since the means and medians are higher than the established limit.

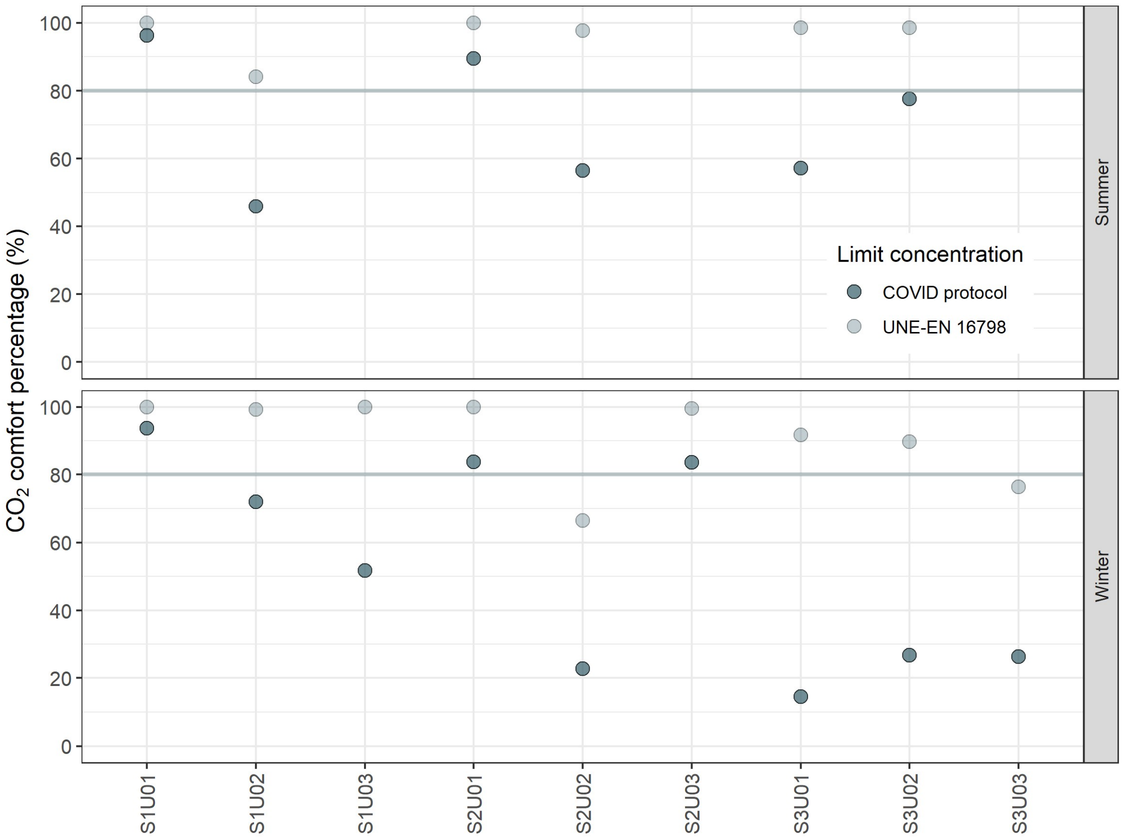


Figure 6-5. CO_2 comfort percentage for a recommended maximum of 700 ppm

Analysing these time values in comfort with the CO_2 concentration limit recommended by the BG is considered a very strict limit value. Even in centres with mechanical ventilation, these values have not been reached. At the same time, comparing S2 and S3 with different mechanical ventilation systems, S2 reaches, on average, better comfort than S3.

In these mechanically ventilated centres, the RTIB standard for a category IDA2 environment limits the maximum indoor CO_2 concentration to 500 ppm above the outdoor concentration. The UNE-EN16798 standard applied in this study is less demanding and limits it to 800 ppm above the outdoor concentration for category II. With this difference of 300 ppm, a comfort limit of 925 ppm is obtained for this case study. Applying this comfort limit gives an average comfort of 76% in winter and 88% in summer, which is considered acceptable.

6.1.2.4 Influence of the HVAC system on the comfort criteria

As developed in the objectives and methodology, a single comfort criterion has been chosen for the three centres (OBJ-5). On the one hand, this facilitates the comparison of the results obtained in the different centres. In addition, it was considered more relevant to choose a criterion based on the adaptive model, as it considers the occupants' adaptive capacity. This model does not consider either the clothing level or the activity level, which directly influences the limits in the heat balance model. This results in a higher comfort range.

Following this criterion, the UNE-EN 16798 standard has been chosen. This standard specifies a criterion of temperature limits based on the PMV-PPD model of ISO 7730 for buildings with HVAC or mechanical cooling systems. These limits define calculation values for the design of the installations in winter and summer. The S1 school has no air-conditioned ventilation systems ventilating naturally, so this criterion is not applicable.

Category II of the UNE-EN 16798 establishes a minimum temperature limit of 20 °C in winter and a maximum temperature limit of 26 °C in summer. With these limits for centres S2 and S3, the percentages of time in comfort during the occupied periods have been obtained (see Figure 6-6).

It can be seen that the summer campaign continues to be the most favourable period for the temperatures reached. However, during the winter, very different results have been achieved: while S2U02 is in comfort more than 90% of the time, the rest of the classrooms reach low values. The classroom with the most significant variation in comfort time and the greatest impact of this change in limits was S3U03, where comfort time was reduced by more than 56%, from 89% to 32%. The only classroom that did not change its comfort time was S3U01 during the summer, always reaching 100% comfort time.

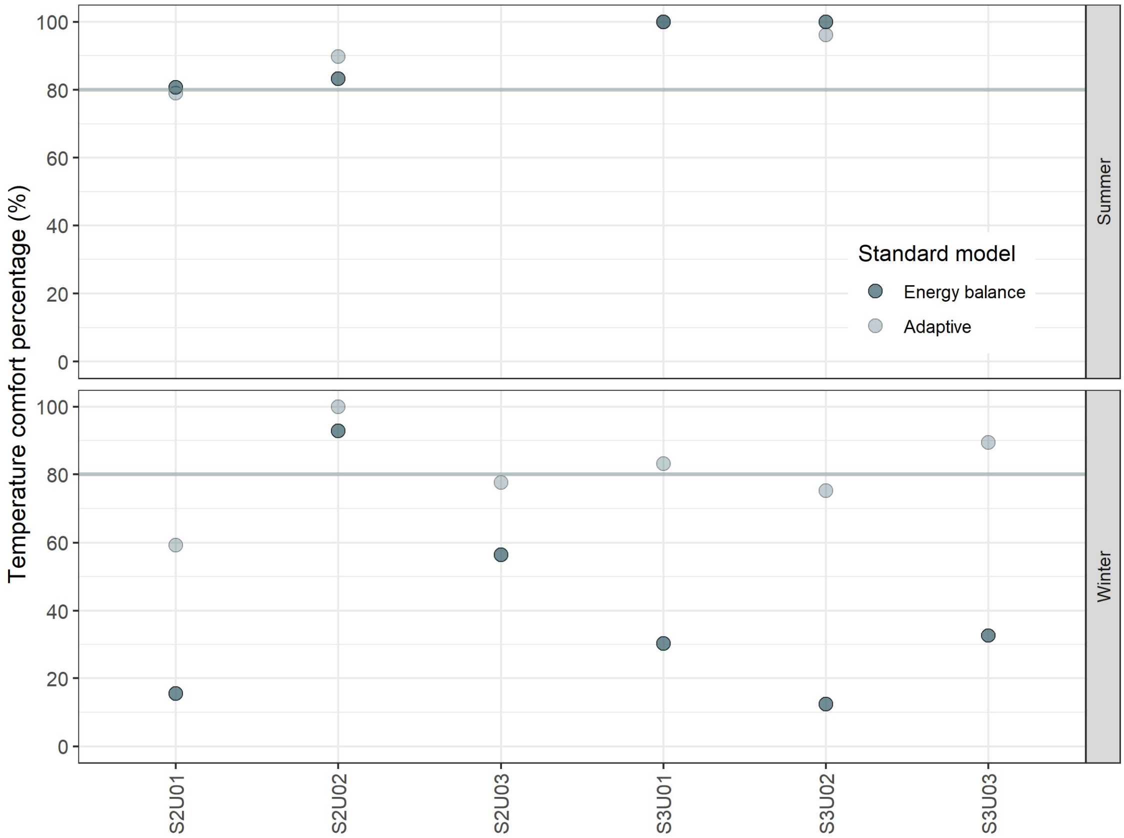


Figure 6-6 Temperature comfort percentage for UNE-EN 16798 models

A clear difference between the two models of defining comfort limits is the lower and upper-temperature limit criterion for both seasons. In the heat balance model, only the minimum temperature limit in winter and the maximum temperature limit in summer are set. As previously mentioned, with other standards such as RTIB, if only the lower limit in winter and the upper limit in summer are considered, calculating overheating in winter or very low temperatures in summer is excluded.

6.1.3 Influencing characteristics in achieving comfort

Previously, in chapter '5.3.3 Relation between comfort and constructive ', the impact of different characteristics on comfort was analysed. These have been chosen according to those that the literature review indicates as relevant. Table 6-5 presents those characteristics that have impacted this study and on which comfort indicator they have produced this impact. All influences considered statistically significant (*p-value* <0.05) occurred exclusively during winter.

Table 6-5. Selection of influential characteristics on comfort during winter.

	Floor	DF	OD	Volume	WWR
Temperature	No	Yes	Yes	Yes	Yes
Relative Humidity	No	No	No	No	No

CO_2	Yes	No	No	No	No
Simultaneous	No	Yes	No	Yes	Yes

At the same time, multiple characteristics did not impact any of the comfort indicators in any of the campaigns. These characteristics were the type of classroom, the heating system, the orientation and the ventilation system.

Also, the measurement campaign only proved significant on the simultaneous comfort indicator ($p = 0.0067$) but had no impact on any other indicator.

Table 6-5 shows that the indicator most affected by the construction properties to achieve comfort is the temperature during winter. The Window to Wall Ratio (WWR) was the main factor in achieving comfortable temperatures. The higher the WWR ratio, the greater the thermal comfort. All the classrooms have this ratio with values higher than the recommended 20%, and excluding the gymnasiums, which are typologically different, the other classrooms have a WWR between 31% and 48%.

Nevertheless, this parameter shows the disparity between campaigns. The influence of WWR on temperature in winter is very high (cor = 0.91). However, it is null in summer (cor = -0.10), contradicting to some extent what was previously analysed in the literature review, where, especially in warmer climates, the dimensioning of openings to avoid overheating is more limited. From this result, it can be interpreted that as there is little or no overheating in summer, the sizing of the openings is crucial to achieving greater comfort in winter.

Another factor that is limited by the size of the openings is the Daylight Factor (DF), the ratio of window area to classroom area, which was also found to be significant ($p = 0.0011$) but with a negative correlation (cor = - 0.895).

Comparing the correlations between the DF and WWR coefficients, both are almost equivalent but of opposite sign. The window surface influences both indicators, but opposite correlations are being obtained. It follows then that the influence of the façade surface and the classroom surface will directly influence the achievement of comfort, both indirectly for WWR and directly for DF.

Similarly, the volume had a moderate negative correlation (cor = - 0.7201), so the larger the room, the lower the temperature comfort. The occupancy density (OD) also significantly impacted reaching comfortable temperatures (cor = 0.6902).

The positive correlation between comfort and OD may contradict what is reflected in the literature review, where it is recommended to limit occupation density as it negatively influences comfort [13], [49]; this may be because classroom occupancy density was not excessively high (< 0.51 student/m^2).

In contrast to the influence of different measured parameters on temperature, particularly in winter, relative humidity is unaffected. In this climate and these selected schools, the most vulnerable classrooms regarding hygrothermal comfort are limited by temperature, not relative humidity.

From the comfort indicator on CO_2 concentration, only the floor was relevant, but neither the ventilation system nor the OD. This result contradicts the evident influence of ventilation systems on air renewal in classrooms. So, despite having ventilation systems that renew the air in very different ways, sufficient significant different comfort values were not obtained. In the literature review, multiple investigations analyse the concentration of CO_2 according to different ventilation systems, comparing averages and improvements of different systems [2], [12], [13]. The next chapter will discuss the outcome and the debate between comfort and ventilation systems.

Analysing the influence of the characteristics on the ability to achieve comfort during summer, it has been observed that the construction characteristics influence no indicator. The comfort achieved in all classrooms during this monitoring campaign is similar. Consequently, there is no statistically significant difference or grouping. Therefore, in this climate, the classrooms can more easily achieve comfort in their interior due to the external environmental conditions during this period based on the current design of the educational centres.

6.2 VENTILATION AND IMPACT ON COMFORT

Following the analysis of the comfort of different construction features, it has already been shown that the ventilation system has no statistically significant influence on the comfort values achieved.

Earlier in the literature review, the debate on which ventilation system achieves the best comfort and CO_2 concentration values is presented. The hypothesis of improved thermal comfort conditions when a mechanical ventilation system has been introduced has been worked out in several studies or by comparing results depending on the ventilation system [12], [13], [16], [24], [26], [32], [49], [54], [55], [151]

However, analysing the values achieved in this research, the ventilation system does not significantly influence any comfort achieved. Moreover, on average, no better values are recorded in mechanically ventilated classrooms, either. In the following, the main arguments and strategies obtained in previous literature have been developed under the interpretation of the results obtained in this research.

6.2.1 Comparison of results between natural and mechanical ventilation.

In the literature review, the main existing ventilation systems defined by different standards have been classified. All ventilation systems have different limitations and strengths, so this chapter will analyse the results obtained depending on the ventilation system and compare them with previous research to analyse whether the results are similar or have the same limitations.

There is much debate about classroom ventilation systems, especially between natural ventilation (NV) and mechanical ventilation (MV) and their improvement of ventilation in classrooms. Although, as already presented above, in section '5.3.3 Relation between comfort and constructive characteristics', no statistically significant relationship was found between any comfort and the ventilation system.

