UNIVERSIDAD
DE GRANADA

TESIS DOCTORAL

DESARROLLO DE UNA METODOLOGÍA PARA LA INTEGRACIÓN DE LA EVALUACIÓN DE LOS FACTORES DE CALIDAD AMBIENTAL INTERIORES EN EL MODELADO DE INFORMACIÓN DE CONSTRUCCIÓN (BUILDING INFORMATION MODELLING)

DEVELOPMENT OF A METHODOLOGY FOR THE INTEGRATION OF THE ASSESSMENT OF INDOOR ENVIRONMENTAL QUALITY FACTORS INTO BUILDING INFORMATION MODELLING

Para la obtención del
GRADO DE DOCTOR INTERNACIONAL POR LA UNIVERSIDAD DE GRANADA
PROGRAMA DE DOCTORADO DE INGENIERÍA CIVIL

Doctorando:
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Para la redacción de esta Memoria de Tesis Doctoral en lo relativo uso de la lengua española. Especialmente, para evitar frases farragosas que nada aportan al contenido científico, en lo referente al género de los sustantivos han sido tenidas en cuenta las normas establecidas por la Real Academia Española (RAE). Ver: https://www.rae.es/dpd/g%C3%A9nero, punto 2. Fecha de la consulta: 3 de febrero de 2022.

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Mención internacional

Con el fin de obtener el Título de Doctor por la Universidad de Granada con Mención Internacional, que el Real Decreto 99/2011 establece en su artículo 15, se han cumplido los siguientes requisitos:

i. Durante el periodo de formación necesario para la obtención del Título de Doctor, el doctorando realizó una estancia de tres meses en Portugal, en la Universidade do Minho, cursando estudios o realizando trabajos de investigación bajo la supervisión y dirección del Dr. Pedro Miguel Ferreira Martins Arezes en el Centro de Investigação ALGORITMI da Ecola de Engenharia.

ii. El Resumen y Resultados que figuran en esta Memoria de tesis doctoral se han redactado y presentado en inglés.

iii. La Tesis ha sido informada por tres expertos doctores: Dra. Alessandra Bonolli, Full Professor at the University of Bologna (Italy) y Dr. Christian Ghiaus, Full Professor at the Centet for Energy and Thermal Sciences of Lyon (France).

iv. Dr. Rui Manuel de Sá Pereira de Lima, experto perteneciente una institución de educación superior no española, con el título de doctor, y distinto del responsable de la estancia mencionada en el apartado i, forma parte del tribunal evaluador de la tesis.

Tesis como agrupación de publicaciones

Esta memoria de tesis doctoral está basada en el reagrupamiento de trabajos de investigación publicados por el doctorando en medios científicos relevantes en su ámbito de conocimiento. Dando cumplimiento al artículo 18.4 de las Normas Reguladoras de las Enseñanzas Oficiales de Doctorado y del Título de Doctor por la Universidad de Granada, se cumplen los siguientes requisitos:

i. La memoria de tesis doctoral consiste en la reagrupación de los seis trabajos de investigación en una memoria, publicados por el doctorando en revistas de alto impacto relevantes para su campo de conocimiento, tal y como recomienda el Consejo Asesor de Escuelas de Doctorado.

ii. Los artículos han sido publicados con fecha posterior a la obtención del título de grado y máster.

iii. Los artículos no han sido utilizados en ninguna tesis previa.

iv. Los coautores de las publicaciones presentadas declaran que ellos no han presentados estos artículos en ninguna otra tesis y no lo harán en el futuro. También se ha indicado la contribución del doctorando a los trabajos mencionados.

v. Esta memoria de tesis doctoral se compone de los mencionados artículos científicos integrados como capítulos en el presente documento.

El doctorando ha respetado todos los derechos de propiedad intelectual relativos a la difusión de los artículos utilizados en la tesis doctoral.

A continuación se resumen los artículos científicos (junto con su factor de impacto) utilizados en el compendio de esta memoria de tesis doctoral:

1. **Aguilar, Antonio J.**, de la Hoz-Torres, María, L., Costa, N., Arezes, P., Martínez-Aires, M. D. & Ruiz, D. P. (2022). *Assessment of ventilation rates inside educational buildings in Southwestern Europe: Analysis of implemented strategic measures*. Journal of Building Engineering, 51, 104204. https://doi.org/10.1016/j.jobe.2022.104204 (F.I.: 7.14; posición 9/138 en *ENGINEERING CIVIL*, D1).

2. **Aguilar, Antonio J.**, de la Hoz-Torres, María L., Oltra-Nieto, Lamberto, Ruiz, Diego P. & Martínez-Aires, Mª Dolores. (2022). Impact of COVID-19 protocols on IEQ and students' perception within educational buildings in Southern Spain. Building Research

& Information, 1-16. https://doi.org/10.1080/09613218.2022.2082356 (F.I.: 4.799; posición 19/68 en *CONSTRUCTION & BUILDING TECHNOLOGY,* Q2).

3. De la Hoz-Torres, María L., **Aguilar, Antonio J.**, Costa, N., Arezes, P., Ruiz, Diego P. & Martínez-Aires, Mª Dolores. (2022). Reopening higher education buildings in post-epidemic COVID-19 scenario: monitoring and assessment of indoor environmental quality after implementing ventilation protocols in Spain and Portugal. Indoor Air, 32(5), e13040. https://doi.org/10.1111/ina.13040 (FI: 6.55; posición 11/68 en *CONSTRUCTION & BUILDING TECHNOLOGY,* Q1).

4. De la Hoz-Torres, María L., **Aguilar, Antonio J.**, Ruiz, Diego P. & Martínez-Aires, Mª Dolores. (2021). *Analysis of impact of natural ventilation strategies in ventilation rates and indoor environmental acoustics using sensor measurement data in educational buildings*. Sensors, 21(18), 6122. https://doi.org/10.3390/s21217223 (F.I.: 3.84; posición 19/64 en *INSTRUMENT & INSTRUMENTATION,* Q2)

5. **Aguilar, Antonio J.**, de la Hoz-Torres, M. L., Martínez-Aires, M. D. & Ruiz, D. P. (2022). *Thermal Perception in Naturally Ventilated University Buildings in Spain during the Cold Season*. Buildings, 12(7), 890. https://doi.org/10.3390/buildings12070890 (FI: 3.32; posición 28/68 en *CONSTRUCTION & BUILDING TECHNOLOGY,* Q2).

6. **Aguilar, Antonio J**., de la Hoz-Torres, María L., Ruiz, D.P. & Martínez-Aires, M.D. (2022) *Monitoring and Assessment of Indoor Environmental Conditions in Educational Building Using Building Information Modelling Methodology*. International Journal of Environmental Research and Public Health. 19(21):13756. https://doi.org/10.3390/ijerph192113756 (FI: 4.614; posición 45/182 en *PUBLIC, ENVIRONMENTAL & OCCUPATIONAL HEALTH,* Q1).

Además de las mencionadas, los siguientes documentos también han sido publicados por el candidato y han contribuido a su formación y desarrollo:

Otras publicaciones en revistas de alto impacto indexadas en JCR (Journal Citation Report):

- **Aguilar, Antonio J.**, de la Hoz-Torres, María L., Martínez-Aires, Mª Dolores, & Ruiz, Diego P. (2022). *Development of a BIM-Based Framework Using Reverberation Time (BFRT) as a Tool for Assessing and Improving Building Acoustic Environment*. Buildings, 12(5), 542. https://doi.org/10.3390/buildings12050542 (FI: 3.32; posición 28/68 en *CONSTRUCTION & BUILDING TECHNOLOGY,* Q2).

- Aguilar**, Antonio J.**, de la Hoz-Torres, María L., Martínez-Aires, Mª Dolores & Ruiz, Diego P. (2021). *Monitoring and assessment of indoor environmental conditions after* *the implementation of COVID-19-based ventilation strategies in an educational building in southern Spain*. Sensors, 21(21), 7223. https://doi.org/10.3390/s21217223 (F.I.: 3.84; posición 19/64 en *INSTRUMENT & INSTRUMENTATION*, Q2).

- **Aguilar, Antonio J.**, de la Hoz-Torres, María L., Martínez-Aires, Maria D.; Diego P. Ruíz. *Review of health and safety management based on BIM methodology = Revisión de la gestión de seguridad y salud basada en la metodología BIM*. Building & Management. https://doi.org/10.20868/bma.2019.2.3919

Otras publicaciones en capítulos de libro:

- **Aguilar-Aguilera, Antonio J.**, De la Hoz-Torres, M. L., Martínez-Aires, M. D., & Ruiz, D. P. (2020). *Management of Acoustic Comfort in Learning Spaces Using Building Information Modelling (BIM).* In Occupational and Environmental Safety and Health II (pp. 409-417). Springer, Cham. https://doi.org/10.1007/978-3-030-41486-3_44 (Q1 en ranking SPI).

Comunicaciones en congresos:

- **Antonio J. Aguilar-Aguilera**, M.L. De la Hoz-Torres, M.D. Martínez-Aires, D.P. Ruiz, *BIM-based framework for indoor acoustic conditioning in early stages of design*, INTER-NOISE 2019 MADRID - 48th International Congress and Exhibition on Noise Control Engineering, 2019.
- **Aguilar Aguilera, Antonio J.**, López-Alonso, Mónica, Martínez-Rojas, María, & Martínez-Aires, María Dolores (2017). *Review of the state of knowledge of the BIM methodology applied to health and safety in construction*. Occupational Safety and Hygiene V, 459-464.

- **Aguilar, Antonio J.**, de la Hoz Torres, M. L., Martínez-Aires, M.D., & Ruíz, D. P. (2019). *Reverberation time analysis using building information modelling*. En 2nd Building and Management International Conference. Proceedings.

Premios:

- Premio a Joven Científico de la Sociedad Española de Acústica (SEA) en el congreso internacional INTERNOISE 19', por el trabajo: "*BIM-based framework for indoor acoustic conditioning in early stages of design*". Año 2019.

- Premio "Andrés Lara" para Jóvenes Investigadores en su Decimoséptima Edición, concedido por la Sociedad Española de Acústica (SEA). Madrid, 18 de Junio de 2019.

- Finalista del I premio INACON a la mejor ponencia "*Reverberation Time Analysis using Building Information Modelling*". 2° Congreso Internacional de Gestión en Edificación

(Building and Management International Conference) BIMIC 2019. Celebrado en la Escuela Técnica Superior de Edificación de la Universidad Politécnica de Madrid, los días 8 – 10 de mayo 2019.

Financiación

A continuación, se detallan las principales fuentes de financiación que han contribuido el desarrollo de esta Tesis Doctoral:

- Contrato de Formación de Profesorado Universitario (FPU) del Ministerio de Educación y ciencia (FPU17/01285), en su resolución del 12 de diciembre de 2017, BOE n° 301.

- Proyecto denominado "Generación de herramientas y propuesta de procesos de actuación para controlar la exposición a factores ambientales usando la prevención desde el diseño sostenible con BIM (FACAMBIM)", (B-TEP-362-UGR18). Financiado por la Junta de Andalucía. Periodo: 01/01/2020 – 30/06/2022.

- Proyecto denominado "Marco de Trabajo basado en BIM para la edificación sostenible a través de la mejora de la calidad ambiental interior" (PID2019-108761RB-I00). Financiado por la Agencia de Investigación Estatal de España y los Fondos de Desarrollo Regionales Europeos. Periodo: 01/06/2020-31/05/2023.

- Ayuda para la realización de estancias breves de cuatro meses en el marco de la Convocatoria de Becas Iberoamérica, Santander Investigación, Santander Universidades 2020 para Estudiantes de programas de Doctorado de la Universidad de Granada.

- Seleccionado por el Consejo General de la Arquitectura Técnica de España en la *IV Convocatoria de Ayudas del Consejo General de la Arquitectura Técnica de España para el Fomento de la Formación de Doctorandos Arquitectos Técnicos*. Curso 2018/2019.

A mis padres y hermanas

“Recuerdas aquellos paseos...”

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RESUMEN

Las condiciones ambientales interiores pueden afectar significativamente a la salud y el confort de los ocupantes de los edificios. Conseguir unas condiciones interiores aceptables es un factor fundamental en el diseño y gestión de las edificaciones ya que las personas suelen pasar aproximadamente entre el 80-90% de su tiempo en espacios interiores. La calidad ambiental interior (en inglés Indoor Environmental Quality, en adelante IEQ) puede estar influenciada no solo por las condiciones exteriores, sino también por el entorno construido del edificio (sistemas constructivos, sistemas de climatización y refrigeración, materiales, geometría, orientación, etc.), así como por el propio comportamiento de los usuarios. La gestión de la calidad ambiental además supone un reto en los espacios densamente ocupados, como es el caso de los edificios de uso educacional.

Considerando que los estudiantes, los profesores y el personal pasan largos períodos del día en estos espacios, unas condiciones deficientes pueden generar insatisfacción e influenciar de forma negativa el aprendizaje y el rendimiento de los estudiantes. De hecho, la pandemia mundial causada por el COVID-19 ha puesto recientemente en el punto de mira los efectos de una deficiente calidad ambiental interior en estos espacios, ya que son entornos de riesgo para la transmisión de virus en el aire, como el virus SARS-CoV-2. Estas circunstancias justifican la necesidad de desarrollar nuevas herramientas para la monitorización, evaluación y gestión de la calidad ambiental interior en los edificios. En el sector de la arquitectura, la ingeniería y la construcción (Architecture, Engineering and Construction, en adelante AEC) están surgiendo nuevas metodologías como el modelado de información de la construcción (Building Information Modelling, en adelante BIM) que puede proporcionar herramientas clave para el desarrollo de metodologías para la gestión de la calidad ambiental en los edificios.

En este contexto, la presente Memoria de Tesis Doctoral se centra en el desarrollo de una metodología para la integración de la evaluación de los factores de calidad ambiental interiores en la metodología BIM.

Para ello, en primer lugar, se realizó un análisis del marco teórico y normativo de la calidad ambiental interior en edificios de alta ocupación, así como de las recomendaciones establecidas por las autoridades sanitarias en materia de protección frente a virus de transmisión aérea. A partir de este análisis se definió una campaña de medición para la caracterización de las estrategias de ventilación natural en edificios educacionales universitarios en el suroeste de Europa (España y Portugal). Durante esta campaña de medición se evaluaron diferentes estrategias de ventilación natural para comprobar si mediante estos sistemas se pueden alcanzar los objetivos de tasas de ventilación marcados por las diferentes normativas pre y post-pandémicas.

En segundo lugar, se realizó una campaña de medición objetiva/subjetiva donde se evaluaron las condiciones ambientales interiores y la percepción y satisfacción de los estudiantes tras la implantación de los protocolos COVID19. Se evaluaron los edificios ubicados en el campus Fuente Nueva (Granada) y en el campus Azurem (Guimarães) recogiendo un total de 931 encuestas. Los resultados mostraron que, aunque las estrategias de ventilación natural proporcionaban una renovación efectiva del aire, también ocasionaban insatisfacción entre los estudiantes. Entre los principales factores de insatisfacción se encontraban los relacionados con el confort térmico y acústico.

Posteriormente, en tercer lugar, a partir de los resultados obtenidos de las campañas anteriores y habiendo identificado las principales causas de insatisfacción, se realizaron ensayos para analizar el impacto de la aplicación de los protocolos de ventilación natural en el ambiente térmico y acústico interior. Por un lado, los resultados mostraron que la estrategia de ventilación natural continua provoca un aumento de entre 6,4 dBA y 12,6 dBA en el nivel de ruido de fondo en las aulas, respecto a un escenario con puertas y ventanas cerradas. Por otro lado, se desarrolló una campaña de medición centrada el análisis de la percepción térmica de los estudiantes durante la estación invernal. Un total de 989 estudiantes participaron en este estudio. Los resultados mostraron que aunque la concentración de CO2 en el 90% de las aulas evaluadas estaba por debajo del valor recomendado (800 ppm), sólo el 18% de las aulas estaban dentro de la zona de confort térmico definida por la normativa nacional.

Finalmente, se ha propuesto un marco de trabajo basado en la metodología BIM para integrar la evaluación de la IEQ y el riesgo de transmisión de virus en el aire en edificios de enseñanza superior. El marco de trabajo desarrollado implementa los datos obtenidos mediante monitorización de sensores y la programación diaria llevada a cabo en el edificio. El sistema proporciona automáticamente la sensación térmica, acústica y lumínica en función a los datos proporcionados por lo sensores en el aula, de tal manera que se puede evaluar y clasificar el rango de confort de los usuario (óptimo, aceptable e inaceptable), así como la probabilidad de infección durante cada clase.

El marco de trabajo generado en esta Tesis Doctoral se constituye como una nueva herramienta para la gestión de la IEQ y la prevención de la transmisión de virus en el aire en edificios de alta ocupación. La evaluación de la IEQ está basada en la respuesta de los usuarios y los datos obtenidos de la monitorización, por lo que los resultados muestran problemas reales de los ocupantes. Los resultados proporcionan información clave para apoyar el proceso de toma de decisiones para la gestión de la IEQ y el control del riesgo de transmisión de virus en el aire. Su aplicación a largo plazo podría proporcionar datos que apoyen la gestión de las estrategias de ventilación y el rediseño de los protocolos.

PALABRAS CLAVE: Calidad ambiental interior, Building Information Modeling, ventilación natural, edificios educacionales, monitorización con sensores

ABSTRACT

The indoor environmental conditions can significantly affect the health and satisfaction of building occupants. In fact, since people tend to spend around 80-90% of their time indoors, providing adequate indoor environmental conditions is an essential factor during the design and management of buildings. Indoor environmental quality (IEQ) is not only influenced by outdoor conditions, but also by the type of built environment (construction systems, air conditioning and cooling systems, materials' characteristics, geometry, orientation, etc.), as well as by the behavior of the building users.

Furthermore, environmental quality management is a challenge especially in densely occupied indoor spaces, such as educational buildings. Given that students, teachers and staff spend long periods of the day in these spaces, poor conditions can lead to dissatisfaction and negatively influence student learning and performance. Indeed, the global pandemic caused by COVID-19 has recently put the spotlight on the effects of poor IEQ in educational buildings, as they are risk spaces for the transmission of airborne viruses such as SARS-CoV-2. These circumstances justify the need to develop new tools for the monitoring, assessment and management of IEQ in buildings. The Architecture, Engineering and Construction (AEC) sector is undergoing profound changes and new methodologies such as Building Information Modelling (BIM) are emerging that can provide key tools for the development of methodologies for the IEQ management.

In this context, the main objective of this thesis has been the Development of a Methodology for the integrations of the IEQ assessment into the BIM methodology.

For this purpose, and as a first step, the IEQ standards and regulations for high-occupancy buildings were analyzed, including the recommendations established by health authorities regarding the prevention of the spread of airborne viruses. Based on this analysis, a measurement campaign was defined for the characterization of natural ventilation strategies in university educational buildings in Southwest Europe (Spain and Portugal). During this field measurement campaign, different natural ventilation strategies were evaluated in order to check whether the ventilation rate targets set by the different pre- and post-pandemic regulations could be achieved by these systems.

Secondly, an objective/subjective measurement campaign was carried out to assess indoor environmental conditions and student perception and satisfaction after the implementation of the COVID19 protocols. The buildings located on the Fuente Nueva campus (Granada) and the Azurem campus (Guimarães) were evaluated and a total of 931 surveys were collected. The results showed that, although natural ventilation strategies provided effective air renewal, they also caused dissatisfaction among students. Among the main dissatisfaction factors were those related to thermal and acoustic comfort.

Subsequently, thirdly, based on the results obtained from the previous measurement campaigns and having identified the main causes of dissatisfaction, field tests were carried out to analyze the impact of the application of natural ventilation protocols on the indoor thermal and acoustic environmental conditions. On the one hand, the results showed that the continuous natural ventilation strategy causes an increase of between 6.4 dBA and 12.6 dBA in the background noise level in the classrooms, compared to a scenario with closed doors and windows. On the other hand, a measurement campaign focused on the analysis of the students' thermal perception was conducted during the winter season, in which a total of 989 students participated. The results showed that although the CO2 concentration was below the recommended value (800 ppm) in 90% of the tested classrooms, only 18% of the classrooms were within the thermal comfort zone defined by national regulations.

Finally, a framework based on BIM methodology has been proposed to integrate the assessment of IEQ and the risk of airborne virus transmission in higher education buildings. The proposed framework integrates the occupants' feedback, the data obtained from sensor monitoring and the classroom daily schedule into the BIM methodology. The system automatically provides the thermal, acoustic and light sensation based on the data provided by the sensors in the classroom, so that the range of user comfort (optimal, acceptable and unacceptable) and the individual airborne virus transmission risk during each class can be evaluated and classified.

The contribution made through this thesis dissertation constitute a new tools whose implementation facilitates the IEQ management and the prevention of airborne virus transmission in high-occupancy buildings. The IEQ evaluation is based on sensor monitoring and a daily schedule, so the results show real problems of occupants' dissatisfaction. The outcomes provide key information to support the decision-making process for managing IEQ and controlling individual airborne virus transmission risks. Long-term application could provide data that support the management of ventilation strategies and protocol redesign.

KEYWORDS: Indoor environmental quality, Building Information Modeling, natural ventilation, educational building, sensor monitoring

PRELIMINAR

Con esta Memoria de Tesis se pretende dar cumplimiento a lo establecido en el Real Decreto/2011, de 28 de Enero (BOE: 10 de Febrero de 2011) por el que se establece la ordenación de las Enseñanzas Universitarias Oficiales, para optar al Grado de Doctor Internacional por la Universidad de Granada.
La Memoria cumple con todos los requisitos establecidos en el artículo 16 en lo referente a Mención Internacional en el título de Doctor:

- Cuenta con dos directores de investigación de la Universidad de Granada: Dra. María Dolores Martínez Aires del Departamento de Construcciones Arquitectónicas y Dr. Diego Pablo Ruiz Padillo del Departamento de Física Aplicada.
- En los Capítulos 2 al 7 se presentan los resultados del trabajo de investigación desarrollado que han sido publicados en revistas indexadas en la base de datos Journal Citation Reports. Concretamente:
    - En el Capítulo 2 se presenta un artículo, aceptado y publicado *on line* (DOI: https://doi.org/10.1016/j.jobe.2022.104204), en la revista Journal of Building Engineering, cuyo Factor de Impacto es 7.14 y su posición en la categoría *Engineering Civil* es 9/138 (D1 y Q1).
    - En el Capítulo 3 se presenta un artículo, aceptado y publicado *on line* (DOI: https://doi.org/10.1080/09613218.2022.2082356), en la revista Building Research & Information, cuyo Factor de Impacto es 4.799 y su posición en la categoría *Construction & Building Technology* es 19/68 (Q2).
    - En el Capítulo 4 se presenta un artículo, aceptado y publicado *on line* (DOI: https://doi.org/10.1111/ina.13040), en la revista Indoor Air, cuyo Factor de Impacto es 6.554 y su posición la categoría *Construction & Building Technology* es 11/68 (Q1).
    - En el Capítulo 5 se presenta un artículo, aceptado y publicado *on line* (DOI: https://doi.org/10.3390/s21217223), en la revista Sensors, cuyo Factor de Impacto es 3.840 y su posición en la categoría *Instrument & Instrumentation* es 19/64 (Q2).
    - En el Capítulo 6 se presenta un artículo, aceptado y publicado *on line* (DOI: https://doi.org/10.3390/buildings12070890), en la revista Buildings, cuyo Factor de Impacto es 3.32 y su posición en la categoría *Construction & Building Technology* es 28/68 (Q2).
    - En el Capítulo 7 se presenta un artículo, aceptado y publicado *on line* (DOI: https://doi.org/10.3390/ijerph192113756), en la revista International Journal of Environmental Research and Public Health, cuya Factor de Impacto es 4.614 y su posición en la categoría *Construction & Building Technology* es 45/182 (Q1).

- Por último, esta Memoria cuenta con los informes favorables de los directores de investigación de la misma, por lo que se deposita en la Secretaria de la Comisión de Doctorado con objeto de que sea conocida e informada por la dicha Comisión de Doctorado de la Universidad de Granada tras su exposición a la comunidad universitaria.

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ACRONIMOS

ACH	Air change per hour
ASHRAE	American Society of Heating, Ventilating, and Air-Conditioning Engineers
C_{MV}	Mechanical Ventilation
C_{AW+2D}	All windows + 2 doors
C_{AW+1D}	All windows + Main door
C_{AW}	All windows
C_{EW+1D}	End windows + Main Door
HVAC	Heating, Ventilation, and Air Condition
IAQ	Indoor Air Quality
IEQ	Indoor Environmental quality
MV	Mechanical ventilation
NDIR	Non-dispersive infrared
NV	Natural ventilation
REHVA	Federation of European Heating, Ventilation and Air Conditioning Associations
RITE	Regulation on Building Heating Installations
SARS-CoV-2	Severe Acute Respiratory Syndrome Coronavirus-2
SHASE	Society of Heating, Air-Conditioning, and Sanitary Engineers of Japan
VR	Ventilation rate
WHO	World Health Organization

1. INTRODUCCIÓN

1.1. Antecedentes. Planteamiento del Problema de Investigación y motivación.

La población urbana pasa más del 80% de sus vidas en el interior de los edificios [1], dónde diversos agentes físicos, químicos o biológicos pueden ocasionar exposiciones nocivas para la salud y condicionar las necesidades objetivas y subjetivas de los usuarios [2]. En general, nos referimos al concepto de calidad ambiental interior (en inglés Indoor Environmental Quality, en adelante IEQ) como el estado de las condiciones ambientales en el interior del edificio en relación a sus efectos sobre la salud y bienestar de los usuarios de los mismos [3]. Estas variables pueden agruparse en cuatro grandes áreas de estudio: calidad térmica, calidad de aire interior, calidad visual y calidad acústica.

Por un lado, la calidad del aire depende de diferentes factores físicos y químicos (relativos a la humedad, temperatura, renovación del aire interior y concentración de contaminantes en el aire). En cuanto a la sensación subjetiva de bienestar térmico, ésta se encuentra determinada por parámetros térmicos y otros relativos a la termorregulación humana. Con relación al bienestar acústico, se define como el nivel de ruido que es confortable para los usuarios y que no causa efectos nocivos sobre la salud. Por último, las condiciones lumínicas interiores deben permitir a los ocupantes el desarrollo normal de las actividades. En este sentido, una mala iluminación puede provocar una disminución del rendimiento, así como producir más errores y accidentes.

Por otro lado, estos parámetros se pueden ver afectados por las condiciones ambientales exteriores, condiciones del edificio (materiales, estructuras y construcción), los sistemas de climatización, disposición del diseño interior, así como el comportamiento de los usuarios. Todos estos factores ambientales pueden ocasionar molestias o riesgos para la salud por separado o en conjunto. Es por ello que la evaluación de los factores IEQ debe hacerse de forma integrada, abordando a todos los agentes desde un enfoque holístico.

No obstante, mantener una IEQ aceptable es un reto en entornos de alta densidad de ocupación, como son los edificios educativos, donde el profesorado, el alumnado y el personal de servicios pasan largos periodos de tiempo (al menos cinco horas al día) [4, 5]. Estos usuarios son vulnerables al impacto de una IEQ deficiente en un entorno donde realizan actividades que requieren un elevado nivel de concentración y trabajo intelectual. De hecho, investigaciones previas concluyeron que unas condiciones acústicas deficientes causan un impacto negativo en el rendimiento académico, psicoeducativo, psicosocial [6] y en los logros académicos del alumnado [7, 8]. Además, también se ha identificado que tienen efectos significativos en la identificación e inteligibilidad de las palabras [9], memoria a corto plazo y comprensión general [10, 11]. Con respecto a la iluminación, estudios previos han señalado que si las condiciones lumínicas en el interior del aula son deficientes, la atención del alumnado y su rendimiento se ve reducido [12]. La iluminación en el aula condiciona la percepción de los estímulos visuales por parte del alumnado, y por consiguiente, su rendimiento académico [13]. Por otra parte, numerosos estudios publicados desde 1960 sugieren una fuerte correlación entre el ambiente térmico y la calidad del aire dentro de las clases con el rendimiento y bienestar del alumnado [14-18]. El proceso de aprendizaje se ve afectado por las condiciones térmicas, de forma que si el entorno genera una incomodidad cálida o fría, o si la temperatura cambia con frecuencia, el progreso del aprendizaje disminuye [19]. En cuanto a unas condiciones de calidad del aire deficientes, la exposición a determinados contaminantes en el aire puede causar un riesgo para la salud a corto y largo plazo, como por ejemplo, enfermedades respiratorias [20, 21], enfermedades cardiovasculares [22], ojos o nariz irritados, nariz tapada, dolores de cabeza, etc. [23]. Además, una calidad del aire deficiente también puede afectar al confort, la productividad y el rendimiento académico de los estudiantes [24-26]. Garantizar una tasa de ventilación adecuada es uno de los elementos clave para no comprometer la calidad del aire, ya que al proporcionar ventilación exterior se pueden diluir los contaminantes generados en el interior hasta niveles que no causen problemas de salud y confort [27]. En el contexto europeo, donde la mayoría de los centros docentes se ventilan mediante medios naturales (a través de puertas y ventanas) [28], asegurar una calidad del aire adecuada en las aulas es más complejo debido a la dependencia de este mecanismo de ventilación de las condiciones ambientales exteriores e interiores. La selección de una estrategia de ventilación adecuada es esencial para cumplir los requisitos de una buena calidad del aire. En este marco se han desarrollado directrices, normativas y estándares internacionales, los cuales establecen requisitos mínimos que deben cumplir los edificios [29-32].

Sin embargo, a pesar de las graves consecuencias de una IEQ inadecuada para los estudiantes y de que unas buenas condiciones ambientales interiores son esenciales para proporcionar un espacio saludable, investigaciones previas han documentado una IEQ inadecuada en los edificios educativos [33-37]. Estas circunstancias han llevado a que en la última década se desarrollen investigaciones con el objetivo de analizar el impacto de la ventilación natural en las condiciones ambientales interiores de estos edificios, y en consecuencia, en sus ocupantes. Así, Sarbu y Pacurar [38] realizaron un estudio para evaluar el confort térmico mediante mediciones subjetivas (cuestionarios) y objetivas (variables físicas) en aulas con ventilación natural en la Universidad Politécnica de Timisoara. En este estudio encontraron que la concentración media de CO_2 era de 1450 ppm y 670 ppm en invierno y verano respectivamente. La razón por la que esta concentración de CO_2 era menor en la estación de verano se debía a que las ventanas se abrían con más frecuencia que en invierno. Se encontraron resultados similares en aulas italianas con ventilación natural por Stabile, Dell'Isola, Russi, Massimo y Buonanno [39] y en aulas ventiladas del Reino Unido por Korsavi, Montazami y Mumovic [40, 41]. Estudios anteriores también concluyeron que la calidad del aire interior se veía muy afectada por los comportamientos adaptativos de los ocupantes. En cuanto a los factores impulsores relacionados con el comportamiento de apertura de las ventanas en las aulas con ventilación natural, Stazi et al. [42] concluyeron que los estudiantes tienden a sufrir una mala calidad del aire durante la temporada de calefacción debido a la priorización de los estudiantes de satisfacer su bienestar térmico. De hecho, Stazi afirmó que la temperatura interior y exterior son los principales factores que impulsan los comportamientos de apertura de ventanas, mientras que la concentración de CO_2 no es un estímulo. Conclusiones similares fueron obtenidas por Duarte et al. [43] y Heracleous y Michael [44] en edificios educativos de Portugal y Chipre, respectivamente.

Además, la preocupación por la IEQ en espacios interiores ha aumento recientemente como consecuencia de la pandemia generada por la COVID-19. Según la Organización Mundial de la Salud, hasta el 14 de octubre de 2022 se habían registrado 6,543,138 muertes y 620,878,405 casos confirmados de COVID-19 en todo el mundo [45]. La transmisión del SARS-CoV-2 se produce cuando las personas no infectadas se exponen a fluidos respiratorios infecciosos tras el contacto con personas infectadas [46]. Entre los factores que contribuyen a aumentar la transmisión se encuentran: el volumen de voz; la actividad física; el uso de mascarillas mal ajustadas; una gran concentración de personas en el mismo espacio; la disminución de la distancia interpersonal; el aumento del tiempo de exposición, etc [47]. Investigaciones recientes han demostrado que la transmisión puede agravarse en espacios interiores y mal ventilados. De hecho, Nishiura et al. [48] afirman que la transmisión de COVID-19 puede ser hasta 18,7 veces mayor en espacios interiores que en espacios al aire libre. Park et al. [49] sugirieron que la ventilación cruzada es más eficiente en comparación con la ventilación unilateral, y recomiendan esta estrategia ventilación para minimizar la posibilidad de infección en edificios públicos de alta densidad de ocupación. Dado que los estudiantes y los profesores pasan largos periodos del día en las aulas, estos espacios están considerados como entornos de riesgo para la transmisión aérea del SARS-CoV-2 [50].