Currently, the Spanish regulation applicable in this field is the RTIB [64], which regulates and mandates the insertion of mechanical systems to guarantee correct indoor air quality in buildings. Alternatively, it also allows the implementation of Heating, Ventilating and Air Conditioning (HVAC) systems to support MV. However, the development of this standard, according to other Spanish authors, still needs to be further developed to include other ventilation and air-conditioning alternatives that comply with the standard [15].

In this research, the school classrooms in S1 with NV, despite not having MV system because it was built before the application of this regulation, have achieved equally good results in some of its classrooms. Next, it will be analysed whether similar results have been obtained in the previous literature considering the ventilation values of the ventilation systems in each case study.

6.2.1.1 Results obtained according to different ventilation systems

Previous research has shown that, on average, the concentration of CO_2 is lower in schools with MV. As in the research and review by Santamouris et al. [12], the median CO_2 concentration obtained in previous studies in more than 300 schools in 17 countries was reviewed. They found that in schools with NV, the median was 1420 ppm, and in schools with MV, it was 910 ppm, with the difference between medians being quite significant, more than 500 ppm.

In this line, the research carried out by Bain-Reguis et al. [13] compared the comfort and ventilation achieved in 19 classrooms in 4 schools in Scotland. The results show how better values have been achieved in mechanically ventilated classrooms when operated correctly, resulting in higher ventilation rates and lower CO_2 concentration.

Similarly, evidence [31], [114] shows that classrooms with NV are less efficient as they achieve lower renovations than with a dual-flow MV system with heat recovery.

In this research, the opposite is happening; classrooms with NV are achieving not only lower CO_2 concentrations but also better overall comfort values. In the review by Singh et al. [2], the CO_2 concentration was also lower in naturally ventilated classrooms than in mechanically ventilated classrooms. However, the authors pointed out that this could be because MV classrooms have a higher occupancy density.

Reviewing the literature, it is observed that normal behaviour in naturally ventilated schools is to obtain higher CO_2 concentrations in winter compared to summer [51], [152] due to the schools' prioritisation of achieving thermal comfort over ventilating the classroom.

In this research, in school S1, naturally ventilated classrooms achieve low CO_2 concentrations in winter and summer. This results in 97% of the time being in comfort in winter and 100% in summer. This case exemplifies the ability to obtain comfort without inserting mechanical ventilation systems, even during unfavourable temperatures.

6.2.1.2 Limitations found in different ventilation systems

Analysing the results obtained, both in this research and in previous literature, multiple limitations have been identified for the different ventilation systems when it comes to achieving thermal comfort or during operation.

In this and previous studies, it has been found that MV systems sometimes are not used as designed. In the case of the S3 centre, its power was reduced to 50% due to noise complaints. The same happened in the research by Almeida et al. [8], where the teachers switched off the ventilation systems. This results in a worse IEQ but still high costs for using and maintaining these systems.

In the S3 centre, during the previous interview with the management team, they also expressed that the measurements of the CO_2 sensor of the mechanical ventilation system were not working correctly. This sensor showed very high measurements before occupation. For example, on a Monday before the centre was occupied, it measured concentrations above 1500 ppm when it had been unoccupied for more than 48 hours.

This malfunction demonstrates, on the one hand, that if it is not functioning as designed, it will not achieve the efficiency and effectiveness for which its operation is designed. This poor performance also directly impacts the IEQ since it will lead to worse classroom environmental conditions.

It is essential to recognise the role of the multiple agents that play a part in guaranteeing correct IEQ in educational centres. In this case, the administration should ensure the correct maintenance of the different facilities and mechanical systems to reach the optimal and efficient conditions that guarantee a correct IEQ.

Another limitation found in previous studies on HVAC systems is that they can generate local thermal discomfort [90], causing specific microclimatic conditions in localised parts of the classroom, affecting the thermal comfort and perception of the occupants [153]. Alternatively, previous studies found that mechanical systems sometimes fail to improve indoor air quality as expected [154].

It is also important to check the correct functioning of the mechanical systems to guarantee the conditions according to their performance. Also, in naturally ventilated centres, it is essential to maintain the enclosure systems properly [13].

Regarding the impact of the ventilation system on the perception of comfort, in the review by Singh et al. [2], students are more sensitive to temperature changes during summer than in winter in naturally ventilated classrooms. So, their thermal perception is affected by the ventilation and air-conditioning system present in the classroom [2], [90], having a more elevated thermal comfort range in naturally ventilated buildings than in mechanical ones [65].

Predicting thermal comfort in buildings with NV is more challenging, as it is strongly dependent on outdoor environmental conditions as opposed to mechanical systems with controlled indoor environmental conditions [155].

The ability to achieve comfort will be limited by the outdoor environmental conditions, both for thermal comfort and ventilation. If the outdoor temperature is unfavourable or reaches extreme values, occupants are expected not to open the windows to maintain thermal comfort indoors, so the lack of ventilation will increase the CO_2 concentration. Furthermore, indoor thermal comfort is not expected to be achieved if ventilation is encouraged during these unfavourable temperatures.

Another limitation of schools with NV and other building typologies with NV is that the airflow cannot be regulated, unlike mechanically controlled ventilation. This situation can lead to vulnerable situations at both ends. On the one hand, there may not be sufficient air renewal to ensure correct air quality, or the uncontrolled air renewal may be too high, and the air velocity inside the building may reach a level that causes discomfort.

In previous studies [31], another limitation found with NV is that it is often not adequately ventilated or does not take advantage of the means available, limiting the capacity for improvement and ventilation during these periods. For example, in many cases, during class time, the doors remain closed due to noise, preventing cross-ventilation and thus reducing the NV capacity of the classroom. At night, for safety reasons, there is also no ventilation, which, especially during hot periods, impacts indoor temperature.

6.2.2 On-demand hybrid ventilation

When it comes to achieving a balance between thermal comfort, ventilation levels and energy consumption, many studies have concluded that on-demand hybrid ventilation achieves the best results [10], [154], [156]–[160].

With NV, if the minimum number of renewals needed is not reached to avoid exceeding CO_2 concentration, a backup system will be needed to ensure correct conditions in the classroom. Meanwhile, too much energy is consumed with MV to ensure correct indoor conditions. If the outdoor environmental conditions are favourable, natural means can be used to achieve comfort without resorting to mechanical systems.

Previous research by Haddad et al. [151] studies the improvement intervention in an Australian school. This school, which was naturally ventilated, had an unfavourable IEQ, where the indoor temperature was very high and CO_2 concentrations of up to 2400 ppm were reached. They intervened by introducing an on-demand ventilation system, which reduced the peak CO_2 concentration to 1335 ppm and, at the same time, improved thermal comfort, maintaining a calculated neutral temperature of 23 ºC.

One aspect to consider in on-demand ventilation systems is the active participation of the occupants. While these systems must consider the control of humans to guarantee conditions of comfort-making control, it is important to know the willingness of the occupants to participate.

The study by Bresa et al. [161] focused on how much occupants participate in advanced control systems and their priorities. This study measured interaction with HVAC control, lighting and other actions. It was found that 47% of occupants consider IAQ the most relevant comfort aspect, followed by thermal comfort (40%) and visual comfort (26%). This study found that despite the desire for more automation systems, there is not as much acceptance of human-centred control. While 67% want access to the control of mechanical systems, only 47% prefer to interact with the control, and 20% of occupants prefer not to have access or interact with the control.

Under this discrepancy, of some occupants having to take active roles in decision-making, there are multiple alternatives. Automated systems based on the Internet of Things or systems with machine learning and Artificial Intelligence can be used to make decisions [67]. This combination of automated systems can ensure optimal solutions for on-demand ventilation, balancing NV and MV.

Within automated systems, one option is to control the opening of windows to promote ventilation according to environmental conditions. In the study by Stazi et al. [162], the thermal comfort and CO_2 concentration were monitored and surveyed in two classrooms. In one classroom, no intervention was carried out; in the other classroom, an automatic window opening system was introduced depending on the indoor environmental conditions. As a result, in the non-intervention classroom, the occupants decided to prioritise thermal comfort, reaching very high CO_2 concentrations. In contrast, in the classroom where the intervention was carried out, the CO_2 concentration was reduced, reaching a maximum of only 1500 ppm, and the thermal comfort of the occupants was maintained. Therefore, automatic systems achieved a correct balance and greater comfort in the classroom.

Along the same lines, Annex 35, created by the International Energy Agency [156], recommends seasonal control of these hybrid ventilation strategies. During winter, the control parameter is indoor air quality, and during summer, the maximum indoor temperature. In addition, the resulting heating or cooling demand may also be necessary to achieve comfort during spring or autumn.

Analysing these results from previous research and the monitored results of this study, the introduction of hybrid ventilation based on on-demand control achieves the best balance between ventilation and comfort in temperate climates, especially during periods of unfavourable temperatures.

6.2.3 Impact on energy consumption of the different ventilation systems

In this study, it was a significant limitation not to have accessible data on energy and heating consumption in the schools. One of the main arguments in the debate between thermal comfort and ventilation and air conditioning systems is the energy consumption required by each.

There is typological diversity in schools with very different needs and behaviours. Even within the same school, the qualities of each classroom may be different, such as the density of occupancy and occupancy schedules [92], affecting energy consumption.

In order to minimise energy consumption, it is necessary to apply different energy sustainability strategies that ensure a balance between reducing energy consumption and achieving comfortable indoor conditions [155] and occupant behaviour [9].

Based on students' perceptions, it has been found that in classrooms with HVAC, the comfort temperature of the students is lower, so the heating temperature is lower, implying 10% less energy consumption without sacrificing thermal comfort [2].

Previous research has analysed the impact of multiple optimisation strategies in centres to achieve this balance between thermal comfort and energy consumption [155], [157], where hybrid ventilation achieves the best balance.

Annex 35 [156], proposed by the International Energy Agency, specifies how hybrid ventilation, through the opening of windows and air conditioning, increases the cooling load when natural means alone are insufficient.

In hot climates, hybrid ventilation minimises the operating cost and energy consumption of annual air-conditioning systems, allowing better thermal comfort [158].

In other climates, NV has been identified through research as a simple opportunity to improve ventilation rates without increasing the energy consumption of the building. In the study by Carvalho et al. [14] in Portugal, where they took advantage of the mild climatic conditions and adaptive thermal comfort model, they improved indoor comfort in classrooms by natural means. In the case of the UK, which also has a cooler temperate climate, it is shown that the NV can achieve sufficient ventilation [163] even during more vulnerable periods such as winter, where sufficient renovations were achieved, and energy consumption was hardly influenced.

The limitations of schools with NV system have already been analysed. In the research by Gil-Baez et al. [15], when outdoor conditions have high noise pollution or the outdoor air quality is not sufficiently adequate, the introduction of hybrid ventilation systems with automated window control and MV with heat recovery can also be a solution to reduce operating costs. In the same study [15], the energy consumption, energy savings and indoor comfort achieved in two schools located in a Mediterranean climate were analysed. The result was that the NV was sufficient to achieve this balance for this climate, even in nZEB schools.

There is widespread application of mechanical ventilation systems with heat recovery systems to achieve HVAC system efficiency. In temperate climates, the heating demand is generally lower than the ventilation demand, as stated by Gil-Baez et al. [110]. These ventilation systems are not the most optimal solution for these climates, as they consume too much electricity. Also, with the current design of more insulated buildings, with small internal heat gains, a heat recovery unit in the ventilation system may become unnecessary.

6.2.4 Advantages of ventilation during break periods

In both the applied standard (UNE-EN 16798 [63]) and in previous research [13], [31], the importance of taking advantage of unoccupied periods or breaks between classes to ventilate classrooms has been highlighted, achieving higher renovations and directly improving indoor air quality.

In the UNE-EN 16798 standard, section B.3.1.5 specifies that during the 2 hours before the occupation, a flow equivalent to 1 volume of the area to be ventilated should be supplied to dilute the building's emissions, specifying a flow of 0.15 l/s-m^2 as sufficient.

In the case of the schools analysed, this value should be reached before the occupation throughout the night, and although the time during breaks is shorter than 2 hours, it is recommended to take advantage of the different breaks throughout the day to promote classroom ventilation.

As seen in Figure 6-1, the evolution of CO_2 concentration on a typical day can be differentiated by the different occupations along the day. The impact of break periods on CO_2 concentration and ventilation during the lessons can be seen.

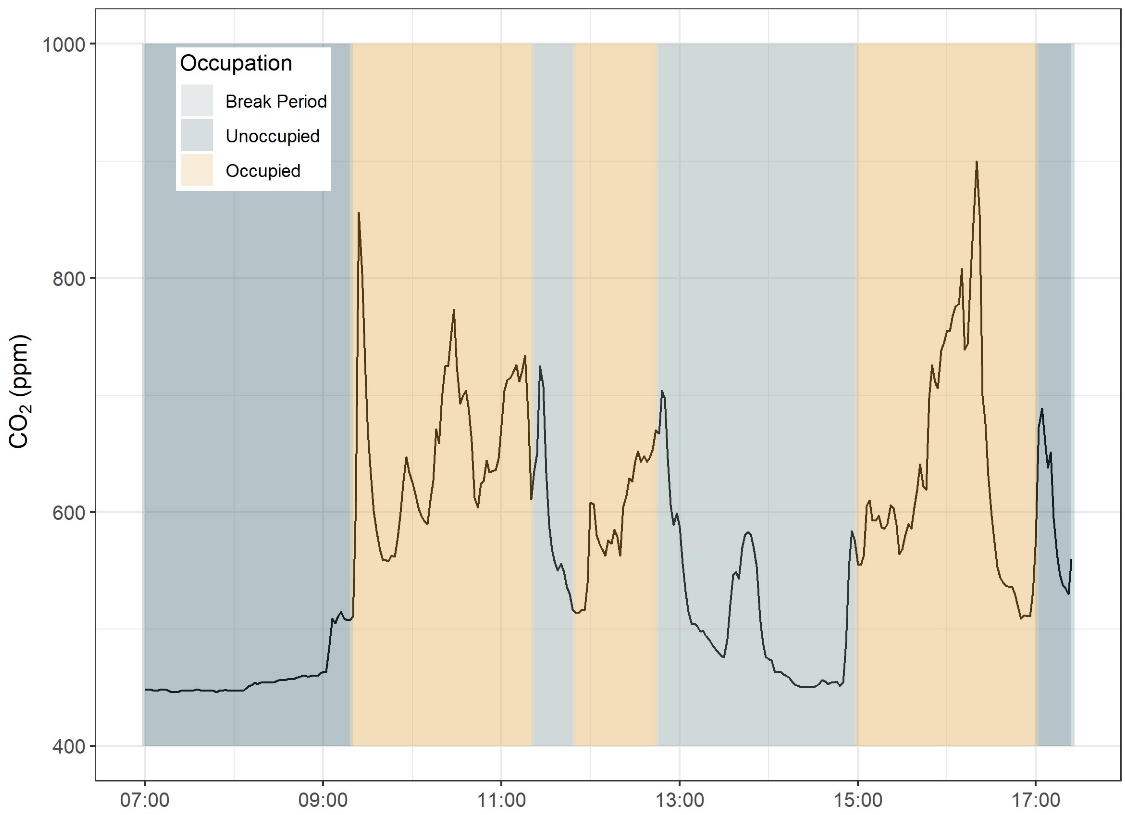


Figure 6-7. CO_2 evolution during a winter day in S1U02 classroom

The renewal rates achieved in each classroom have been calculated, considering the values of CO_2 concentration obtained during the break periods. For this purpose, the decay calculation method, by which the factor air change rate ($A_{D)}$ (h^{-1}) is obtained, has been used [72] (Equation 6-1).

$$A_D = 1/\Delta t \ ln\{(C1 - CR)/(C0 - CR)\}$$

Equation 6-1 Decay air change rate calculation.

This calculation is considered sufficient and significant when there is a difference of more than 100 ppm during the period evaluated. The ventilation rate for a classroom with this method A_D is calculated using two CO_2 measurements (Equation 6-1), where Δt is the elapsed time between the two measurements. C0 and C1 are these CO_2 measurements expressed in ppm. CR is the concentration of CO_2 that is reached in a steady state when the occupancy in the classroom is reduced.

To calculate the CR value, when the steady state is reached, CO_2 concentration values have been chosen after several hours of unoccupied time, choosing as a value the average minimum concentration for each classroom during the unoccupied periods.

For the calculation of the factor A_D, have been chosen where the most significant variation occurs during the break, i.e. where the difference in CO_2 is the most significant, being aware that the selected breaks are the most favourable cases for this calculation.

Following this method of calculation, the following figure in Figure 6-8 represents the renovations achieved in each classroom during the selected significant break periods.

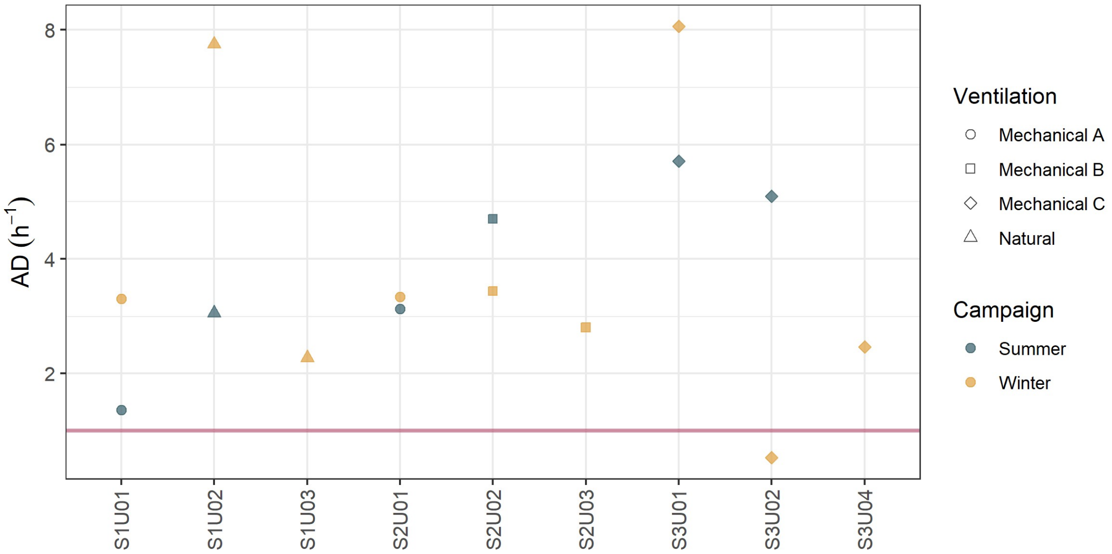


Figure 6-8. Ventilation during rest periods

Figure 6-8 shows that in all the classrooms during the selected break, the air renewal achieved exceeds 1 volume, as required by the UNE, except for the S3U02 classroom during winter, which only reaches 0.53 h^{-1}.

After this, the lowest value was reached in S1U01 in summer with 1.36 h^{-1} and the highest in S3U01 in winter with 8.06 h^{-1}. No apparent difference was found between the campaigns, with some classrooms having better renovations in winter (S1U02) and others better in summer (S3U02) regardless of the school in which they are located. In school S1, classrooms S1U02 and S1U03 are naturally ventilated. This strategy ensures sufficient classroom air renewal during breaks, as observed in previous research [13].

Similarly, in the research by Santamouris et al. [12], this difference is presented in the ventilation achieved during lessons and breaks in 27 naturally ventilated schools. The authors obtained ventilation between 2 and 11 l/p/s during lessons and between 2 and 20 l/p/s during breaks. The renovations during breaks were up to 4 times higher than during lessons.

Unoccupied periods, like break periods, can be used to ventilate and improve indoor environmental conditions. During periods of nighttime unoccupancy in certain climates, it is a proven strategy to avoid overheating during the day. By lowering the outside temperature during the night by taking advantage of the thermal inertia of the building and the NV that is produced, the temperature inside the building is reduced through the concept known as passive cooling [110], [142], [145].

6.3 ADAPTATION AND OCCUPANTS INFLUENCE

Adaptive thermal comfort models take into account the adaptive capacity of the occupants. The occupants can take measures on themselves that allow them to achieve comfort. Moreover, unlike heat balance models, these thermal comfort models are not influenced by the level of activity or clothing that defines the comfort ranges.

The strong influence that occupants have in achieving thermal comfort is influenced by the context in which it is measured. In this case, the monitoring was carried out in the context of a pandemic caused by COVID-19. Therefore, a COVID protocol was active in the educational centres, emphasising ventilation in the classrooms to reduce the viral load and prioritising this ventilation over thermal comfort.

6.3.1 Influence of the COVID protocol during monitoring

Knowing the context of the research is relevant when extrapolating the results obtained. Since the COVID protocol, there has been a change in the behaviour of the occupants in the educational centres. At the same time, this is a significant limitation, as it is not the usual behaviour and limits the extrapolation and generalisation of the results to other case studies.

This COVID protocol was intended to follow the recommendations of the Basque Government, which suggested not exceeding the CO_2 concentration of 700 ppm. Even following the recommendation in all centres to ventilate more, as presented above, almost no centre has achieved such low CO_2 concentrations, which is a somewhat unachievable limit.

Considering the priority that this COVID protocol gives to ventilation over thermal comfort has allowed to observe the ventilation capacity of the classrooms and the influence on thermal comfort. A key role was played by awareness-raising and dissemination among teachers and students, who altered their behaviour to follow this protocol.

Other studies have been carried out in the same context. For example, several classrooms were monitored in the government-mandated study by Bain-Reguis et al. [13] during the winter period of 2020-2021 in Scotland [164]. The limit of CO_2 was set at 1500 ppm in classrooms (in gymnasiums and music rooms 800 ppm), and the temperature was to remain above 17°C. These limits are much less strict than those applied in Spain and consider not only CO_2 concentration but also thermal comfort. Even though these limits are more achievable, it was observed that schools with NV especially did not achieve these comfortable conditions.

In the same period, in the Netherlands, a study was carried out in different educational institutions [49]. This study monitored before and during COVID-19. In this context, the COVID protocol required opening windows and doors to improve classroom ventilation. This study assumed that NV is a reinforcement for increased ventilation in schools with MV. The authors argue that despite improvements in ventilation rates being recorded, the main factor involved was decreased occupation density rather than the flow generated by opening windows. Thermal comfort was not optimal in either of the two periods analysed. The authors conclude that there are limitations in these centres to achieving thermal comfort and proper ventilation in the classrooms and suggest the introduction of on-demand ventilation systems.

Two studies carried out during the same period have been selected in Spain. The first was in the autonomous community of Andalusia [163], where IAQ and thermal comfort were measured in schools with NV. Higher concentrations of CO_2 were reached in high schools than in schools, but good comfort conditions were recorded in both. The authors concluded that in this climate, following the recommendations of the COVID protocol, ventilating between classes and, at the end of the day, sufficient comfort conditions and IAQ are achieved.

The second study in the autonomous community of Extremadura [50] was monitored at the university during exam periods in January 2021. During this period, distancing and ventilation measures were introduced. All classrooms in the centre are naturally ventilated, and during this examination period, windows and doors were kept fully open to ensure higher ventilation rates. As a result, low CO_2 concentrations were obtained, and thermal comfort was only negatively affected when the outside temperature was below 12°C.

In these studies with temperate climates similar to that of Vitoria-Gasteiz, it can be concluded that natural ventilation can achieve comfort values. However, when outside temperatures are very low, thermal comfort can be compromised in some cases, depending on the design of the building. It has been observed that in some of these studies, a balance between thermal comfort, ventilation and IAQ is achieved.

The influence and impact that the COVID protocol has had on indoor environmental conditions mean that it will influence classroom behaviour in the future, raising awareness in schools of the importance of ventilation and maintaining healthy classroom conditions.

6.3.2 Adaptation opportunities

The results show that classrooms with very similar characteristics achieve different comfort levels. It is interpreted that the behaviour of the classroom occupants and their ability to adapt their environment to comfortable conditions play a decisive role. As the author Korsavi identifies in his thesis [1], the adaptive capacity of learners and teachers is grouped into two types.

First, personal adaptation means making changes at the individual level; for example, changing clothing, thus changing the level of isolation (clo), the activity level (metabolic rate), posture, hydration or ventilation.

Second is an environmental adaptation, which consists of changing environmental conditions that can be achieved by controlling accessible operating systems, such as mechanical systems or opening windows and doors.

These adaptive capacities aim to achieve thermal comfort. It is also relevant to achieve other types of comfort that are part of the IEQ [1] and achieve a balance between these.

Following the opportunities for adaptation to achieve comfort, Bain-Reguis et al. [13] recommend reducing the occupancy density in classrooms to ensure better comfort values to reduce CO_2 concentration, as in the study by Ding et al. [49].

In classrooms, it is often the teachers rather than the students who control changing environmental conditions. Although this study did not survey occupants' perceptions of thermal comfort, previous research has demonstrated the difference between occupants' perceptions of thermal comfort and measured thermal comfort [26], [36], [39], [54], [90], [165] and also between the age of the students [26], [115] [90].

This discrepancy in the perception of thermal comfort by age is relevant since, during primary and pre-elementary education, students are not as able to act and do not perceive comfort as much. In secondary and higher education levels, there is this personal adaptation behaviour.

In this research, in the secondary school, environmental adaptation by the students was nullified, as windows were limited to opening with keys only accessible to the teaching staff, limiting the student's ability to achieve comfort.

A key aspect is measuring the students' perception of comfort during occupancy and not only considering current design regulations. In studies such as the one by Aparicio-Ruiz et al. [54], a discrepancy has been found between the monitored values considered comfort and the students' perceived comfort, finding a negative correlation between the measured values and the surveys.

Other studies assess perception, like the research carried out by Ma et al. [51], where they found no relationship between students' perceived IAQ and CO_2 concentration. Perception does not correspond to actual values, so the authors recommend monitoring these values to ensure a correct IEQ.

Also, as was found in the investigation carried out by Wargocki and Da Silva [19], when occupants had the opportunity to visualize the monitored data, indoor comfort conditions significantly improved compared to when the monitored data was not visualized.

Finally, cultural factors are a key aspect to consider in adapting and perceiving thermal comfort. Specifically, about the ventilation system, in our context, there is a perception that with natural ventilation, we achieve greater satisfaction, better ventilation and better environmental conditions than with mechanical ventilation [166], [167].

7 CONCLUSIONS

7.1 MAIN CONCLUSIONS

Ensuring correct environmental air quality in educational centres is a key objective, as it impacts the health and performance of its occupants. Its youngest occupants, students, are more vulnerable as they are still at a developmental age. Therefore, achieving indoor comfort is a priority.

Following the previous objectives and research questions, a methodology was proposed and implemented in three case studies in Vitoria-Gasteiz, Basque Country. In this context, the comfort achieved and the influences that have impacted this comfort were analysed.

Following the validation of the methodology and the results obtained, it is considered favourable to be able to implement this methodology in other schools. The main conclusions are developed below after applying the methodology in the selected case studies.

7.1.1 Comfort

The design of the monitoring protocol has been a key factor. This protocol has made it possible to obtain data on hygrothermal comfort (temperature and relative humidity) and ventilation (CO_2 concentration) in schools in the Basque Country. Specifically, it is applied in three educational centres in Vitoria-Gasteiz, two primary schools and one secondary school.

The periods in which the monitoring protocol has been applied allow to know the environmental conditions in the most vulnerable periods of the school calendar, the coldest and hottest days. This continuous monitoring in each centre has made it possible to determine whether comfort conditions are being achieved during the different phases of occupation that characterise schools in classrooms with different characteristics and vulnerabilities.

In the monitoring results, on average, all measured parameters obtained greater comfort in summer than in winter. Generally, adequate comfort is achieved in both seasons during the occupied periods, except for the gymnasiums (S1U01 and S2U01) during winter, which reach temperatures far from comfort.