A la vista de estas circunstancias, los gobiernos adoptaron medidas para minimizar la posibilidad de contagio, entre las que se incluyeron el cierre de los edificios educativos. Como resultado, casi la mitad de los estudiantes del mundo se vieron afectados por esta medida y más de 100 millones de niños quedaron por debajo del nivel mínimo de competencia lectora [51]. La Organización de las Naciones Unidas para la Educación, la Ciencia y la Cultura (UNESCO) advirtió que era fundamental dar prioridad a la recuperación de la educación para evitar una catástrofe generacional [51]. En consecuencia, la adopción de estrategias efectivas para controlar el riesgo de infección y la adaptación de los centros docentes se constituyeron como procesos esenciales para mitigar el impacto del cierre de los edificios educativos. La reapertura de estos edificios ha tenido muchas implicaciones socioeconómicas en todos los países, por lo que se tomaron diferentes medidas para garantizar que estos espacios eran seguros. Las directrices de prevención del Gobierno español establecieron como obligatorio el uso de mascarillas bien ajustadas (una mascarilla quirúrgica como mínimo), la reducción del volumen de la voz en las conversaciones, el aumento de la distancia interpersonal, la reducción del tiempo de contacto (por ejemplo, reduciendo la ocupación de los espacios interiores) y la mejora de la ventilación. En el caso de espacios naturalmente ventilados, se recomienda la ventilación cruzada (abrir puertas y/o ventanas en lados opuestos) [47]. En el caso de la ventilación mecánica, requiere especial atención a la configuración del sistema, para reducir la recirculación de aire y aumentar el caudal de aire exterior. La tasa de ventilación recomendada en los espacios interiores es de 12,5 litros/segundo por persona (L/s/p) para una buena calidad del aire, lo que corresponde aproximadamente a 5-6 renovaciones de aire por hora (en adelante ACH). Estas circunstancias determinan que uno de los retos más exigentes a los que se enfrentan los gestores de los edificios educativos en la actualidad sea la gestión de la IEQ [52].

En este sentido, las nuevas metodologías emergentes en el sector de la Arquitectura, Ingeniería y Construcción (AIC) están cambiando el paradigma de la gestión del diseño, ejecución y mantenimiento de los edificios. Tradicionalmente se han empleado métodos basados principalmente en documentos y planos en 2D. Pero esta tendencia está cambiando, pues se está implementando la metodología Building Information Modeling (modelado de información de la edificación en español, en adelante BIM) como herramienta fundamental en la industria de la AIC [53]. BIM, como metodología, consiste en la creación, gestión y almacenamiento de la información de las propiedades y características de las diferentes partes del edificio, no solo referente a sus propiedades geométricas o visuales, sino relativas también a otras no geométricas, mediante una participación y colaboración entre los diferentes agentes que intervienen en el proceso constructivo [54]. El modelo BIM resultante se trata de una representación digital de todas las características físicas y funcionales de un edificio, una base de datos de información fiable durante toda su ciclo de vida. La concentración de toda la información y datos del proyecto en un único modelo permite adquirir una visión global y una mayor coordinación de todas las partes del mismo, anticipándose así a los problemas que puedan aparecer en fases posteriores de construcción, explotación y mantenimiento, con una gestión más eficiente de los proyectos de construcción.

Recientes investigaciones han puesto de manifiesto el potencial uso de la metodología BIM junto con los datos de monitorización a través de sensores de las variables ambientales interiores para gestionar las instalaciones y los edificios. Así, Natephra et al. [55] desarrolla un marco de trabajo basado en BIM mediante simulación 4D y sensores con el objetivo de evaluar y analizar las condiciones térmicas en el interior de edificios. Habibi [56] realiza un análisis del confort térmico en función de la orientación y situación geográfica del edificio mediante el empleo de metodología BIM. Azhar [57] y Jalaei and Jrade [58] realizan una implementación de sistema canadiense de certificación de edificios verdes (LEED) mediante metodología BIM para evaluar parámetros de sostenibilidad e IEQ. Marzouk and Abdelaty [59] desarrolla un marco de trabajo en BIM para la monitorización de la temperatura y partículas en suspensión en estaciones de metro. Cheung et al. [60] desarrollaron un sistema para integrar una red de sensores de gases peligrosos en la metodología BIM. Nojedehi et al. [61] definieron una metodología para integrar los datos relativos a la gestión y mantenimiento de los edificios en BIM, con la finalidad de mejorar estos procesos. Alavi et al. [62] propusieron la implementación de una metodología basada en un enfoque probabilístico para evaluar el confort de los ocupantes a través de BIM. Artan et al. [63] definieron un sistema de evaluación post-ocupación integrado en BIM para edificios de oficinas. Chang et al. [64] desarrollaron una plataforma basada en BIM la gestión del ahorro energético a través de la medición de las condiciones ambientales interiores. Desogus et al. [65] evaluaron el uso integrado de la metodología BIM y los sistemas IoT, concluyendo que el modelo BIM permite la gestión de información útil sobre el edificio, función clave para una gestión eficaz y precisa del mismo.

Estos estudios evidencian el potencial uso de la metodología BIM durante la fase de gestión y mantenimiento de los edificios.

En este contexto, la presente memoria de Tesis Doctoral aborda el problema actual de la gestión de los factores de calidad ambiental interior en el nuevo contexto generado por la pandemia provocada por la COVID-19 en edificios de uso educacional. Por un lado, analizando los protocolos de ventilación exigidos por las autoridades sanitarías y su impacto en la calidad ambiental interiores. Por otro, evaluando el impacto de los nuevos protocolos pandémicos en la percepción de los usuarios sobre las condiciones ambientales interiores. Finalmente, generando y evaluando un marco de trabajo para la integración de la gestión de estos factores en la metodología BIM.

1.2. Objetivos

La investigación que se presenta en esta Memoria de Tesis Doctoral tiene como Objetivo General: desarrollo de una metodología para la integración de la evaluación de los factores de calidad ambiental interiores en el modelado de información del edificio (Building Information Modelling, BIM). Este Objetivo General se desglosa en los siguientes Objetivos Específicos:

O1. Analizar las estrategias de ventilación y la probabilidad de infección por transmisión de virus aéreos en interior de edificios educacionales del sureste de España durante el escenario pandémico y su comparación con las estrategias implementadas en Portugal.

O2. Evaluar las condiciones ambientales interiores (térmicas, acústicas y lumínicas) en espacios docentes y el impacto de los protocolos pandémicos en la percepción y satisfacción de los ocupantes tras la reapertura de los centros docentes en España y Portugal.

O3. Análisis de las variables que se han detectado que generan mayor insatisfacción en los ocupantes (térmica y acústica) de los edificios de enseñanza superior del sur de España tras la implantación de los protocolos pandémicos.

O4. Desarrollar un marco de trabajo basado en BIM para integrar la evaluación la calidad ambiental interior y del riesgo de infección por virus de transmisión aérea en edificios universitarios. (*Develop a framework based on BIM methodology to integrate the assessment of IEQ and the risk of airborne virus transmission in higher education buildings.*)

1.3. Metodología

La propuesta metodológica para desarrollar la investigación se adapta a cada uno de los objetivos específicos.

M1. Para alcanzar el O1 se realizó una revisión del marco teórico y normativo de la calidad ambiental interior, así como los requisitos y medidas de ventilación en espacios docentes recomendados tanto por instituciones nacionales como internacionales (ASHRAE, REVHA, ISO, WHO, etc.). También se revisaron los protocolos de ventilación establecidos por los ministerios competentes del Gobierno de España y Portugal en relación a la pandemia del COVID-19. Posteriormente, se realizó un estudio previo de los edificios ubicados en el Campus de Azurém (Guimarães, Portugal) y en el Campus de Fuentenueva (Granada, España). A partir de dicho estudio se seleccionaron los espacios docentes (aulas) representativos para su caracterización. Una vez identificados estos espacios, se procedió a definir las diferentes posibles estrategias de ventilación en función del tipo de espacio. Posteriormente, se realizaron ensayos mediante el método de decaimiento y se analizaron y evaluaron los resultados obtenidos.

M2. Para alcanzar el O2 se propuso el desarrollo de una campaña de medición consistente en la evaluación de la calidad ambiental interior de los espacios de enseñanza-aprendizaje y el impacto de los protocolos COVID-19 en la percepción y satisfacción de los ocupantes de estos espacios. Para ello, se realizó una evaluación objetiva (campaña de monitorización) y subjetiva (cuestionario) de forma simultánea en el Campus de Fuentenueva de la Universidad de Granada (Granada, España) y en el Campus Azurem de la Universidad de Minho (Guimarães, Portugal). Los resultados obtenidos se utilizaron para analizar las condiciones ambientales interiores y compararlas entre ambos campus.

M3. Para alcanzar la primera fase del O3 se realizaron ensayos para el análisis y caracterización del impacto de las estrategias de ventilación natural en la calidad del ambiente acústico interior. Para este fin, tres escenarios con diferentes configuraciones de apertura de ventanas y puertas fueron seleccionados para comprobar la eficiencia de la ventilación natural. Para caracterizar el ambiente acústico interior se midió el nivel de ruido de fondo en las diferentes configuraciones. Para ello, se siguió una metodología en dos fases: en la primera, se midió el ruido de fondo en el aula con todas las puertas y ventanas cerradas. Posteriormente, en la segunda fase, se midió el ruido de fondo con la configuración de ventilación natural seleccionada en función de los resultados experimentales (es decir, la configuración que proporcionaba el valor de ACH requerido).

M4. Para alcanzar la segunda fase del O3 se desarrolló una campaña de medición de las condiciones térmicas interiores durante la estación fría del curso académico 21/22 en el Campus de Fuentenueva de la Universidad de Granada (Granada, España). Con este propósito se realizó una encuesta basada en un cuestionario simultáneamente con una campaña de monitorización con sensores durante actividades docentes en la universidad.

M5. Para alcanzar el O4 se evaluó la integración de la evaluación de la calidad ambiental interior y el riesgo de contagio de virus de transmisión aérea en edificios de enseñanza superior a través de la metodología BIM. Con tal fin se desarrolló un marco de trabajo basado en cuatro fases principales: (1) obtención de la opinión de los ocupantes sobre la calidad ambiental interior; (2) monitorización de las variables ambientales interiores del edificio; (3) integración de los datos obtenidos en las fases 1 y 2 en el modelo BIM y realización de la evaluación; y (4) visualización de los resultados en la interfaz del software BIM y generación de informes. La aplicación del marco de trabajo propuesto se ilustro mediante su aplicación en un caso de estudio.

La Figure 1-1 muestra un esquema del enfoque metodológico empleado para alcanzar los objetivos definidos y su relación con las publicaciones que conforman esta Memoria de Tesis Doctoral.

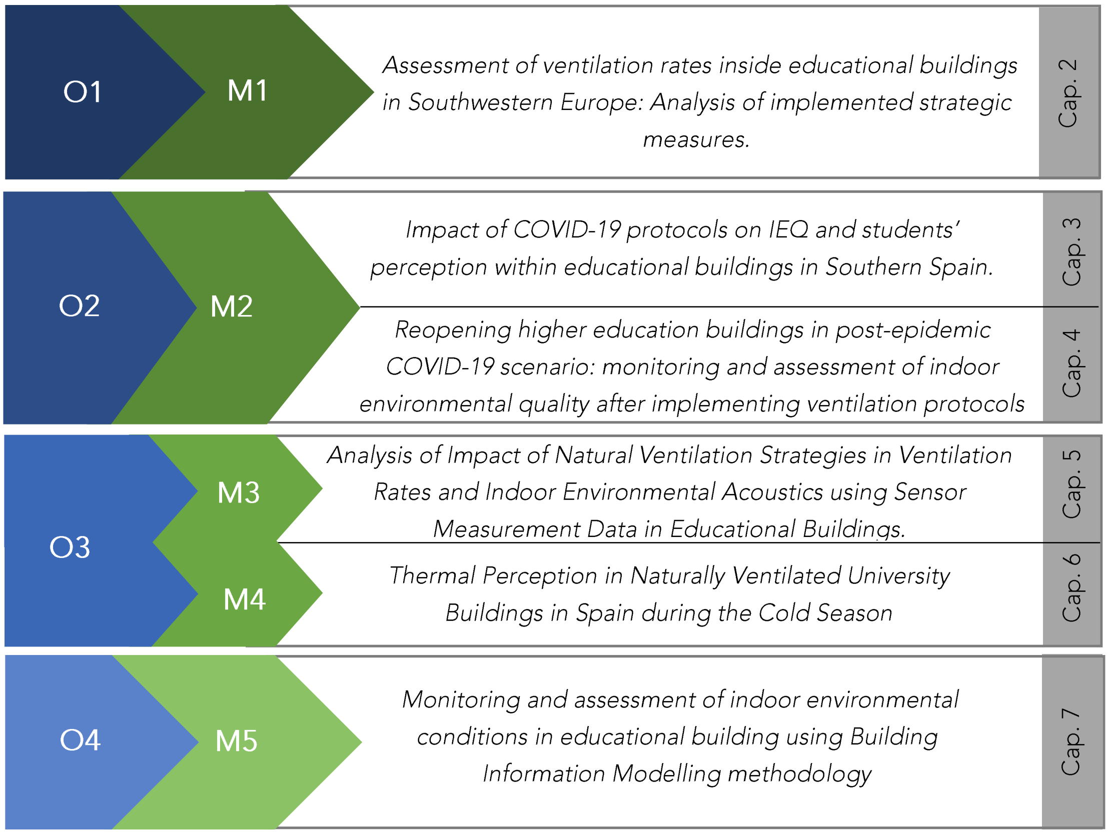


Figure 1-1 Esquema del enfoque metodológico y su relación con las publicaciones.

1.4. Estructura y coherencia entre las publicaciones

En este capítulo se describe la estructura y coherencia de cada una de las publicaciones integradas en la presente memoria de tesis doctoral. Dichas publicaciones están orientadas y planificadas para la consecución del objetivo general definido. Los resultados están todos agrupados en las subsecciones del **Capítulo 4 Resultados** y presentan la forma de artículos científicos publicados. La Figure 1-2 muestra el esquema de la estructura de la investigación.

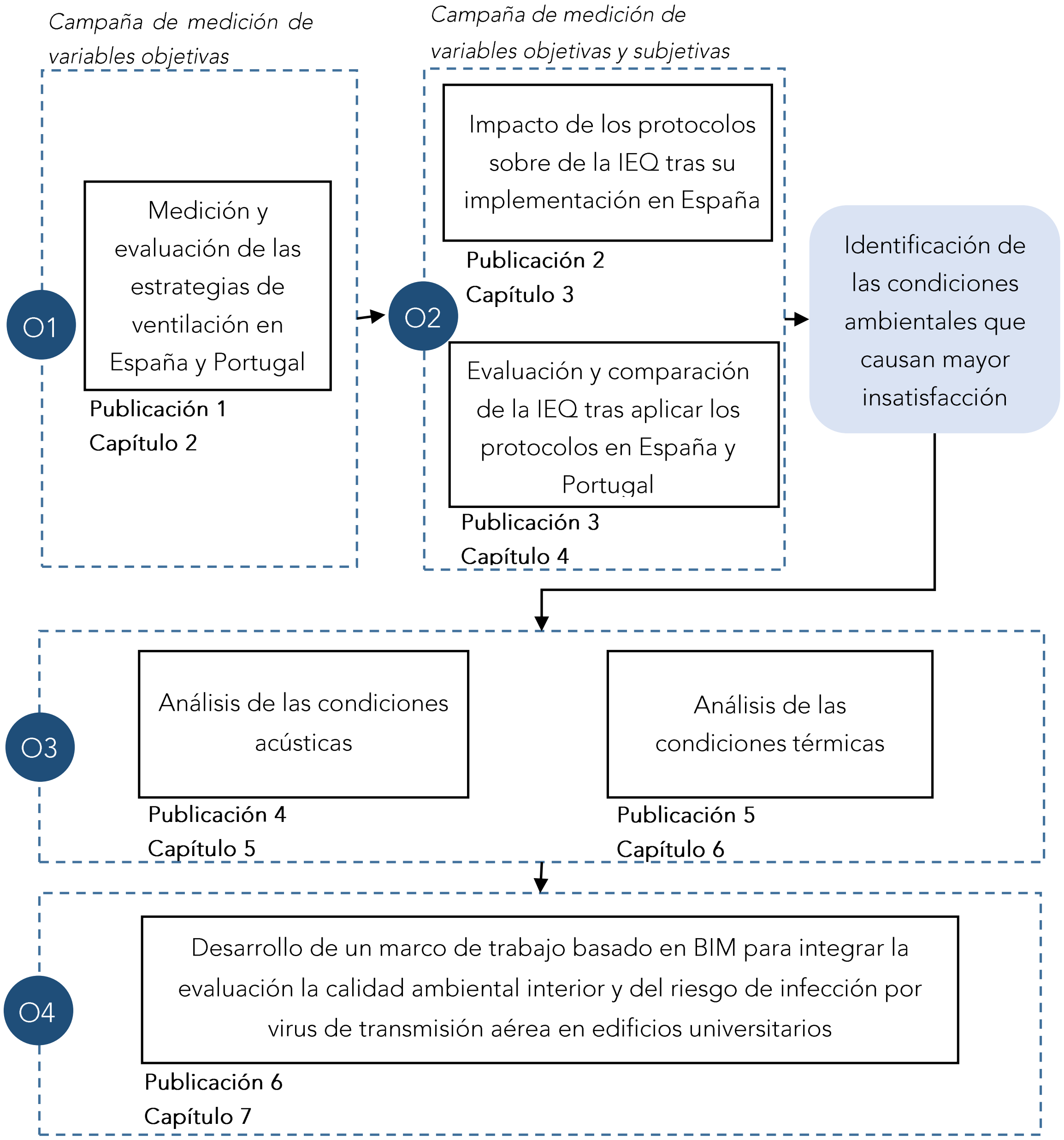


Figure 1-2. Esquema de la estructura de la investigación.

En primer lugar, la publicación *"Assessment of ventilation rates inside educational buildings in Southwestern Europe: Analysis of implemented strategic measures"* presenta una campaña de medición para la caracterización de la estrategias de ventilación natural en edificios educacionales universitarios en el suroeste de Europa (España y Portugal). Esta publicación desarrolla el O1, evalúa diferentes configuraciones de ventilación natural y analiza si se pueden alcanzar los objetivos de tasas de ventilación marcados por las diferentes normativas pre y post-pandémicas. Además se evaluaron dichas estrategias de ventilación en relación a su efectividad para la gestión del riesgo de infección por virus de transmisión aérea según el modelo de Wells-Riley.

La publicación *"Impact of COVID-19 protocols on IEQ and students' perception within educational buildings in Southern Spain"* se centra en una campaña de medición objetiva/subjetiva donde se evalúan las condiciones ambientales interiores y la percepción de los estudiantes sobre las mismas tras la implementación de los protocolos de ventilación analizadas en la publicación anterior. Posteriormente, la publicación *"Reopening higher education buildings in post-epidemic COVID-19 scenario: monitoring and assessment of indoor environmental quality after implementing ventilation protocols in Spain and Portugal"* amplia la campaña de medición al campus Azurém (Portugal) y compara los resultados obtenidos en ambas localizaciones. Estas publicaciones dan respuesta al O2. A partir de los resultados obtenidos se observó que las condiciones ambientales interiores se veían condicionadas por los protocolos de ventilación, siendo el ambiente térmico y acústico los que mostraron un mayor grado de insatisfacción en los estudiantes.

De tal forma, para alcanzar el O3, la publicación *"Analysis of impact of natural ventilation strategies in ventilation rates and indoor environmental acoustics using sensor measurement data in educational buildings"* analiza el impacto de la aplicación de los protocolos de ventilación natural en el ambiente acústico interior y la publicación *"Thermal Perception in Naturally Ventilated University Buildings in Spain during the Cold Season"* presenta el análisis de la percepción térmica de los estudiantes durante la temporada de invierno.

Finalmente, a partir del conocimiento adquirido de las investigaciones previas, la publicación *"Monitoring and assessment of indoor environmental conditions in educational building using Building Information Modelling methodology"* desarrolla un marco de trabajo basado en la metodología BIM para integrar la evaluación de la IEQ y el riesgo de transmisión de virus en el aire en edificios de enseñanza superior.

En su conjunto, la investigación desarrollada a través de las 6 publicaciones plantea una evaluación desde el punto inicial de caracterización y evaluación de la ventilación en edificios de uso educacional, adaptándose a las nuevas situaciones provocadas por la pandemia del COVID19. Posteriormente se analiza la respuesta subjetiva de los usuarios para conocer su percepción sobre la calidad ambiental interior (acústica, térmica y lumínica). Los resultados obtenidos permiten identificar aquellas variables que generan un mayor grado de insatisfacción en los alumnos, sobre las que posteriormente se realiza un análisis más pormenorizado para su evaluación. En base al conocimiento adquirido se propone el desarrollo de un marco de trabajo integrado en BIM, alcanzando así el O4.

RESULTADOS

2. Assessment of ventilation rates inside educational buildings in Southwestern Europe: analysis of implemented strategic measures.

The work in this chapter is based upon the following publication: Aguilar, A. J., de la Hoz-Torres, M. L., Costa, N., Arezes, P., Martínez-Aires, M. D., & Ruiz, D. P. (2022). *Assessment of ventilation rates inside educational buildings in Southwestern Europe: Analysis of implemented strategic measures*. Journal of Building Engineering, 51, 104204. https://doi.org/10.1016/j.jobe.2022.104204

2.1. Introduction

Indoor Environmental Quality (IEQ), and in particular the Indoor Air Quality (IAQ), is a crucial aspect to consider in the design of educational buildings. As these buildings are often designed for high occupancy density for long periods of the day, the quality of the indoor built environment is crucial to providing a healthy, safe and comfortable space [66]. In addition, exposure to indoor air pollutants might exacerbate diseases, such as asthma, or allergies [67] and can lead to a risk of short and long-term health problems, including various respiratory diseases [20, 21], cardiovascular diseases [22], irritated nose and/or eyes, headaches, etc. [23]. Therefore, IAQ is an essential parameter for the well-being of students and teachers, as it can have a direct impact on concentration, productivity and academic achievement [68].

However, previous studies have shown that educational spaces in non-retrofitted buildings in Southern Europe do not have suitable conditions of comfort and IAQ [33]. Moreover, even in those educational buildings that have been retrofitted, the effect of the intervention showed some differences from what was expected at the design stage [33]. In fact, the effects of poor IAQ in these spaces have recently been put in the spotlight due to the global pandemic caused by COVID-19 since they are risk environments for the transmission of airborne viruses such as the Severe Acute Respiratory Syndrome Coronavirus-2 (SARS-CoV-2) [50]. This fact is a critical issue and has resulted in increased concern among building managers about IAQ. Measures to contain the transmission of SARS-CoV-2 constitute a major challenge inside enclosed environments such as classrooms. An asymptomatic, infected teacher or student could spread a virus-containing aerosol inside classrooms if the air is not adequately renewed. Factors that contribute to the increased transmission of SARS-CoV-2 include: high voice volume, intense physical activity, lack of well-fitting masks, large numbers of people in the same space, decreased interpersonal distance, increased exposure time and poor indoor Ventilation Rate (VR) [47].

On the basis of this evidence, governments took a wide range of measures in response to the COVID-19 outbreak, including the closure of educational buildings. As a result, millions of students were affected by it [51]. In the case of Spain and Portugal, a state of emergency was declared on 15/03/2020 and 18/03/2020, respectively. Teaching/learning activities took place off-campus in both countries from that date onwards, for the rest of the academic year. In order to mitigate the impact of this decision, infection risk control strategies were adopted and educational spaces were adapted over the next academic year (2020-2021). In this context, international organizations have published recommendations and guidelines to provide a basis for protecting public health from the adverse effects of air pollutants. The Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) and the American Society of Heating, Ventilating, and Air-Conditioning Engineers (ASHRAE) have published recommended ventilation control measures after recognizing the potential for indoor airborne hazards [69, 70]. More specifically, the REHVA COVID19 Guidance document [70] states that, in rooms and classrooms where no national ventilation regulation exists, an Indoor Climate

Category II (10–15 L/s per person outdoor airflow rates in offices and 8–10 L/s per person in meeting rooms and classrooms) is the typical sizing according to ISO 17772-1:2017 [71] and EN 16798-1:2019 [72]. In this regard, the World Health Organization (WHO) has also recommended measures, which include ensuring effective ventilation by frequently opening windows and doors [73].

In addition, CO_2 concentration was suggested as indicator of an effective ventilation. REHVA also recommends installing CO_2 sensors to warn against under-ventilation in indoor spaces such as classrooms and meeting rooms. Indeed, previous research studies have shown that CO_2 concentration is an indicator of ventilation efficiency [74]. REHVA also suggests using a traffic light indicator based on the level of concentration in the classroom: green light when the level is below 800 ppm (good ventilation), yellow/orange light when the concentration level varies between 800 – 1000 ppm (acceptable ventilation) and red light when the concentration level is above 1000 ppm (unacceptable ventilation). This system looks for providing information to the occupants in order to trigger prompt action to achieve sufficient air renovation.

This monitoring system is especially relevant in spaces with natural or hybrid ventilation systems, where ventilation control requires for action from building occupants (i.e. opening doors and windows). The CO_2 concentration data obtained from monitoring provides key information to both manage building facilities and identify poorly ventilated spaces where the risk of indoor-cross contamination via aerosol is very high [70]. In the case of spaces mechanically ventilated, reducing air recirculation and increasing the VR are suggested by the REHVA Guidance [70]. However, most educational buildings in Europe do not have mechanical ventilation systems [28]. Therefore, since the ventilation system determines the strategies that can be implemented to control or increase the air renewal rate, increasing VR in these spaces can only be achieved through natural ventilation.

As can be seen, the analysis and management of ventilation strategies is crucial to ensuring that spaces are healthy and safe. Air flow measurements [75], CO_2 generated by building occupants [76], injection of a tracer gas [77] and comparison of outdoor indoor gas concentrations [78] are methods used to determine ventilation metrics (i.e. ACH (h^{-1}), VR per person (dm^3/s per occupant) and VR ($m^{-3}h^{-1}$)) [27].

Previous studies have used these methods to assess the probability of the airborne spread of SARS-CoV-2 (COVID-19 virus) [49, 79]. Berry et al. [80] reviewed methods to reduce the probability of the airborne spread of COVID-19 virus in ventilation systems and enclosed spaces. They highlighted that ventilating an enclosed space is an effective way to reduce the concentration of airborne particles carrying COVID-19. Li et al. [81] concluded that there is evidence of an association between the transmission and spread of infectious diseases (i.e. measles, Tuberculosis (TB), chickenpox, anthrax, influenza, smallpox, and SARS) and the ventilation and the control of airflow direction in buildings. In addition, Guo et al. [82] analyzed the operation guidelines from different countries (including ASHRAE, REVHA, SHASE, the Architectural Society of China, and the Chinese Institute of Refrigeration). This review concluded that all guidelines emphasize the importance of ventilation (both natural and mechanical), which can effectively decrease the concentration of virus-containing droplets. However, it is still unclear as to the specific ventilation rate that can eliminate the risk of transmission of airborne particulate matter. Pan et al. [83] concluded that Heating, Ventilation, and Air Conditioning (HVAC) system design should be adaptive, in anticipation of the needs of emerging situations, such as the pandemic. The supply of fresh air, in higher volumes, should be considered in the design. Li and Tang [84] evaluated the VR in spaces of an outpatient building in Shenzhen. The average VR in the 20 waiting rooms was 77.6 m3/h (2 times of the Chinese standard). The study concluded that the design of semiclosed hospital street reduces the infection risk of COVID-19 since it improves the natural ventilation. Park et al. [49] conducted field measurements to analyze natural ventilation strategies by opening windows in a school building in Korea to address the COVID-19 situation. The authors recommended cross-ventilation to minimize the possibility of infection in high-density public buildings compared to unilateral ventilation. Kurnitski et al. [85] proposed a new design method to calculate outdoor air ventilation rates to control respiratory infection risk in indoor spaces. This model was evaluated using different case studies (offices, classrooms, meeting areas and cafeteria). The Category I ventilation rate prescribed in the EN 16798-1 standard satisfied many, but not all, types of spaces examined.

Nevertheless, despite the impact of the compulsory preventing ventilation measures on indoor air quality and occupant health, very little related research has been conducted in Southwestern Europe due to the time that has elapsed since the outbreak of the COVID-19 pandemic. In this context, the aim of this study is to analyze the ventilation strategies in teaching spaces in university buildings located in Portugal and Spain. For this purpose, a representative sample of teaching spaces located in the Azurém Campus (Guimarães, Portugal) and the Fuentenueva Campus (Granada, Spain) were selected for the analysis. The field measurements and subsequently data post-processing followed the following phases: 1) study of the characteristics of the indoor spaces at the Azurem Campus and Fuentenueva Campus; 2) definition and selection of different ventilation strategies in each teaching space; 3) assessment of the VR using the decay method; 4) estimation of the CO_2 concentrations and identification of the probability of airborne virus infection risk as a function of the VR obtained in the field measurements.

2.2. Materials and methods

In order to characterize the ventilation strategies implemented in educational buildings in Portugal and Spain, field measurements were carried out with the aim of analyzing their impact on the IAQ and the safety of the built environment. With this objective in mind, two university campuses (Azurém Campus of the University of Minho and Fuentenueva Campus of the University of Granada) were selected for the study. The experimental campaign was carried out from March to July 2021.

2.2.1. Area description and climatic conditions

The educational buildings are located at the Fuentenueva Campus of the University of Granada (Granada, Spain) and the Azurém Campus of the University of Minho (Guimarães, Portugal). Figure 2-1 shows the location of the two campuses. The climate in Granada is classified as Csa, according to the Köppen-Geiger climate classification. It is characterized by short, very hot and mostly clear summers and long, cold and partly cloudy winters. During the course of the year, the temperature generally varies from 0°C to 34°C and rarely drops below −4°C or rises above 38°C. The climate in Guimarães is classified as Csb, according to the Köppen-Geiger climate classification. It is characterized by short, warm, dry, and mostly clear summers and cold, wet, and partly cloudy winters. During the course of the year, the temperature typically varies from 5°C to 28°C and rarely drops below 0°C or rises above 33°C.

Figure 2-1 Locations of Fuentenueva Campus (Granada, Spain) and Azurém Campus (Guimarães, Portugal).

The classrooms were selected in order to provide a representative sample of typical classrooms on both campuses. Fourteen classrooms were selected between the two sites, eight of them at Azurém and six at Fuentenueva. The classrooms are located in 4 buildings on the Azurém Campus (A1: School of Engineering, A2: School of Architecture, A3: School of Science and A4: Pedagogical Complex) and in 2 buildings on the Fuentenueva Campus (F1: Advanced Technical School for Building Engineering and F2: Advanced Technical School for Civil Engineering). Table 2-1 shows the characteristics of the classrooms. Appendix A shows the layouts of the classrooms tested in this study.

Table 2-1. Buildings and selected classrooms.

Campus	Building	Class	Ventilation System	Windows Orientation	Area (m^2)	Volume (m^3)	Normal occupation (seats)	COVID occupation (seats)
Azurém	A1	A1-1	NV	SE	76	218	48	24
		A1-2	M	SW	85	287	80	40
	A2	A2-1	NV	NW	68	196	53	27
		A2-2	M	NW	127	341	122	60
	A3	A3-1	NV	NE	68	185	41	23
		A3-2	M	SW	50	148	60	30
	A4	A4-1	NV	SE	48	151	30	19
		A4-2	M	SE	132	470	130	65
Fuentenueva	F1	F1-1	NV	N	172	518	156	78
		F1-2	NV	S	174	522	156	78
		F1-3	NV	W	265	796	91	45
	F2	F2-1	NV	S	106	410	76	38
		F2-2	NV	W	164	542	62	32
		F2-3	NV	SW-NE	175	500	61	35

* M – Mechanical ventilation; NV – Natural Ventilation. SE – Southeast; SW – Southwest; NE – Northeast; NW – Northwest; W – West; S – South; N – North.

2.2.2. Description of the tests

In order to quantify the VR, different configuration scenarios were defined and evaluated during the tests. In the case of mechanically ventilated classrooms, standard operation was evaluated. For the other classrooms, different window and door opening configurations were established. Table 2-2 shows a summary of the different configurations tested.

Table 2-2. Description of the different configurations evaluated during the tests.

	Ventilation configurations
C_{MV}	Mechanical Ventilation
C_{AW+2D}	All windows + 2 doors
C_{AW+1D}	All windows + Main door
C_{AW}	All windows
C_{EW+1D}	End windows + Main Door

The method used in the experimental test was the decay method. This method consists of increasing a tracer gas concentration by using a generator source in the unoccupied indoor space until a homogeneous and well-mixed mixture is reached [27, 86, 87]. Subsequently, without the gas source, the rate of decreased concentration of the tracer gas is determined under a ventilation rate strategy. In this study, carbon dioxide (CO_2) was used in the tests.

The decay method uses CO_2 as a tracer gas, and it is based in the Equation (2-1). From this equation, the CO_2 concentration C(t) in an effective mixed zone at time t is given by:

$$\ln[C(t) - C_{out}] = \ln[C(t_1) - C_{out}] - ACH(t - t_1) \qquad (2\text{-}1)$$

where C_{out} is the outdoor CO_2 concentration, $C(t_1)$ is the CO_2 concentration at initial time and ACH is the air change per hour. This equation assumes that the concentration distribution in an effective mixed zone is maintained uniform and the ventilation rate does not fluctuate over time [88].

When the measured data are obtained from the sampling in multiple times during the decay process, the multipoint decay method is used. The least square method is applied to calculate the air change per hour (ACH) [89] to those data measured in field measurements. Equation (2-2) shows the expression used to calculate it.

$$ACH_C = \frac{\left(\sum_{j=1}^{n} t_j\right)\cdot\ln[C(t_j) - C_{out}] - n\cdot\sum_{j=1}^{n} t_j\cdot\ln[C(t_j) - C_{out}]}{n\cdot\sum_{j=1}^{n} t_j^2 - \left(\sum_{j=1}^{n} t_j\right)^2} \qquad (2\text{-}2)$$

where C denotes the ventilation configuration under study, ACH_C is the air change per hour with the ventilation strategy selected, j is the counter of data samples, n is the number of data samples, t_j is the j-th time value, and $C(t_j)$ is the CO_2 concentration at t_j.

Since the multi-point decay method was applied, the UNE-EN ISO 12569:2017 standard [34] establishes the following procedure to calculate the level of confidence for the estimated airflow rate ($\overline{ACH}$). The confidence intervals denoted as F_{ACH} for the estimated ACH can be calculated for a level of confidence of $100(1 - \propto)$ as:

$$F_{ACH} = \overline{ACH} \pm E_{ACH} \cdot t(k-2, 1-\propto) = \overline{ACH} \pm e \qquad (2\text{-}3)$$

where $t(k-2,1-\propto)$ is the value calculated from the Student's t-distribution table; k being the number of samples, $1-\propto$ is the confidence level of ACH (set up as $\propto = 0.05$ and the results are analyzed at a confidence interval of 95%) and E_{ACH} being the predicted standard error for the specific airflow rate ACH (the regression coefficient) which is the standard deviation of the sample mean or the mean variance.

Taking into account the previous equations (2-1 and 2-2), the experimental setup to analyse the decay process of the gas concentration was divided into two phases, on the basis of the continuous monitoring carried out by CO_2 sensors. During the first phase, five sensors were evenly distributed throughout the classroom (Annex A shows the location of the sensors in each classroom). The outdoor CO_2 concentration was then measured before the start of the test. Next, windows and doors were closed, and in those cases where the classroom has mechanical ventilation systems installed, the system was switched off. With this setup, the CO_2 concentration inside the classroom was increased using a source of this tracer gas, in this case dry ice [79]. In order to achieve a homogeneous concentration, two fans were used to mix the generated CO_2 into the air in the room. Once the required CO_2 concentration level was reached (around 2000 ppm), the CO_2 source was removed and the fans were turned off, thus ending the first phase. In the second phase, the ventilation strategy under study was set up (i.e. windows and doors are opened according to Table 2-2). Once the CO_2 level decayed 37% of its peak concentration above the background, the test ended [86, 87]. This process was repeated to analyze all the ventilation strategies identified for each classroom are analysed. It should be remarked that the room must be unoccupied during the experimental test.

HOBO® MX1102 sensors were used to measure CO_2 concentration at know times during the experimental tests. The sensing method of this instrument is based on non-dispersive infrared (NDIR) absorption and a measurement range from 0 to 5000 ppm (accuracy ± 50 ppm ± 5% of readings at 25°C, less than 90% RH non-condensing and 1.013 mbar).

The ACH is a parameter that is regulated in the national ventilation regulations of many countries. Regarding Spanish regulations, the Real Decreto 1027/2007 [90] states that, depending on the use of the building, a minimum indoor air quality (IDA) is established. This parameter is equivalent to the categories defined in the EN 16798-3 standard [91] about ventilation for non-residential buildings (the categories are shown in Table 2-3). In the case of spaces dedicated to teaching and learning uses, a minimum Category 2 is required by the Regulation on Building Heating Installations (RITE) [90]. In the case of Portugal's national regulations, Decree-Law n.° 118/2013 [92] establishes a minimum outdoor air flow rate value of 24 $m^3/(h\cdot$ occupant) for teaching/learning spaces. This required value is between Category 3 and Category 4 of the EN 16798-3 standard.

Table 2-3. IDA categories. (RITE)

Category	Outdoor air flow rates [dm^3/s per occupant]
1 (optimum air quality)	20.0
2 (good quality air)	12.5
3 (medium air quality)	8.0
4 (low quality air)	5.0

2.2.3. Evaluation of the CO_2 concentrations and airborne virus infection risk.

Since the health and safety of indoor spaces can be compromised when rooms are not well ventilated, as the risk of cross-contamination through aerosols is very high, CO_2 concentration is a parameter that can be used to warn against lack of ventilation. In fact, during the COVID-19 pandemic, monitoring of CO_2 concentration levels has been highlighted as an indicator of indoor air quality and ventilation effectiveness. In this study, based on the data obtained from the field measurements, the indoor CO_2 concentration trend is estimated for different occupancy scenarios (100% and COVID protocol). For this purpose, a mass balance equation of the tracer gas (i.e. CO_2) concentration was used. This expression can be expressed as Equation (2-4):

$$V\,\frac{dC_t}{dt} = Q\left(C_{OUT} - C(t)\right) + E(t) \qquad (2\text{-}4)$$

where V is the volume of the indoor space; C_{OUT} is the outdoor CO_2 concentration level; $C(t)$ is the CO_2 concentration in the room at time t; $E\,(t)$ is the CO_2 emission rate of indoor sources at time t and Q is the volumetric airflow rate of outdoor or replacement air. If Q. C_{OUT} and E are assumed constant. The previous equation can be solved as follows:

$$C_t = C_{out} + \frac{E}{Q} + \left(C_0 - C_{out} - \frac{G}{Q}\right) \cdot e^{-\frac{Q}{V} \cdot t} \qquad (2\text{-}5)$$

where C_0 is the CO_2 concentration at t=0. In addition. if the outdoor C_{OUT} is assume equal to the initial CO_2 concentration (C_0) and ACH is expressed as ACH = G/V. Equation (2-5) can be expressed as follow:

$$C_t = C_{out} + \frac{E}{Q}\left(1 - e^{-\frac{Q}{V} \cdot t}\right) \qquad (2\text{-}6)$$

$$C_{in}(t) = C_{out} + \frac{E}{V \cdot ACH}\left(1 - e^{-ACH \cdot t}\right) \quad [ppm] \qquad (2\text{-}7)$$

where $C_{in}(t)$ is the CO_2 concentration at any time point (t), C_{out} is the outdoor CO_2 concentration, E is the overall exhaled CO_2 emission rate in the indoor environment under study (this value depends on the activity level, age and gender), V is the volume of the indoor space and ACH is the air change per hour. Therefore, the indoor CO_2 concentration (for known and steady state outdoor CO_2 concentration and emission rate) depends on the volume and ACH of the indoor space. In this study, since occupants are seated during lectures, the assumed E value was 0.0042 L/s ·occupant [93].

If the classroom ventilation requires action by the occupants (i.e. natural ventilation or hybrid systems), REHVA recommends the use of the CO_2 concentration level as a ventilation indicator during pandemic situations. Specifically, the REHVA guidelines recommend setting a warning signal when 800 ppm is exceeded and an alarm to trigger rapid action to achieve sufficient ventilation when 1000 ppm is exceeded, even in situations where occupancy has been reduced [70]. In addition, with regard to national regulations, the maximum CO_2 concentration limit is 1250 ppm and 900 ppm in the Portuguese and Spanish regulations, respectively (assuming an outdoor CO_2 concentration of 400 ppm in the case of the Spanish regulations).

As can be seen, since the control of virus-containing aerosol concentrations depends on ventilation solutions when the social distance is greater than 1.5 m, the CO_2 concentration can be used to assess the effectiveness of ventilation and, thus, the likelihood of infection. The risk of infection can be calculated for different activities and rooms using a standard Wells-Riley airborne disease transmission model, which can be calibrated for viruses such as SARS-Cov-2 by adjusting the correct source intensity, i.e. quanta emission rates. Equation (2-8) shows the Wells-Riley equation model [94].

$$P = \frac{C_i}{C_S} = 1 - e^{-I\,q\,p\,t\,/\,ACH} \qquad (2\text{-}8)$$

where P is the probability of infection risk, C_i is the number of cases that develop infection, C_S is the number of susceptible people, I is the number of infectors (I=1 has been assumed in this study), q is the quantum generation rate by an infected person (h^{-1}), t is the exposure time (h), ACH is the air change per hour in the room (m^3/h) and p is the pulmonary ventilation rate of susceptible people. In this study, a quanta emission rate equal to $5.0\ quanta/h$ has been assumed and, since students are sitting, p has been assumed to be $p = 0.54\ m^3/h$ [95, 96].

The Wells-Riley method assumes a steady-state infectious particle concentration that varies with the VR and well-mixed room air. In consequence, it supposes a limitation in large rooms where the virus concentration is not necessarily well-mixed in the air. Moreover, the quanta emission rates are currently being researched, are not definitive and the uncertainty of these values is high [70, 97, 98].

2.3. Results and discussion

2.3.1. Ventilation rate assessment

This section shows the results from the field measurement campaign carried out in the selected classrooms at both locations. In this study, occupancy has been considered at a normal scenario (100% occupancy) and COVID protocol scenario (reduced occupancy as a measure taken during the reopening of the centers to minimize the transmission of SARS-CoV-2 in educational centers in 2021). Table 2-4 and Figure 2-2 show the results obtained from the tests performed in the Azurém Campus.

Tabla 2-4 ACH (h^{-1}) results through different ventilation configurations at Azurém Campus.

Building	Room	Ventilation configuration	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	$\overline{\mathbf{ACH}}$	National Limit ACH*		REVHA recommended ACH	
									Normal occup.	COVID occup.	Normal occup.	COVID occup.
A1	A1-1	C_{AW-MD}	**15.76±1.61**	**10.51±0.42**	**7.95±0.35**	**9.56±0.23**	**8.27±0.18**	**10.41±0.77**	5.3	2.6	7.9	4.0
		C_{EW-MD}	**6.64±0.49**	**5.60±0.48**	**6.63±0.26**	**6.45±0.26**	**6.17±0.23**	**6.30±0.36**				
		C_{AW}	3.85±0.09	3.32±0.05	3.08±0.03	2.81±0.08	2.86±0.05	3.18±0.06				
	A1-2	C_{MV}	3.7±0.04	3.54±0.07	3.33±0.09	3.32±0.06	3.45±0.04	3.47±0.06	6.7	3.3	10.0	5.0
A2	A2-1	C_{AW-MD}	**9.62±0.55**	**8.13±0.24**	**7.74±0.41**	**9.03±0.51**	**7.29±0.28**	**8.36±0.42**	6.5	3.3	9.7	5.0
		C_{EW-MD}	**7.18±0.55**	**8.28±0.22**	**8.01±0.38**	**7.08±0.41**	**6.42±0.25**	**7.39±0.38**				
		C_{AW}	3.55±0.11	1.37±0.04	1.64±0.02	1.79±0.06	1.76±0.05	2.02±0.06				
	A2-2	C_{MV}	2.23±0.04	2.41±0.02	2.68±0.04	2.28±0.03	3.26±0.04	2.57±0.03	8.6	4.2	12.9	6.3
A3	A3-1	C_{AW-MD}	4.00±0.19	**5.79±0.27**	**5.96±0.27**	**11.51±0.31**	**6.94±0.27**	**6.84±0.26**	5.3	3.0	8.0	4.5
		C_{EW-MD}	2.42±0.04	2.89±0.05	3.13±0.05	2.92±0.16	3.32±0.10	2.94±0.09				
		C_{AW}	1.65±0.03	1.75±0.03	2.00±0.04	2.79±0.09	2.51±0.07	2.14±0.06				
	A3-2	C_{MV}	1.61±0.03	1.52±0.02	1.80±0.01	1.97±0.02	1.89±0.02	1.76±0.02	9.7	4.9	14.6	7.3
A4	A4-1	C_{AW-MD}	4.89±0.14	**8.53±0.40**	**5.04±0.14**	**5.80±0.14**	**5.51±0.34**	**5.95±0.26**	4.8	3.0	7.2	4.5
		C_{EW-MD}	3.45±0.07	**4.68±0.27**	3.35±0.08	4.42±0.06	**4.86±0.25**	4.15±0.17				
	A4-2	C_{MV}	1.75±0.02	1.82±0.03	1.69±0.02	1.92±0.02	2.04±0.01	1.84±0.02	6.6	3.3	10.0	5.0

* These values have been calculated based on the Portuguese national regulations.

** Bold numbers indicate that the value is higher than the REHVA recommended ACH value assuming the COVID-19 rule-based occupation.

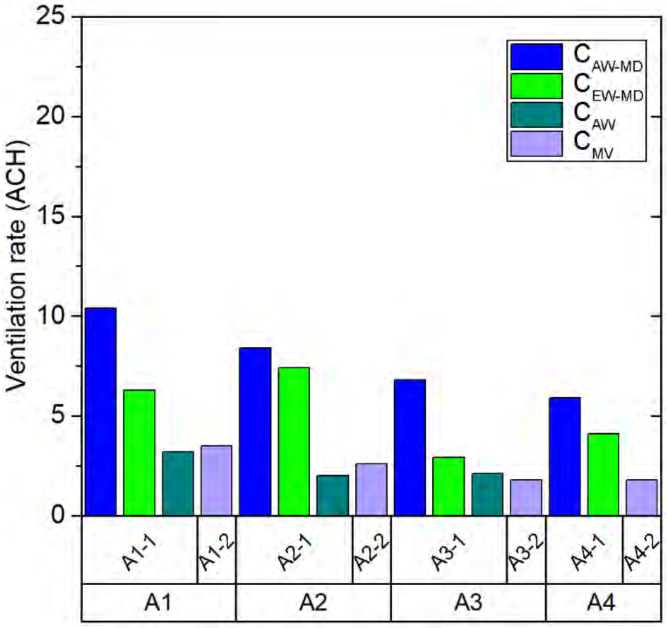


Figure 2-2. VR results obtained from the measurement campaign carried out at Azurém Campus.

In addition, Table 2-5 and Figure 2-3 show the results obtained from the tests performed at Fuentenueva Campus.

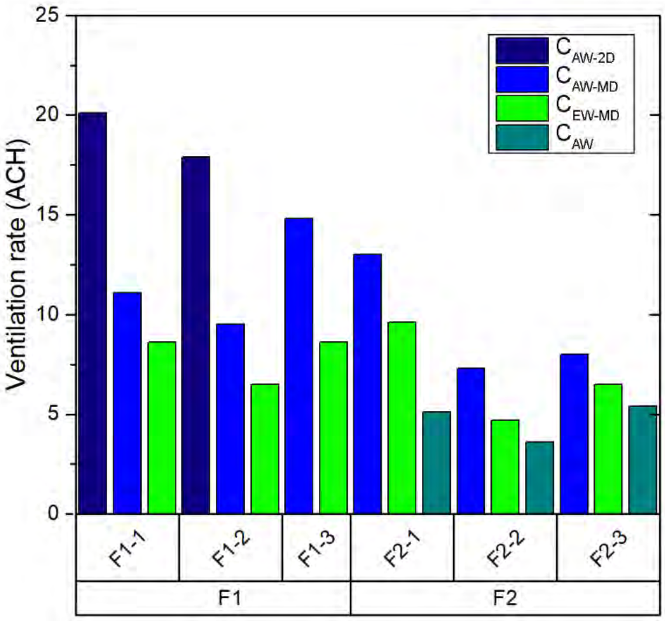


Figure 2-3. VR results obtained from the measurement campaign carried out at Fuentenueva Campus.

Table 2-5. ACH (h^{-1}) results through different ventilation configurations at Fuentenueva Campus.

Building	Room	Ventilation configuration	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	$\overline{ACH}$	National Limit ACH*		REVHA recommended ACH	
									Normal occup.	Covid occup.	Normal occup.	Covid occup.
F1	F1-1	$C_{AW\text{-}2D}$	**27.09±1.13**	**28.17±0.97**	**15.12±0.62**	**12.61±0.48**	**17.44±0.53**	**20.09±0.79**	13.6	6.8	10.8	5.4
		$C_{AW\text{-}MD}$	**10.09±0.43**	**11.69±0.52**	**11.29±0.42**	**11.00±0.45**	**11.48±0.37**	**11.11±0.44**				
		$C_{EW\text{-}MD}$	**7.45±0.15**	**9.60±0.19**	**9.33±0.09**	**8.08±0.14**	**8.14±0.20**	**8.52±0.16**				
	F1-2	$C_{AW\text{-}2D}$	**20.17±0.57**	**19.05±0.47**	**19.84±0.4**	**17.85±0.77**	**12.55±0.48**	**17.89±0.55**	13.4	6.7	10.8	5.4
		$C_{AW\text{-}MD}$	**9.44±0.24**	**10.97±0.49**	**9.17±0.18**	**9.83±0.36**	**8.31±0.22**	**9.54±0.32**				
		$C_{EW\text{-}MD}$	**6.07±0.12**	**7.12±0.09**	**6.83±0.14**	**5.72±0.10**	**6.53±0.18**	**6.45±0.13**				
	F1-3	$C_{AW\text{-}MD}$	**16.03±1.66**	**14.45±0.68**	**16.54±0.78**	**16.96±2.59**	**10.21±0.46**	**14.84±1.47**	5.1	2.5	4.1	2.0
		$C_{EW\text{-}MD}$	**6.66±0.39**	**11.40±0.41**	**7.85±0.56**	**9.09±0.83**	**7.97±0.22**	**8.59±0.52**				
F2	F2-1	$C_{AW\text{-}MD}$	**11.81±0.55**	**10.17±0.37**	**13.03±0.93**	**18.13±1.10**	**11.63±0.71**	**12.95±0.78**	8.3	4.2	4.2	6.7
		$C_{EW\text{-}MD}$	**7.52±0.63**	**12.89±0.67**	**6.49±0.36**	**7.82±0.17**	**13.32±1.09**	**9.61±0.66**				
		C_{AW}	5.94±0.26	5.15±0.11	5.19±0.10	4.36±0.14	4.67±0.07	5.06±0.15				
	F2-2	$C_{AW\text{-}MD}$	**6.70±0.35**	**6.76±0.18**	**6.81±0.48**	**8.82±0.45**	**7.60±0.32**	**7.34±0.37**	5.1	2.7	4.1	2.1
		$C_{EW\text{-}MD}$	**5.03±0.15**	**5.00±0.17**	**5.05±0.12**	**3.81±0.11**	**4.56±0.22**	**4.69±0.16**				
		C_{AW}	**4.17±0.16**	**4.18±0.14**	**3.51±0.16**	**3.32±0.11**	**2.95±0.11**	**3.63±0.14**				
	F2-3	$C_{AW\text{-}MD}$	**8.41±0.19**	**7.99±0.21**	**8.34±0.21**	**7.78±0.17**	**7.28±0.12**	**7.96±0.18**	5.5	3.2	4.4	2.5
		$C_{EW\text{-}MD}$	**6.78±0.28**	**6.06±0.47**	**6.60±0.45**	**6.33±0.08**	**6.53±0.14**	**6.46±0.32**				
		C_{AW}	**5.70±0.22**	**5.52±0.14**	**5.36±0.14**	**5.00±0.10**	**5.20±0.08**	**5.36±0.14**				

* These values have been calculated based on the Spanish national regulations.

** Bold numbers indicate that the value is higher than the REHVA recommended ACH value assuming the COVID-19 rule-based occupation.

It should be noted that those classrooms with mechanical ventilation systems (C_{MV}) either do not have windows, or they are not operable, so these spaces cannot be naturally ventilated. Such classrooms were only found in the Azurém Campus. All the classrooms in the Fuentenueva Campus had no mechanical ventilation system, so they could only be ventilated naturally through doors and windows.

In this sense, the mechanically ventilated spaces of the Azurém Campus were among the lowest ACH values (ranging from 1.8 to 3.5 h^{-1}). Since it is not possible to establish another ventilation strategy for this type of classroom, the only possible action to increase the VR is to modify the mechanical ventilation system. If these results are compared with the ventilation requirements of the Portuguese regulations, none of the mechanically ventilated classrooms meet the minimum ventilation requirement, assuming 100% occupancy. Moreover, if it is taken into account that the REHVA recommendation to prevent the transmission of airborne disease is more restrictive, the REVHA recommended ACH value is not reached in any of the cases.

Regarding the naturally ventilated classrooms, the ventilation strategies have been defined based on the characteristics of the classrooms. In the Azurém Campus, the configuration that provides the highest ACH value is $C_{AW\text{-}MD}$, whereas the one that provides the lowest is C_{AW}. From the results obtained it can be concluded that, assuming 100% occupancy for each of the classrooms, it is possible to implement at least one window and door opening configuration that provides the VR required by the Portuguese ventilation regulations. Nevertheless, in the case of the mechanically ventilated classrooms, in the 100% occupancy scenario none of the ventilation configurations provides a VR that reaches the REHVA recommended value (except for the A1-1 $C_{AW\text{-}MD}$ configuration). However, if the COVID occupancy scenario is considered, the $C_{AW\text{-}MD}$ cross-ventilation configuration provides a VR that reaches the REHVA's recommended ACH.

In the case of the Fuentenueva Campus, only two of the classrooms evaluated have two access doors (F1-1 and F1-2), see Fig. A2-14 and A2-15 in Annex A. In this case, the opening of both doors and all windows ($C_{AW\text{-}2D}$) is the ventilation configuration that provides the highest ACH (17.9 to 20.1 h^{-1}). In contrast, the configuration that provides the lowest ACH is the C_{AW}. As in the results obtained in the tests performed at the Azurém Campus, and assuming the 100% occupancy scenario, there is at least one natural ventilation strategy for each classroom that provides the VR required by the Spanish ventilation regulations. As this VR requirement is more restrictive than the REHVA recommendations, all of the natural ventilation configurations that reach the minimum required by the Spanish regulations, provide a higher VR value than the REHVA recommendations.

In summary, in both locations, the cross-natural ventilation configuration (i.e. $C_{AW\text{-}MD}$ and $C_{AW\text{-}2D}$) provided more effective air renovation than the single-side ventilation configuration (i.e. C_{AW}). Moreover, it should be pointed out that the possible configurations that can be implemented in each classroom depend on its characteristics and, hence, the VR that is possible to achieve with these strategies is conditioned by the classroom design.

2.3.2. CO_2 concentration and infection rates estimation

The CO_2 concentration inside the classrooms was estimated based on the results obtained in the field measurements and the occupancy. Additionally, the probability of COVID infection risk has also been estimated. A 2 hour duration was assumed to calculate the probability, due to the fact that it is the average lecture time in both universities. The results obtained are shown in Table 2-6.

Table 2-6. CO_2 concentration results according to the expected classroom occupancy (normal occupancy and COVID protocol occupancy).

Building	Room	Normal Occup.	COVID Occup.	Ventilation configuration	ACH	CO_2 Steady-State		Probability of infection
						Normal occup.	Covid occup.	
A1	A1-1	48	24	C_{AW-MD}	10.4	745	585	0.36%
				C_{EW-MD}	6.3	960	695	0.56%
				C_{AW}	3.2	1487	967	0.94%
	A1-2	80	40	C_{MV}	3.5	1641	1039	0.67%
A2	A2-1	53	27	C_{AW-MD}	8.4	915	676	0.48%
				C_{EW-MD}	7.4	983	712	0.54%
				C_{AW}	2.0	2516	1513	1.40%
	A2-2	122	60	C_{MV}	2.6	2520	1463	0.69%
A3	A3-1	41	23	C_{AW-MD}	6.8	925	709	0.61%
				C_{EW-MD}	2.9	1612	1104	1.19%
				C_{AW}	2.1	2068	1367	1.45%
	A3-2	60	30	C_{MV}	1.8	3903	2201	1.96%
A4	A4-1	30	19	C_{AW-MD}	5.9	949	762	0.85%
				C_{EW-MD}	4.1	1183	915	1.14%
	A4-2	130	65	C_{MV}	1.8	2765	1577	0.62%
F1	F1-1	156	78	C_{AW-2D}	20.1	644	530	0.08%
				C_{AW-MD}	11.1	829	624	0.14%
				C_{EW-MD}	8.6	949	685	0.18%
	F1-2	156	78	C_{AW-2D}	17.9	670	544	0.09%
				C_{AW-MD}	9.5	895	657	0.16%
				C_{EW-MD}	6.5	1117	769	0.23%
	F1-3	91	45	C_{AW-MD}	14.8	534	475	0.07%
				C_{EW-MD}	8.6	619	518	0.12%
F2	F2-1	76	38	C_{AW-MD}	13	770	559	0.20%
				C_{EW-MD}	9.6	896	610	0.26%
				C_{AW}	5.1	1321	782	0.45%
	F2-2	62	32	C_{AW-MD}	7.3	825	556	0.22%
				C_{EW-MD}	4.7	1052	634	0.31%
				C_{AW}	3.6	1247	701	0.39%
	F2-3	61	35	C_{AW-MD}	8.0	651	553	0.20%
				C_{EW-MD}	6.5	706	585	0.24%
				C_{AW}	5.4	765	619	0.28%

The CO_2 concentration results, assuming normal occupancy (100%), show that the values obtained in more than 50% of the scenarios in Azurém Campus are above 1000 ppm, where the $C_{AW\text{-}MD}$ configuration is the one with the lowest concentrations. In the COVID occupancy scenario, most of the classrooms have CO_2 concentration levels below 1000 ppm, except for classrooms with mechanical ventilation systems and the single-side natural ventilation configuration C_{AW}.

Regarding the results obtained for the Fuentenueva Campus, the estimated levels of CO_2 concentration in the classrooms assuming normal occupancy (100%), show that most of the classrooms exceed the limit of good ventilation recommended by REHVA, with the $C_{AW\text{-}MD}$ and $C_{AW\text{-}2D}$ configurations (configurations with all possible windows and doors open) providing the best results. These results are similar to those obtained at the Azurém campus. In the case of the COVID occupancy scenario, all ventilation configurations show CO_2 concentrations below 800 ppm.

As can be seen, the CO_2 concentration in indoor spaces is related to different factors such as the volume of the space, the VR and the number of CO_2 generation sources (i.e. occupants). Figure 2-4 shows the estimated CO_2 concentrations based on these factors. Given that CO_2 concentration is a parameter that has been recommended for the assessment of the effectiveness of indoor ventilation, this color map can be used to quickly identify how to adapt these factors in order to ensure that the CO_2 concentration limits are not exceeded. From this figure and to accomplish the required limits, the following measures could be adopted: (1) limitation of space occupancy, (2) increase of VR or (3) mixture of both options.

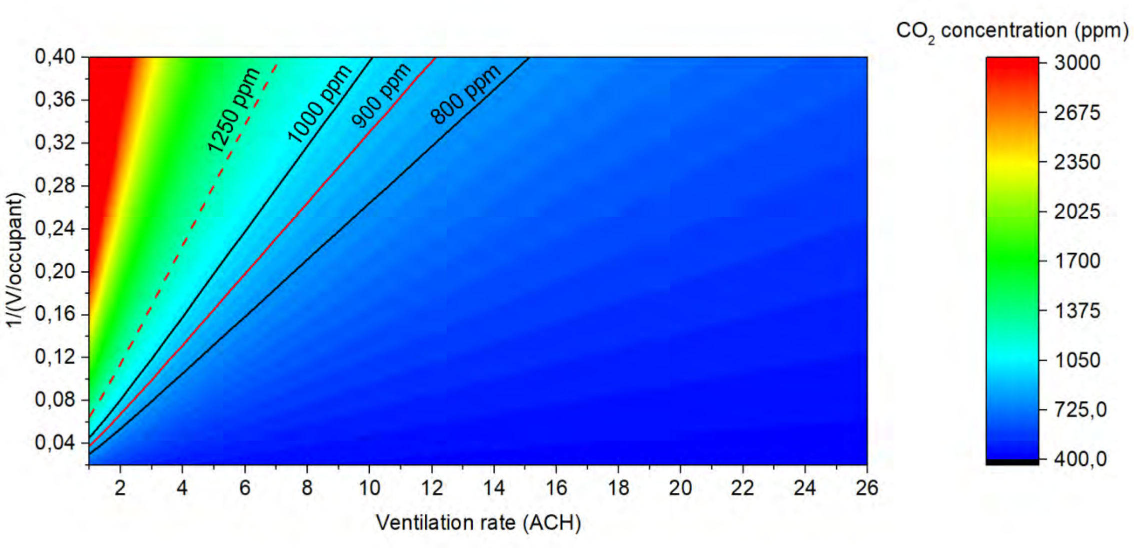


Figure 2-4. . CO_2 concentration (color map) as a function of the VR and the ratio of occupant and volume in indoor spaces. Portuguese limit CO_2 concentration (dashed red line); Spanish limit CO_2 concentration (solid red line) and REHVA recommended CO_2 concentration (both solid black line, 800 and 1000 ppm).

The first option requires limiting the number of occupants in the room to ensure that the CO_2 concentration remains below the limit. This measure has to be implemented in those spaces where the maximum achievable VR is limited (e.g. classrooms with mechanical ventilation systems sized below the required or recommended ACH value, ventilation limitations arising from design characteristics, etc.) For example, as can be seen in Fig. 4, if the objective is to maintain the CO_2 concentration at a level of 1.000 ppm in a classroom whose volume and ACH is 300 m^3 and 4 h^{-1} respectively, the maximum occupant/volume ratio in that scenario is 0.10 occupants·m^{-3}. i.e., 30 occupants. However, many teaching spaces are designed for high volume occupancy with a low VR, so severely limiting the number of occupants can lead to under-utilization.

Regarding the second option, the VR can be increased in those spaces where the CO_2 concentration limit is exceeded while maintaining a 100% occupancy. This measure is easily implemented in mechanically ventilated spaces where the size of the ventilation system can be increased. However, ACH values above 10 are hardly achievable through natural ventilation, which is the system mostly used in the analyzed classrooms. This is similar in other European countries, where most schools (86%) use natural ventilation; 7% of schools use assisted ventilation and 7% of schools use mechanical ventilation [28]. For example, classroom A2-2, (whose volume and occupancy is 341 m^3 and 120 seats, respectively) requires 15 h^{-1} to maintain the CO_2 concentration at a level around 1000 ppm (as shown in Fig. 4). Moreover, in continuously naturally ventilated classrooms with high ACH values, IEQ variables (such as temperature or pollutants) are closely related to the outdoor environment. Therefore, keeping the indoor temperature in a comfortable range will require higher energy consumption in the heating and cooling systems of educational buildings. Consequently, in many cases, adapting spaces to limit the level of CO_2 concentration may require a combination of the aforementioned measures, i.e., both increasing the ventilation strategy to achieve a minimum ACH value while limiting the number of occupants.

With respect to the analysis of the values obtained for the probability of infection using the Wells-Riley equation (Equation 2-8) (Table 2-6), it is possible to conclude that all classrooms have a probability of infection of less than 1%, exception the scenarios of Azurém Campus for classrooms A2-2 (C_{AW}), A3-1 (C_{EW-MD} and C_{AW}), A3-2 (C_{MV}) and A4-1 (C_{EW-MD}). Therefore, it can be seen that, although in the estimation of CO_2 concentration we obtain values above 1000 ppm, it does not necessarily imply a high probability of infection risk. Therefore, although a high level of CO_2 concentration indicates poor ventilation, it does not establish a high risk of airborne transmission in the case of COVID-19. In this regard, the duration of the class, the occupancy and the dimensions of the room should be taken into account when assessing the COVID-19 airborne transmission risk.

The individual infection risk calculated for different classrooms as a function of VR and volume, assuming a class duration of 2 hours, is shown in Figure 2-5. As expected, higher VR ratios provide probabilities of infection of less than 1%. Furthermore, according to the Wells-Riley equation, the higher the volume of the room, the lower the concentration of the virus, resulting in lower individual infection risk. As can be seen in Fig. 5, ACH of 17 h^{-1} is required in a typical 100 m^3 classroom, compared to 8 h^{-1} in a 200 m3 classroom. As shown in Table 2-4 and 2-5, the most common natural ventilation ACH values are between 2 and 9 h^{-1}, for the tested classrooms. To achieve higher values of VR, the required ventilation strategies are configuration solutions of the type $C_{AW\text{-}MD}$ and $C_{AW\text{-}2D}$ (i.e. ventilation strategies with all possible windows and doors open). These types of natural ventilation strategies also present problems due to their impact on the recommended IEQ factors, especially those related to thermal and acoustic comfort [44, 99, 100].

In the case of mechanically-ventilated classrooms, achieving such high levels of VR results in an increase in energy costs, with the possible consequence of non-compliance with energy saving regulations. Consequently, the selection of teaching/learning spaces and ventilation strategies is a crucial process in the management and adaptation of university spaces to such pandemic events.