Analysing the periods in which comfort temperatures are not reached, the slight overheating suffered by some classrooms during the winter season stands out. Although these percentages are very low (S1U02 and S2U03, 3% and 1% respectively), it is important to consider their future evolution. The increasingly insulated and airtight design and increased outside temperatures due to climate change will increase the overheating phenomenon.

In these case studies, relative humidity was not a limitation in achieving hygrothermal comfort. Although low relative humidities were obtained in some cases, the temperature was a more limiting parameter for achieving hygrothermal comfort.

Analysing the CO_2 concentration, the average concentration was lower in summer than in winter, with all classrooms during their occupied period reaching comfort more than 84% of the time, except in winter in classrooms S2U02 (66%) and S3U03 (76%). So overall, great comfort is achieved generally in the classrooms, with the exceptions previously analysed.

Despite achieving great comfort, it was found that during break periods, some classrooms, especially in school S3, had high CO_2 concentration. Proving some difficulties to renew the indoor air, and not enough ventilation is achieved by mechanical means in this short break times.

The comfort criterion chosen (UNE-EN 16798) has influenced the interpretation of the results. A significant difference in the comfort criterion has been observed between standards and previous research. Beyond adaptive modelling or heat balance, the comfort temperature ranges are very different. Also, for relative humidity or indoor CO_2 concentration, the limits considered as comfort vary significantly between different standards or recommendations. These differences in defining comfort have many limitations. This disparity should be reviewed, and a common framework should be found.

7.1.2 Influential features

Constructively, the three schools are similar; their constructive differences correspond mainly to the evolution of the minimum requirements of the standards. In the case of the newer schools, the maximum thermal transmittance and the mechanical systems implemented have improved.

Following the characterisation of the centres carried out in phase I of the methodology, in phase III, the impact of these characteristics on the comfort achieved was studied. The influence was found to be statistically significant when $p>0.05$.

There is no characteristic influence on summer, so generalised comfort is achieved in all classrooms. Therefore, the outdoor environmental conditions in this climate and the current design of schools allow this comfort to be achieved.

In winter, the relative humidity is not influenced by any building characteristics. For the CO_2 concentration, only the floor on which the classroom is located had an influence, with the result that the ventilation system had no influence.

Temperature was the parameter most affected in winter by different construction characteristics, influencing WWR (cor = 0.91), DF (cor = -0.90), volume (cor = -0.72), and OD (cor = 0.69), having similar impact on the simultaneous comfort.

7.1.3 Ventilation

With the results obtained from the monitoring in the case studies, the ventilation system does not have a statistically significant impact on comfort, within the debate generated by some previous research, where some argue that comfort results were improved with MV, in this case, good hygrothermal comfort and ventilation conditions are achieved in both cases.

No statistical difference was found between ventilation systems, and even during the winter season, the NV, which should be more vulnerable, these classrooms in some cases achieved better comfort than others with MV. The S3 school achieves the worst average CO_2 concentration in comfort 86% of the time during winter occupancy. So, despite being the most recent construction, no significant improvement is recorded. In summer, it is achieved by S1 with 92%. Both comfort percentages are optimal, but this proves that no significant improvement is made in those classrooms with MV system.

Being aware of the opportunities and limitations of different ventilation systems, the NV is sufficient in this climate to achieve comfort, and according to previous research, it does not significantly impact energy consumption.

At present, advantage should be taken of the systems available in each centre. In all centres, the opening systems should be in a good state of maintenance. In centres with MV, proper operation and maintenance of the mechanical systems must be ensured to achieve the efficiency for which they are designed.

In NV schools, breaks between classes should be used for extra ventilation, and cross ventilation should be used where possible. Night ventilation should be implemented, especially during hot periods, to reduce indoor temperatures and avoid overheating.

When outdoor environmental conditions are very vulnerable, such as very high or low temperatures, noise pollution or poor outdoor air quality, hybrid ventilation with on-demand control is the system of choice to overcome the limitations of natural ventilation. It is the one that achieves the best balance between comfort and energy consumption.

7.1.4 Adaptation

Adaptive comfort models consider the ability of occupants to adapt by different means and achieve comfort.

To achieve comfort, the ability of occupants to alter environmental conditions is relevant. The building must enable them to make decisions and change the indoor environmental conditions, with measures such as decentralised control of mechanical systems or allowing them to interact with the building, such as opening windows. In this study, comparing classrooms with similar characteristics but achieving different levels of comfort, those classrooms that allowed greater adaptability are the ones that have achieved the best comfort.

In the context of monitoring, there has been a change in the usual behaviour of the occupants due to the COVID protocol. This protocol has shown the ability to achieve better results when ventilation is prioritised over thermal comfort, especially during winter, when the usual behaviour is to prioritise thermal comfort. It has been observed that thermal comfort has not been sacrificed in classrooms that have followed this protocol, and at the same time, good ventilation values have been obtained.

Although the protocol has been in place for a limited period, this behaviour change impacts the future of classroom environmental conditions, as awareness has been raised about the importance of ventilation and maintaining healthy classroom conditions.

Previous studies have shown no relationship between air quality perception and CO_2 concentration, so monitoring and real-time visualisation of this monitoring is necessary to ensure correct IEQ in classrooms. When occupants are aware of the environmental conditions beyond their perception, they can make better decisions to achieve comfort. From the design of educational centres, occupants must be provided with tools that allow them to adapt and achieve better comfort.

7.2 LIMITATIONS OF THE STUDY

Analysing the results obtained, different limitations have been identified in the context of the behaviour in the case studies and their selection.

First, the sample size was small compared to the number of educational centres in the autonomous community. Although the sample was chosen to be representative, in the Basque Country, many different types of buildings and locations with very different microclimates affect the comfort and perception of their occupants.

In addition, one limitation concerning the representativeness of the centres chosen is that all three have been built recently. As can be seen in 10.2 ANNEX 2: Characterisation of schools in the Basque Country, most schools are very old buildings, most of them not renovated, which will have other constructive limitations regarding achieving comfort.

Therefore, as it is not a completely random sample, it does not comply with the principle of different statistical calculations. Being such a small sample can lead to misleading results. Therefore, the methodology proposed is intended to be applied in future research to more schools in the Basque Country to know in detail what the behaviour is like and to take into account multiple characteristics that cannot be extrapolated because the sample is limited.

Another limitation, which is simultaneously an opportunity, has been the measurement context. The COVID protocol was a temporary measure that influenced and changed classroom behaviour, prioritising ventilation over thermal comfort. Therefore, as this is not the usual behaviour, the extrapolation of conclusions is limited for the future.

From the accessible data on schools, not having more detail on their construction and energy consumption has been a limitation when studying the impact of different characteristics on thermal comfort and possible vulnerabilities.

When applying the monitoring protocol, due to technical limitations (number of sensors available), it was not possible to measure the same number of classrooms in winter as in summer. The results obtained in summer were especially limited to determining the comfort achieved in the most vulnerable periods.

7.3 FUTURE INVESTIGATIONS

Once the main conclusions of this thesis have been reached and the most relevant limitations have been detected, new questions have arisen. Below, different lines of research are presented to complete this research according to the questions that have arisen and are considered relevant (Figure 7-1).

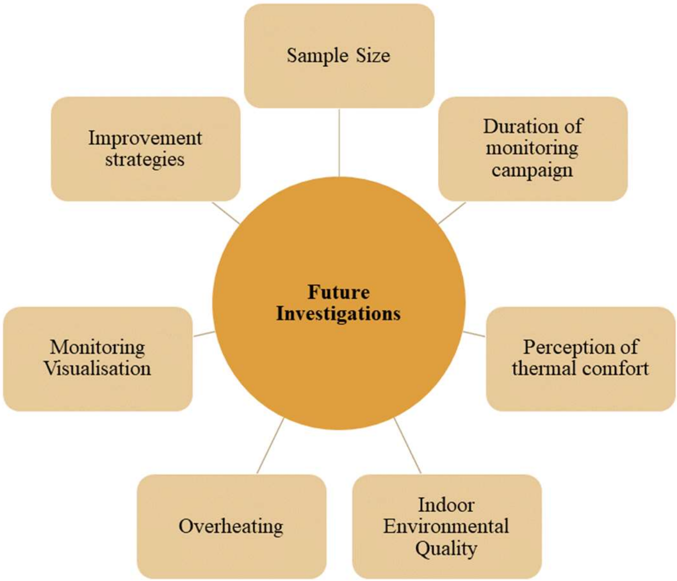


Figure 7-1. Future investigation topics

First, as mentioned in the limitations of this research, the sample size is not large or random enough. After validating the application of the methodology in three case studies, it should be completed with more schools. From a statistical point of view, to have a broader range of characterisation of the schools, especially considering the year of construction.

It could also be relevant to extend the monitoring campaigns, not only to find out what happens during the most unfavourable temperature periods. It would be interesting to extend this to the entire school calendar to discover how comfort evolves throughout the school year and to detect whether specific vulnerabilities are amplified during the rest of the school year.

The relevance of the perception of thermal comfort has been presented. In addition to applying a methodology with quantitative methods, it could be complemented with qualitative methods, which allow to know the perception and possible discrepancy between the comfort perceived by the occupants and the real monitored values. Since this perception plays a key role in adaptation actions, future research should be complemented with surveys and assess the comfort students and teachers perceive.

This research has focused only on hygrothermal comfort and ventilation. However, other factors must be considered to ensure correct indoor environmental quality, and a balance must be maintained between them. Future research should, therefore, also study and monitor indoor air quality, acoustic comfort and lighting comfort.

There are many hypotheses for future research concerning overheating, such as that some classrooms already suffer. New research can investigate the influence of the ventilation system and climate change on this overheating or what strategies should be followed to reduce the negative impact of this increase in outdoor temperatures on classroom comfort.

One of the main conclusions reached is the importance of visualising the monitored data to ensure comfort and to be able to take adaptive actions. Future research could complement this line of investigation with artificial intelligence or machine learning tools. Study the optimisation of comfort and energy consumption with automated tools based on monitored values without resorting to the direct action of the occupants.

Finally, once these case studies have analysed which construction features impact thermal comfort and ventilation, it would be interesting to complete this research with different improvement strategies focused on these features. These would allow energy retrofitting strategies to be applied to increase the resilience of schools and achieve better comfort now and in the future.

8 DISSEMINATION OF THE RESULTS

As attached in 10.5 ANNEX 5: Journal Publications, multiple publications and contributions to congresses have been made to disseminate the results achieved during the development of this thesis. Other articles are now being developed.

8.1 PUBLICATIONS IN JOURNALS

Authors: **Anna Figueroa**, Alba Arias, Xabat Oregi, Iñigo Rodriguez

Title: Evaluation of passive strategies, natural ventilation and shading systems, to reduce overheating risk in a passive house tower in the north of Spain during the warm season.

Journal: Journal of Building Engineering (Q1, Impact factor: 7.144)

Key: A Volume: 43 Pages, initial: 102607

Date: 11-2021

Place of publication: Elsevier. Journal of Building Engineering

Authors: Silvia Perez-Bezos, **Anna Figueroa-Lopez**, Matxalen Etxebarria-Mallea, Xabat Oregi, Rufino Javier Hernandez- Minguillon

Title: Assessment of social housing energy and thermal performance in relation to occupants' behaviour and COVID-19 influence. A case study in the Basque Country, Spain

Journal: Sustainability (Q2, Impact factor: 3.889)

Key: A Volume: 14 (9) Pages, initial: 5594

Date: 06/05/2022

Place of publication: MDPI, St. Alban-Anlage 66, 4052 Basel, Switzerland

Authors: **Anna Figueroa-Lopez**, Xabat Oregi, Marta Almeida, Rufino J. Hernández-Minguillón

Title: Evaluation of hygrothermal comfort in educational centres by monitoring three case studies with different ventilation systems in Vitoria, Spain

Journal: Journal of Building Engineering (Q1, Impact factor: 7.144)

Code: A Volume: 65 Pages, initial: 105591

Date: 05-04-2023

Place of publication: Elsevier, Journal of Building Engineering

8.2 INTERNATIONAL CONFERENCES

Authors: **Anna Figueroa**, Alba Arias, Xabat Oregi, Iñigo Rodriguez

Title: Analysis of overheating risk in Passivhaus dwellings during warm season. Focalizing in shadow systems strategies to mitigate it.

Type of participation: Oral communication

Congress: EESAP11 + CICA4 - 11th European Conference on energy efficiency and sustainability in architecture and planning and the 4th International Congress on Advanced Construction

Publication: ISBN 978-84-1319-308-3

Venue: Online Date: 01-12-2020

Authors: Alba Arias, **Anna Figueroa**, Xabat Oregi, Iñigo Rodriguez

Title: Analysis of overheating risk in Passivhaus dwellings during warm season and the night natural ventilation strategies to mitigate it

Type of participation: Oral communication

Congress: EESAP11 + CICA4 - 11th European Conference on energy efficiency and sustainability in architecture and planning and the 4th International Congress on Advanced Construction

Publication: ISBN 978-84-1319-308-3

Venue: Online Date: 01-12-2020

Authors: Markel Arbulu, Markel Rueda-Esteban, **Anna Figueroa-López**, Silvia Perez-Bezos, Xabat Oregi

Title: Methodology for the sustainability of energetic refurbishment of residential buildings based on the life cycle assessment and calibration by real data

Type of participation: Poster

Congress: EPS forum

Venue: Paris Date: 2/4-06-2022

Authors: **Anna Figueroa**, Xabat Oregi, Alexander Martin, Rufino Hernandez

Title: Critical Analysis Of Monitoring Indoor Air Quality In Education Centres

Type of participation: Oral communication

Conference: CESB22 Central Europe Towards Sustainable Building 2022

Publication: ISBN: 978-80-01-07096-3

Venue: Prague, Czech Republic Date: 04/06-07-2022

Authors: Markel Arbulu, Markel Rueda-Esteban, **Anna Figueroa-López**, Silvia Perez-Bezos, Xabat Oregi, Rufino J. Hernández-Minguillón

Title: Environmental and economic life cycle evaluation of residential buildings refurbishments by the calibration with monitored data

Type of participation: Oral communication

Congress: EESAP13 - 13th European Conference on energy efficiency and sustainability in architecture and urbanism

Publication: ISBN: 978-84-1319-499-8

Venue: Donostia, Spain Date: 05/06-10-2022

Authors: Alexander Martín-Garín, Silvia Perez-Bezos, **Anna Figueroa-Lopez**, Markel Arbulu, Markel Rueda-Esteban, Xabat Oregi

Title: Monitoring and energy management strategy during the energy refurbishment plan of the social rental housing stock of the Basque Country

Type of participation: Oral communication

Congress: EESAP13 - 13th European Conference on energy efficiency and sustainability in architecture and urbanism

Publication: ISBN: 978-84-1319-499-8

Venue: Donostia, Spain Date: 05/06-10-2022

Authors: **Anna Figueroa-Lopez**, Xabat Oregi, RufinoJ. Hernández-Minguillón

Title: Analysis of the hygrothermal comfort and relationship with the characteristics of the building in three educational centres with different ventilation systems in Vitoria-Gasteiz, Spain.