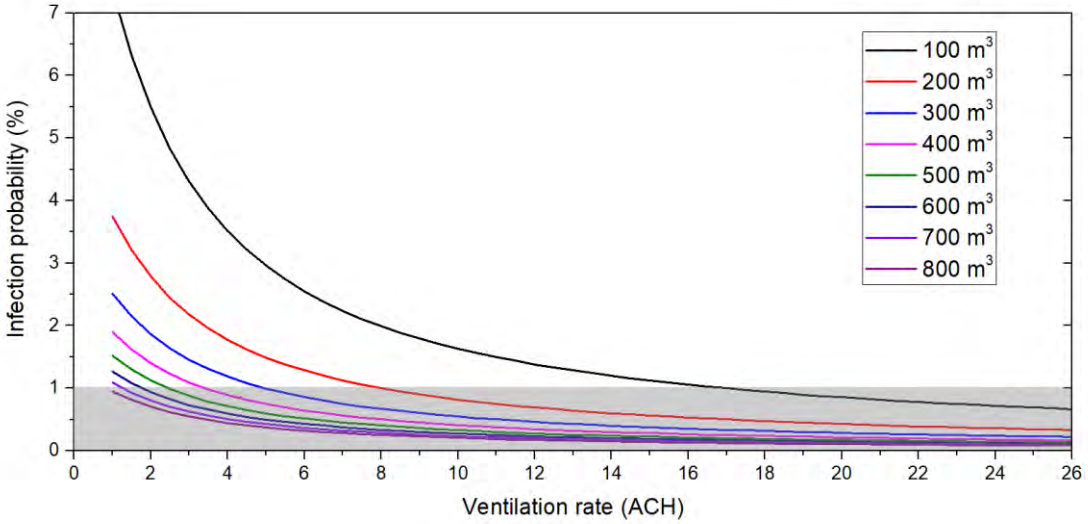


Figura 2-5. Infection probability as a function of ventilation rate and different dimension of classroom, estimated using the Wells-Riley equation.

In summary, while the results of this study show that it is important to analyze and select an appropriate ventilation strategy and configuration inside classrooms, the characteristics of some of these spaces (number of windows, configuration of the mechanical ventilation system, etc.) limits achieving a suitable VR. This fact is decisive in ensuring that the use of educational spaces is safe and healthy in the face of such an alarming situation as the COVID global pandemic.

The retrofitting of public spaces to make them more sustainable through the adoption of strategies, measures and constructive solutions has been a concern at European level, with a particular focus on educational buildings. Directive 2010/31/EU sets targets for reducing energy consumption with the aim of "*promoting the improvement of the energy performance of buildings*". Specifically, the directive states that all new buildings should be Nearly Zero Energy Buildings by 2020 and public buildings by 2018.

In this context, the retrofitting and renovation process of existing educational buildings offers an exceptional opportunity to not only take into account improvements in the energy performance of buildings but also, to ensure retrofitting measures that will guarantee an adequate IAQ after the renovation, at the design phase of the building. However, given that retrofitting interventions require a high level of time and money for the design and execution of works, building managers may be limited in adapting buildings. In these cases, where the required IAQ standards are not achieved, organizational measures and ventilation strategies must be implemented to minimize the IAQ impact on occupants' health, despite the possible under-utilization of spaces.

Finally, if these conclusions are going to be extrapolated to other situations or contexts, it should be taken care of some characteristics of the methodology or the experimental setup presented in this study that may condition further results, coming from the influence of the effect of indoor and outdoor environmental conditions. In fact, the local and particular conditions of each indoor space, as well as the wind speed and outdoor temperatures are critical variables and the validity of the results are conditioned on compliance with the values used in the experimental tests used in this research. Since this study assesses continuous natural ventilation strategies, the indoor environmental condition is highly affected by the outdoor conditions, and in our research, the indoor air temperature was close to the outdoor air temperature, so when there is a significant thermal gradient, the results obtained should be revised.

In addition, risk control of infection through natural ventilation has some constraints as it was stated in reference [49]. The natural airflow rate is generated by two driving forces (wind and temperature difference), and they may change quickly. For example, the normal operation of natural ventilation systems may be affected by unfavorable weather conditions or windows or doors not opened [101-103], possibly changing the direction or velocity of room outdoor winds. For these cases and since the probability of infection risk increases if ACH decreases (Wells-Riley equation model (2-8)), the influence of these parameters is relevant, and, for example, in lower wind condition, ACH will decrease and the risk of infection may increase [101]. Consequently, the effects of these factors should be analysed and considered if different climatic circumstances apply for each experimental situation.

2.4. Conclusion

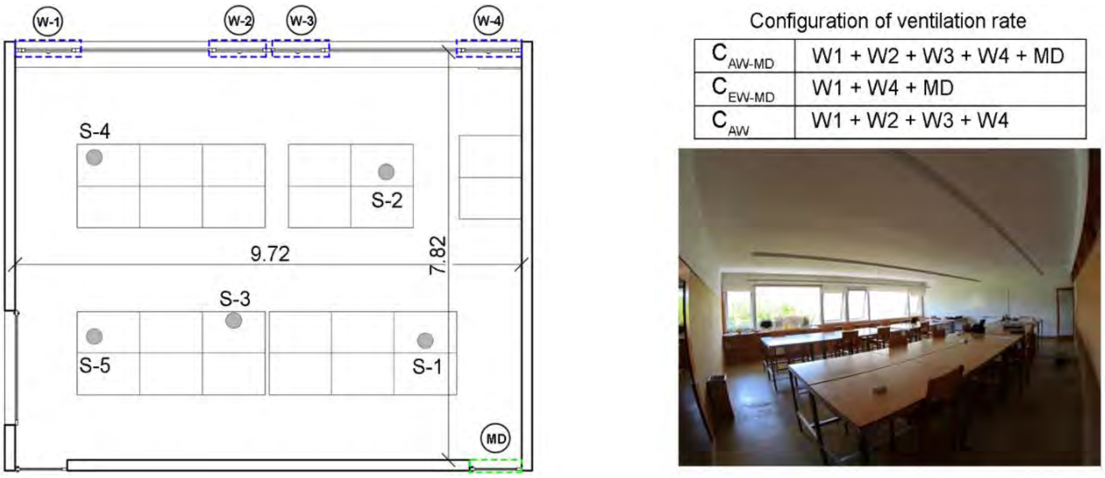
In this study, field measurements were carried out in order to analyze ventilation strategies in educational buildings located in Southern Europe. Two university campuses (the Azurém Campus in Portugal and Fuentenueva Campus in Spain) were selected and ventilation tests were conducted in representative classrooms at both locations. Based on the analysis and discussion of the obtained results, the following conclusions can be drawn:

- Ventilation strategies have to be reconsidered as a consequence the COVID-19 pandemic emergency. The results obtained from measurements of natural ventilation strategies show that the selection of the appropriate combination of door and window openings can provide sufficient air renewal. The VR value obtained ranged from 2.0 to 20.1 h^{-1}, indicating that the selection of the correct combination is not trivial but requires consideration by building managers. In addition, cross-ventilation strategies provide much more effective air renewal (i.e. C_{AW-MD}) than single-sided opening strategies (C_{AW}).

- Regarding mechanical ventilation systems, given that the spaces do not have accessible windows to provide additional natural ventilation, it is not possible to implement hybrid ventilation strategies. The VR value obtained in the mechanically ventilated classrooms ranged from 1.8 to 3.5 h^{-1}. Therefore, retrofitting interventions should consider increasing the VR of mechanical ventilation systems to make the buildings more resilient to future pandemics.
- Indoor CO_2 concentration shows a wide dispersion with the different ventilation configurations, ranging from 534 to 3903 ppm, considering the sizing and occupancy of the original room design. In some cases, these obtained values are higher than those recommended by the WHO for indoor educational spaces. However, with the protocol for the reduction of room occupancy due to COVID-19 during the academic year 2020/2021, the CO_2 concentration is significantly reduced, ranging from 475 to 2201 ppm (a reduction between 11 and 44%).
- Regarding the infection risk, it is only higher than 1% in four of the scenarios studied (A2-2, A3-1, A3-2 and A4-1). The analysis of the results has shown that, although the estimated CO_2 level is above the REHVA recommended level for good ventilation, it does not necessarily imply that the risk of infection is higher.
- The characteristics and equipment in classrooms influence the possible ventilation strategies that can be implemented. For this reason, and given the limitation to achieve adequate indoor air quality, retrofitting interventions in teaching spaces should not only prioritize energy efficiency, but should also ensure the IAQ is safe for the occupants. In the case of buildings where retrofitting is not possible in the short term, ventilation strategies should be analyzed and protocols (e.g. occupancy limitation, ventilation strategies, etc.) should be established to ensure that they are safe for use.

Finally, in light of the consequences of the recent COVID-19 pandemic, the ventilation rate of buildings must be improved, either through adaptations of spaces or the adoption of protocols, to ensure that they are safe for occupants to use. Additionally, it is recommended that an action plan be developed that establishes protocols that not only meet national indoor air quality standards, but also activate previously established protocols, in the event of a new outbreak of an airborne virus. This rapid response will enable the continued safe use of spaces without disrupting the learning of millions of students around the world. Future research should address the development of monitoring devices (e.g. IEQ sensors) where, apart from CO_2 concentration, the assessment of infection risks and indoor ventilation needs to be evaluated.

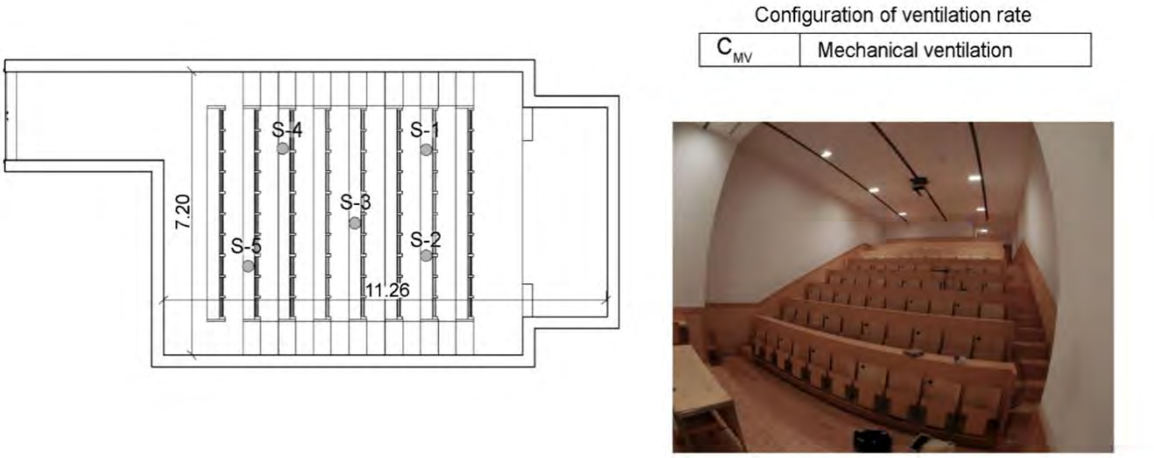
2.5. Appendix A



Configuration of ventilation rate

C_{AW-MD}	W1 + W2 + W3 + W4 + MD
C_{EW-MD}	W1 + W4 + MD
C_{AW}	W1 + W2 + W3 + W4

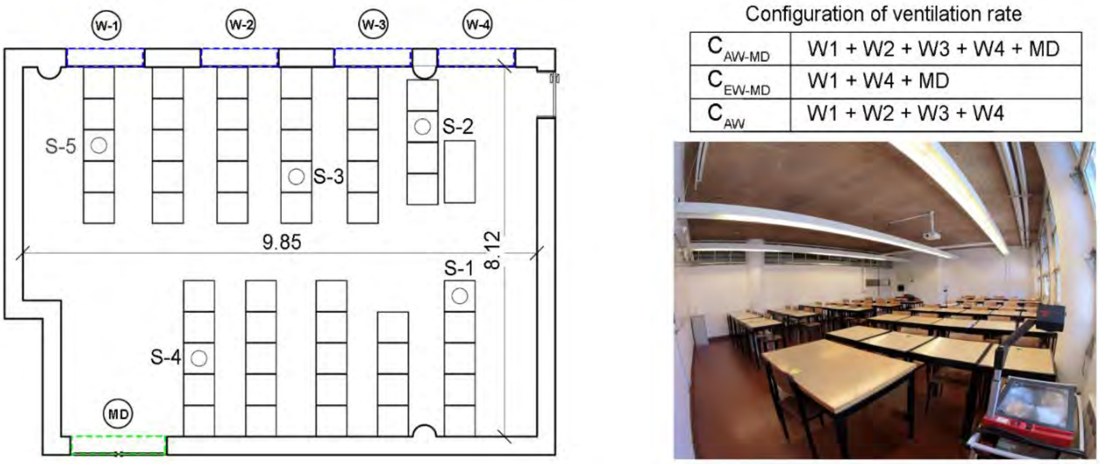
Figure A2-6. Dimension and configuration of classroom A1-1 (Dimensions in meters).



Configuration of ventilation rate

C_{MV}	Mechanical ventilation

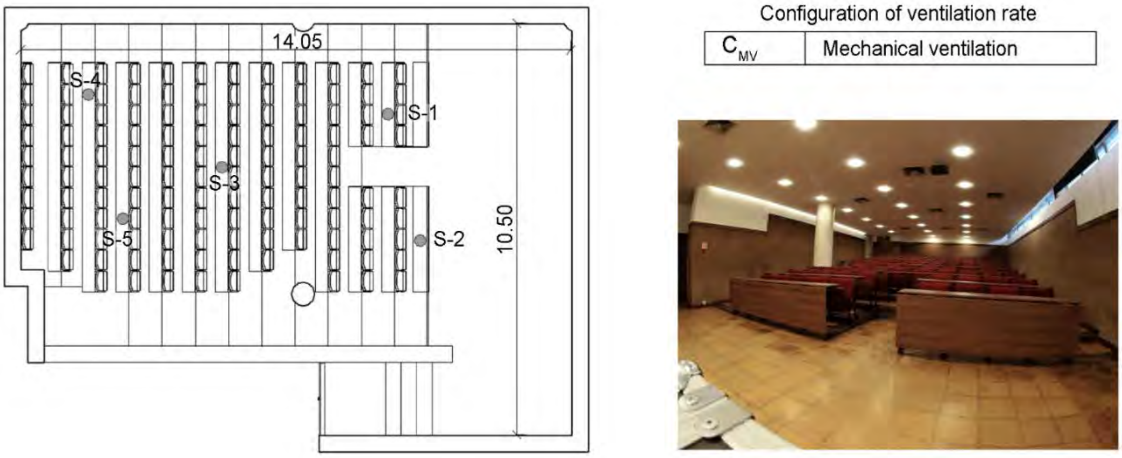
Figure A2-7 Dimension and configuration of classroom A1-2 (Dimensions in meters).



Configuration of ventilation rate

C_{AW-MD}	W1 + W2 + W3 + W4 + MD
C_{EW-MD}	W1 + W4 + MD
C_{AW}	W1 + W2 + W3 + W4

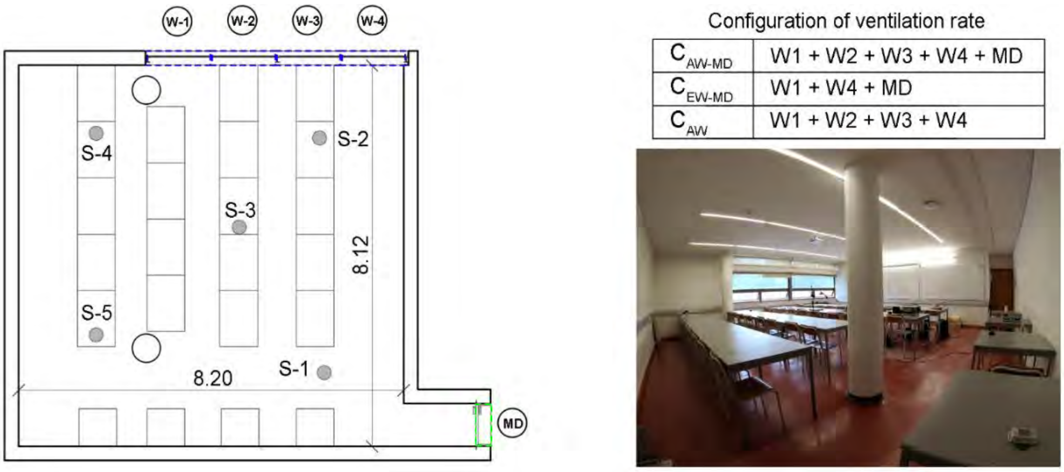
Figure A2-8. Dimension and configuration of classroom A2-1 (Dimensions in meters).



Configuration of ventilation rate

C_{MV}	Mechanical ventilation

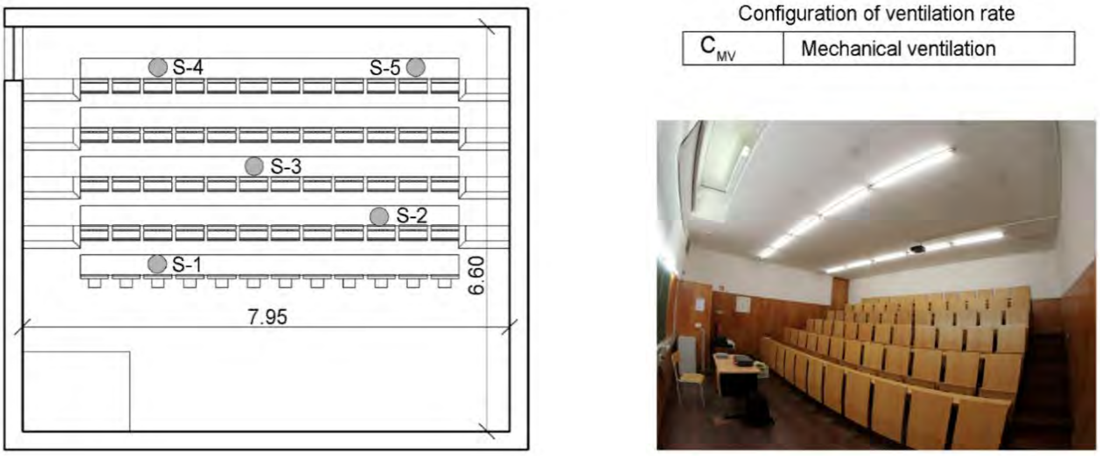
Figure A2-9. Dimension and configuration of classroom A2-2 (Dimensions in meters).



Configuration of ventilation rate

$C_{AW\text{-}MD}$	W1 + W2 + W3 + W4 + MD
$C_{EW\text{-}MD}$	W1 + W4 + MD
C_{AW}	W1 + W2 + W3 + W4

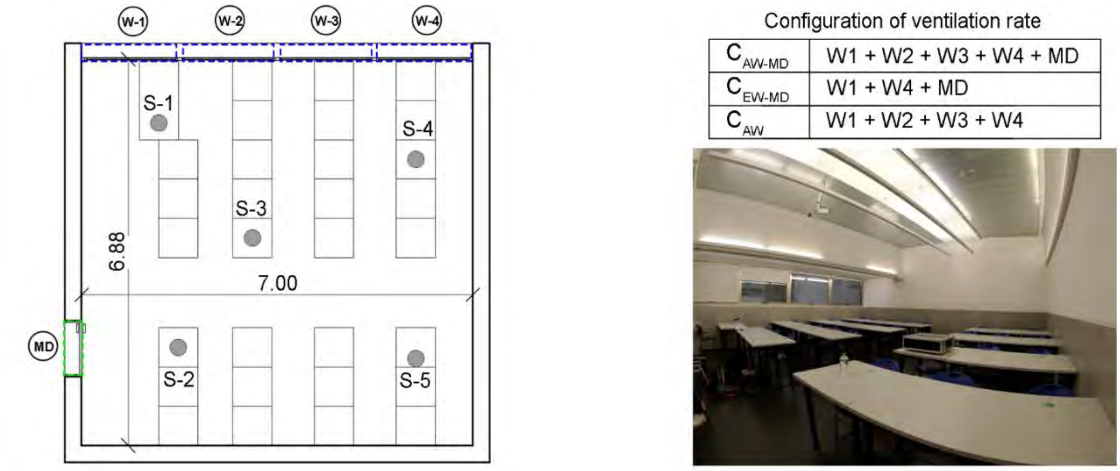
Figure A2-10. Dimension and configuration of classroom A3-1 (Dimensions in meters).



Configuration of ventilation rate

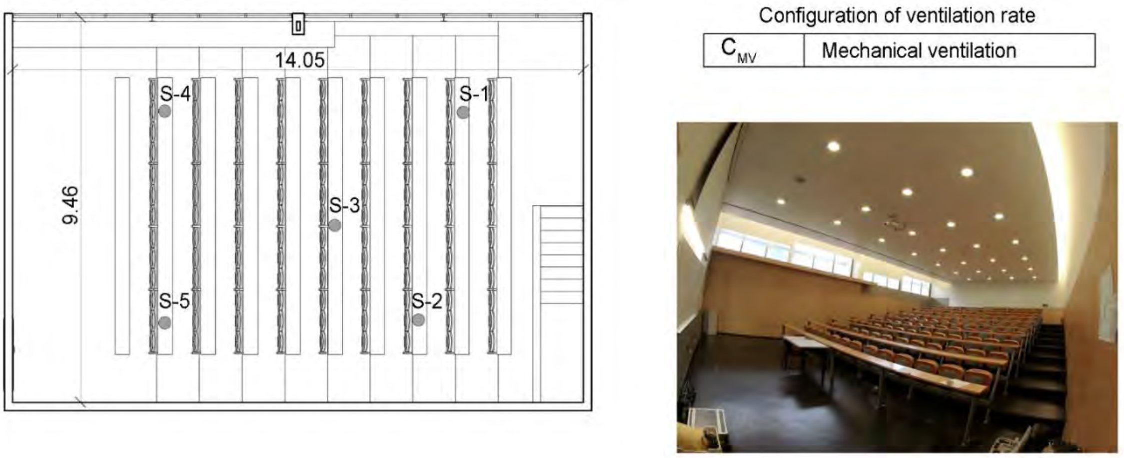
C_{MV}	Mechanical ventilation

Figure A2 11. Dimension and configuration of classroom A3-2 (Dimensions in meters).



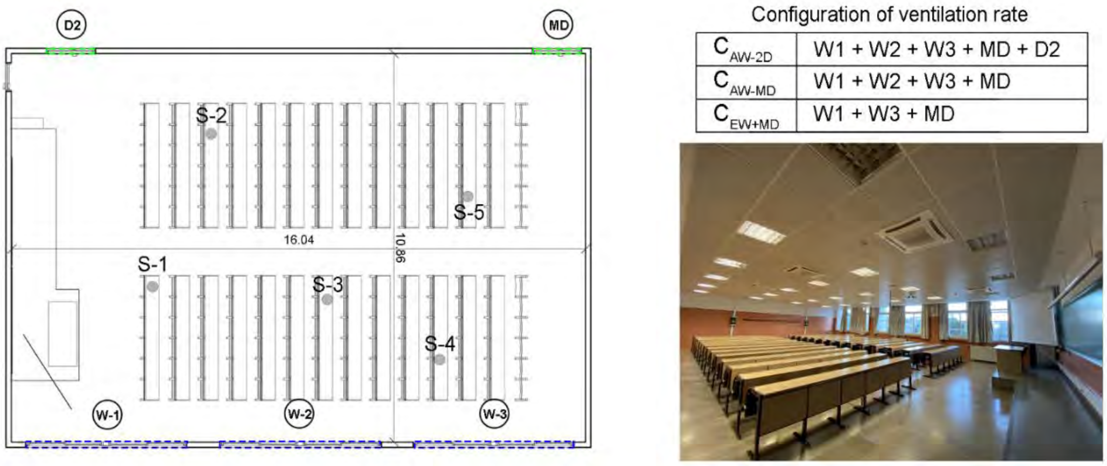
Configuration of ventilation rate	
$C_{AW\text{-}MD}$	W1 + W2 + W3 + W4 + MD
$C_{EW\text{-}MD}$	W1 + W4 + MD
C_{AW}	W1 + W2 + W3 + W4

Figure A2-11. Dimension and configuration of classroom A4-1 (Dimensions in meters).



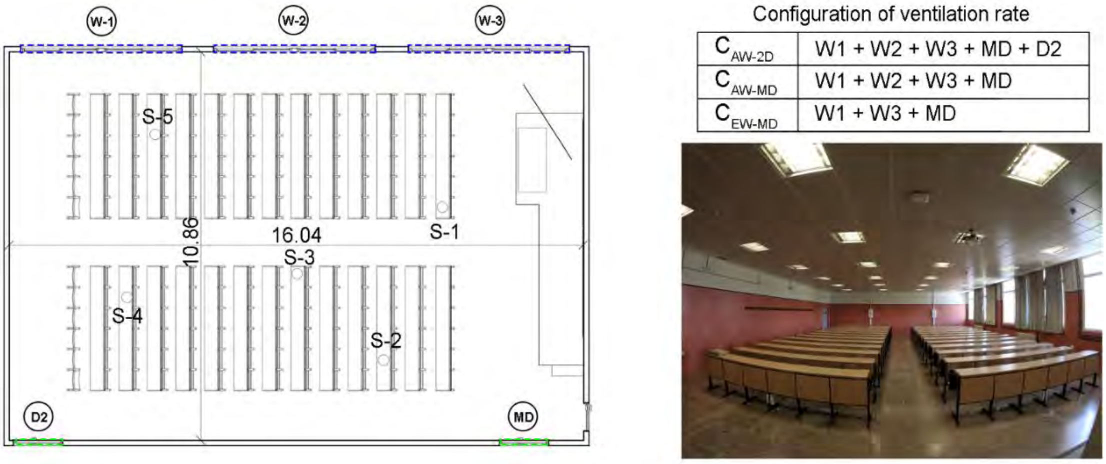
Configuration of ventilation rate	
C_{MV}	Mechanical ventilation

Figure A2-12. Dimension and configuration of classroom A4-2 (Dimensions in meters).



Configuration of ventilation rate	
$C_{AW\text{-}2D}$	W1 + W2 + W3 + MD + D2
$C_{AW\text{-}MD}$	W1 + W2 + W3 + MD
C_{EW+MD}	W1 + W3 + MD

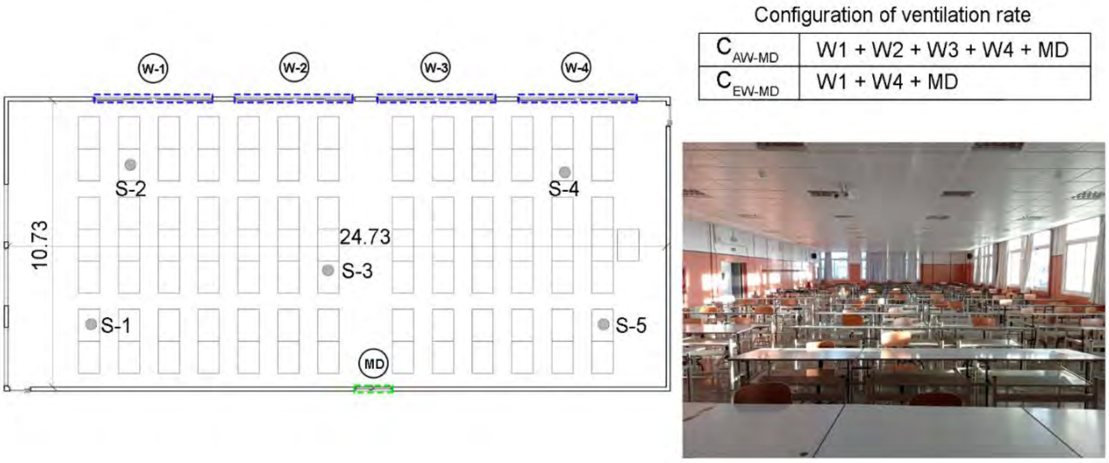
Figure A2-13. Dimension and configuration of classroom F1-1 (Dimensions in meters).



Configuration of ventilation rate

$C_{AW\text{-}2D}$	W1 + W2 + W3 + MD + D2
$C_{AW\text{-}MD}$	W1 + W2 + W3 + MD
$C_{EW\text{-}MD}$	W1 + W3 + MD

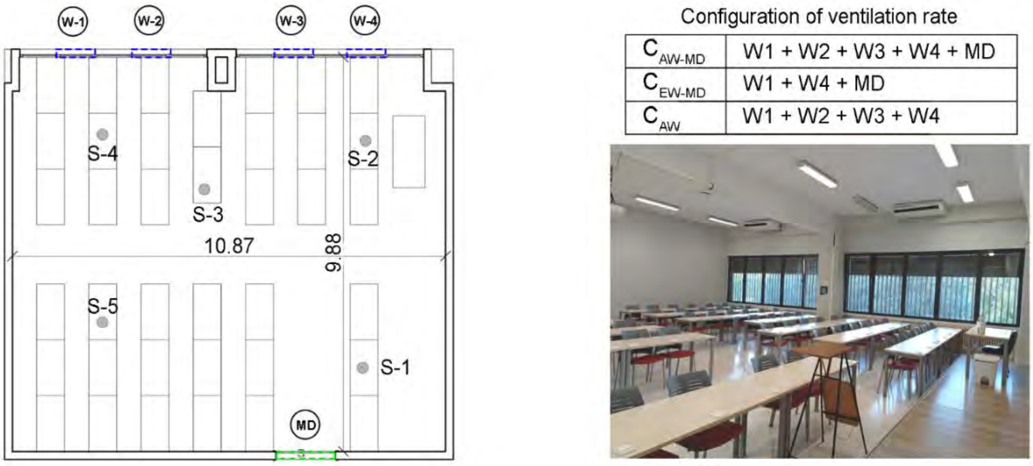
Figure A2-14. Dimension and configuration of classroom F1-2 (Dimensions in meters).



Configuration of ventilation rate

$C_{AW\text{-}MD}$	W1 + W2 + W3 + W4 + MD
$C_{EW\text{-}MD}$	W1 + W4 + MD

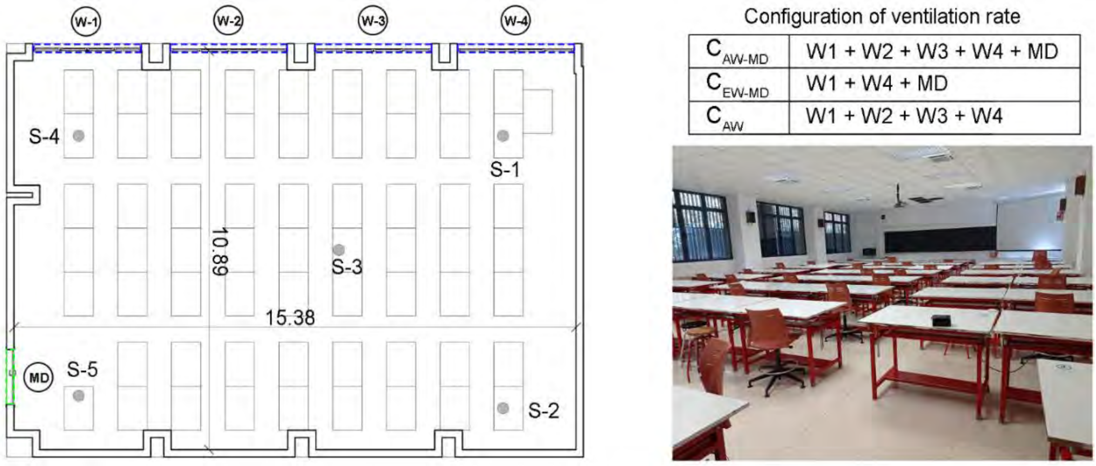
Figure A2-15. Dimension and configuration of classroom F1-3 (Dimensions in meters).



Configuration of ventilation rate

$C_{AW\text{-}MD}$	W1 + W2 + W3 + W4 + MD
$C_{EW\text{-}MD}$	W1 + W4 + MD
C_{AW}	W1 + W2 + W3 + W4

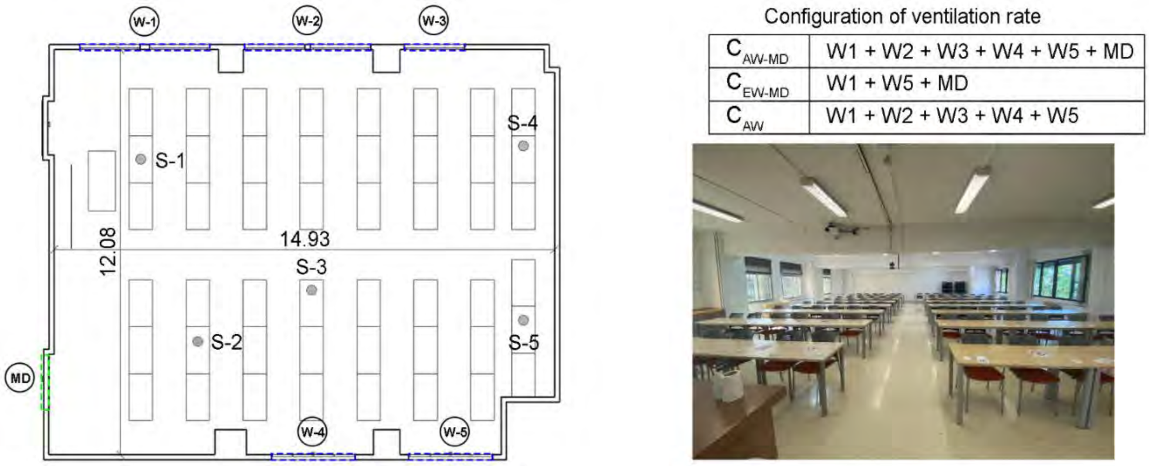
Figure A2-16. Dimension and configuration of classroom F2-1 (Dimensions in meters).



Configuration of ventilation rate

$C_{AW\text{-}MD}$	W1 + W2 + W3 + W4 + MD
$C_{EW\text{-}MD}$	W1 + W4 + MD
C_{AW}	W1 + W2 + W3 + W4

Figure A2-17. Dimension and configuration of classroom F2-2 (Dimensions in meters).



Configuration of ventilation rate

$C_{AW\text{-}MD}$	W1 + W2 + W3 + W4 + W5 + MD
$C_{EW\text{-}MD}$	W1 + W5 + MD
C_{AW}	W1 + W2 + W3 + W4 + W5

Figure A2-18. Dimension and configuration of classroom F2-3 (Dimensions in meters).

3. Impact of COVID-19 protocols on IEQ and students' perception within educational buildings in Southern Spain.

The work in this chapter is based upon the following publication: Aguilar, A. J., de la Hoz-Torres, M. L., Oltra-Nieto, L., Ruiz, D. P., & Martínez-Aires, M. D. (2022). *Impact of COVID-19 protocols on IEQ and students' perception within educational buildings in Southern Spain*. Building Research & Information, 1-16. https://doi.org/10.1080/09613218.2022.2082356

3.1. Introduction

Indoor air quality (IAQ) has received growing attention in recent years due to its short and long-term impacts on occupants' health and well-being [104, 105]. Considering the pollutant concentrations in indoor air [31, 106] and the fact that people tend to spend approximately 90% of their time indoors, the built environment is an important element in its occupants' health and pollutant exposure [107, 108]. Ventilation measures, such as ensuring an adequate ventilation rate (VR), provide an outdoor airflow that removes or dilutes indoor-generated pollutants and improve IAQ. Ventilation standards and guidelines in European countries, and elsewhere, state that building ventilation is mandatory in order to ensure a satisfactory IAQ level and a healthy indoor built environment [5]. However, maintaining an acceptable IAQ is a challenge in highly occupied environments such as educational buildings, where teachers, students and staff spend long periods of time (at least five hours per day) [4, 5].

Nevertheless, despite the fact that good indoor environmental conditions are essential to providing a healthy, safe, productive and comfortable space, previous research studies have documented inadequate indoor environmental quality (IEQ) in educational buildings [33-37]. In view of the serious consequences of poor IEQ on students, in recent years previous research has been conducted with the aim of analysing the impact of natural ventilation on indoor environmental conditions in educational buildings. These research works were performed in pre-pandemic scenario. Thus, Sarbu and Pacurar [38] conducted a study to evaluate thermal comfort by subjective (using questionnaires) and objective (physical variables) measurements in two naturally ventilated classrooms in the Polytechnic University of Timisoara. They found that the average CO_2 concentration was 1450 ppm and 670 ppm in winter and summer respectively. The reason that this CO_2 concentration was lower in the summer season was that the windows were opened more often than they were in winter. Similar results were found in Italian natural ventilated classrooms by Stabile, Dell'Isola, Russi, Massimo and Buonanno [39] and UK ventilated classrooms by Korsavi, Montazami and Mumovic [40, 41].

Previous studies also concluded that indoor air quality was strongly affected by the adaptive behaviors of the occupants. Regarding the driving factors related to the window-opening behavior in natural ventilated classrooms, Stazi, Naspi, Ulpiani and Di Perna [42] concluded that students tend to suffer from poor air quality during heating season due to the students' prioritization of satisfying thermal perceptions. Indeed, Stazi affirmed that indoor and outdoor temperature are the main factors driving window-opening behaviors, while CO_2 concentration is not a stimulus. Similar conclusions were obtained by Duarte et al. [43] and Heracleous and Michael [44] in educational buildings in Portugal and Cyprus, respectively.

However, building occupants' behaviours and natural ventilation strategies have been modified as a results of the COVID-19 pandemic. The IAQ and indoor CO_2 concentration have recently been highlighted since teaching-learning spaces have become high risk environments for the transmission of Severe Acute Respiratory Syndrome Coronavirus-2 (SARS-CoV-2). Since this is an infectious virus that is mainly airborne, students or teachers could potentially be infected by inhaling a virus-containing aerosol generated when an infected individual exhales, speaks, shouts, coughs or sneezes [109]. This fact makes it critical to manage IAQ in classrooms. Moreover, the COVID-19 pandemic has impacted the opinion in buildings engineering regarding healthy buildings [110] and has showed up the importance of ventilation [111].

In these circumstances, the closure of educational buildings was a measure taken by governments all over the world, in order to contain the virus transmission, in response to the COVID-19 outbreak. Despite the fact that learning activities were moved off-campus through the implementation of digital tools, this change posed difficulties of adaptation for teachers and students. This decision has affected more than 1.5 billion students worldwide and has had a severe impact on the learning process [112]. Research conducted by Odriozola-González, Planchuelo-Gómez, Irurtia and Luis-García [113] showed that 50.43% of the respondents at a Spanish University presented a moderate to severe impact of the outbreak. Therefore, Educational Institutions decided to return to face-to-face delivery of some academic activities (e.g. exams and assessments) in order to minimise the impact of the situation on their communities. Consequently, the return to the classroom required the implementation of measures to ensure a safe indoor environment for students and teachers.

In this regard, while the selection of an appropriate ventilation strategy in naturally ventilated classrooms can provide effective ventilation and low levels of CO_2 concentration, it also has an impact on all other indoor environmental variables. Ventilation levels affect indoor air temperature, air quality and acoustic parameters and they also impact, in a more indirect manner, the learning performance and capacity of students [34, 99, 114]. IEQ factors have been associated with student learning and achievements, as well as illness and adverse health symptoms, leading to student absenteeism [25, 67, 115-117].

Recent research conducted during the COVID-19 pandemic scenario has evaluated the impact of natural ventilation protocols in the indoor physical environmental variables of classrooms in regions with similar climate conditions. Thus, in Villanueva et al. [118] was assessed indoor air conditions in 19 schools (pre-school, primary and secondary) and it was found that most classrooms met the increased ventilation conditions through natural ventilation systems, although a total of 5 (26%) classrooms were found to exceed the recommended CO_2 concentration limit value (700 ppm) set by the COVID protocols. In a related research, Gil-Baez, Lizana, Villanueva, Molina-Huelva, Serrano-Jimenez and Chacartegui [111] evaluated environmental conditions in schools with natural ventilation systems during the COVID-19 pandemic. The results showed that natural ventilation systems can ensure adequate indoor air quality without compromising comfort conditions in mild weather conditions. However, these previous research studies have not conducted an evaluation of student satisfaction and sensation based on direct methods (i.e. surveying occupants) during the COVID-19 scenario. Therefore, with the aim of complementing this issue, the problem statement of the present work is to analyse the influence of COVID-19 protocols through the use of direct methods (sensor monitoring and a field survey campaign) in educational buildings to drive conclusions from the impact of these protocols on the indoor environmental conditions.

In addition, it should also be borne in mind that exam period has an important impact on the student body in any academic year. From the analysis of the evolution of the pandemic event, it is observed that new peaks of the crisis caused by COVID-19 may occur during exam periods. In order to prevent the spread of COVID-19 in university spaces, the IEQ of teaching-learning spaces should be assessed during exams after the reopening of educational buildings. However, a very limited research has been conducted during extreme events such as the COVID-19 pandemic, which had analyzed the impact of the application of these extraordinary protocols on the indoor environmental conditions in educational buildings. In this sense, the objective of this study is to evaluate the indoor environmental quality of teaching-learning spaces and the impact of COVID-19 protocols on students' perception and satisfaction during exams after the reopening of educational buildings. For this purpose, an on-site monitoring campaign and a questionnaire survey were conducted simultaneously during two periods of exams on Fuentenueva Campus at the University of Granada.

3.2. Methodology

3.2.1. Study area and building description

The Fuentenueva Campus is located in Granada, Andalusia (37°11′N, 3°36′W). This Campus is sited in the urban part of the city. Granada has a Mediterranean climate with hot and dry summers and cool damp winters. It is also characterised by strong daily and seasonal variations in temperature (AEMET, 2021) . The daily average temperatures and RH is 34°C and 37% in the hottest month (July) and 13°C and 72% in the coldest (January). However, night temperatures can drop to ~1°C in the coldest month.

Ten classrooms were selected in three educational buildings of the Fuentenueva Campus, for this research study. The ventilation system of the buildings is based on natural ventilation. All classrooms have manually operated windows on at least one side (see Figure 1 in the supplementary material online). The classrooms were selected according to the reopening plan of the University of Granada (UGR, 2020) . The characteristics of the classrooms are shown in the Table 1 in the supplementary material online. The heating system was operating during the study and none of the classrooms had air conditioning equipment or mechanical ventilation systems. The guidelines for the return to face-to-face activity were based on maximising occupancy while respecting the 1.5 m distance rule between users. In addition, priority was given to classrooms with natural cross ventilation between doors and windows.

3.2.2. COVID-19 protocols in teaching-learning spaces

As in many countries, a COVID-19 protocol were adopted in the teaching-learning spaces with the aim of maintaining a sufficient fresh air supply to obtain a low virus level concentration and therefore preventing virus transmission. Specifically, the University of Granada approved a plan (UGR, 2020) based on the recommendations of the Ministry of Health of the Spanish Government (2020) and taking into account the current status of these spaces, as was stated in the WHO (2015) report. In this context, the COVID-19 protocols implemented during the examination period included: physical distancing (at least 1.5 m), wearing a face mask, handwashing, maintaining healthy facilities and increasing natural ventilation. In fact, the Ministry of Health of the Spanish Government (2020) recommended that the ventilation rate should be at least 12.5 litres/second per person in teaching-learning spaces. Since an increase of the ventilation rate is required, two strategies can be adopted: natural ventilation (increasing the flow of outside air through windows and doors according to the characteristics of the classroom) or mechanical ventilation (by increasing system capacity). In the case of educational buildings in Southern Spain, as in most European countries, classrooms are naturally ventilated (WHO, 2015) and thus the contingency and action plan for COVID-19 drawn up by the universities considered these circumstances. In this sense, the plan drawn up by the University of Granada (similar to others from European educational organisations) stated the following protocol in classrooms for the academic activities: one hour before the start of classes, all windows and doors were opened. This configuration was maintained during the face-to-face teaching-learning activities. Finally, the windows remained opened for one hour after the end of the activities. In addition, it also stated that one of the measures of ventilation required for the reopening of educational centres was: "even if the weather conditions are adverse, ventilation must be carried out by means of natural ventilation through open windows and doors" (UGR, 2020) .

3.2.3. Data collection

In order to assess the IEQ factors in classrooms during the exams, objective (on site monitoring) and subjective (questionnaire survey) data collection were carried out. A measurement campaign was performed between January and July 2021. The campaign was divided into two monitoring periods: P1 (during the 3rd wave of COVID-19 infections, a period when restrictions on citizens were in place) and P2 (between the 3rd and 4th wave of infections, during a period of relaxation of the measures and reopening of educational centres).

3.2.4. Questionnaire survey

In this study, university students who were performing face-to-face academic activities during both periods were selected. The subjective responses of the participants were collected through a questionnaire. The used questionnaire comprised five parts: 1) General information, 2) Acoustic comfort, 3) Lighting comfort, 4) Thermal comfort, and 5) Overall comfort. These questions and the 7-point Likert scale with 0 as neutral is based on the UNE–CEN/TR 16798-2:2019 scale and the questionnaire was validated by an focus expert group prior to be applied to the respondents.

In 'General information' (1), respondents answered questions about their age, sex and type of mask used during the exam session. In parts 2), 3) and 4), they responded to questions about their satisfaction, sensation and performance interference, in terms of acoustics, lighting and thermal environmental conditions. A 7-point Likert scale was used to evaluate IEQ. The satisfaction ratings ranged from 'very satisfied' (+3) to 'very dissatisfied' (-3). For sensation, the range for acoustic was from 'too quiet' (+3) to 'too noisy' (-3), for light from 'too bright' (+3) to 'too dark' (-3) and for thermal from 'too hot' (+3) to 'too cold' (-3). For interference assessment, the range was from 'enhances a lot' (+3) to 'interferes a lot' (-3). In addition, participants reported possible causes of dissatisfaction and interference for each of the variables analysed. Participants could select one or more causes of dissatisfaction. Finally, part 5) evaluated the overall satisfaction and interference (acoustic, lighting and thermal). The questions contained in the questionnaire are provided in Table 2 in the supplementary material online.

In addition, clothing insulation was annotated by the researchers during the survey time using a checklist from UNE 7730 Standard. Based on these data, clothing insulation was then calculated following Tables C.1 and C.2 in the UNE 7730 Standard.

3.2.5. IEQ monitoring

In addition to the questionnaire survey, IEQ sensor monitoring was carried out during the face-to-face exams. The duration of the measurement was between 1.5 and 2.0 hours, according to the exam duration. For this purpose, temperature (°C), relative humidity (%), air speed (m/s), lighting (lux), CO_2 concentration (ppm) and sound pressure level (dBA) were measured. All variables were measured in 1 minute intervals. Table 3-1 shows the characteristics of the sensors used. The sensors were placed around the classroom close to the students, 0.6 m above the floor and with a separation >1 m from surrounding surfaces.

Tabla 3-1. Sensor characteristics

Sensor	Variable	Range measurement	Accuracy
HOBO® MX1102	Temperature	0 to 50°C	±0.21°C
	RH	1 to 90%	±2%
	CO_2	0 to 5,000 ppm	±50 ppm ±5% of reading
HOBO® MX1104	Light	0 to 167,731 lux	±10% typical for direct sunlight
HD403TS2 Delta OHM®	Air velocity	0.1 to 5 m/s	± 0.2 m/s + 3% f.s.
Imperum-R TECNITAX® Ingeniería	Sound pressure level	35–115 dBA	± 1 dBA

Outdoor climatological physical data were obtained from a meteorological station located at the Cartuja Campus of University of Granada. The data were provided by the State Meteorological Agency of Spain (AEMET) .

3.2.6. Statistical analysis

The statistical analysis focused on analysing the existence of differences between the probability distributions for both periods (P1 and P2), age, sex and different types of masks. The normality of the data was checked by goodness-of-fit tests (P-P probability plots and the Kolmogorov-Smirnov test). Regarding normal distributions, the parametric paired t-test was used. For the rest, the non-parametric Mann-Whitney U test was used. Levene's test for equality of variances was used to check the homoscedasticity requirement during the performance of the paired t-test. In addition, a study of the correlations between the different variables was carried out. Parametric Pearson correlations was used in the analysis. SPSS software (v. 23.0) was used in the statistical analysis.

3.3. Results

3.3.1. On-site IEQ monitoring

Table 3-2 shows the objective values obtained from the sensors during IEQ measurements in the periods P1 and P2. As can be seen, the mean outdoor temperature in P1 was 12.2°C (± 4.6°C), while the indoor temperature was 18.4°C (± 2.1°C). In contrast, the mean outdoor and indoor temperature was 26.3°C (± 6.1°C) and 27.4°C (± 2.0°C) respectively in P2. Regarding RH, in P1 it was 46.3% (± 9.8%) and in P2 it was 34.5% (± 7.5%).

The values defined by Spanish state regulations (RITE, 2007) in the winter season are 21-23°C and RH between 40-50%, and in the summer season 23-25°C and RH between 45-60%. From the analysis of these values, it can be concluded that indoor temperature was outside the comfort range defined in state regulations in P1, while the RH was within the defined ranges in the same period. The same case can be observed in P2 for both mean indoor temperature and RH. Similar results have been shown in previous studies carried out in educational buildings in a Mediterranean climate during the COVID-19 pandemic. Gil-Baez et al. [111], found indoor temperatures ranging from 18.61° to 24.41°C inside classrooms, while HR values ranged from 32.42% to 67.90%.

For air velocity, the mean value obtained was 0.11 m/s (± 0.08 m/s) in P1 and 0.08 m/s (± 0.04 m/s) in P2. The air velocity is moderate given the natural ventilation strategies implemented in the classrooms. Regarding CO_2 concentration, the average levels obtained were low (517 ppm and 440 ppm in P1 and P2, respectively). These levels are derived from the protocol established for COVID-19 spread control (the limitation of occupancy inside the classrooms and 1.50 m social distance, combined with natural cross ventilation between doors and windows). The values are far below the recommendations established in international guidelines, such as those indicated by the WHO (2000) and RITE (2007) (i.e. 1000 ppm and 900 ppm, respectively) .

The mean lighting values in the P1 and P2 periods were 351 lux and 527 lux, the latter being higher due to the higher number of sunshine hours. Finally, with respect to the indoor acoustic environment, the continuous sound pressure level (L_{Aeq}) during the exams in P1 and P2 was 57.0 dBA and 54.5 dBA, respectively. In this sense, there were unusually high values for the academic activities being carried out (exams). This was evident, since keeping the windows and doors open causes an increase in background noise levels derived from traffic (in an urban area of Granada), as well as the rest of the activities occurring around the University.

Table 3-2. Main values obtained for the IEQ measurements during the 2 periods

	Indoor Temperature (°C)		Outdoor Temperature (°C)		HR (%)		Air velocity (m/s)		CO_2 (ppm)		Lighting (lux)		L_{Aeq} (dBA)	
Period	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2
Max	21.6	29.3	21.8	33.7	62.6	48.3	0.28	0.16	668	576	506	815	62.6	64.3
Min	15.6	22.0	7.5	16.7	27.9	24.5	0.03	0.01	401	397	310	221	51.6	49.8
Average	18.4	27.4	12.2	26.3	46.3	34.5	0.11	0.08	517	440	351	527	57.0	54.5
Median	18.1	27.8	10.7	25.0	47.9	35.3	0.08	0.08	510	428	356	558	56.5	53.7
SD	2.1	2.0	4.6	6.1	9.8	7.5	0.08	0.04	83	46	134	185	2.9	4.1

3.3.2. Questionnaire survey responses

3.3.2.1. General information

A total of 491 questionnaires were obtained during the measurement campaign, of which 57 (12%) were discarded due to incompleteness, resulting in a total of 434 valid questionnaires (222 corresponding to P1 and 212 corresponding to P2). Table 3-3 shows the general information from the participants. The age range of the majority of the survey respondents was between 18 and 25 years, with a similar distribution in both periods (71% and 87% in P1 and P2, respectively). This age range is usual among undergraduate students. In terms of the distribution of men and women, they are similar in both periods (65-59% and 35-41%, respectively). Since students were siting during face-to-face exams, this is considered a sedentary activity and the metabolic rate is assumed to be 1.2 met. In addition, the median insulation clothing value obtained in P1 and P2 were 0.74 clo and 0.57 clo respectively, with a difference between periods of 0.17 clo. Figure 3-1 shows the clothing insulation values of students during the survey time in periods P1 and P2.

Table 3-3. General information from questionnaire survey participants.

Variable		Responses	
		P1	P2
Age	n/a	5 (2%)	9 (4%)
	18-25	157 (71%)	184 (87%)
	+25	60 (27%)	19 (9%)
Sex	Male	144 (65%)	125 (59%)
	Female	78 (35%)	87 (41%)
Type of mask	n/a	4 (2%)	0 (0%)
	FFP2	136 (61%)	85 (40%)
	Surgical	61 (27%)	101 (48%)
	Cloth	16 (7%)	20 (9%)
	Other	5 (2%)	6 (3%)

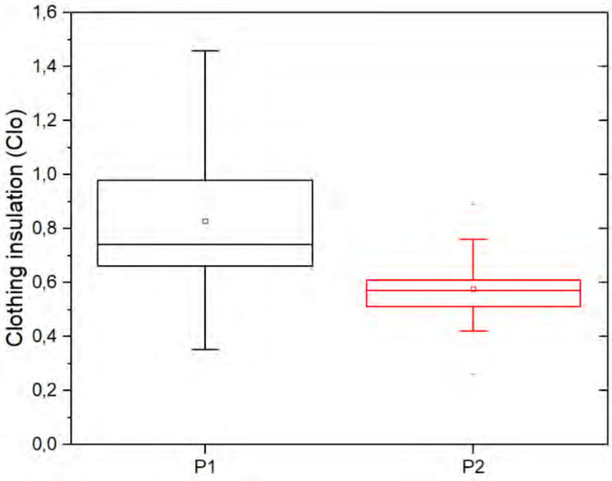


Figure 3-1. Clothing insulation values in P1 and P2.

Regarding the use of masks, there is a clear difference between P1 and P2. During the first period, the use of FFP2 type masks was the most common (61%) compared to surgical (27%). However, during the P2 period, the percentage of users using surgical masks (48%) was higher than that using FFP2 (40%). It should be noted that Granada was facing the 3rd wave of the COVID-19 pandemic during P1, compared to P2, when it was at a plateau prior to the escalation of the 4th wave.

3.3.2.2. Indoor acoustic environment

Figure 3-2 shows the results obtained during P1 and P2 in relation to the indoor acoustic environment. As can be seen, the results of question acoustic satisfaction show a low percentage of dissatisfaction (the sum of very dissatisfied, dissatisfied and slightly dissatisfied) of 27% in P1 and 12% in P2. This was in contrast to 64% and 80% of satisfied (the sum of slightly satisfied, satisfied and very satisfied) in both periods, respectively.

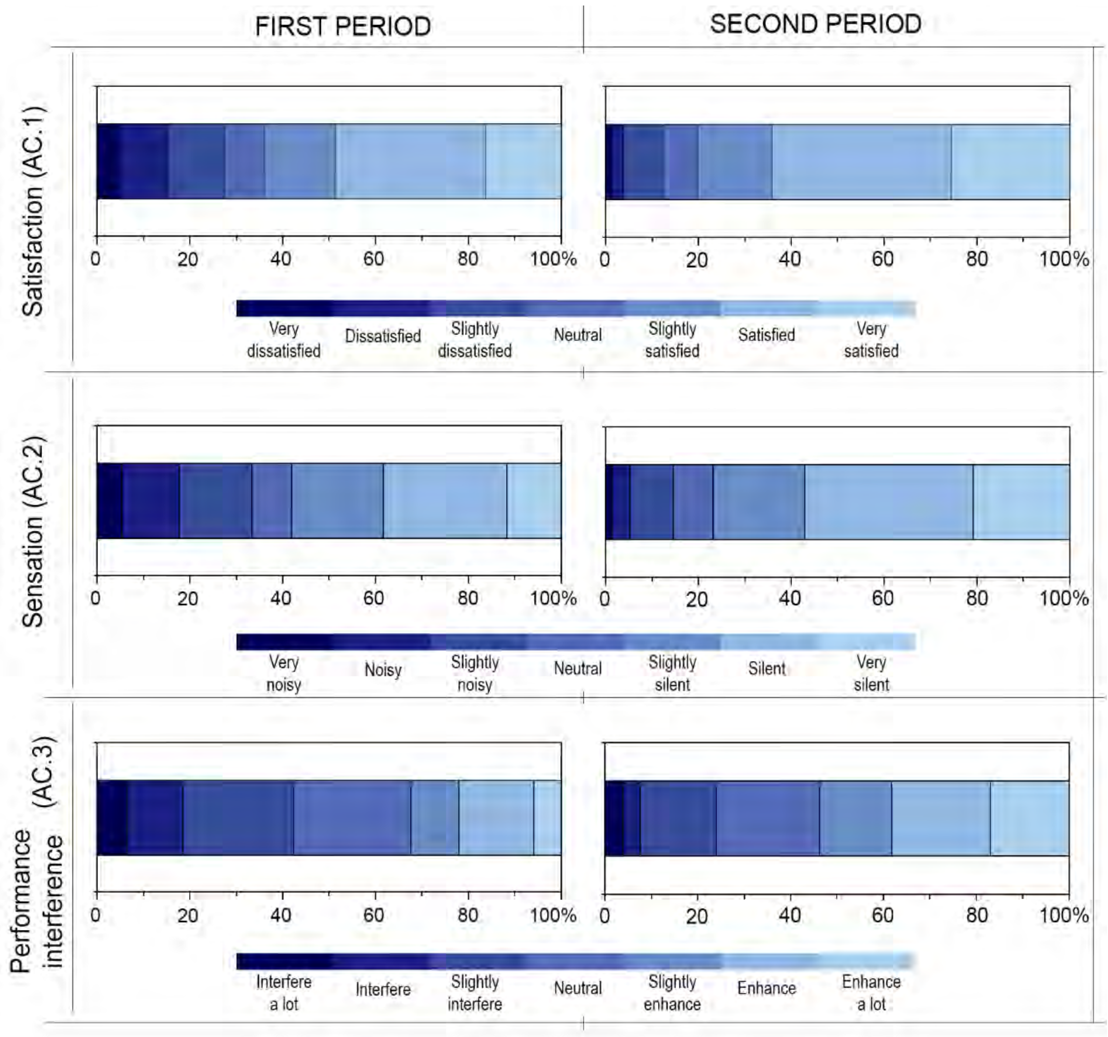


Figure 3-2. Distribution of votes for indoor acoustic environment questions.

Regarding the results obtained in acoustic sensation, only 18% in P1 and 5% in P2 considered the noise level in the classroom to be noisy or very noisy. Consequently, regarding the perception of the interference of the noise factor with student performance, 42% indicated (in question AC.3 about acoustic impact on task performance) that the noise interfered with them (considering the sum of interferes a lot, interferes and interferes a little) in P1, and 24% in P2. Figure 3-3 shows the causes of dissatisfaction with the indoor acoustic environment. It should be noted that, in both P1 and P2, the sum of the three main causes of dissatisfaction (>70%) came from noise sources outside the classroom (i.e. outdoor traffic noise, other outdoor noise and people talking in neighbouring areas).

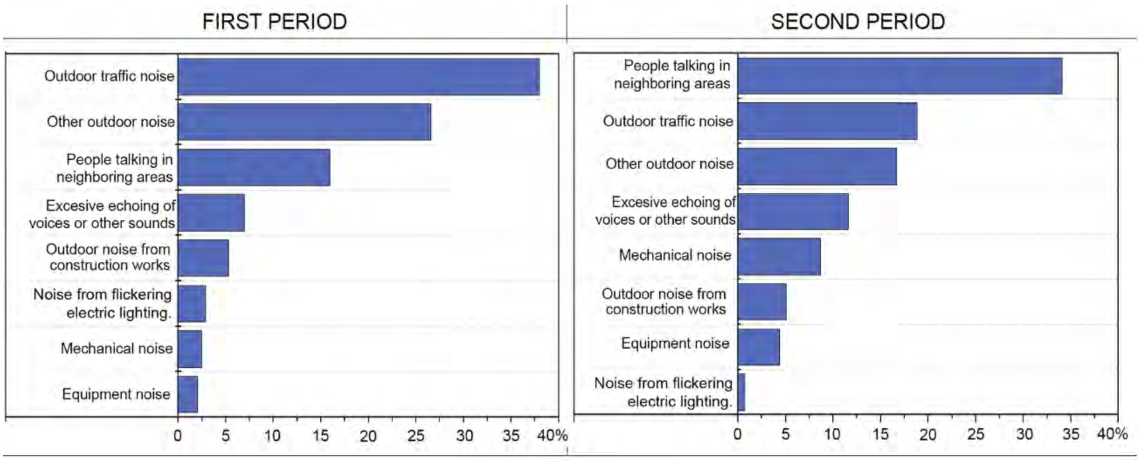


Figure 3-3. Analysis of the dissatisfaction causes regarding the indoor acoustic environment.

3.3.2.3. Indoor lighting environment

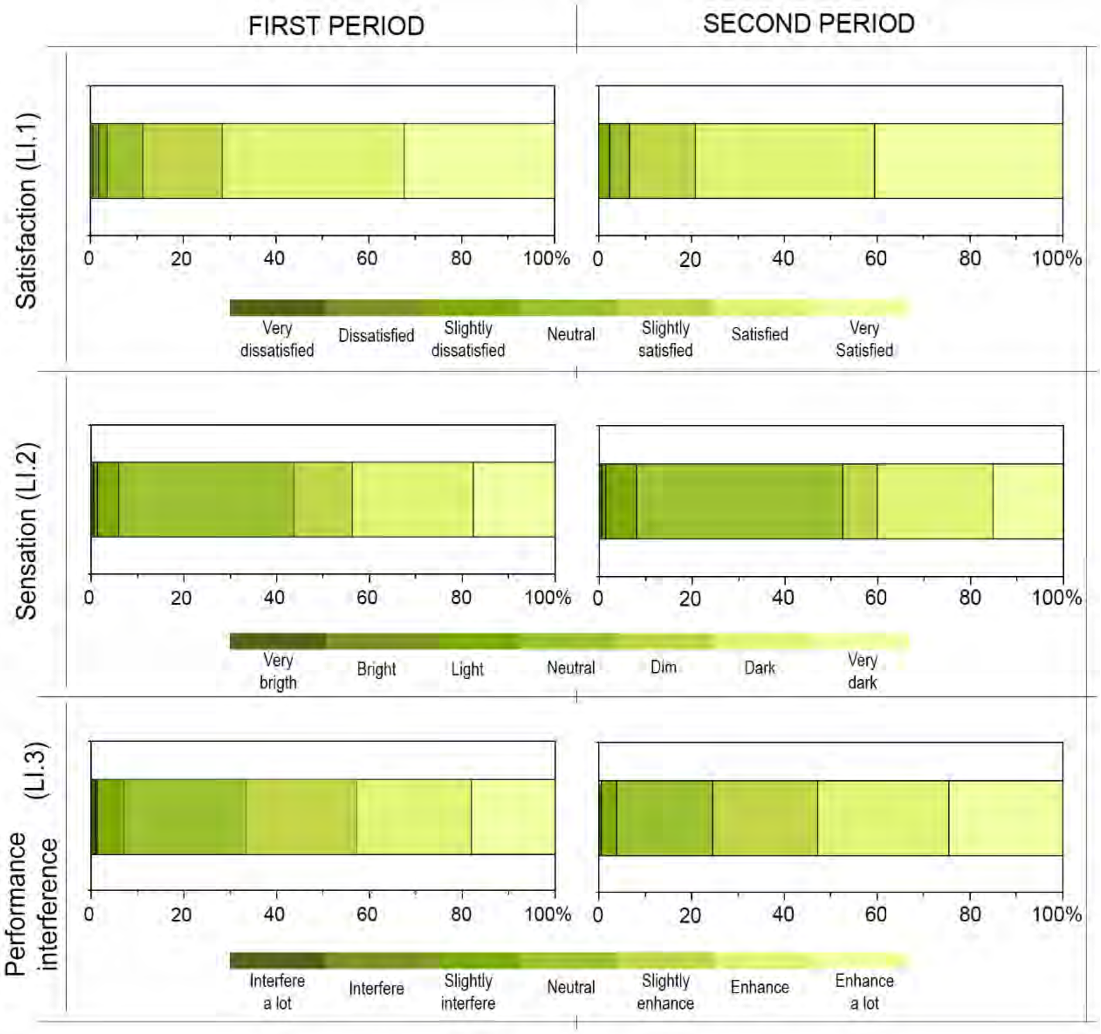


Figure 3-4. Distribution of votes for indoor lighting environment questions.

The obtained results related to indoor lighting environment showed that 89% of respondents were satisfied with the interior lighting in P1, increasing to 93% in P2 (Figure 3-4). In the case of lighting sensation, 18% and 15% of respondents indicated that the environment was too dark in P1 and P2, respectively; with 0% indicating that the lighting environment was too bright in both cases.

In addition, regarding the interference of the lighting environment with the students' performance, 7% indicated that it interfered with the activity in P1, compared to 3% of students that indicated that it interfered in P2. Among the causes of dissatisfaction (Figure 3-5), insufficient daylight is the most frequently indicated in both periods (25% in P1 and 19% in P2); followed by "electric lighting is an undesirable color" (16%) in P1 and "shadows on the workspace" (19%) in P2. It should be pointed out that the protocol implemented as a consequence of COVID-19 had no impact on classroom lighting. The opening of doors and windows and the distribution of students in the classroom during exams did not change the interior lighting of the classroom.

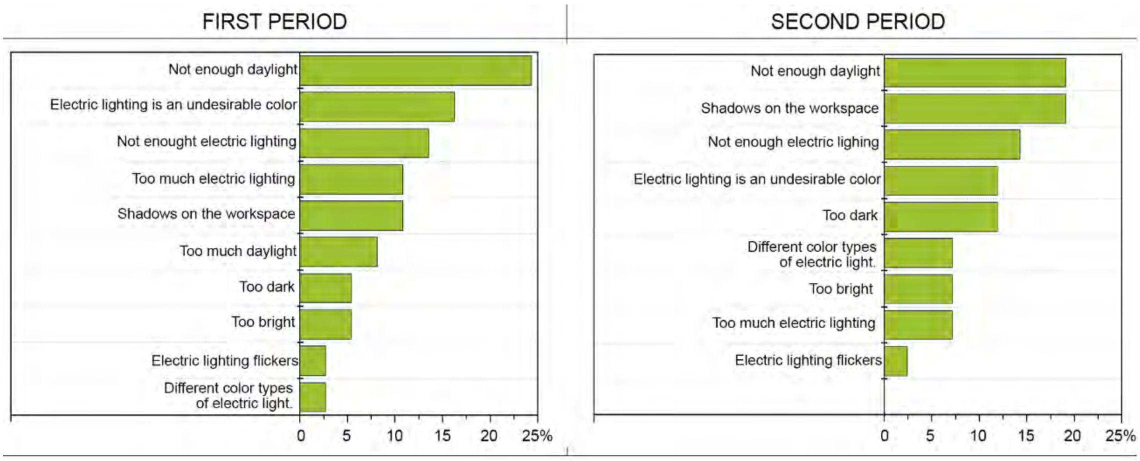


Figure 3-5. Analysis of the dissatisfaction causes regarding the indoor lighting environment.