Type of participation: Oral communication

Congress: 1st International Multidisciplinary Congress of Doctoral Students, CIMED 2023

Publication: ISBN: 978-84-1319-499-8

Venue: San Cristóbal de La Laguna, Spain Date: 22/24-03-2023

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10 ANNEXES

10.1 ANNEX 1: COMPILATION OF PREVIOUS LITERATURE

Study relevant information							
Number of schools	Education level	Season	Weather	Climate	Country	Year	DOI
8	secondary	Fall	Warm	Cfa	Nepal	2021	10.1016/j.buildenv.2020.107523
13	primary and secondary	Winter	Cold	Bsk and Bwk	China	2020	10.1016/j.buildenv.2020.106802
1	primary	Summer	Temperate	Csa	Spain	2021	10.1016/j.buildenv.2021.108089
9	primary and secondary	Fall	Cold	Bsk and Bwk	China	2021	10.1016/j.buildenv.2021.107803
1	primary	Annual	Temperate	Csa	Turkey	2022	10.1177/1420326x221080566
25	primary and secondary	Dry season and	Warm	Aw	Madagascar	2018	10.1016/j.scs.2017.11.029
1	primary	Winter	Warm	Bwh	Saudi Arabia	2021	10.1016/j.asej.2021.02.008
1	secondary	Dry season and	Warm	Aw	Nigeria	2022	10.37934/araset.29.1.6275
3	Pre-elementary, primary and secondary	Annual	Temperate	Csa	Spain	2022	10.3989/ic.87607
1	secondary	Another	Warm	Cfa	Taiwan	2021	10.3390/buildings11060248
4	primary	Summer	Warm	Bsh	Iran	2016	10.1080/09613218.2016.1259290
1	primary	Summer	Temperate	Cfb	UK	2019	10.1177/0143624418815785
2	primary and secondary	Fall	Warm	Bsh	Jordan	2019	10.1016/j.aej.2019.06.001
8	primary	Annual	Temperate	Dfb	UK	2020	10.1016/j.enbuild.2020.109857
-		Natural	Warm	Cfa and Aw	Taiwan	2021	10.1016/j.egyr.2021.08.197
3	primary	Dry season and	Warm	Aw	Nigeria	2021	10.1108/ijbpa-07-2020-0056
8	primary	Summer	Temperate	Cfb	UK	2017	10.1016/j.buildenv.2016.10.009
1	university	Fall and spring	Temperate	Csa	Turkey	2021	10.1016/j.jobe.2021.102697
8	secondary	Dry season (?)	Warm	Am	Indonesia	2018	10.3390/buildings8040056
11	primary and secondary	Summer	Warm	Cfa	Australia	2018	10.1016/j.buildenv.2017.10.031
2	primary and secondary	Fall and spring	Temperate	Cfb	Colombia	2021	10.1016/j.buildenv.2021.107682
1	primary and secondary	Fall, winter and	Cold	Dfc	Sweden	2018	10.1016/j.buildenv.2018.03.019
14	secondary	Winter, spring	Temperate	Csa, Dfb,	USA, Australia,	2021	10.1111/josh.12986
2	secondary	?	Warm	Af	Indonesia	2022	10.3390/su142315663
1	secondary	Monsoon and	Warm	Bsh	India	2018	10.1016/j.buildenv.2018.05.051
9	primary and secondary	Fall, winter and	Temperate	Csa	Spain	2019	10.3390/su11143948
1	secondary	Summer	Temperate	Dfb	USA	2021	10.1016/j.jobe.2020.101731
1	primary	Winter	Temperate	Cfb	New Zealand	2022	10.3390/ijerph19105811
11	secondary	Fall, winter and	Temperate	Cfb	Netherlands	2023	10.1016/j.buildenv.2022.109922
1	university	Winter	Temperate	Csa	Spain	2022	10.1016/j.ijheh.2021.113910
1	primary	Winter	Temperate	Dwa	China	2020	10.3390/en13225958

Comfort					
Standard	**Comfort model**	**Methodology**	**Characteristics analysed**	**Ventilation**	**Number of classrooms**
-	Adaptative +	Questionnaire and	Building materials, façade, floor, n° windows	NV	24
ASHRAE 55	Adaptative +	Questionnaire and		NV	26
ISO 7730	Adaptative +	Questionnaire and	Materials, surface, ventilation	2 NV + 1	3
-	Rational	Questionnaire and	NA	NV	26
	Rational	Simulation	Façade orientation and opening size	NV + Cooling	1
ASHRAE 55	Adaptative +	Questionnaire and	Surface, orientation, thermal transmittance,	NV	25
	Rational	Questionnaire and	Thermal transmittance and materials	NV + AC	
ASHRAE 55	Rational	Questionnaire and	Materials	NV	21
RTIB	Rational	Monitoring	Year, materials, surface	NV	9
? + ISO 7730	Adaptative	Simulation	Orientation, WWR, materials, transmittance	NV + AC	1
ENS35 090 (UK)	Adaptative +	Questionnaire and	General construction terms	NV	28
BB101 (UK)	Adaptative	Simulation	Orientation, transmittance, materials, year,	NV	10
ASHRAE 55 (monitoring) and ISO7730 (simulation)	Adaptative +	Monitoring and	Orientation, surface, materials, windows	NV	8
EN 15251	Adaptative +	Questionnaire and	Orientation, shape, windows	NV	32
Other	Adaptative +	Simulation	orientation, WWR, insulation, window	NV+AC/hybrid	-
ASHRAE 55	Adaptative +	Questionnaire and	NA	NV	6
EN 15251 + TM52	Adaptative +	Questionnaire and	Ventilation	NV	27
ISO 7730	Rational	Monitoring and	Surface, orientation, materials, thermal	MV	-
ASHRAE 55 (vote)	Rational	Questionnaire and	Surface, floor, orientation	NV	48
ASHRAE 55	Adaptative +	Questionnaire and	Ventilation	NV +	-
ASHRAE 55	Adaptative +	Questionnaire and	Surface, orientation, materials, ventilation	NV	20
ASHRAE 55	Rational	Questionnaire and	Surface, orientation, materials, windows	MV	5
ASHRAE 55	Rational	Questionnaire	Ventilation,	MV	
NA	Rational	Questionnaire and	NA	NV	-
ASHRAE 55 and NBC 2016-IMAC	Adaptative	Questionnaire and	Orientation, materials, windows,	NV	4
ISO 10551 + ASHRAE + own ATC	Adaptative +	Questionnaire and	Orientation, ventilation, materials,	NV	46
ASHRAE 55, CIBSE TM 52 and UNE-EN 16798	Adaptative +	Monitoring	Surface, thermal transmittance	NV	6
WHO	Rational	Monitoring	Orientation, materials, windows	NV	3
Dutch Fresh Schools guidelines	Adaptative +	Monitoring	HVAC, occupancy, ventilation, surface	Both	31
RITE	Rational	Monitoring	Occupation, surface, windows	NV	7
GB/T17226-2017	Adaptative +	Questionnaire and	Orientation, floor, occupation, window	NV	4

Other		Monitored parameters						
Improvement strategies	Analysis typology	Outdoor	Solar	CO2	Air velocity	Globe	Relative	Air temperature
No	Mean and standard deviation				Y	Y	Y	Y
No	average, maximum, minimum, and	Y	Y	Y	Y	Y	Y	Y
No	min, max, med	Y			Y	Y	Y	Y
No	new index				Y	Y	Y	Y
Yes								
No	mean, max, min, Chi-square test				Y		Y	Y
Yes	-		Y					Y
No	mean, max, min, SD				Y	Y	Y	Y
No				Y				Y
Yes								
No		Y		Y	Y	Y	Y	Y
No				Y				Y
No	average				Y		Y	Y
No					Y	Y	Y	Y
	regression							
No		Y				Y	Y	Y
No						Y		Y
Yes							Y	Y
No	regression				Y		Y	Y
Yes		Y						Y
No	correlation, t-test, chi-squared	Y			Y	Y	Y	Y
No				Y		Y	Y	Y
No	NA							Y
No	Machine Learning between Regression				Y	Y	Y	Y
No	mean, maximum, minimum and standard	Y			Y	Y	Y	Y
No		Y			Y	Y	Y	Y
No	mean, maximum, minimum			Y	Y		Y	Y
Yes	fluctuation. Mean, max, min						Y	Y
No	Mann-Whitney U-tests and Wilcoxon	Y		Y				Y
No	average, maximum, minimum, and	Y		Y	Y	Y	Y	Y
No	average, maximum, minimum, and	Y		Y			Y	Y

10.2 ANNEX 2: CHARACTERISATION OF SCHOOLS IN THE BASQUE COUNTRY

This annexe characterises all the educational centres in Basque Country (BC). This characterisation has been carried out as a pretext to be able to select the three case studies in a logical and representative way that forms part of the analysis of this thesis. Those characteristics considered to have a more significant influence have been defined and characterised in the 4 METHODOLOGY chapter of this thesis.

10.2.1 Introduction and objective

The final objective of this characterisation is to identify those educational centres built in different periods of standards, which will form part of the case studies in the analysis of the thesis. These standards have set different construction limits of maximum thermal transmittances, as well as the implementation of different installations. The ventilation system is particularly interesting in this thesis, as it has been developed in the 2 LITERATURE REVIEW.

Therefore, this annex will define and classify their properties, needs, requirements and limits that impact classroom hygrothermal comfort and ventilation.

For this purpose, a list was obtained of all the educational centres in BC through the Basque Government that had students enrolled during the 2020-2021 academic year, obtaining a total of 1142 centres. The most relevant information appeared in this list: address, municipality and type of centre. Using this data, those properties considered to be of interest were identified using their respective cadastres[1,2,3] and with the help of map viewers.

Universities have been excluded from this analysis, as the behaviour of their occupants is very different from that of other educational centres due to the older age of the occupants, different and complex timetables, multiple unique buildings and different classroom behaviours.

10.2.2 Characterisation and results

Once the list of educational centres has been obtained, the most relevant characteristics will be analysed. These characteristics have been grouped into typologies, year of construction and location.

[1] Diputación Foral de Álava, “Castatro.” https://catastroalava.tracasa.es/navegar/ (accessed Dec. 01, 2022).
[2] Diputación Foral de Gipuzkoa, “Catastro.” https://ssl6.gipuzkoa.eus/CATASTRO/map.htm? (accessed Dec. 01, 2022).
[3] Diputación Foral de Bizkaia, “Catastro.” https://appsec.ebizkaia.eus/O4GC000C/vistas/visor.xhtml? (accessed Dec. 01, 2022).

10.2.2.1 Typologies

The typologies refer to two characterisations. First, according to the category the school belongs to, by the age of the students (Table 10-1). Second, according to the ownership of the school.

Due to the great variety of types of education and classification that exist, it has been decided to group according to age: pre-elementary (3 to 5 years), primary (6 to 12 years), secondary (12 to 18 years), or if the type of education is other than regulated by age alone. There are also centres where the different age groups have been combined.

Table 10-1. Classification of BC educational centre typologies.

IES	Instituto de Enseñanza Secundaria	Secondary
EIC	Escuela Internacional de Cocina	Other
CEIP	Colegio de Educación Infantil y Primaria	Infant-Primary
CPEIPS	Centro Privado de Educación Infantil, Primaria y Secundaria	Infant-Primary-Secondary
CPES	Centro Privado de Educación Secundaria	Secondary
CIFP	Centro Integrado de Formación Profesional	Other
IMFPB	Instituto Municipal de Formación Profesional Básica	Other
EIMU	Escuela Infantil Municipal	Infant
CPEI	Centro Privado de Educación Infantil	Infant
CEPA	Centro de Educación de Personas Adultas	Other
CPIFP	Centro Privado Integrado de Formación Profesional	Other
CPI	Centro Público Integral	Infant-Primary-Secondary
EIPR	Escuela Infantil Privada	Infant
CPEIP	Centro Privado de Educación Infantil y Primaria	Infant-Primary
CPEPS	Centro Privado de Educación Primaria y Secundaria	Primary-Secondary
CPE	Centro Privado Extranjero	Infant-Primary-Secondary
CPEP	Centro Privado de Educación Primaria	Primary
CPFPB	Centro Privado de Formación Profesional Básica	Other
CPEE	Centro Privado de Educación Especial	Infant-Primary
CPEPA	Centro Privado de Educación de Personas Adultas	Other
CPED	Centro Público de Enseñanzas Deportivas	Other
EEI	Escuela de Educación Infantil	Infant
CEE	Centro de Educación Especial	Infant-Primary

All the schools obtained in the database were analysed considering this classification. The results are shown below in Figure 10-1 and Figure 10-2.

Grouping by age, in Figure 10-1, the most abundant type of centre is pre-elementary education, which represents 54.38% of the centres, followed by primary education (46.06%), secondary education (32.57%) and finally, other centres (29.07%).