3.3.2.4. Indoor thermal environment

Figure 3-6 shows the results obtained in the questionnaire survey concerning the thermal environment inside the classrooms. It should be noted that of all the different factors analysed, thermal environment is the only one that provides opposite responses in the two periods. The dissatisfaction rate was 53% and satisfaction rate was 31% in P1, compared to 17% and 66% in P2, respectively.

Regarding thermal sensation in P1, 28% indicated cool-cold and 33% slightly cool. In P2, on the contrary, 24% indicated warm-hot and 27% slightly warm. This is due to the fact that P1 coincided with the winter season and P2 with the spring-summer season. As for the evaluation of interference performance, 53% of the respondents indicated that the indoor thermal environmental condition interfered at least slightly during P1. By contrast, in P2, 49% indicated that the indoor thermal environment improved their ability to perform their work.

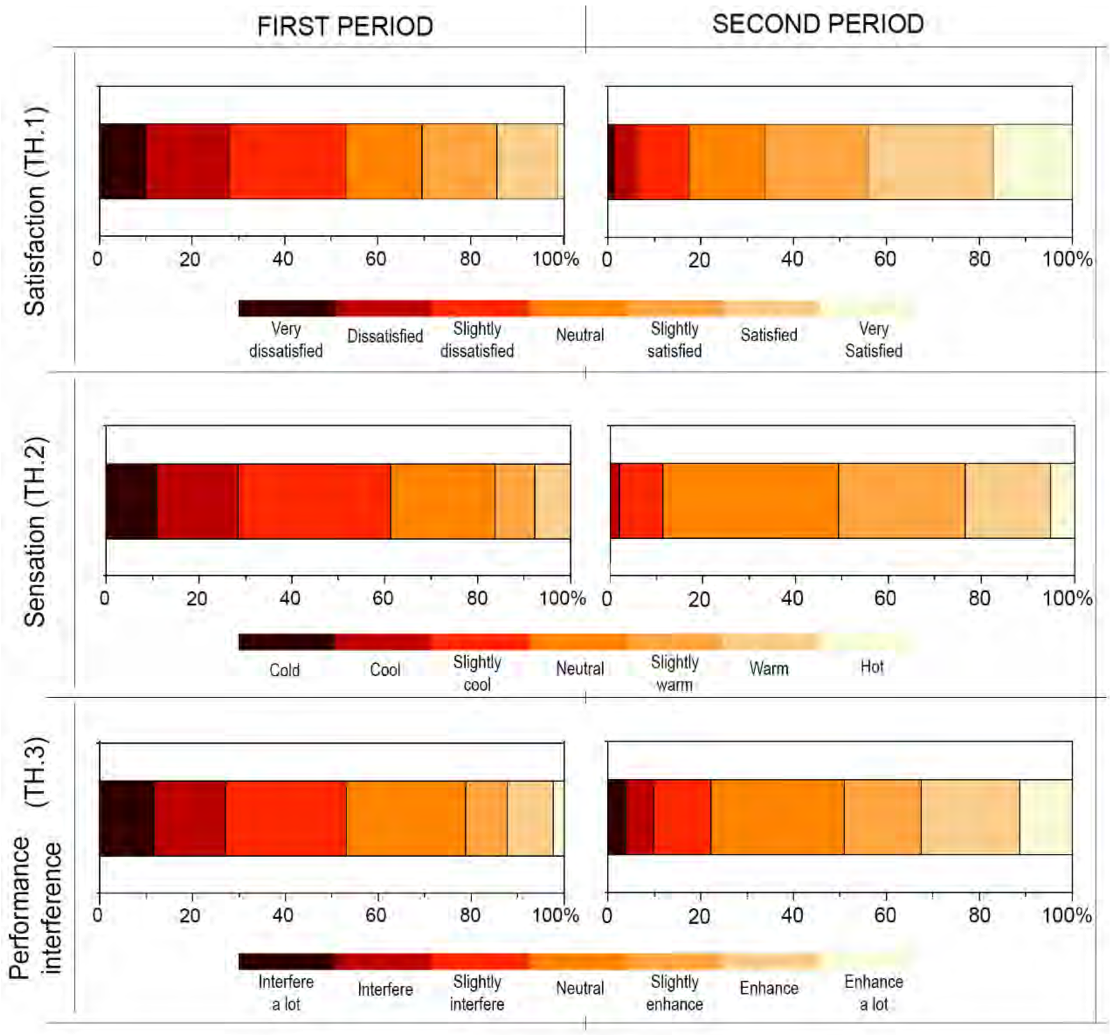


Figure 3-6. Distribution of votes for indoor thermal environment questions.

Figure 3-7 summarises the main causes of dissatisfaction with the indoor thermal environment. It can be seen that, in both periods, drafts are the main cause of dissatisfaction. This cause is especially important in P1, constituting one third of the votes among the causes of dissatisfaction. The second most-voted cause was that the air movement was too high (16%). Both causes are directly related to the COVID-19 contingency plan measures (keeping doors and windows open). The next cause is related to the heating system not responding fast enough (14%). In this sense, the facilities are not designed to meet the demands of this new pandemic situation.

During P2, drafts account for about a quarter of the votes indicated among the causes of thermal discomfort (22%). This cause is followed by 'surfaces around me are warmer/cooler' (14%) and 'the air movement is too low' (14%). In this sense, the social distance (at least 1.5 m) caused the students to be evenly distributed throughout the classroom. Therefore, some students were closer to the windows than the rest. This fact resulted in some students being more exposed to air currents than others were and, therefore, were more exposed to solar radiation.

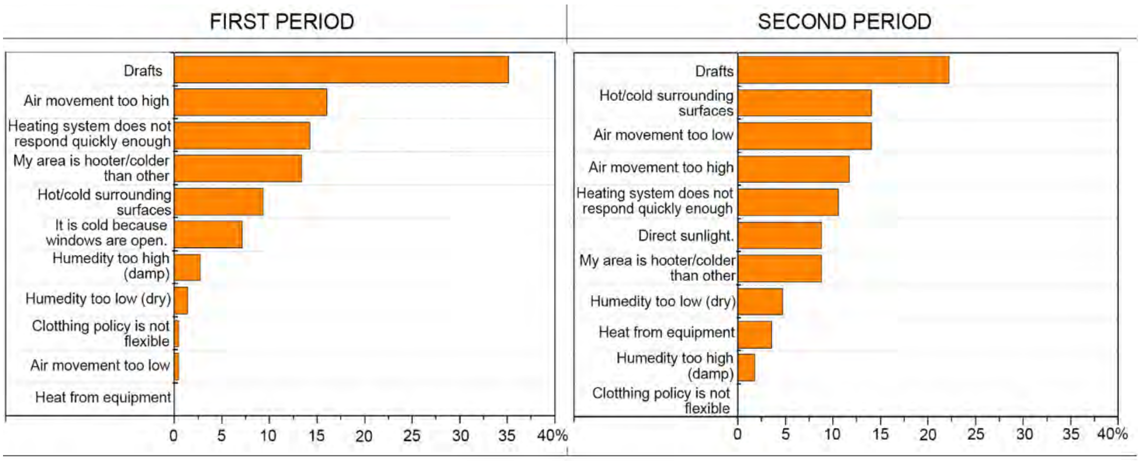


Figure 3-7. Analysis of the dissatisfaction causes regarding the indoor thermal environment.

3.3.2.5. Overall satisfaction

Finally, Figure 3-8 shows the overall satisfaction of students with the indoor environment. The results show that 65% of the respondents were satisfied with the overall IEQ in the classroom in P1 while, during P2, the overall satisfaction rose to 87%. Moreover, only 36% indicated that the IEQs were an improvement during P1, compared to 68% in P2. Furthermore, the results show that during P1 (corresponding to the winter season), the opening of doors and windows to achieve good ventilation was more dissatisfying than P2. In this regard, during P1, 31% of the responses indicated that their productivity was decreased by the indoor environmental conditions.

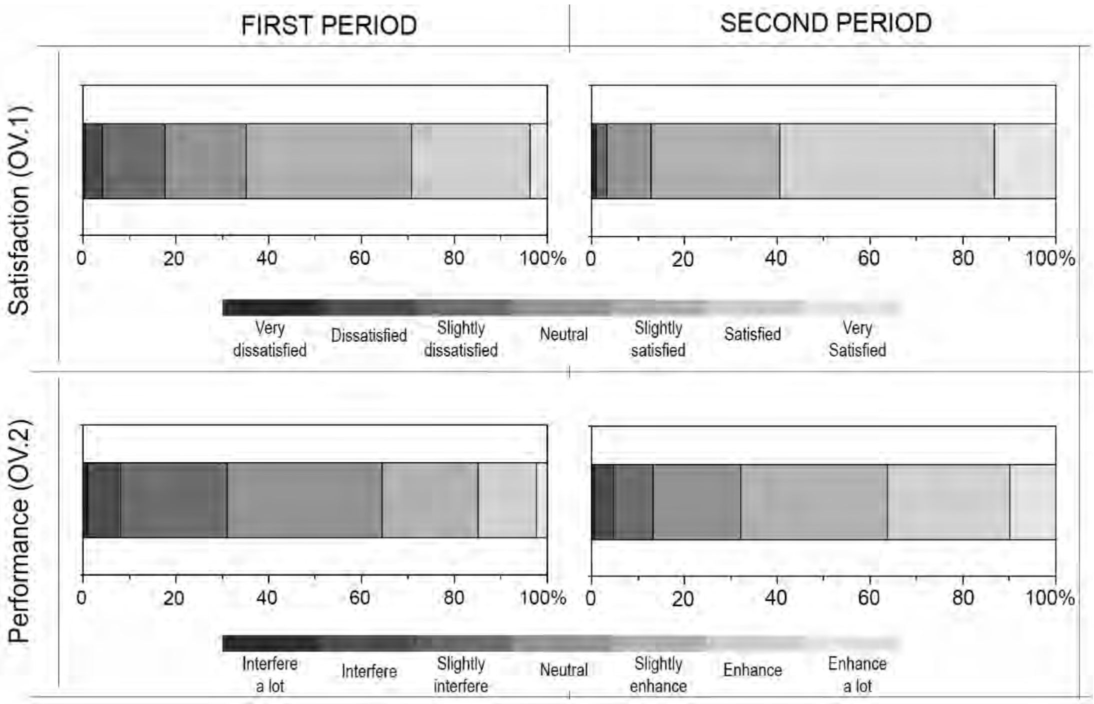


Figure 3-8. Distribution of votes for overall indoor environment conditions

3.3.2.6. Statistical analysis and correlations

Firstly, since the measurement campaign was carried out in two different periods (P1 and P2), a t-test was conducted, in order to determine if there was a significant difference in the response obtained between the two periods (data provided in Table 3-3 in the supplementary material online). The obtained results about the indoor acoustic, thermal and lighting environment showed that the difference between the mean values of satisfaction, sensation and performance interference were statistically significant (con $p < 0.000$ in all the cases), with the exception of lighting sensation, whose mean values were not significantly different between periods ($p = 0.175$).

Regarding the overall indoor environment, the results obtained show that there were significant differences between the mean values of overall workspace satisfaction (OV.1) and overall impact on task performance (OV.2) ($p < 0.001$ in both cases). In addition to the previous analysis, it was found that no significant differences were observed in the sex distribution in both periods. Moreover, no significant differences were observed in any of the variables' distributions according to sex.

Secondly, since it was found that the surgical mask and the FFP2 mask were the ones most used by the students, a t-test was performed to determine if there are differences between the answers provided according to the type of mask used. The results show that there are significant differences in acoustic satisfaction ($p < 0.001$), acoustic sensation ($p < 0.001$), acoustic impact on task performance ($p = 0.003$) and thermal satisfaction ($p = 0.009$).

Finally, the values obtained from the correlation analysis are shown in Figure 3-9. On the one hand, the results suggest that the overall satisfaction of students during exams (OV.1) is conditioned by multiple factors. It is worth noting the positive relationship with AC.2 ($\rho = 0.66$, $p < 0.001$), in which it can be seen that a quiet environment contributes to increasing overall satisfaction and improved student performance.

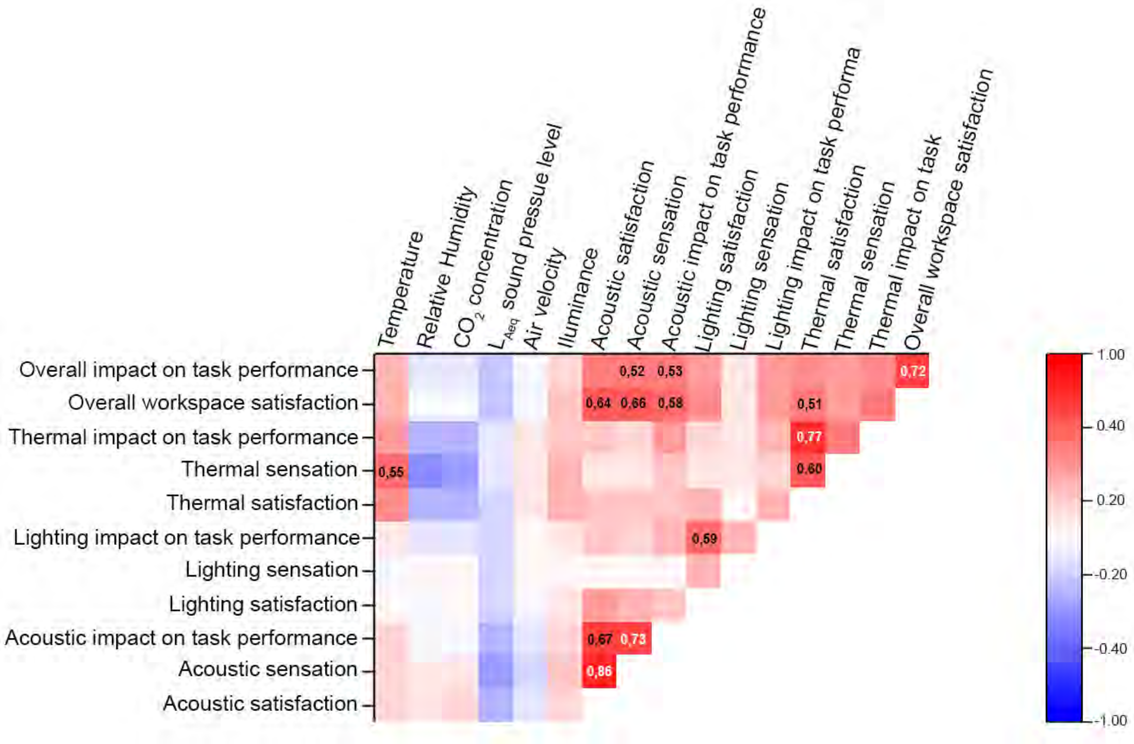


Figure 3-9. Correlation analysis.

Moreover, overall workspace satisfaction (OV.1) shows a moderate correlation with thermal environment satisfaction (TH.1) ($\rho = 0.51$, $p < 0.001$). These correlations suggest that the indoor acoustic environment, as well as the thermal environment, have a greater influence on overall satisfaction than the variables related to the lighting of the indoor environment. In addition, in relation to OV.2 performance, the only variable with a moderate correlation was the indoor acoustics (AC.2) ($\rho = 0.52$, $p < 0.001$).

On the other hand, in relation to thermal satisfaction and thermal sensation, it is observed that, in the range of temperatures in which the measurement campaign was carried out, there is a positive relationship between the interior temperature and the students' thermal satisfaction and sensation with it ($\rho = 0.44$, $p < 0.001$ and $\rho = 0.55$, $p < 0.001$, respectively). In contrast, a negative relationship is obtained between the acoustic satisfaction and acoustic sensation with the L_{Aeq} sound pressure level, the quieter the environment, the more satisfied students are with it ($\rho = -0.31$, $p < 0.001$ and $\rho = -0.35$, $p < 0.001$, respectively).

Figure 3-10 shows the relationship between thermal, acoustic and lighting sensation votes with the indoor temperature, sound pressure level and lighting, respectively. As can be seen, with the exception of the relationship between TSV and temperature, the obtained coefficients of determination (R^2) are quite low. Previous research reported that the individual differences between subjects affect the high variability of sensation votes and this result in a low coefficient of determination [124]. From these results, the neutral temperature obtained was 23.2 °C. The differences between the neutral temperature and the average indoor temperature obtained in P1 (18.4 °C) was -4.81 °C and in P2 (27.4 °C) was +4.2 °C. Regarding the acoustic sensation votes, students considered that L_{Aeq} above 60 dBA were noisy. Finally, regarding the lighting sensation votes, the range of lighting values measured in this study (200-800 lux) were considered as a bright environment.

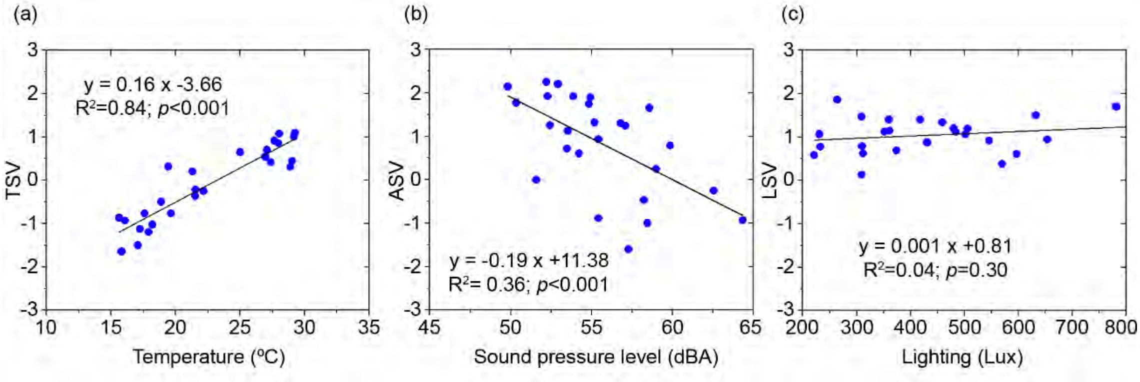


Figure 3-10. (a) Relationship between TSV and temperature. (b) Relationship between ASV and sound pressure level. (c) Relationship between LSV and Lighting.

3.4. Discussion

The results highlight that the natural ventilation strategies were effective since the average indoor CO_2 concentration level was 517 ppm in P1 and 440 ppm in P2. If these values are compared with other results found in other studies carried out during the COVID-19 pandemic period in similar climatological regions, it is observed that similar low concentration values were also reported in studies conducted in educational buildings [118, 125]. In contrast, Gil-Baez et al. [111] reported higher CO_2 concentrations (between 969 - 2919 ppm). These values were higher since, unlike our study, the windows and doors remained closed during part of the time of the study. The same reason explains that the results obtained in our study differ from those found by other research carried out in Southern Spain prior to the COVID-19 outbreak. So, Fernández-Agüera, Campano, Domínguez-Amarillo, Acosta and Sendra [126] conducted on sited measurements in classrooms and found CO_2 concentration values above 1000 ppm, with higher values during winter season due to the ventilation strategy (windows and doors were closed in the around 60% of the classrooms analysed).

In terms of the indoor air temperature and RH, in our research it was measured an average temperature of 18.4 °C (ranged from 15.6° to 21.6°) and an average HR of 46.3% (ranged from 27.9% to 62.6%) in P1, while in P2 it was 27.4 °C (ranged from 22.0° to 29.3°) and 34.5% (ranged from 24.5% to 48.3%), respectively. These values are similar to those obtained for other authors in the period of the COVID19 pandemic [111, 125] but they are quite different from the pre-pandemic time period. Indeed, Fernández-Agüera et al. [126] reported values between 37 - 59 % and temperature values between 17.8 - 24.2 °C during mid-season, and between 44 - 64 % and 19.2 – 22.7 °C respectively during winter season).

The average air velocity was 0.11 m/s (ranged between 0.03 - 0.28m/s) in P1 and 0.08 m/s (0.01-0.16) in P2. Miranda et al. [125] reported lower values in their measurement campaign conducted in winter season (air velocity ranged from 0.003 to 0.12). These results are in accordance with the ventilation strategy adopted in each case.

Regarding the indoor acoustic environment, the L_{Aeq} was 57.0 dBA in P1 and 54.5 dBA in P2 respectively. Previous field tests developed by the authors [127] showed that natural ventilation strategies through opening windows and doors affect the indoor acoustics quality during the teaching process. In fact, it was found that background noise level can be increased between 6.4 dBA and 12.6 dBA in contrast to the same scenarios with closed doors and windows.

With regard to the data obtained from the occupant surveys, it is interesting to note that the average overall satisfaction was 65% during P1 and 87% during P2. The highest percentage of dissatisfied students in both periods is related to the indoor thermal conditions (53% in P1 and 17% in P2). The continuous natural ventilation by opening doors and windows has conditioned the indoor temperature of the classroom, resulting in wider temperature ranges in both periods than the values reported in studies carried out before the COVID-19 pandemic [126]. Before the implementation of the epidemic protocols, students could open and close windows freely. However, during the pandemic, windows had to be kept open even if outdoor environmental conditions were adverse. Furthermore, from the obtained results, it was observed that students were more satisfied with a slightly warm environment versus a cooler environment. This is reflected by the fact that the percentage of dissatisfied students is higher in the season when the average indoor temperature was lower (winter, i.e. P1). In comparison to P1, natural ventilation during P2 can lead to an improvement of the indoor thermal environment, since ventilation can regulate the indoor temperature. Previous studies reported improvement of the indoor thermal environment through natural ventilation. Heracleous and Michael [114] concluded that, since classrooms in Southern European countries have been diachronically naturally ventilated, natural ventilation strategies can improve thermal comfort in intermediate seasons (fresh outdoor airflow is welcomed by the occupants in the classrooms). However, measures to reduce the risk of overheating must be adopted in the warmer periods [43].

It is also interesting to note that the clothing insulation values obtained in both periods (0.74 clo in P1 and 0.57 clo in P2) are similar to the values reported in a previous study conducted before COVID-19 pandemic (0.56 clo in warm seasons and 0.77 clo in winter season) [128]. If the obtained values are compared with those reference clothing insulation values set in the Spanish state regulation [90] for sedentary activities (1.2 met), it is found that the clothing insulation value obtained during P2 is similar (RITE states a 0.5 clo value for the warm season) but the value obtained in P1 is lower (RITE states a 1.0 clo value for the cold season). In this sense, the high percentage of dissatisfied students in P1 may be influenced by both factors: (1) students were dressed with inadequate clothing insulation and (2) the temperature inside the classroom was lower as a result of the implemented COVID-19 protocols.

In addition, it should be noted that wearing a face mask may affect the thermal comfort of students. In fact, previous research have showed that the type of mask and the ambient temperature affect thermal comfort [129].

It is also remarkable that the second indoor environmental condition with the highest percentage of dissatisfied students was the acoustic conditions. This percentage was much higher in the first period (P1) than in the second (P2). In fact, if the L_{Aeq} values are compared between both periods, it can be observed that the average level in P1 (57.0 dBA) is also higher than the average level obtained in P2 (54.5 dBA). Since the academic activities in which the measurement campaign was conducted were exams, where the activity does not require teacher/student interaction, noise can be an important factor in student performance. In this sense, there is a relationship between the protocol implemented to ensure effective ventilation of the classroom (all doors and windows open during the academic activity) and the L_{Aeq} level inside the classroom. External noise sources contribute to increasing indoor L_{Aeq} noise levels to a greater extent than in pre-pandemic conditions (closed windows and doors). This fact is conditioned by the location of the university campus in the centre of the urban part of Granada. Previous studies have already highlighted that noise pollution is a problem in educational buildings in large cities [131-133], so this is exacerbated by the measures implemented as a result of the COVID-19 pandemic.

In summary, acoustic and thermal conditions have influenced the student's satisfaction. Indeed, the statistical analysis results have shown a moderate-high relationship between the overall students' satisfaction with acoustic satisfaction and with thermal satisfaction (ρ=0.64; p<0.001 and ρ=0.51; p<0.001, respectively). Since pandemic protocols and ventilation strategies influence environmental conditions, their modification and adaptation could provide safe and secure spaces for the people and the environment. It should bear in mind that the percentage of students dissatisfied with the indoor environmental conditions in classrooms after implementing the COVID-19 protocols was higher in P1 than in P2. This fact suggests that pandemic protocols should be rethought and different strategies should be designed to adapt them to each seasonal period. Adaptations to improve indoor thermal conditions have to be prioritized during cold season since it was one of the major causes of students' dissatisfaction. The redesign process of ventilation protocols should give priority to ensuring an indoor temperature close to the neutral temperature (23.3°C). Additionally, given the influence of acoustic conditions on overall student satisfaction, this process has also to prioritize providing suitable acoustic conditions during both time periods, avoiding high noise level values that have been rated by students as noisy (60.0 dBA).

Finally, this research shows that a COVID-19 ventilation strategy based on continuous natural ventilation through windows and doors provides effective air renewal and low CO_2 concentrations, but it does not ensure a minimum IEQ and occupant satisfaction. In addition, it should be taken in into account that natural ventilation strategies based only in the subjective physical response of students are not able to provide a minimum IAQ during severe conditions (winter and fall), so a ventilation strategy based on only those subjective data is not suitable [134]. In view of these facts, the selection of the ventilation strategy based on taking into account both an effective air renewal for low CO_2 concentrations and IEQ factors for occupant satisfaction becomes essential in this process and pandemic protocols should consider these findings in the process of redesigning ventilation strategies.

3.5. Limitations

The measurement campaign conducted in this study was carried out only during the months when face-to-face activities took place in educational buildings in the academic year 2020-2021. These activities only included exams, since all the other learning activities were moved off-campus (on line) in order to prevent the virus transmission. Therefore, the obtained results should not be extended without further analysis to other seasons or scenarios where different ventilation strategies could have been implemented (i.e. windows are not continuously opened or the classroom is mechanically ventilated).

Additionally, it should be noted that this measurement campaign has been conducted in university educational buildings. Further research will be needed in order to expand these results to other types of educational buildings and scenarios, since their characteristics may be different (spaces with less surface area, higher occupancy density, ventilation systems, etc.).

3.6. Conclusion

The situation arising from the pandemic caused by COVID-19 has led to an increased interest in achieving a good IAQ in the indoor built environment. The characteristics of educational buildings (high occupancy density and natural ventilation systems in most of the spaces) result in challenging conditions for building engineers and managers. These circumstances have led to the implementation of protocols to increase the air change rate in classrooms through the opening of windows and doors. Consequently, in addition to IAQ, the other IEQ factors have been affected by these measures, providing values very different from those expected under normal operating conditions.

This research shows that the implemented protocols have had an impact on student satisfaction regarding the indoor built environment. Although ventilation strategies have provided effective air renewal, it is clear that they have also disturbed indoor environmental conditions in classrooms, and not always in the sense of an IEQ improvement. In this sense, it should be noted that academic activities such as exams provide stress to students, which in turn can be also affected by poor IEQ conditions in classrooms. The obtained results show that pandemic protocols should not only prioritise ensuring a good IAQ but also the rest of IEQ factors by considering how the extend of this condition and its potential to disturb the student performance could be. In view of these facts, and given that most educational building in Europe are naturally ventilated, the finding of the current study could be successfully used to define and redesign the ventilation pandemic protocols of educational building in countries with similar climatic conditions (e.g. Mediterranean climate). Future research studies should address the development of systems and devices combined with redesigned safety protocols that ensure not only that indoor spaces are safe but also that they maintain acceptable levels of satisfaction in relation to IEQ. This is crucial in order to make buildings resilient and minimise the impact of pandemics on the learning process of future generations

4. Reopening higher education buildings in post-epidemic COVID-19 scenario: monitoring and assessment of indoor environmental quality after implementing ventilation protocols in Spain and Portugal

The work in this chapter is based upon the following publication: de la Hoz-Torres, M. L., Aguilar, A. J., Costa, N., Arezes, P., Ruiz, D. P., & Martínez-Aires, M. D. (2022). *Reopening higher education buildings in postepidemic COVID-19 scenario: monitoring and assessment of indoor environmental quality after implementing ventilation protocols in Spain and Portugal*. Indoor Air, 32(5), e13040. https://doi.org/10.1111/ina.13040

4.1. Introduction

The pandemic outbreak of COVID-19 has led to a disruptions in human activities and basic needs of the population worldwide. The rapid spread of the Severe Acute Respiratory Syndrome Coronavirus-2 (SARS-CoV-2) virus has resulted in the suspension of many agricultural, industrial and commercial activities, causing negative impact in both the global industrial and economic sectors and a deterioration in the global economy [135, 136]. The adopted measures to limit the spread of SARS-CoV-2 have also profoundly affected the education sector worldwide. More than 1.5 billion learners (89.4% of the total enrolled learners) were affected by the closure of educational buildings when schools and higher education institutions were closed in 185 countries on April 2020 [137]. The southwestern European countries, namely, Spain and Portugal, were also severely affected by the COVID-19 pandemic. The strict lockdown measures were decreed on March 12 and 13 in Portugal and Spain, respectively [138, 139]. These measures included the closure of playgrounds, schools and universities, and this situation lasted until early May in Spain and June 20 in Portugal.

Educational institutions faced these circumstances and took steps to suddenly change the teaching activities and start using online teaching methodologies. However, although this adaptation allowed the academic process to continue, teachers and students found it difficult to adapt to this new scenario. A recent research study concluded that 50.43% of the respondents of Spanish Universities presented a moderate to severe impact of the outbreak [113]. In the light of these facts, educational buildings were reopened for some learning activities, during epidemic conditions, in order to mitigate the impact of online teaching on university communities. As a consequence, this process required implementing measures to protect the health, safety and welfare of educational building occupants from the spread of SARS-CoV-2. Given that teachers, students and staff spend long periods per day in these buildings, the first consideration to maintaining a healthy environment and reduce exposure risk is a dilution of pollutants within the indoor space. Although indoor air management will not stop the spread of COVID-19 on its own, it can reduce the number of people infected when occupants also follow measures to control and stop infection (e.g., the use of masks and practicing good hand hygiene) [136, 140-142].

International organizations also published guidelines in which ventilation was considered an important factor in the safety of indoor spaces. World Health Organization (WHO) guidelines recommended 1000 ppm as the CO_2 concentration limit [123]. The Federation of European Heating, Ventilation and Air Containing Associations (REHVA) recommended 8-10 L/s per person in meeting rooms and classrooms [70]. In addition, the guidelines drawn up by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) also suggested lowering the number of building occupants and to increase outdoor air ventilation. Additionally, they recommended that ventilation systems must be run at a maximum of 2 hours before and after occupancy for pre- and post-occupancy flushing [143]. Therefore, given the importance of ventilation in educational buildings, the contingency and action plan for COVID-19 established in engineering schools and faculties by Spanish and Portuguese Universities also refer to ventilation among their defined measures. For example, the plan established by the University of Granada also considers the recommendation to ventilate before and after occupancy as a reopening measure for educational centres, and it even specified that "even if the weather conditions are adverse, ventilation must be carried out by means of natural ventilation through open windows and doors" [120]. In addition, the "Plano de Contingência" (Contingency Plan) COVID-19 draw up by the University of Minho also stated "good ventilation and frequent air renewal must be ensured, for example, by opening doors and windows. If mechanical ventilation is used, it should be in extraction mode and never in recirculation mode" [144].

Fortunately, the efforts of researchers and the rollout of effective vaccines have made society hopeful for a return to the "new normal". On 1 September 2021, the proportion of the population who had received all the doses prescribed by the vaccination protocol in Portugal and Spain was 75.5 % and 72.0 %, respectively [145]. Indeed, Portugal had the highest COVID-19 vaccination rate in the world in September [146]. Consequently, given the percentage of vaccinated people in the university community compared to that for the 2020-2021 academic year, the COVID-19 contingency plans approved by the different faculties and engineering schools were adapted to allow for the highest possible attendance in the 2021-2022 academic year. The main objective was to ensure a safe, secure and suitable indoor space for full face-to-face attendance in a new normal scenario of post-epidemic conditions [120, 147]. In this sense, except for the 1.5 meters social distance, all the measures stated in the COVID-19 contingency plans remained in place in the educational buildings.