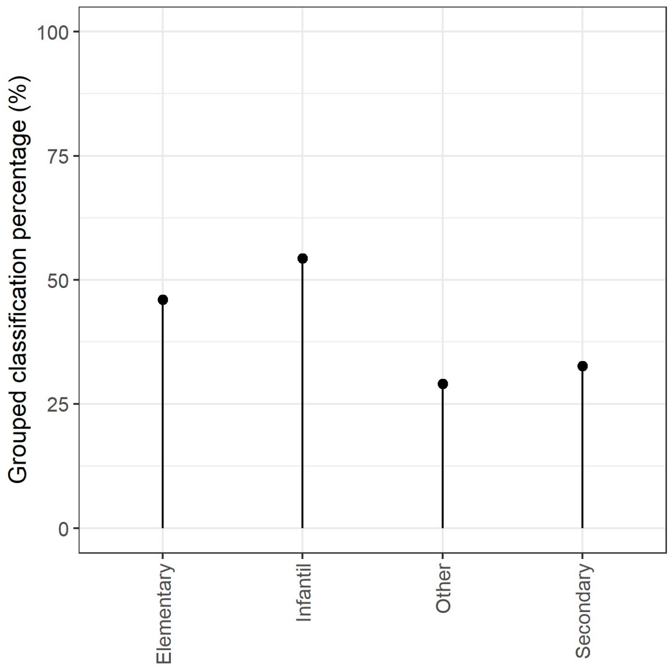

Figure 10-1 Grouped classification of the typology of centres

In more detail, analysing which age groups are part of the same school (Figure 10-2), not counting those classified as other, which are highly representative of the total (29.07%). It can be seen that the most abundant are pre-elementary together with primary (29.16%), followed by pre-elementary with primary and secondary (16.20%) and then exclusively secondary schools (15.85%).

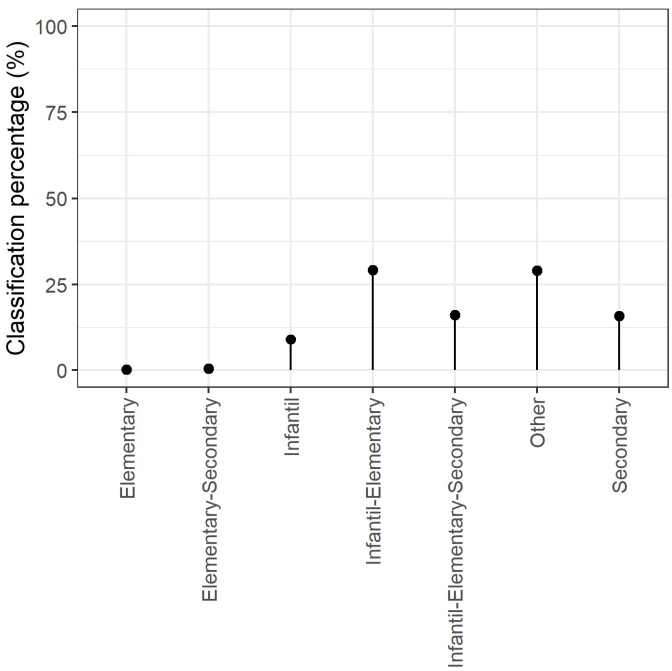

Figure 10-2 Classification of centre typology

Each centre's property type was added to this classification, Figure 10-3. This property classification influences the possibility of decision-making and investment in the different centres. It has been observed that most centres are public, 68.56%, compared to 31.44% private.

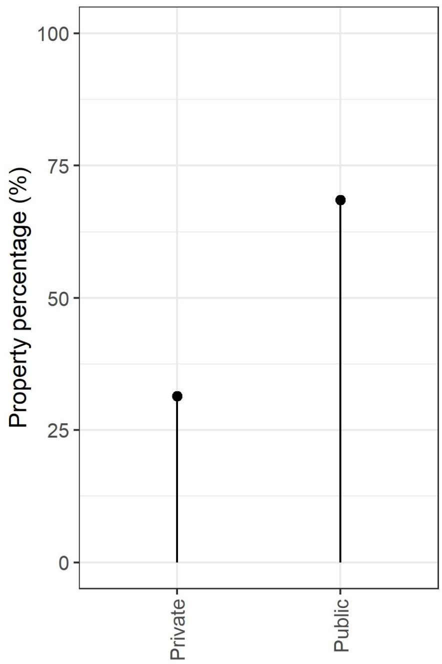

Figure 10-3 Property classification of centres

10.2.2.2 Year of construction

Through the address of each centre, it has been possible to obtain, using the provincial cadastres, the year of construction of each centre. In turn, the cadastre also included the year of additions or renovations. This second piece of information was a significant limitation, as it was not specified whether it was a complete renovation of the building or just a part of it. There were also multiple dates, so it was often unknown to which part of the building each date belonged.

As a common criterion, the date that appeared as an addition or renovation was chosen and considered the general date for the entire construction. In the case of multiple dates in this section, only the oldest has been considered as the year of construction and the most recent as the date of renovation.

Different construction properties of the building can be determined from these dates of construction and renovation. Depending on the year of construction and the Spanish building standards over the years, it is possible to determine thermal properties, such as the maximum transmittance of the different building envelopes or ventilation systems required by each standard.

These constructive limitations set by the standard over the years vary from the materials to be used, the thermal transmittance of the envelope or the ventilation and infiltration system of the building. In Spanish regulation, these limit values of thermal transmittance for each envelope type have been limited by the Technical Building Code (TBC) since 2006 in the Basic Document on Energy Saving (DB-HE)[4]. For the coldest climate, it limits transmittance in roofs to 0.46 W/m²K, in facades to 0.74 W/m²K and openings to 3.1 W/m²K. In 2013, the TBC DB-HE[5] increased its requirements, resulting in a maximum transmittance in roofs of 0.35 W/m²K for the coldest climate, 0.55 W/m²K for facades and 2.5 W/m²K for cavities. And since 2019, the TBC DB-HE[6] , in the coldest climate, limits roofs to 0.33 W/m²K, façades to 0.37 W/m²K and openings to 1.8 W/m²K. Before the TBC, in *the Norma Básica de la Edificación* (NBE), NBE-CT-79[7], these values were much higher, limiting transmittance in roofs to 0.7 W/m²K and 1.2 W/m²K for façades, and without any limitation for openings.

Concerning the ventilation system, since its publication in the Regulation on Thermal Installations in Buildings in 2007[8], ventilation in buildings must be ensured by mechanical or hybrid means. After its update in 2020 and consolidation in 2021[9] further changes were introduced. The 2021 version allows the introduction of alternative systems that justifiably ensure energy efficiency and sustainability objectives.

In addition to the age of the building, the condition and maintenance of the building influence the quality and perception of future occupants. For this reason, the date of renovation has also been considered, not only for building improvements according to the new standards but also to assess whether the building stock of educational establishments is outdated.

Then, Figure 10-4, Figure 10-5, Figure 10-6, and Figure 10-7 graphically show the year of construction and state of renovation of all the educational centres in BC.

First, Figure 10-4 shows the number of centres built annually since records have been kept, with centres as old as the CPEIPS San Antonio Ikastetxea, built in 1490. It can be seen that the majority of centres have been built throughout the 20th century,

[4] Ministerio de Vivienda, Código Técnico de la Edificación. Documento Básico Ahorro de energía (DB-HE). 2006.
[5] Ministerio de Fomento, Código Técnico de la Edificación. Documento Básico Ahorro de energía (DB-HE). 2013.
[6] Ministerio de Fomento, Código Técnico de la Edificación. Documento Básico Ahorro de energía (DB-HE). 2019.
[7] Ministerio de Obras Públicas y Urbanismo, "NBE-CT-79 : condiciones térmicas en los edificios," Norma Básica la Edif., 1979.
[8] Asociación Técnica Española de Climatización y Refrigeración (ATECYR), "Reglamento de Instalaciones Térmicas en los Edificios," p. 172, 2007, [Online]. Available: www.idae.es

[9] Gobierno de España, Reglamento de instalaciones térmicas en los edificios (RITE). 2021, pp. 1–97. [Online]. Available: https://www.boe.es/buscar/act.php?id=BOE-A-2007-15820

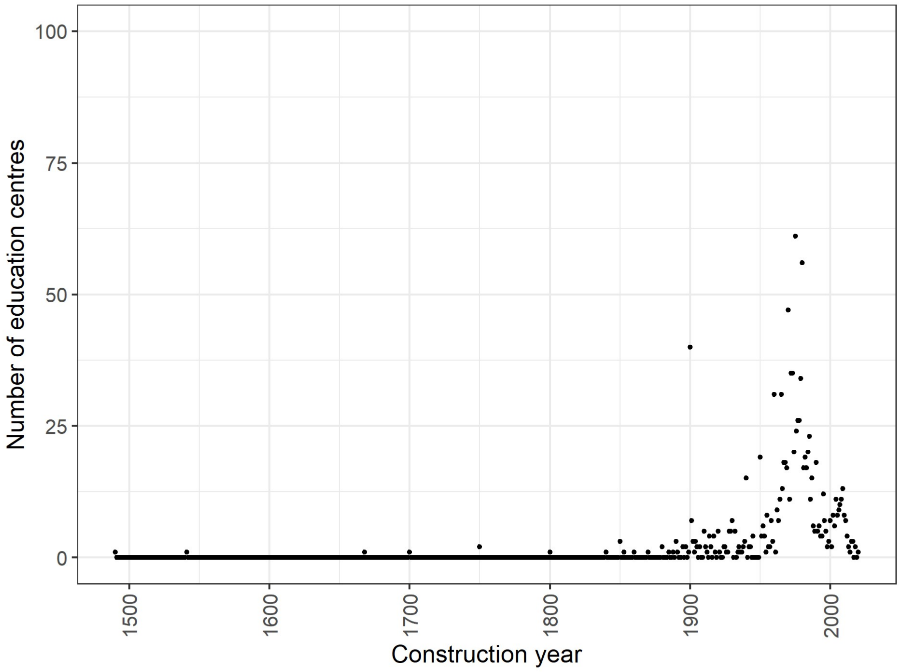

Figure 10-4 Number of centres by year of construction

Then, in Figure 10-5, the following figure zooms in on the constructions from 1900 to the present day, where a construction boom is observed in the 1970s, with 1975 being the year in which the most constructions were carried out, a total of 61 centres.

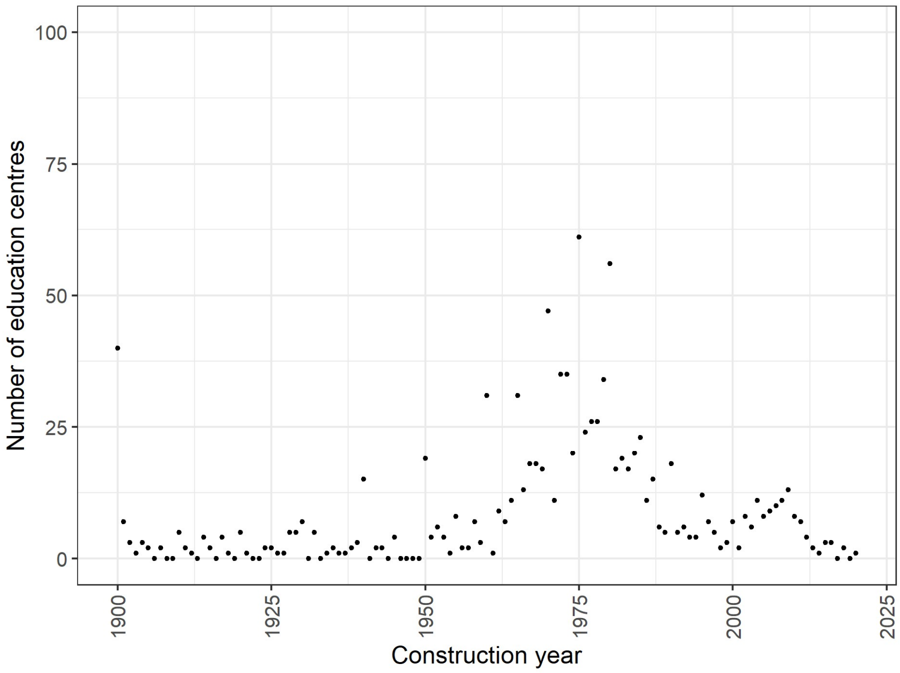

Figure 10-5 Number of centres by year of construction after 1900

As the year of construction is considered relevant for the different requirements governed by the TBC and the NBE, the centres have been grouped according to the period that governs them, as shown in Figure 10-6. This figure also shows whether each centre has undergone renovation work.

First of all, it can be observed that most of the educational centres were built before any regulation (before 1979), including a large number of centres built before 1900 (a total of 67 centres), followed by constructions after these and before the TBC (2007) and decreasing exponentially as new regulations were introduced. It is also observed that most centres have not been renewed, with 26.09% renewed versus 73.91% not renewed.

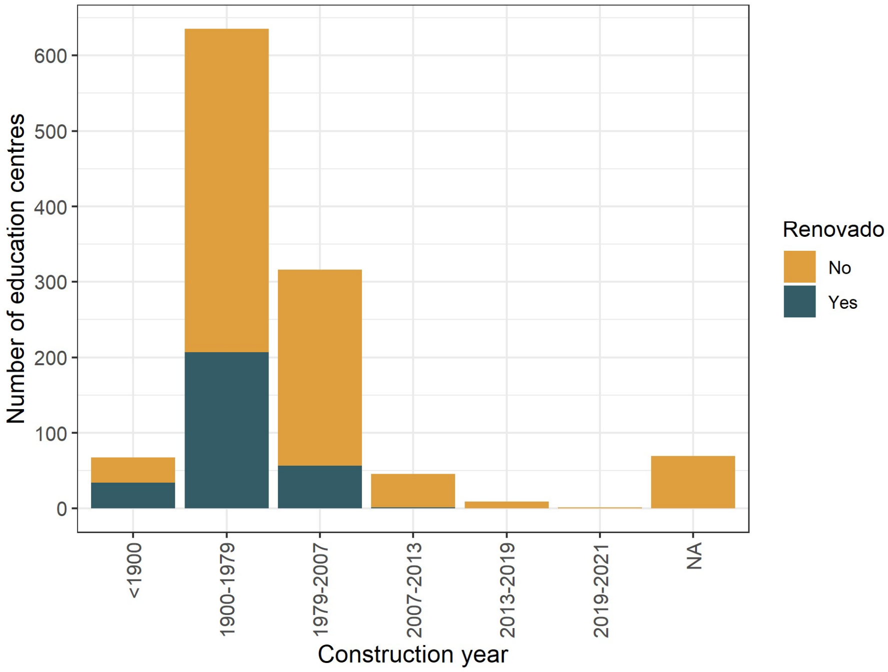

Figure 10-6 Number of centres by year of construction and renovation according to technical regulation

Graphically, Figure 10-7 shows the relationship between the year of construction and the periods of regulations (1979 and 2007) for those buildings that have been renovated. It has been found that only 23.49% of the renovations took place after 2007, when the obligation of mechanical or hybrid systems in buildings was introduced.