In this context, the start of the 2021-2022 academic year began with face-to-face learning and the application of a conditionally normal scenario. However, since these measures and protocols affect the indoor environmental conditions in this new normal scenario, the occupant satisfaction and the indoor environmental quality (IEQ) of educational building may be affected by them. Increasing the amount of outdoor air affects indoor environmental factors (such as the background noise, air temperature, and relative humidity (RH)) and, as a consequence, occupant' performance may be affected [34, 99, 114, 148]. Indeed, previous research studies concluded that a poor indoor environmental quality is associated with adverse health effects and illness, leading to student absenteeism [149, 150]. However, given the short time that has elapsed since society has suddenly been forced to adapt to the "new normal", very little research has been published related to the impact of the new post-epidemic protocols on the indoor environmental variables in educational buildings. To address this gap, the aim of this study was to analyse the satisfaction and perception of university students in this new scenario of post-epidemic conditions. For this purpose, a measurement campaign was conducted in educational buildings in Portugal (Azurém Campus, University of Minho) and Spain (Fuentenueva Campus, University of Granada). This study assessed the indoor environmental conditions and the sensation and satisfaction of the students with the indoor acoustics, lighting and thermal conditions along with their subjective perception of the impact of these variables on their academic performance. The findings will support decision making for the redesign and development of protocols, thus minimizing student dissatisfaction and ensuring that educational centres are safe.

4.2. Materials and Methods

A questionnaire and IEQ monitoring were conducted at the Azurém Campus (University of Minho, Guimarães, Portugal) and at the Fuentenueva Campus (University of Granada, Granada, Spain). Field measurements were performed during the re-opening of the educational buildings in the 2021/2022 academic year (during the period of September – November 2021).

4.2.1. Educational buildings case studies

Guimarães is located in the northern part of Portugal (41°26′42″N - 8°17′27″W), and the climate belongs to Csb category according to the Köppen-Geiger climate classification. This area is characterised by cold and rainy winters and hot and slightly humid summers, with an average annual temperature range from 5-28°C. Granada is located in the southern part of Spain (37°10′41″N - 3°36′03″W), and its climate is classified as Csa. Granada is characterised by cold winters (partly cloudy) and hot summers. The annual temperature varies from 0 °C to 34 °C, and at certain times of the year, the thermal oscillation during the day is large, often exceeding 20 °C in one day.

In both locations, an analysis of the characteristics of teaching and learning spaces was conducted to select representative classrooms on both campuses. For this purpose, building managers were asked to identify the different spaces used for undergraduate lecture classes of each campuses. These classrooms used for the undergraduate students were chosen since they have the largest number of occupants. Among these classrooms, the measurement campaign was carried out in those ones with the dimensions, occupation and layout representative of the spaces used for this activity in each of the buildings. The selection criteria were the same in both campuses. As a result of this process, 8 classrooms distributed in 4 buildings at the Azurém Campus and 7 classrooms distributed in 2 buildings at the Fuentenueva Campus were selected in the IEQ measurement campaign.

A summary of the selected buildings, classrooms, and number of surveyed students is shown in Table 4-1.

Table 4-1. Summary of the investigated buildings.

Campus	Building	Number of surveyed students (n)	Average occupancy density (m^2/person)	Lighting system	Type of windows	Finish materials		
						Floor	Wall	Ceiling
Azurém (Portugal)	B1	42	1.3	Suspended and mounted fluorescent luminaire	Aluminum/metal glazed windows	Wood	Gypsum plaster	Acoustic plasterboard
	B2	49	1.2			Vinyl/wood	Gypsum plaster / wood	Plaster
	B3	81	1.2			Ceramic tile	Gypsum plaster / cork	Acoustic plasterboard
	B4	45	1.3			Vinyl	Gypsum plaster / wood	Acoustic plasterboard
Fuentenueva (Spain)	B5	111	1.1	Mounted fluorescent luminaire	Aluminum glazed windows	Terrazzo	Gypsum plaster	Registrable suspended ceiling
	B6	113	1.8			Natural stone	Ceramic tile	Registrable suspended ceiling

4.2.2. IEQ Sensors and experimental setup

The IEQ monitoring campaign was conducted during normal lessons (1.5 - 2 hours), during the mid-season (from September to November, 2021) in both locations. Different indoor parameters were recorded during the IEQ measurement: air temperature (°C), radiant temperature (°C), RH (%), air velocity (m/s), CO_2 concentration (ppm) and light intensity (lux). In addition, the sound pressure level (dBA) in each classroom was measured. Table 4-2 shows a summary of the main characteristics of the used sensors. All parameters were measured in 1 minute logging intervals. The sensors were placed in the middle of the classrooms, separated >1 m from the surrounding surfaces and at a height of 0.6 m.

Table 4-2. IEQ sensors characteristics

Variable	Sensor	Range	Accuracy
Mean radiant temperature	FPA805GTS AHLBORN	–50 to 200 °C	0.1 °C
Air velocity	HD403TS2 Delta OHM®	0.1 to 5 m/s	± 0.2 m/s + 3% f.s.
Air temperature	FHAD 46-C41A AHLBORN	-20 to +80 °C	Typical ±0.2 K at 5 to 60 °C maximum ±0.4 K at 5 to 60 °C maximum ±0.7 K at -20 to +80 °C
Relative humidity	FHAD 46-C41A AHLBORN	0 to 98 % RH	±2.0 % RH in range from 10 to 90 % RH ±4.0 % RH in range from 5 to 98 % RH
CO_2 concentration	HOBO® MX1102	0 to 5.000 ppm	±50 ppm ±5% of reading
Light intensity	HOBO® MX1104	0 to 167,731 lux	±10% typical for direct sunlight
Sound pressure level	Imperum-R TECNITAX® Ingeniería	35 to 115 dBA	± 1 dBA

Outdoor climatological data were taken from meteorological stations close to the study area. For the area of Portugal, the data were obtained from IPMA (Portuguese Institute for Sea and Atmosphere) [151] and for the area of Granada, the data were obtained from AEMET (State Meteorological Agency [119]).

Additionally, based on the indoor air temperatures and radiant temperatures values obtained from the sensor monitoring campaign, the operative temperatures were calculated. This variable is used in Spanish and Portuguese legislation to define upper and lower limits requirements of thermal quality in the indoor environment. In the case of Spain, two ranges are defined. For the summer months (assuming 0.5 clo value and an estimated percentage of dissatisfied between 10-15%), the range (R_{S-S}) is from 23-25 °C. For the winter months (assuming

1 clo value and the same estimated percentage of unsatisfied), the range ($R_{S\text{-}W}$) is from 21-23 °C. The Portuguese legislation only establishes an annual range (R_P), which is wider than that established in the Spanish legislation and sets the operating temperature limits from 20 to 25 °C. The operative temperature values obtained from the field measurements were compared with the indoor thermal quality requirement ranges of each country.

4.2.3. Data collection and analysis from questionnaires

A paper-based cross-sectional questionnaire was conducted in this study. The construction of the questionnaire involved the following steps: firstly, the prototype questionnaire was built by the research group using the UNE–CEN/TR 16798-2:2019 Standard for the evaluation of the indoor environmental quality. Specifically, this study followed the recommended procedures and questionnaires given in this Standard for the systematic registration of subjective reactions of building occupants. The questionnaire was divided into sections containing items related to thermal, lighting, acoustical and air quality indoor environment. These items followed the guidelines established in UNE-EN 10551:2019 for subjective assessment of physical environment. Subsequently, in order to validate the prototype questionnaire, a focus group comprised of an expert panel was conducted. A total of 8 experts participated in this process, including professors and students of the related disciplines in university degrees. As a result of this expert panel, the clarity of the formulation, and the adequacy of the specific vocabulary for the textual product was analysed. The items related to indoor air quality in the original UNE–CEN/TR 16798-2:2019 Standard were not used in our research because the experts mentioned the possible bias in the subjective assessment of this factor, since the students had to wear a face mask at any time during the lecture class. Finally, the results obtained from this process were analyzed and the questionnaire were set up.

The questionnaire was divided into a general information section, sections addressing the acoustic, lighting, and thermal comfort and a section which addressed the overall evaluation of the IEQ. The general information section collected demographic data (such as the age and gender of the subjects) as well as the type of mask and clothing that the subjects were wearing during the survey. The clothes selected from a checklist by the participants were used to estimate the clothing insulation value (EN ISO 7730)[122]. Based on these data, together with the operative temperature and the metabolic rate, the predicted mean vote (PMV) was calculated.

Regarding the IEQ questions, the thermal satisfaction vote (TSAV), lighting satisfaction vote (LSAV) and acoustic satisfaction vote (ASAV) were examined in the questionnaire based on a 7-point scale (from -3 for "very dissatisfied" to 3 for "very satisfied"). In addition, a 7-point scale was also used to examine the thermal sensation vote (TSV, from -3 for "cold" to 3 for "hot"), lighting sensation vote (LSV, from -3 for "very bright" to 3 for "very dark") and acoustic sensation vote (ASV, from -3 for "very noisy" to 3 for "very silent"). Participants were asked to select the causes of dissatisfaction using a checklist covering the thermal, lighting and acoustic situations.

Moreover, to examine the perceived interference/enhancement of the indoor environmental conditions on the performance of the students, the perceived thermal impact on learning performance (PTILP), perceived acoustic impact on learning performance (PAILP) and perceived lighting impact on learning performance (PLILP) were also assessed. For this purpose, the questionnaire included the following three direct questions: "Does the acoustic quality in your classroom space enhance or interfere with your ability to get your academic work done?" "Does the lighting quality in your classroom space enhance or interfere with your ability to get your academic work done?" And "Does the thermal quality in your classroom space enhance or interfere with your ability to get your academic work done?" A 7-point scale was used in these questions (from -3 for "interferes a lot" to 3 for "enhances a lot"). It should be remarked that this study subjectively evaluates the perceived impact of indoor environment on the performance of students.

Finally, two questions about the overall indoor environmental conditions were included in the questionnaire. The first one was about the overall satisfaction (OV1) (with a 7-point Likert scale from -3 for "very dissatisfied" to 3 for "very satisfied"). The last direct question (OV2) was "Please estimate how your productivity is increased or decreased by the environmental conditions in this building (i.e., thermal, lighting and acoustics)". This was also graded with also a 7-point scale (from -3 for "decreases a lot" to 3 for "increases a lot"). The questionnaire was validated by a focus expert group prior to be applied to the respondents.

The field study followed the recommended procedures states in Annex F of UNE-CEN/TR16798-2:2019 and ISO 10551:2019 in order to provide consistency, reliability of results and meaningful comparison data obtained from investigation internationally. The questionnaire surveys were conducted during middle morning or middle afternoon, no just after arrival or after a lunch break. The questionnaires were filled out during the last 15 minutes of each lecture class to lessen the lecture disturbance. This decision was intended to maximize the exposure of the university students to the indoor environmental condition of the classroom since the survey was conducted at the end of the class (ensuring that the students had been sitting in the classroom for at-least 1 hour and minimizing the influence of metabolic rate on the thermal evaluations by the students).

After the field measurement campaign, the collected data were analysed to estimate the satisfaction, sensation and impact on the learning activities of the students with the indoor environmental conditions. The average satisfaction score was calculated for each question as an arithmetic mean of the votes obtained from each campus. Moreover, from the results obtained for the thermal, lighting and acoustic satisfaction questions, the rate of satisfaction (RS) and dissatisfaction (RD) were calculated for each of the indoor environmental variables (see Equations 4-1 and 4-2):

$$\begin{aligned} &Rate\ of\ Dissatisfaction\ (RD) \\ &= \frac{"Very\ dissatisfied"\ votes + "Dissatisfied"\ votes + "Slightly\ dissatisfied"\ votes}{Total\ votes} [\%] \end{aligned} \tag{4-1}$$

$$Rate\ of\ Satisfaction\ (RS) = \frac{"Very\ satisfied"\ votes + "Satisfied"\ votes + "Sightly\ satisfied"\ votes}{Total\ votes}\ [\%] \tag{4-2}$$

In addition, the rate of interference (RI) and the rate of enhancement (RE) were estimated for each variable from the results obtained from the PTILP, PLILP and PAILP questions (Equations 4-3 and 4-4):

$$Rate\ of\ Interference\ (RI) = \frac{"Interfere\ a\ lot"\ votes + "Interfere"\ votes + "Slightly\ interfere"\ votes}{Total\ votes}\ [\%] \tag{4-3}$$

$$Rate\ of\ Enhancement\ (RE) = \frac{"Enhance\ a\ lot"\ votes + "Enhance"\ votes + "Slightly\ enhance"\ votes}{Total\ votes}\ [\%] \tag{4-4}$$

4.2.4. Statistical analysis

In order to determine whether there are significant differences between the probability distributions of the results for both campuses, a statistical analysis of the data obtained in the measurement campaigns were carried out. For this purpose, the probability distribution of the data was evaluated using the Kolmogovrov-Smirnov test. Non-parametric test (Mann-Whitney U test or Kruskal Wallis test) was applied to the non-normally distributed means of data in order to examine the statistical significance of possible difference between both campuses. Furthermore, Spearman correlation test was determined between: (1) the satisfaction and the interference on the learning performance for each IEQ factor, (2) the satisfaction of IEQ factor and the overall satisfaction; and (3) interference of each IEQ factor and the overall interference.

In addition, a tendency analysis were carried out on the obtained data sets. Linear and polynomial fits were used to assess the relationship between the values of the subjective and objective IEQ factors. IBM SPSS statistic (version 23.0) was used to perform all the statistical analyses.

4.3. Results

The general information of respondents is summarized in Table 4-3. A total of 440 students (217 from Azurém Campus and 223 from Fuentenueva Campus) participated in this field study. Since all the university students who participated in the surveys were sitting and listening to the lecturers during the measurements, a metabolic rate of 1.1 was met, as stated in ISO 7730 [122]. On both campuses, the majority of respondents were between 18 and 25 years old (87.1% on Azurém Campus and 91.0% on Fuentenueva Campus), and most of them were wearing a surgical mask (90.3% and 70.4% in Azurém and Fuentenueva, respectively).

Table 4-3. General information.

Variable		Response	
		Portugal	Spain
Age	n/a	9 (4.1%)	11 (5.0%)
	18-25	189 (87.1%)	203 (91.0%)
	+25	19 (8.8%)	9 (4.0%)
Sex	n/a	0 (0%)	1 (0.4%)
	Male	91 (41.9%)	144 (64.6%)
	Female	126 (58.1%)	78 (35.0%)
Type of mask	n/a	1 (0.5%)	6 (2.7%)
	FFP2	6 (2.8%)	39 (17.5%)
	Surgical	196 (90.3%)	157 (70.4%)
	Cloth	12 (5.5%)	17 (7.6%)
	Other	2 (0.9%)	4 (1.8%)

Regarding to the type of clothing the students were wearing, the value for the clothes was estimated using the conventional clo table defined in ISO 7730 [122]. Figure 4-1 shows the distribution of the clothing insulation values for the students from Azurém Campus and Fuentenueva Campus.

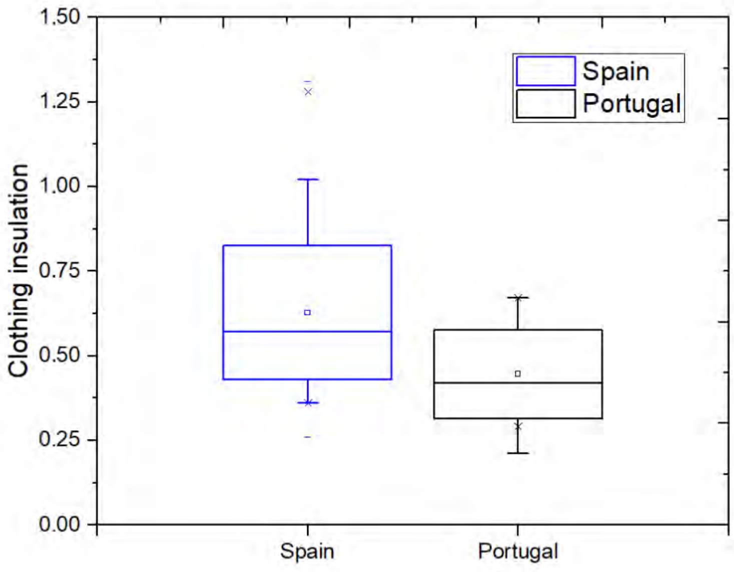


Figure 4-1. Distribution of insulation clothing values.

4.3.1. Indoor environmental monitoring results

The results obtained from the sensor monitoring in both campuses are summarized in Table 4-4. The mean outdoor air temperature obtained during the measurement survey was very similar in both locations (18.6 °C in Guimarães and 19.5 °C in Granada). However, the range was wider in Granada (from 6.8 to 30.2 °C) than in Guimarães (from 15.2 to 23.7 °C). The difference between the mean operative temperatures during the survey in both locations was less than 1 °C. As in the case of the outdoor temperature, the range of values measured at the Azurém Campus (max. 25.5 °C and min 20.5 °C) was narrower than those measured at the Fuentenueva Campus (max. 28.1 °C and min 16.8 °C).

Table 4-4. Results obtained from the field measurements.

	Indoor air Temperature (°C)		Radiant Temperature (°C)		Operative Temperature (°C)		RH (%)		Air velocity (m/s)		CO_2 (ppm)		Lighting (lux)		L_{Aeq} (dBA)	
Country	P*	S*	P	S	P	S	P	S	P	S	P	S	P	S	P	S
Max	25.6	28.0	25.4	28.5	25.5	28.1	69.7	50.1	0.08	0.09	1100	617	567	691	58.0	58.0
Min	20.5	16.3	20.5	17.3	20.5	16.8	28.7	28.1	0.01	0.01	400	399	112	316	38,6	43.6
Average	23.2	23.3	23.0	24.0	23.1	23.7	52.4	38.3	0.03	0.03	742	519	301	434	47.2	49.7
Median	23.4	25.3	23.2	25.8	23.3	25.6	54.9	37.6	0.02	0.01	791	517	277	377	45.7	47.8
SD	1.9	4.0	1.8	3.8	1.8	3.8	16.0	6.9	0.02	0.03	215	83	177	113	7.5	4.9

* P indicates Portugal (Azurém Campus) and S indicates Spain (Fuentenueva Campus).

Based on the data obtained from the field measurements, the PMV was calculated. Figure 4-2a shows the mean PMV values obtained in each classroom against the indoor operative temperature. Regarding the operative temperature values obtained from the Azurém Campus, most of them were in the range defined by the Portuguese legislation for indoor thermal quality (R_P). However, half of them were below the lower limit for category 4 stated by the UNE-EN ISO 7730:2006 standard. With respect to the values obtained from the Fuentenueva Campus, the operative temperature had a wider range than the Azurém Campus. Only three of all the values are in one of the two ranges (R_{S-W} and R_{S-S}) established in the Spanish legislation. However, although some of these values are outside these ranges, they are in the categories defined by the UNE-EN ISO 7730:2006 standard.

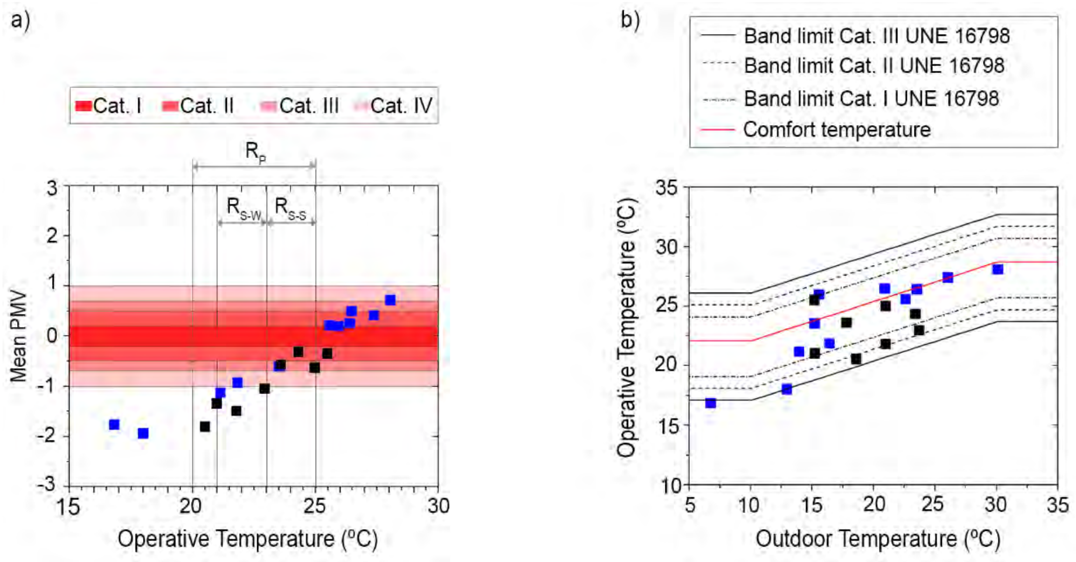


Figure 4-2. (a) PMV versus operative temperature and (b) operative temperature versus outdoor temperature. The black squares are from the Portugal dataset, and the blue squares are from the Spain dataset

Figure 4-2b shows the operative temperature versus the outdoor temperature. The limits of the adaptive method defined in the UNE-EN 16798-1:2020 standard are included in the Figure. This method is used when thermal conditions can be regulated through the opening and closing of windows and doors, which is applicable during intermediate seasons (i.e., spring and autumn). On both campuses, the obtained values are in category I and II, as defined in the standard.

Regarding the RH, the mean indoor value was lower in Granada (38.3%) than Guimarães (52.4 %), and the indoor air velocity was similar in both locations. The CO_2 concentration level value in Guimarães (ranging from 400 to 1100 ppm) was higher than the values measured in Granada (ranging from 399 to 617 ppm). If both the average CO_2 concentration levels are compared with the recommended limit values stated in the international guidelines, it should be noted that the average level is below the limit recommended the REHVA (800 ppm) and the WHO (1000 ppm). Therefore, although the maximum level measured at the Azurém campus is 100 ppm above the WHO recommended limit, it is possible to state that the ventilation protocols were effective in most of the scenarios analysed. In addition, the mean lighting value was 301 lux in Guimarães and 434 lux in Granada. Finally, the average background noise sound pressure level L_{Aeq} value obtained at Azurém Campus was 47.2 dBA, and at Fuentenueva Campus, it was 49.7 dBA.

4.3.2. Subjective indoor environmental evaluation

The results obtained from the analysis of the data collected in the field surveys are shown in this section. Figure 4-3 summarizes the TSAV, LSAV and ASAV results obtained from the students on the environmental indoor conditions during the field survey. First, based on these results, it can be stated that the greatest difference in the RS between both campuses is in relation to the thermal environment. The RD was only 10% in Azurém Campus, while in the Fuentenueva Campus, it amounted to 36%. In addition, regarding the results of the response from the students to their lighting and acoustic satisfaction, the obtained RS values are similar for the Azurém Campus and Fuentenueva Campus (77% and 83% in the case of lighting RS, and 74% and 69% regarding acoustic RS, respectively).

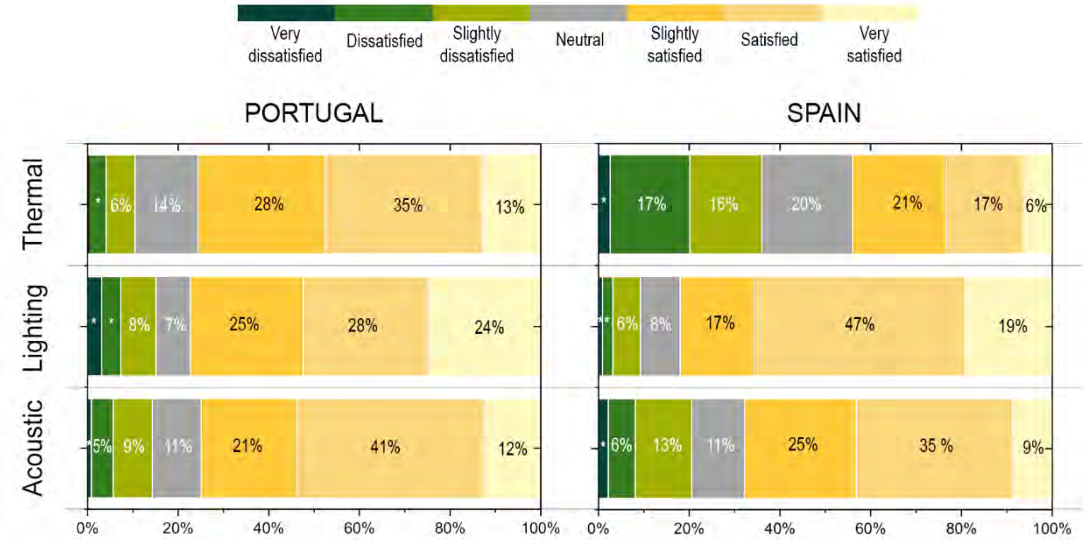


Figure 4-3. TSAV, LSAV and ASAV values obtained in Portugal and Spain. * indicates the percentage is <5%.

The results regarding the response from the students for the TSV (Figure 4-4) show that the mean values were 0.41 in Guimarães and -0.05 in Granada. It should be noted that the students tended to feel neutral in both locations, in fact, no student at the Azurém Campus identified the indoor thermal environment as either cold or hot. At this campus, the sum of "cool" and "slightly cool" responses was 12%, and the sum of "slightly warm" and "warm" was equal to 41%. In contrast, the number of students who voted that the indoor space was “cold” and “hot” at the Fuentenueva Campus was 2% in both cases. The sum of the responses that indicate "cool" and "slightly cool" is higher than that obtained for the Azurém Campus (31%), while the sum of “slightly warm” and “warm” provides a value of 30%.

As stated in ASHRAE-55 (2004), when at least 80% of the votes from occupants are within the three central categories of the scale (i.e., -1, 0, and 1), the indoor thermal environment is perceived as comfortable or acceptable. In this study, 79% and 70% of votes from the students are within the three central categories for the Azurém Campus and Fuentenueva Campus, respectively.

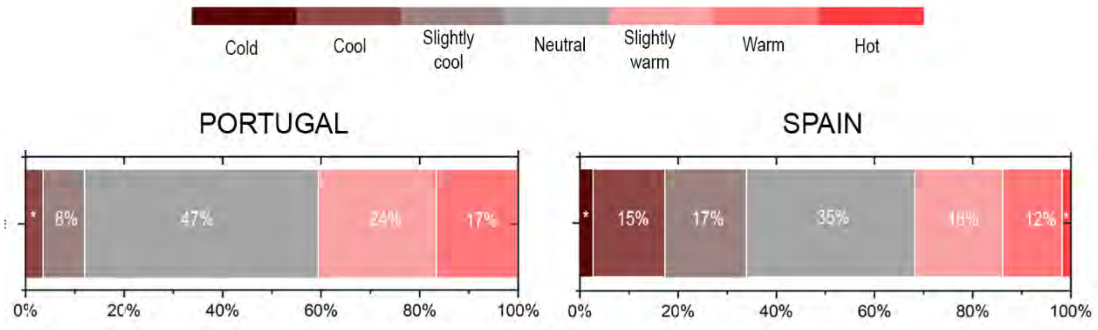


Figure 4-4. TSV values obtained in Portugal and Spain. * indicates the percentage is <5%.

With respect to the LSV responses from the students (Figure 4-5), the mean obtained values were 0.91 in Guimarães and 0.43 in Granada. A total of 61% of the students from the Azurém Campus indicated that lighting inside classroom was "dim", "very dark" or "dark". However, only a 10% of the students indicated that the indoor lighting environment was "light", "bright" or "very bright".

In the case of the Fuentenueva Campus, the results are very different than those from the Azurém Campus. Only 21% indicated that it was "dim", "dark" or "very dark". It is worth noting that if these results are compared with the LSAV, the students were satisfied with these conditions even though they mainly rated the LSV as "neutral", "dim" and "dark" in both locations.

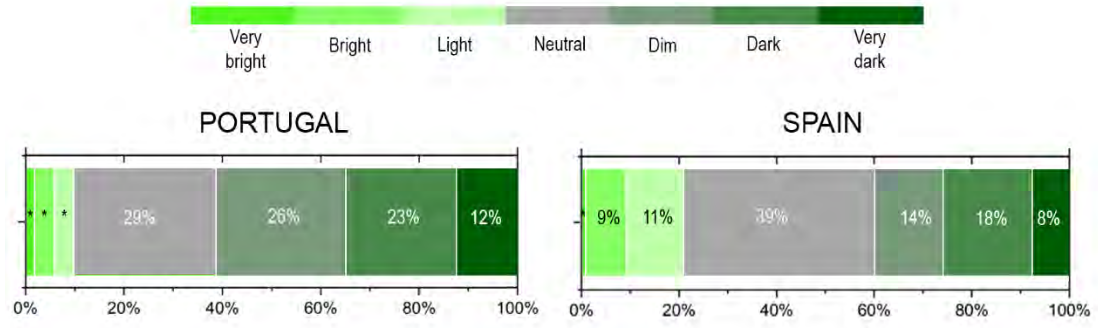


Figure 4-5. LSV values obtained in Portugal and Spain. * indicates the percentage is <5%.

Regarding the responses from the students about the ASV (Figure 4-6), the results show a lower distribution of votes for "neutral" than for the TSV and LSV. The mean ASV values were 0.96 in Guimarães and 0.63 in Granada. The sum of the responses from students who indicated that the indoor acoustic environment was "very noisy", "noisy" or "slightly noisy" was 16% for the Azurém Campus. This value increased to 26% for the Fuentenueva Campus. The location of the campus and the activities that take place around them is an aspect to consider when evaluating these results. The Azurém Campus is located on a larger area than Fuentenueva Campus, and its educational buildings are surrounded by green spaces and landscaped areas. In contrast, the Fuentenueva Campus is located in the centre of the city of Granada, a tramway crosses the campus, and its buildings are surrounded by main streets with a high volume of traffic.

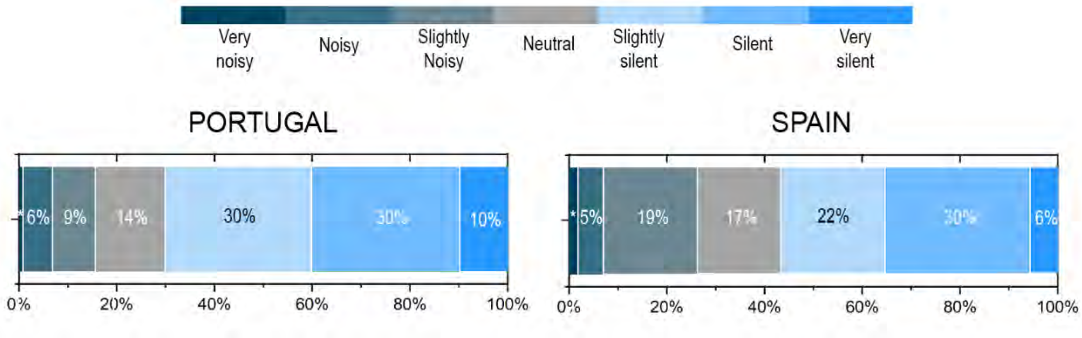


Figure 4-6. ASV values obtained in Portugal and Spain. * indicates the percentage is <5%.

In addition to an analysis of the sensation votes and satisfaction votes on the thermal, lighting and acoustics of the indoor environmental conditions, the RI and RE of the PTILP, PLILP and PAILP responses were analysed (Figure 4-7). Regarding the Azurém Campus, the obtained results show that the environmental condition that most contributes to enhancing student performance in class is the lighting condition (RS = 77%) followed by the thermal condition (RS = 71%) and, to a lesser extent, the acoustic condition (RS = 67%). In fact, it is the acoustic condition that showed the highest RI value (20%).

Nevertheless, the responses obtained from the survey conducted at the Fuentenueva Campus show that the indoor environmental factor that generates the greatest interference with student learning performance is the thermal condition (RI=36%) followed by the acoustic condition (RI=23%) and, to a much lesser extent, the lighting condition (RI=12%).

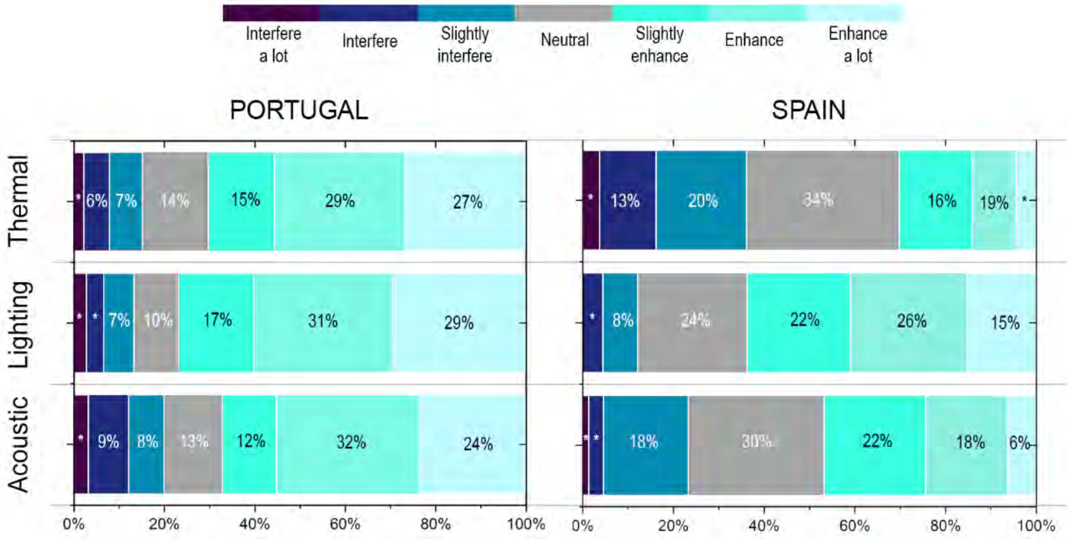


Figure 4-7. PTILP, PLILP and PAILP values obtained for Portugal and Spain. * indicates the percentage is <5%.