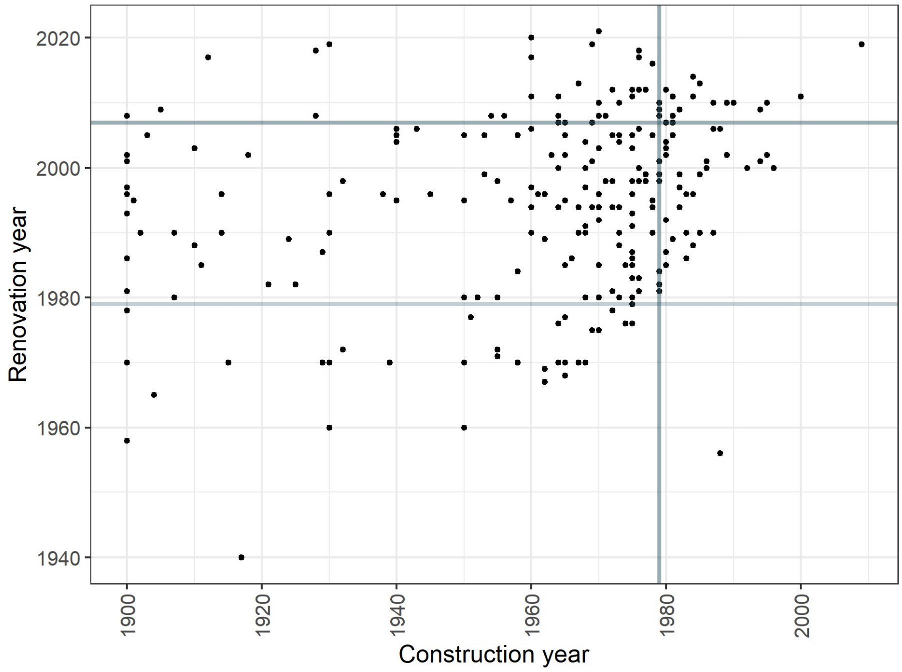

Figure 10-7 Years of construction and refurbishment of the centres

10.2.2.3 Location

Concerning the location of the educational centre, only two properties were extracted, the municipality and province of the centre, which already appeared in the information provided by the Basque Government. Subsequently, the centre's location to other buildings was deduced from the land registers, classifying it as isolated or part of another building, for example, on a ground floor or mezzanine floor. A significant limitation found in this analysis has been to be able to specify the location of the centre to the urban centre, not being able to classify it as urban or rural.

Analysing in which province each centre is located, Figure 10-8 in descending order, 49.74% are in Vizcaya, 34.76% in Guipúzcoa and 15.49% in Álava. According to Köppen-Geiger's climate classification[10] and the work carried out by Herández et al.[11], the historical model shows that most of the Basque Country is within the temperate C climates, with constant rainfall throughout the year. In the Ebro axis, a transformation is observed from temperate climates with dry and mild summers (Csb) to temperate climates with dry and hot summers (Csa). The transition zone is the one that would experience the most notable changes. The most significant transformation is from Cfb (humid with mild summer) to Cfa (humid with warm summer) on the Cantabrian slope mountain range.

[10] H. E. Beck, N. E. Zimmermann, T. R. McVicar, N. Vergopolan, A. Berg, and E. F. Wood, "Present and future Köppen-Geiger climate classification maps at 1-km resolution," *Sci. Data*, vol. 5, no. 1, p. 180214, Dec. 2018, doi: 10.1038/sdata.2018.214.

[11] R. Hernandez, M. Martija, J. D. Gomez de Segura, and S. Gaztelumendi, "Evolution of Köppen-Geiger's climate classification in the Basque Country in the context of climate change," 2021. doi: https://doi.org/10.5194/ems2021-248.

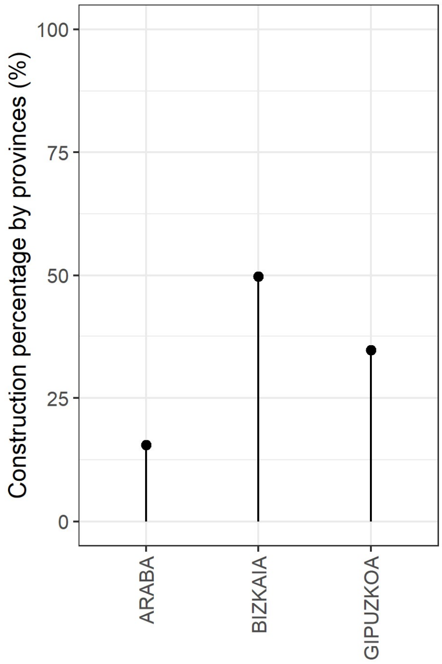

Figure 10-8 Location of the centres by province

Regarding location with other buildings, Figure 10-9 shows that most centres are isolated, the only construction on the parcel (85.38%). Most non-isolated centres (14.26%) occupying a floor or part of another building have been kindergarten centres occupying other buildings' ground floors.

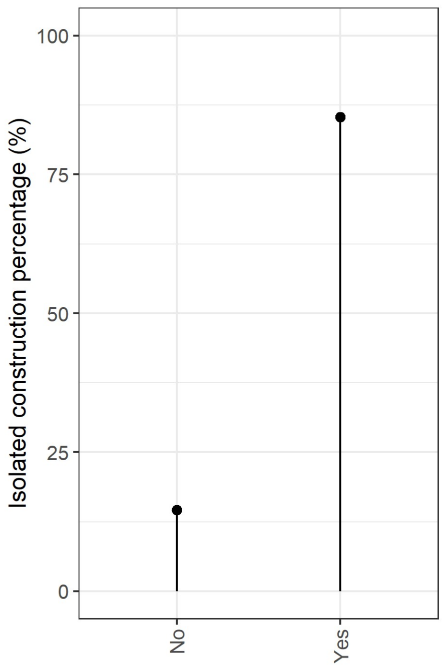

Figure 10-9 Isolated location of the centres

In addition, it was found during the cadastral search that up to 17.51% did not appear as an educational centre in the cadastres. This lack of updating or considering another use before education can be a significant limitation. Mainly, if this analysis and search were carried out by automated means, these centres would not have been considered in the analysis.

10.2.2.4 Conclusion

Following this analysis, which is intended to serve as a pretext for the selection of case studies for this thesis, several conclusions have been reached:

- Schools with a mechanical ventilation system due to their year of construction or possible incorporation due to the year of renovation are not representative; only over 5 % have been considered possible.
- Most buildings are outdated, built in periods before regulations and techniques, and not renovated, serving as a criterion for not choosing these centres as case studies, as it is considered that they do not meet minimum thermal performance standards and need to be refurbished to guarantee minimum comfort inside.
- Most of the centres are publicly managed and owned, which influences the possibility of making decisions for improvement. The Basque Government can intervene in its centres with a general common framework and positively impact society and the education of most schoolchildren and the different agents occupying the centres in the BC.

10.3 ANNEX 3: CHARACTERISATION OF CASE STUDIES

10.3.1 School S1: CEIP Ibaiondo

					IBAIONDO SECONDARY SCHOOL (S1)		
Building level	**Year**	**Year of construction**			2006		
		Year of renovation			NA		
	Location	**City**	**City name**		Vitoria-Gasteiz		
			Population		≈ 250000 hab		
			Population density		897.88 hab/km^2		
			Climate (Köppen-Geiger)		Cfb		
		Situation	**Location in the city**		Urban periphery - Lakua		
			Proximity sources		Main road (Portal de Foronda) <100m		
	Students	**Classification**			Primary school and nursery		
		Age group			3 to 12		
		Number of students (2020-2021)			657 (22-25 students per classroom Primary) and 18 in nursery which 443 primary school (rest nursery)		
	Construction	**Number of floors**			PB+1 and PB+2		
		Orientations			Mainly north and south		
		Installations	**Ventilation system**	**Natural**	In classrooms		
				Hybrid	None		
				Mechanical	Yes, only in the gym		
			Heating system	**Centralized**	Yes		
				Active during monitoring	Yes		
				Operation system	External control		
			Cooling system		None		
		General conditions			Mould has been detected (and currently solved) on the last floors due to water infiltrations from the ceiling		
Classroom level	**Classroom selected**				6 Ath	4year A	Gym
	Occupancy (average)				25	14	25
	Volume	**Classroom volume (m^3)**			155.67	160.89	2019.49
		Classroom surface (m^2)			52.77	54.54	327.84
		Classroom occupancy density (m^2 /student)			0.47	0.26	0.08
		Volume occupancy density (m^3 /student)			0.16	0.09	0.01
	Location within the school	**Floor**			2nd floor	Ground Floor	Ground Floor
		Orientation			North	South	South
	Solar Protection	**Typology**			Blinds	Blinds	NA
		Operation			Operation automation can be operated by teachers/students in the classroom, and there is also an automated remote control to shut down every night.	Operation automation can be operated by teachers/students in the classroom, and there is also an automated remote control to shut down every night.	NA

	Construction	**Façade surface (m^2)**		21.06	22.44	141.8
		Window area (m^2)		6.64	8.78	110.42
		Window opening capacity (m^2)		3.28	2.50	0
		Relation window/opaque façade (WWR)		0.32	0.39	0.78
		Ratio window surface/classroom surface (Daylight factor)		0.13	0.16	0.34
Activity	**Occupancy**	**Building occupancy hours**		From 9:15 to 17:00		
		Timetable of other extracurricular activities in the school		Currently, due to COVID, there are none, but next year, they will take place in the outdoor area of the school		
	Cleaning	**Frequency of cleaning**		Every afternoon, with windows opened and when finished they close. The dining room is cleaned after lunch.		
	Ventilation	**Ventilation protocol**	**During occupancy**	Always at least 5 cm 24/7	Always at least a smaller window	None
			Overnight	Minimum and blinds closed	None	None
			Ventilation frequency recording	None	None	None
				During summer, the teacher was engaging and opened the windows for better ventilation. During winter, a different teacher was not as dedicated but obeyed the minimum requirement for ventilation and took advantage of breaks for better ventilation.	The corridor door and small window were always kept open for cross-ventilation. Nevertheless, the large door connected to the outside was only opened when a suitable outdoor temperature was achieved.	The gym had no special activity to improve its ventilation performance.

10.3.2 School S2: CEIP Mariturri

					CEIP MARITURRI (S2)		
Building level	**Year**	**Year of construction**			2016		
		Year of renovation			NA		
	Location	**City**	**City name**		Vitoria-Gasteiz		
			Population		≈ 250000 hab		
			Population density		897.88 hab/km^2		
			Climate (Köppen-Geiger)		Cfb		
		Situation	**Location in the city**		Urban periphery - Zabalgana		
			Proximity sources		Industrial complex >2km		
	Students	**Classification**			Primary school and nursery		
		Age group			2 to 12		
		Number of students (2020-2021)			703 (which 433 primary school, rest nursery)		
	Construction	**Number of floors**			PB+1 and PB+3		
		Orientations			Mainly east and west		
		Installations	**Ventilation system**	**Natural**	"Natural+System AIRE		
				Hybrid			
				Mechanical	Yes, multiple units		
			Heating system	**Centralized**	Yes		
				Active during monitoring	Yes		
				Operation system	External control		
			Cooling system		None		
		General conditions	**Windows, structure, opaque surfaces**		General conditions are excellent, although some infiltrations from the terraces were reported when it rains heavily.		
Classroom level	**Classroom selected**				5th B	4yearA	Gym
	Occupancy (average)				25	16	25
	Volume	**Classroom volume (m^3)**			146.67	167.50	1049.88
		Classroom surface (m^2)			48.89	56.78	202.66
		Classroom occupancy density (m^2 /student)			0.51	0.28	0.12
		Volume occupancy density (m^3 /student)			0.17	0.10	0.02
	Location within the school	**Floor**			2nd floor	Ground floor	Ground floor
		Orientations			West	South	There were no windows, but they were connected to the main building from the west and south.
	Solar Protection	**Typology**			Blinds	None	None
		Operation			Operation automation can be operated by teachers/students in the classroom, and there is also an automated remote control to shut down every night.		
	Construction	**Façade surface (m^2)**			25.19	17.22	108.3
		Window area (m^2)			9.68	8.24	50.38

		Window opening capacity (m²)		6.4	4.49	NA
		Relation window/opaque façade (WWR)		0.38	0.48	0.47
		Ratio window surface/classroom surface (Daylight factor)		0.20	0.15	0.25
Activity	**Occupancy**	**Building occupancy hours**		From 9:00 to 16:30		
		Timetable of other extracurricular activities in the school		Currently, due to COVID, there are none, but next year, they will take place in the outdoor area of the school		
	Cleaning	**Frequency of cleaning**		Common areas constantly and classes every afternoon		
	Ventilation	**Ventilation protocol**	**During occupancy**	Winter: 5min/1 hour	Based on teacher	None
			Overnight	Completely opened	None	None
			Ventilation frequency recording	None	None	None
				The teachers' attitude was not very dedicated, and they only opened the Windows in the swing position all day, not taking advantage of the breaks.	The outdoor door and window were always kept closed. The door connected to the corridor was always kept open. Occupation in the pre-elementary classroom was not continuous, and not always the same teachers as they swung their everyday classroom occupation.	The gym had no special activity to improve its ventilation performance.

10.3.3 School S3: IES Zabalgana

				ZABALGANA SECONDARY SCHOOL (S3)		
Building level	**Year**	**Year of construction**		2018		
		Year of renovation		NA		
	Location	**City**	**City name**	Vitoria-Gasteiz		
			Population	≈ 250000 hab		
			Population density	897.88 hab/km^2		
			Climate (Köppen-Geiger)	Cfb		
		Situation	**Location in the city**	Urban periphery - Zabalgana		
			Proximity sources	Industrial complex <700m		
	Students	**Classification**		High school		
		Age group		12 to 18		
		Number of students (2020-2021)		403 (363 Secondary, 33 baccalaureate)		
	Construction	**Number of floors**		PB+2		
		Orientations		Mainly east and west		
		Installations	**Ventilation system** – **Natural**	Limited window opening		
			Ventilation system – **Hybrid**	NA		
			Ventilation system – **Mechanical**	Yes, centralized		
			Heating system – **Centralized**	Yes		
			Heating system – **Active during monitoring**	Yes		
			Heating system – **Operation system**	External operation		
			Cooling system	None		
		General conditions	**Windows, structure, opaque surfaces**	General conditions are excellent, and no reported conveniences		
Classroom level	**Classroom selected**			2NDE	1 Bacc A	Technology
	Occupancy (average)			20	15	20
	Volume	**Classroom volume (m^3)**		136.15	136.15	287.24
		Classroom surface (m^2)		48.80	48.80	107.18
		Classroom occupancy density (m^2 /student)		0.41	0.31	0.19
		Volume occupancy density (m^3 /student)		0.15	0.11	0.07
	Location within the school	**Floor**		1st floor	2nd floor	1st floor
		Orientations		West	West	East and north
	Solar Protection	**Typology**		Blinds	Blinds	Blinds
		Operation		Operation automation can be operated by teachers/students in the classroom, and it has an automated remote control to shut down every night.	Operation automation can be operated by teachers/students in the classroom, and it has an automated remote control to shut down every night.	Operation automation can be operated by teachers/students in the classroom, and it has an automated remote control to shut down every night.
	Construction	**Façade surface (m^2)**		22.72	22.72	57.81
		Window area (m^2)		8.98	8.98	17.81
		Window opening capacity (m^2)		5.93	5.93	8.86

		Relation window/opaque façade (WWR)		0.40	0.40	0.31
		Ratio window surface/classroom surface (Daylight factor)		0.18	0.18	0.17
Activity	**Occupancy**	**Building occupancy hours**		From 8:00 to 15:00		
		Timetable of other extracurricular activities in the school		Some sports are played outside in teams after classes. And some afternoons reinforcement classes are held in some classrooms (not in the one monitored)		
	Cleaning	**Frequency of cleaning**		Every afternoon, with windows opened and when finished they close. Common areas are cleaned during the afternoon.		
	Ventilation	**Ventilation protocol**	**During occupancy**	Always small opening but depends more on subject perception (only teachers have the key to open the windows)		
			Overnight	Blinds closes at night	Blinds closes at night	Blinds closes at night
			Ventilation frequency recording	Sometimes - COVID teacher	Sometimes - COVID teacher	Sometimes - COVID teacher
				In all three classrooms, windows were kept closed as the mechanical ventilation operated. But when teachers perceived they opened the windows,		

10.4 ANNEX 4: TABLES STATISTICAL CALCULATIONS

Table 10-1 Kruskal-Wallis test result for each comfort and campaign

Comfort		Campaign
Simultaneous	p	0.006717
	X^2	7.3472
	df	1
Temperature	p	0.09775
	X^2	2.7418
	df	1
Relative Humidity	p	0.1498
	X^2	2.0741
	df	1
CO_2	p	0.8103
	X^2	0.057613
	df	1

Table 10-2 Kruskal-Wallis test results for qualitative data

Comfort	Season		Ventilation	Heating	Orientation	Floor	Classroom
Simultaneous	Winter	p	0.2474	1.0000	0.6952	0.3256	0.5688
		X^2	4.1333	0.0000	1.4444	2.2444	3.8667
		df	3	1	3	2	5
	Summer	p	0.5433	NA	0.5319	0.3679	0.4625
		X^2	2.1429	NA	2.2000	2.0000	2.5714
		df	3	NA	3	2	5
Temperature	Winter	p	0.1341	1.0000	0.4854	0.1942	0.2521
		X^2	5.5778	0.0000	2.2444	3.2778	6.6000
		df	3	1	3	2	5
	Summer	p	0.4306	NA	0.7006	0.6201	0.5988
		X^2	2.7574	NA	1.4211	0.9559	1.8750
		df	3	NA	3	2	5
Relative Humidity	Winter	p	0.2411	0.1213	0.1171	0.4029	0.4463
		X^2	4.1961	2.4000	5.8889	1.8179	4.7563
		df	3	1	3	2	5
	Summer	p	0.8091	NA	0.3916	0.8510	0.4068
		X^2	0.9677	NA	3.0000	0.3226	2.9032
		df	3	NA	3	2	5
CO_2	Winter	p	0.1460	0.0528	0.1136	0.0424	0.2504
		X^2	5.3793	3.7500	5.9598	6.3218	6.6207
		df	3	1	3	2	5
	Summer	p	0.1829	NA	0.3618	0.0951	0.1829
		X^2	4.8529	NA	3.2000	4.7059	4.8529

	df	3	NA	3	2	5

Table 10-3 Correlation test result for quantitative data

Comfort	**Season**		**Occupation density**	**Volume**	**WWR**	**DF**
Simultaneous	Winter	p	0.2800	0.0175	0.0044	0.0269
		cor	0.4047	-0.7597	-0.8423	-0.7256
	Summer	p	0.9140	0.5230	0.6250	0.7788
		cor	-0.0574	0.3300	0.2555	0.1486
Temperature	Winter	p	0.0396	0.0287	0.0007	0.0011
		cor	0.6902	-0.7201	0.9093	-0.8950
	Summer	p	0.4715	0.9135	0.8513	0.5054
		cor	0.3691	0.0578	-0.0994	-0.3432
Relative Humidity	Winter	p	0.9353	0.4112	0.2319	0.8458
		cor	-0.0318	-0.3136	-0.4434	-0.0760
	Summer	p	0.4462	0.5565	0.4679	0.6826
		cor	0.3888	0.3051	0.3719	0.2149
CO_2	Winter	p	0.2894	0.7657	0.3993	0.7839
		cor	-0.3975	-0.1163	0.3212	0.1071
	Summer	p	0.2458	0.5217	0.3813	0.1803
		cor	-0.5619	0.3310	0.4411	0.6297

10.5 ANNEX 5: JOURNAL PUBLICATIONS

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Evaluation of passive strategies, natural ventilation and shading systems, to reduce overheating risk in a passive house tower in the north of Spain during the warm season

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ABSTRACT

During the last decade in the European Union, some targets have been set to reduce energy consumption in buildings, promoting the construction of nearly Zero Energy Buildings and under certificates as Passivhaus.

Different regulations define indoor comfort, also Passivhaus standards, considered in this study. Previous studies research the risk of overheating in these buildings, particularly during hot seasons, recommending multiple strategies that are described in this project.

This study aims to detect the best natural ventilation and shading strategies to mitigate overheating issues during the hot period in a Passivhaus certified residential tower in Bilbao. The study will be carried out by dynamic simulations. It has been analysed different factors in order to quantify their direct impact on the indoor temperature, proving that overheating can occur, especially during the hot season.

The research will conclude that corner-oriented and crossed-oriented flats work better than the single-oriented for natural ventilation, producing more renovations per hour. Shading systems work better when located outside and are mobile. When combining the best previous strategies, the temperature achieves Passivhaus limitations, but high airspeed rates occur, preventing users' comfort. To achieve Passivhaus limitations is necessary to regulate different opening strategies to avoid high airflow rates and combine different passive strategies.

1. Introduction

During the last decade, energy consumption in the European Union related to buildings reaches 40% of the total consumption [1]. In Spain, considering only residential buildings, it represents 18% of the total national consumption [2], and 17% in the Basque Country [3].

The EU has adopted several strategies and targets to reduce energy consumption. The most relevant in this area are 2020 [4], 2030 [5] and 2050 [6] objectives. The main instrument has been the Energy Performance of Building Directive [1], which promotes buildings with zero or nearly Zero Energy Building (nZEB). In Spain, some policies have also been established to achieve a reduction in energy demand in buildings, implementing the directive on energy self-consumption generated by renewable energies [7]. Furthermore, in response to the shared health crisis due to COVID-19, new energy measures have been approved in 2020 [8]. They promote the necessity of encouraging the decarbonisation and sustainability agenda, to ensure that investments in renewables, energy efficiency and new production processes act as a green brake for economic recovery.

Looking for energy demand reduction, a followed trend, not only in Spain but also in Europe, has been to build under some energy certifications. This is the case of the Passivhaus (PH) certificate, which was developed in Germany and Sweden as a research project to minimise the total energy demand [9,10]. The concept of PH consists of designing with low energy consumption, low energy demand and airtight buildings. Some studies show that buildings with this certificate consume 80%–90% less energy for heating and cooling than conventional buildings, with only an increase in construction cost of 5%–10% [9,10].

To achieve this comfort balance and low energy demand, the PH establishes the minimum criteria for residential buildings, where internal gains and heat recovery systems ensure the thermal balance in the ventilation systems during cold periods and shading systems in the warm periods. It must also have appropriate thermal insulation and windows.

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sustainability

MDPI

Article

Assessment of Social Housing Energy and Thermal Performance in Relation to Occupants' Behaviour and COVID-19 Influence—A Case Study in the Basque Country, Spain

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Abstract: Evidence shows that people have a major impact on building performance. Occupants' impact is especially important in social housing, where their occupants may present greater vulnerabilities, and their needs are not always considered. This study aims to analyse the socio-demographic influence in social rental housing concerning hygrothermal comfort and energy consumption in a case study located in Vitoria, Spain during the first 4-month period of 2020 and 2021 (during and after COVID-19 lockdown). An innovative data management system is included, where the users and administration can see in real-time the temperature and consumption in the dwellings. A 2-phase method has been applied; phase 1 is associated with outdoor climate conditions, building properties and social profile. Phase 2 determined the results in energy consumption, indoor hygrothermal comfort and occupant energy-use pattern. The results show that the comfort levels and energy consumption vary according to the analysed social profiles, as well as the heating activation periods and domestic hot water system usage. In conclusion, socio-demographic characteristics of social housing households influence the hygrothermal comfort of their dwellings, occupants' behaviour and heating and domestic hot water energy consumption.

Keywords: social housing; long-term monitoring; occupant behaviour; indoor hygrothermal comfort; energy consumption

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1. Introduction

In the European Union (EU), the analysis of the final end-use of energy developed in 2018 show that households were responsible for 26.1% of energy consumption, the second sector of the 3 dominant categories (transport, households, industry) dealing with the highest energy consumption [1]. Among the EU countries, Spanish buildings accounted for 30% of final end-use energy consumption in 2018, and the residential sector alone represented 17.1% [2]. With regards to the household energy consumption for space heating, space cooling, water heating, cooking and electrical appliances, they reached 42.2%, 1%, 17.3%, 7.5% and 32%, respectively, of the total consumption [3].

Furthermore, several studies show that the concurrence of low construction quality and energy inefficiency of buildings [4], combined with the role of the user [5] and the low socio-economic profile [6], lead to situations of energy vulnerability. The central role of occupants for achieving energy savings is increasingly recognised, and it is even more important in the social housing sector, where the environmental value is combined with the social purpose of reducing inequalities and energy vulnerability.

Households that are in a vulnerable situation are often unable or have significant difficulties in facing the economic expense required to maintain their housing in hygrothermal

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Evaluation of hygrothermal comfort in educational centres by monitoring three case studies with different ventilation systems in Vitoria, Spain

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ABSTRACT

Indoor Environmental Quality has an impact on the health of its users, especially in educational centres due to the vulnerability of its occupants and high occupancy density. This study aims to analyse the hygrothermal comfort of three case studies with different ventilation systems located in the same city by monitoring. For this purpose, a three-phase methodology was proposed. First, a characterization of the case studies has been made. Second, the results obtained in the monitoring of temperature, relative humidity and CO_2 concentration during the occupied period have been analysed. Third, the hygrothermal comfort according to UNE-EN 16798 for each classroom has been compared. As a result, overall better comfort is achieved during summer than in winter. The ventilation system used in each centre has not had a great impact comparing the classrooms, being all of them in comfort for more than 80% of the occupied period. All classrooms had comfortable temperatures more than 80% of the time in summer and 70% in winter but the gymnasiums presented very low temperatures, especially during winter. In conclusion, comfort has been achieved as well in naturally as in mechanically ventilated classrooms.

1. Introduction

Indoor Environmental Quality (IEQ) [1] is the combination of various factors such as air pollution, thermal comfort and psychological factors. Within these factors, ventilation is a key factor in ensuring correct indoor air quality (IAQ). IEQ has an impact on the physical and mental health of its occupants [2]. This impact has very diverse effects, affecting the most vulnerable groups such as children, who are still at development age and have a higher respiration rate than adults, which makes them more sensitive [3]. Some of these symptoms are headaches, coughing or similar, but it also has an impact on stress and concentration levels [4]. Failure to ensure proper indoor air and environmental quality can have a long-term impact on health [5].

Nowadays, buildings are becoming more airtight and proper ventilation systems must be ensured. In the case of Europe, the majority of the building stock is buildings without any mechanical ventilation systems, which are considered to be naturally ventilated. Most studies analysing comfort and ventilation have been carried out in offices and dwellings, but not so much in schools [6], as these

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