Regarding the overall environmental conditions (Figure 4-8), it should be noted that the RS for the students at Azurém Campus (77%) was slightly higher than that for the students at the Fuentenueva Campus (71%). However, a different distribution was found in the responses given the OV2 question (Figure 4-9): 75% of students at the Azurém Campus indicated that their productivity was at least slightly increased by the environmental conditions (i.e., thermal, lighting and acoustic) in the building while they were doing the questionnaire. In contrast, this value increased to 48% in Fuentenueva Campus. In addition, the percentage of students giving a neutral answer to this question was higher at the Fuentenueva Campus than at the Azurém Campus.

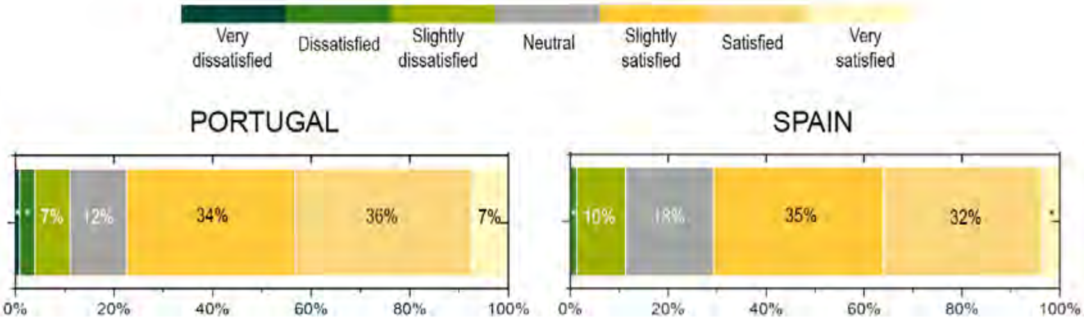


Figure 4-8. Overall satisfaction vote in Portugal and Spain. * indicates the percentage is <5%.

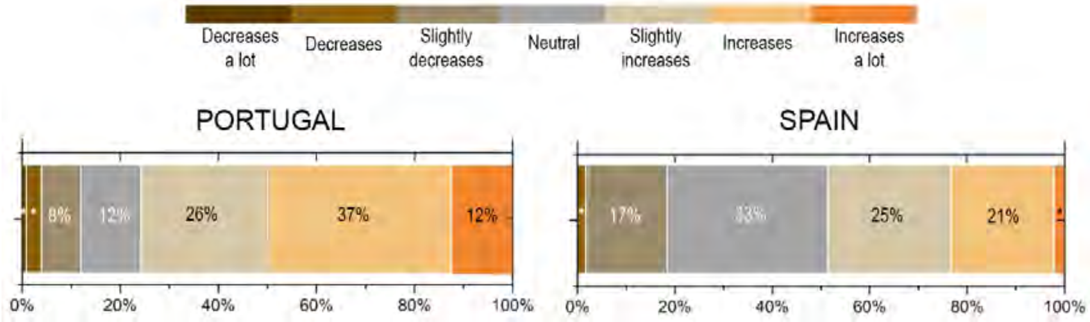


Figure 4-9. Perceived impact of thermal, lighting and acoustic environmental conditions on the productivity of the students. * indicates the percentage is <5%.

4.3.3. Causes of dissatisfaction

Figures 4-10 and 4-11 show the main causes of dissatisfaction at the Azurém and Fuentenueva campi, respectively. Regarding the Azurém Campus, students were found to be dissatisfied with the thermal environment due to drafts (25%), the HVAC systems not working quickly enough (14%), slow air movement (13%) and humidity that was too high (13%). In relation to indoor lighting, the main causes of dissatisfaction were not enough daylight (29%), the space was too dark (26%) and not enough electric lighting (16%). Indeed, 71% of the causes of dissatisfaction were related to the lack or shortage of lighting in the classroom. This can be also observed in the data obtained during the field monitoring campaign on this campus (the minimum is 112 lux). In terms of acoustic dissatisfaction, students highlighted people talking in neighbouring spaces (36%) and excessive echoes (30%) as the main causes. Other external noise represented only 11%. The opening of doors and windows influences indoor acoustic conditions. Almost 50% of the causes were related to this factor. In fact, noise from corridors and indoor/outdoor common areas were the main dissatisfaction causes. It should be noted that one third of the dissatisfaction was caused by classroom architectural design (i.e., echoes). In addition, it should be noted that the mean sound pressure level (background noise) measured in the classrooms was above the level recommended by the WHO.

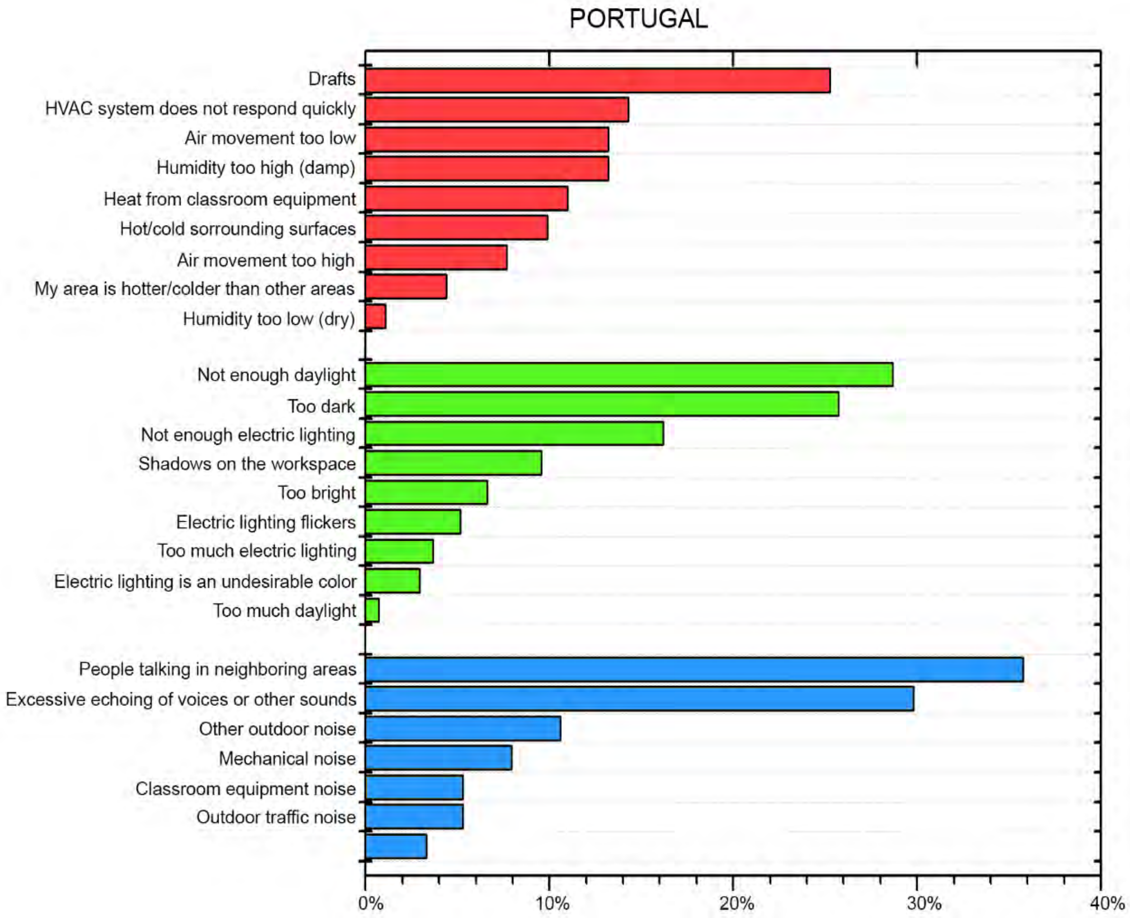


Figure 4-10. Causes of dissatisfaction in Portugal.

Among the causes of thermal dissatisfaction on the Fuentenueva campus (Figure 4-11), we found that drafts were the primary cause, with a value of 26%. This cause was followed by hot/cold surrounding surfaces (16%) and high air movement (13%). Two of these three causes are closely related to the measure of increasing the air exchange ratio in the classroom through natural ventilation (opening doors and windows generates drafts inside a classroom).

Regarding the indoor lighting environment, students have identified shadow effect in their workspace (23%), too much brightness (18%) and too much electric lighting (17%) as being the causes of the most dissatisfaction. These causes are opposite to those indicated by the students at the Azurém Campus.

In terms of acoustic dissatisfaction, outdoor traffic noise accounted for about one third of the votes among the causes of acoustic dissatisfaction (32%). Other external noise (25%) and people talking in neighbouring spaces (22%) represented almost half of the causes of dissatisfaction. As pointed out in the previous section, the Fuentenueva Campus is located in the centre of the city of Granada, so urban noises (e.g., traffic noise and noise from outdoor activities) influence the acoustic environmental conditions inside the classroom. This fact is aggravated due to the increase in the natural air renewal rate in the classrooms.

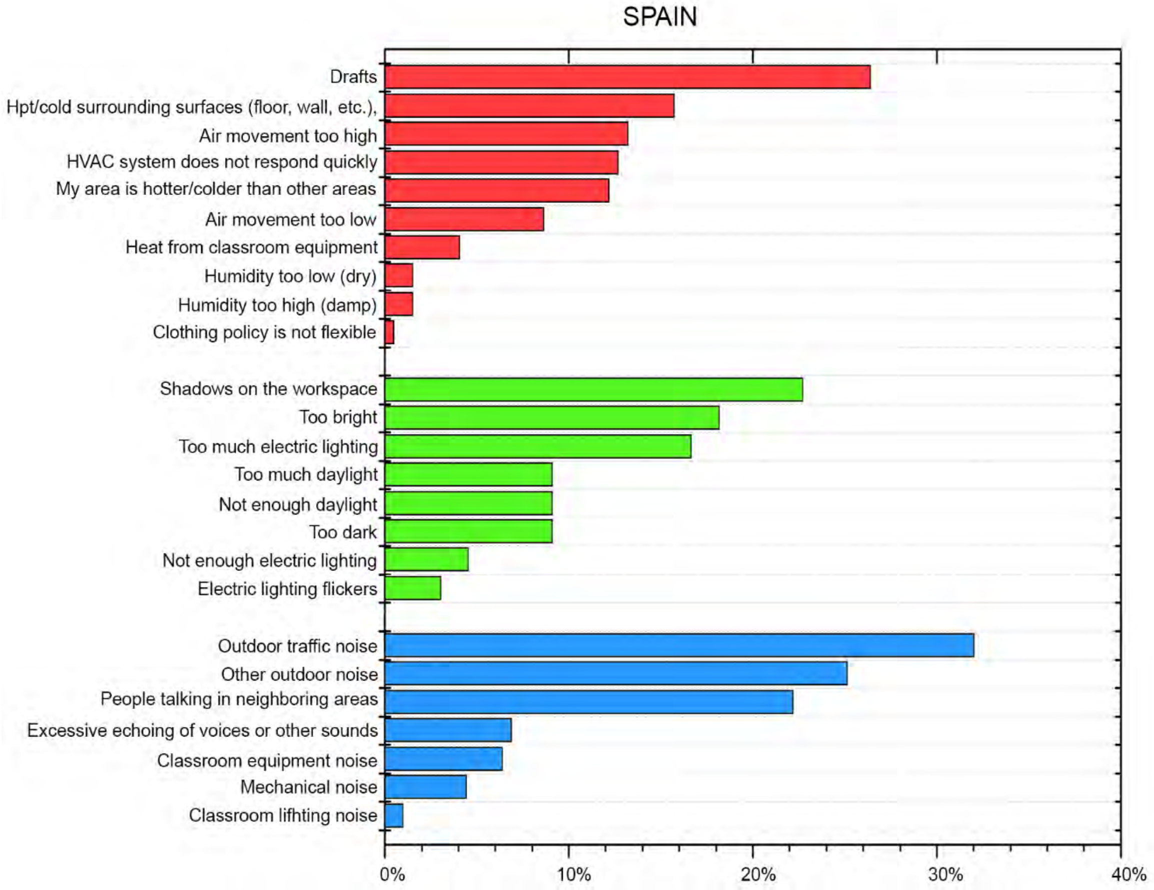


Figure 4-11. Causes of dissatisfaction in Spain.

4.3.4. Statistical analysis

This section shows the results obtained from the statistical analyses. Firstly, regarding the significant difference between the data obtained from both campuses, Kosmogorov-Smirnov test showed that the data did not met the normal distribution. Therefore, the Kruskal-Wallis test was used to examine the statistically significant difference between the groups. The results showed statistically significant difference between satisfaction, sensation and performance interference of all IEQ factors for the different campuses ($p < 0.02$), with the exception of light satisfaction ($p > 0.05$) (see Table B4-5 in Appendix B).

Secondly, Figure 4-12 shows the relationship between the satisfaction ratings of each variable (i.e., the thermal, lighting and acoustics) with its respective objective variable (i.e., the operating temperature, brightness and sound pressure level).

The relationship between the TSAV and the indoor operative temperature is shown in Figure 4-12a. The resulting equations and coefficient of determination (R^2) for both Spain and Portugal are shown in the scatter and Table B4-6 in Appendix B. A moderate relationship is shown for the Spain dataset ($R^2 = 0.52$; $p < 0.05$). The results show a higher thermal satisfaction when the operative temperature ranges from 21-27 °C in both locations. However, the mean TSAVs were below 0 when the operating temperature was outside this range. The significant of the association between TSAV and indoor operative temperature was examined using

Spearman correlation (Table B4-9). The results showed that a relationship between both variables ($\rho = 0.305$; $p < 0.01$). However, the results obtained from the measurement campaign carried out in Portugal, the results revealed an insignificant correlation between both variables.

Regarding the relationship between the mean LSAV and the mean lighting as well as the relationship between the ASAV and the background noise sound pressure level are shown in Figures 4-12b and 4-12c, respectively (Table B4-6). In the case of lighting satisfaction, at the Azurem campus, a nonlinear relationship was observed in the data set (Fig. 12b) that can be modeled as a polynomial fit. This may be due to the fact that too bright or too dark illuminance may cause discomfort. In the Fuentenueva campus data set (Fig. 12c), no relationship was observed. A negative linear relationship was observed for acoustic satisfaction for both campuses. In fact, similar results were reported in previous studies for both variables[152-154]. The same results were observed in the Spearman correlation test results, except for the relationship between ASAV and L_{Aeq} for Azurem Campus, showing a significant association between both variables ($\rho = -0.289$; $p < 0.001$) (Table B4-9).

Similar results were found from the analysis of the relationships between the interference votes and each of the indoor environmental variables (Figures 4-12d, 4-12e and 4-12f and Table B4-6). The coefficients of determination were low in all the cases. Regarding Spearman correlation test, the results indicated significant association between PTILP - T_{op} ($\rho = 0.307$; $p < 0.001$) in the case of Spain (Table B4-9).

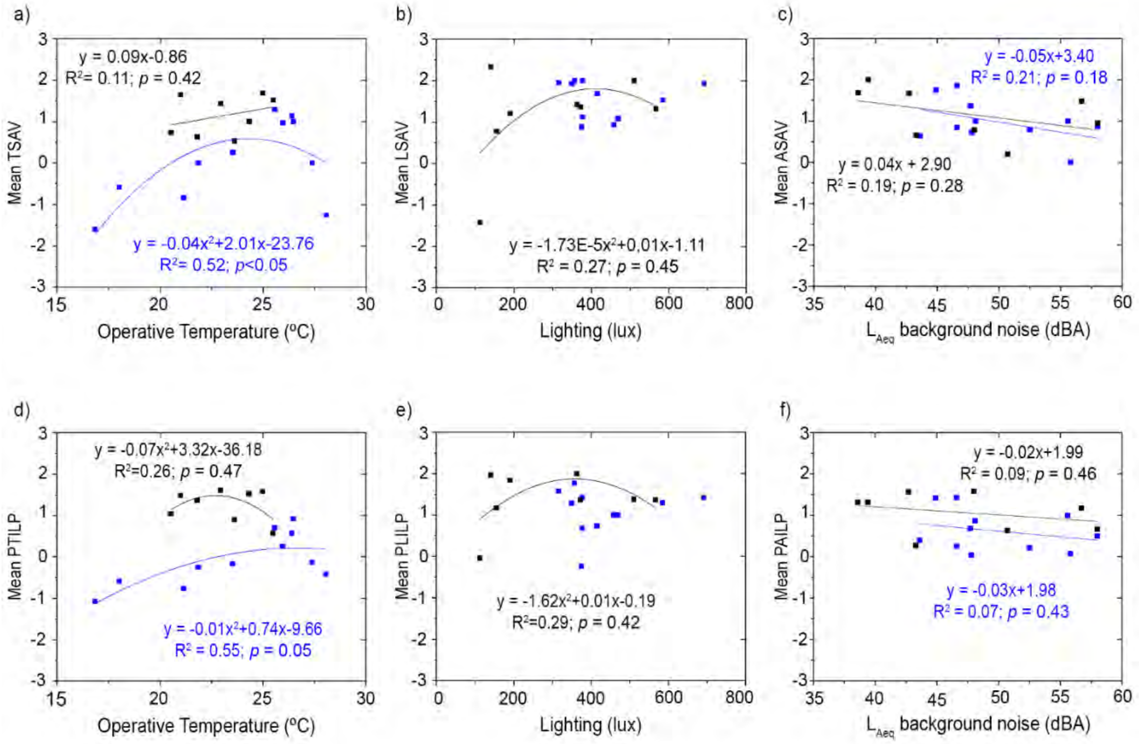


Figure 4-12. (a) TSAV versus operative temperature, (b) LSAV versus lighting, (c) ASAV versus background noise sound pressure level, (d) PTILP versus operative temperature, (e) PLIP versus lighting, and (f) PAILP versus background noise sound pressure level. The black squares indicate the Portugal dataset, and the blue squares indicate the Spain dataset. Statistical information is shown in Table B4-6 in Appendix B.

Since the operative temperature is the only indoor environmental variable that has shown a moderate-strong relationship with the TSAV and PTILP, the relationship between this variable and the TSV was analysed. The results are shown in Figure 4-13.

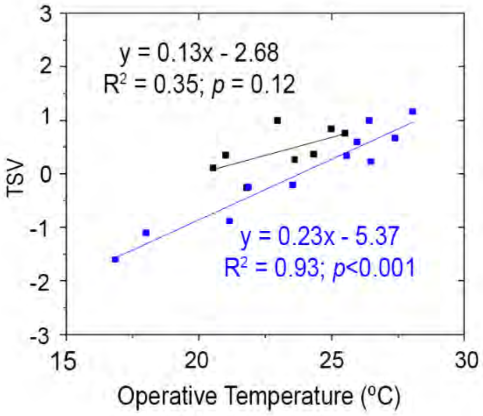


Figure 4-13. Linear regression of the TSV between indoor operative temperatures. Statistical information is shown in Table B4-8 in Appendix B.

As observed, the obtained coefficient of determination in Spain is much higher than that in Portugal. This value may be influenced by the fact that the range of measured operating temperature data at the Azurém Campus was much narrower than the range measured at

Fuentenueva Campus. However, previous studies showed similar values for the coefficient of correlation since there was a high variability for the TSV in each indoor air temperature [124, 155, 156]. Based on these results, the neutral temperature was calculated by a substitution of 0 for the TSV in both equations. Students from the Fuentenueva Campus had warmer preferences than the students from the Azurém Campus, since the neutral temperature obtained for the Azurém Campus (20.6 °C) was lower than that obtained for the Fuentenueva Campus (23.3 °C). In addition, Spearman correlation coefficient between these variables revealed a moderate-strong correlation in Spain (ρ = 0.533; $p < 0.001$) and a significant association in Portugal (ρ = 0.202; $p = 0.003$).

Additionally, the relationships between question OV.1 and the thermal, lighting and acoustic satisfaction votes were analysed. The linear regression results are shown in Figures 4-14a, 4-14b and 4-14c and Table B4-7. The mean overall satisfaction vote obtained from Portugal show a moderate relationship with the acoustic satisfaction vote (R^2 = 0.68; $p<0.05$) and thermal satisfaction vote (R^2 = 0.58; $p < 0.05$) and a weak relationship with the lighting satisfaction vote (R^2 = 0.36; $p = 0.11$). In the case of Spain, the mean overall satisfaction vote results show a moderately strong relationship with the thermal satisfaction vote (R^2 = 0.70; $p < 0.001$) and a moderate relationship with the lighting satisfaction vote (R^2 = 0.65; $p < 0.01$). In fact, Spearman correlation test indicated similar results: there was also a strong relationship between OV.1 and ASAV (ρ = 0.540; $p < 0.001$) in the case of Portugal, and between OV.1 and TSAV (ρ = 0.522; $p < 0.001$) in the case of Spain (Table B4-10). The results suggest that the satisfaction of Portuguese students was more influenced by the indoor acoustic conditions, while the satisfaction of the Spanish students was more influenced by the indoor thermal conditions.

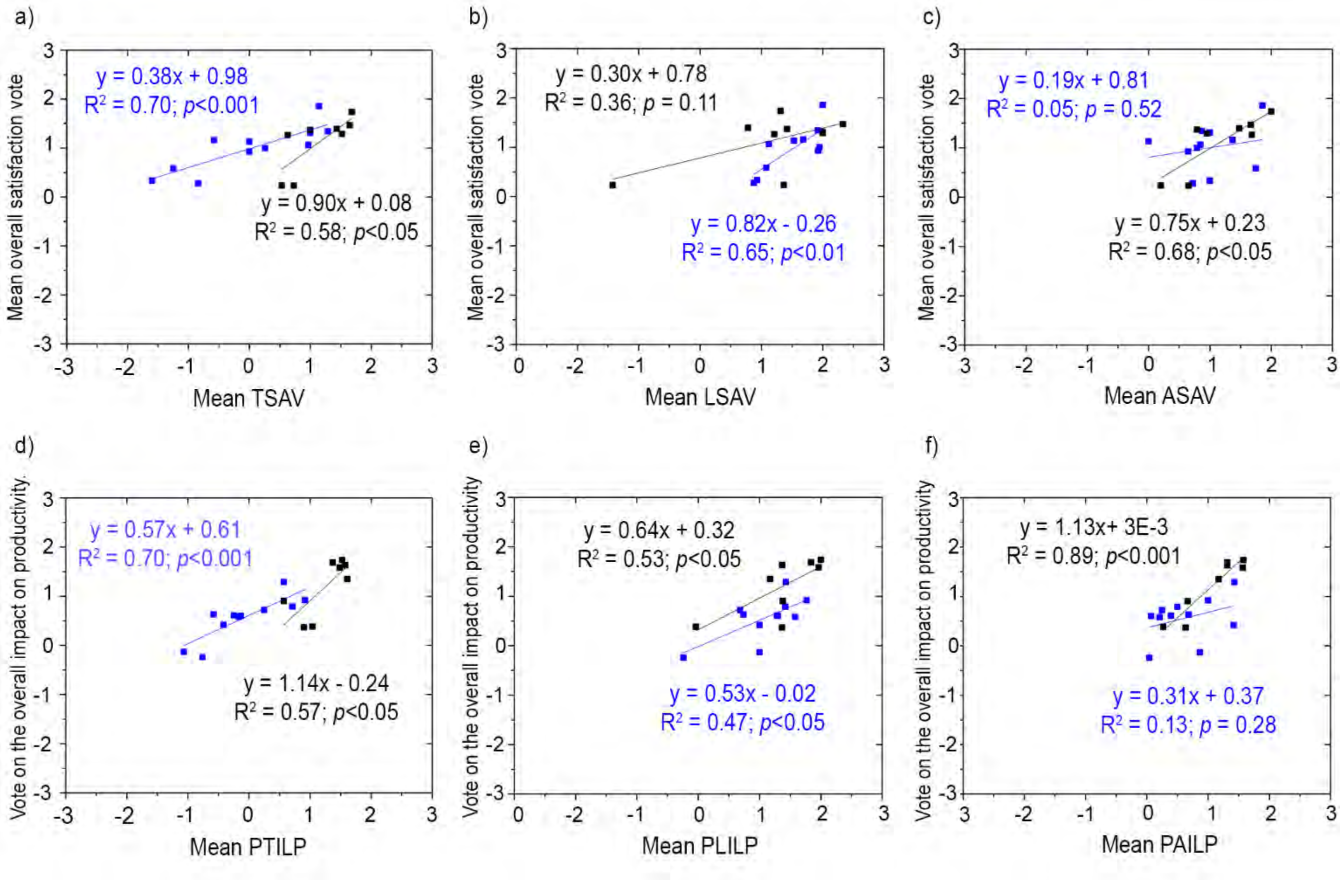


Figure 4-14. Linear regression of: (a) OV1 and TSAV, (b) OV1 and LSAV, (c) OV1 and ASAV, (d) OV2 and PTILP, (e) OV2 and PLILP, and (f) OV2 and PAILP. The black squares indicate the Portugal dataset, and the blue squares indicate the Spain dataset. Statistical information is shown in Table B4-7 in Appendix B.

The variation of the vote from the Portuguese students on the impact of general environmental conditions on their productivity is explained by the impact of the classroom acoustic conditions. This is indicated by a strong relationship between both variables (R^2=0.89;p<0.001). In addition, there was a moderate relationship between the interference of the lighting and thermal conditions on student performance (R^2 = 0.53; p < 0.05 and R^2 = 0.57; p < 0.05, respectively). However, Spearman correlation test provide closer values for interference of acoustic (ρ = 0.581; p < 0.001), thermal (ρ = 0.609, p < 0.001) and lighting (ρ = 0.546; p < 0.001) (Table B4-10).

Nevertheless, the analogous analysis of the responses obtained from the Spanish students at the Fuentenueva Campus shows a weak relationship with the indoor acoustic conditions (R^2 = 0.13; p = 0.28) and a weak-moderate relationship with the indoor lighting conditions. On the contrary, it shows a strong relationship with the impact of thermal conditions on student performance (R^2 = 0.70; p < 0.001). In fact, Figure 4-12d already showed a moderate relationship between indoor operative temperature and the impact on student performance. Spearman correlation coefficients were closed for the three variables.

4.4. Discussion

Previous studies carried out in educational buildings during mid-season prior to COVID-19 pandemic period found narrower ranges of variations for both variables (17.8 – 24.2 °C and 37-59% in Spain [126], and 20 – 23 °C and 30-60 % in North-Portugal [157]). Therefore, it is observed that the variation range of both variables is wider after the re-opening of the educational buildings as a consequence of the natural ventilation strategy.

In addition, this ventilation strategy of opening of doors and windows improved the indoor air quality inside the classrooms, as can be seen from the obtained CO_2 concentration levels. Both campuses had acceptable ventilation rates, with CO_2 concentrations ranging from 400 to 1000 ppm in Guimarães and from 399 to 617 ppm in Granada. Other studies conducted during the pandemic found similar CO_2 concentrations results [111, 158, 159]. These values are lower than the CO_2 concentration reported by previous studies conducted before the COVID-19 pandemic, i.e. Fernández-Aguera et al. [126] found that CO_2 concentration level ranged between 591 – 1995 ppm in educational buildings in South Spain, and Madureira et al. [157] reported that the 1000 ppm CO_2 concentration was exceeded during 70% of the occupation measurement time in educational buildings in North Portugal. Although these measures clearly improved the ventilation rates, they also caused an increase in background noise sound pressure levels inside the classrooms. Opening windows and doors for natural ventilation in classrooms do compromise the acoustic envelope insulation [160]. Indeed, an average of 47 dBA and 49 dBA were obtained respectively in Guimarães and Granada. Both values are above the recommended limit stated by the WHO for teaching-learning spaces (i.e., 35 dBA) [161].

The data obtained from the questionnaire showed significant differences between both campuses. Indoor acoustics and indoor lighting were the environmental variables with which Portuguese students were most dissatisfied. In contrast, Spanish students indicated that they were more dissatisfied with the indoor thermal environment.

Additionally, it should be noted that Spearman correlation test revealed a strong relationship between OV.1 and acoustic satisfaction in the dataset obtained from Portugal students ($\rho = 0.540$). In the case of Spanish students, a strong relationship was revealed by the Spearman correlation test between OV.1 and thermal satisfaction ($\rho = 0.522$).

Moreover, the variables that generated the greatest interference with the learning performance were the acoustic and thermal conditions for Portuguese and Spanish students, respectively.

The greatest cause of dissatisfaction indicated by the Spanish students related to the indoor thermal conditions was "drafts". Although the mean air velocity value was below 0.1 m/s during the field measurement campaign, values close to it may result in a risk of cold airflow for students. In contrast, the Portuguese students reported that their greatest cause of dissatisfaction was the indoor acoustic conditions due to "people talking in neighbouring areas. These causes of dissatisfaction are clearly related to the measures implemented due to the COVID-19 pandemic. Although the measure of social safety distance (1.5 m) was already removed, natural ventilation (through doors and windows) is still in place. As a consequence, some students were closer to the windows and may be exposed to drafts, while the others claimed that they did not experience enough air movement.

Regarding the relationship between the subjective responses and thermal sensation, the thermally acceptable zone ranged from 21.0-27.0 °C in both locations, and thermal neutrality was 20.7 °C at the Azurém campus and 23.3 °C at the Fuentenueva campus. It was found that students from the Fuentenueva campus had warmer preferences (neutral temperature = 23.3 °C) than students from the Azurém campus (neutral temperature = 20.7 °C). Warmer climatic conditions prevailing in Granada compared to Guimarães may influence the warmer thermal preference in Fuentenueva campus.

4.5. Research limitations

This study analysed the impact of post-epidemic protocols implemented in higher education buildings through a sensor monitoring campaign that has been conducted simultaneously with a questionnaire survey to examine the perceived impact of indoor environment on students. Although environment surveys are tools widely used to evaluate the sensation and satisfaction of occupants, they also have shortcomings when assessing some aspects such as the emotional state of the occupants [162]. Future research should consider the development of new methodologies that will focus on analysing the possible influence of these circumstances on students' behaviour, emotion and IEQ satisfaction, including the assessment of the impact on learning performance using objective test (e.g. mathematical calculations, concentration ability tests, etc.).

Additionally, it should be noted that the target population in this study were young university students who may be not as sensitive to indoor environmental conditions as other groups (e.g. elder people [163]). Since this is our target population, the results should not be extrapolated to other population groups without further analysis and verification. Therefore, further research would be needed to expand this analysis to different populations (e.g. children or older adults) since their distinguishing features and characteristics may affect the reported results.

In addition, it is noteworthy that the indoor air temperature was close to the outdoor air temperature due to the continuous ventilation strategies. Therefore, there was not a significant thermal gradient since the indoor environmental condition is highly affected by the outdoor conditions. These factors influenced the natural airflow rate, which is generated by two driving forces (wind and temperature differences) and they may change quickly. Although the average air velocity obtained from the field measurements did not exceed 0.1 m/s inside the classroom, the students closest to the openings (windows or doors) could feel it. Therefore, the PMV method may be unreliable under these circumstances and it should be used as an orientative or reference value for this study, since the thermal sensation of the occupants has been directly measured through the thermal sensation vote obtained from the questionnaire survey.

4.6. Conclusions

This study evaluated indoor environmental conditions during the re-opening of educational buildings in the post-epidemic COVID-19 scenario following the implementation of the "new normal" strategic measures in Spain and Portugal. Although post-epidemic protocols have provided effective air renewal and the mean CO$_2$ concentration levels remained below 900 ppm, the results suggest that their implementation have a significant impact in the degree of satisfaction with indoor environmental variables. The results of this study indicate that students are mostly dissatisfied with the acoustic and thermal conditions. In addition, the students indicated that these variables also affected their learning performance.

In addition, statistically significant differences were found between the preferences of the student from Fuentenueva campus and Azurem campus: Spanish students indicated warmer preference (neutral temperature = 23.3 °C) than Portuguese students (neutral temperature = 20.7 °C). In this sense, actions are needed to minimize the interference on students learning performances considering the preferences of individuals. This research shows that the impact follows well defined patterns that can be used for fine-tuning the final protocols that would be applied in this post-epidemic circumstances. For example, based on the results obtained in this research, the adaptation of the protocols during mid-season should consider prioritizing the improvement of acoustic conditions in the case of Azurém Campus, and minimizing the impact of thermal conditions in the case of Fuentenueva Campus. In any case, post-epidemic measures implemented during conditional normality scenario in educational buildings should improve these indoor environmental conditions, keeping spaces safe while minimizing the impact of post-epidemic protocols on student learning performance.

4.7. Appendix B

Table B4-5. Results obtained from the Kruskal Wallis test to determine the significant differences between the data obtained in Portugal and Spain.

	Satisfaction			Sensation			Interference		
	TSAV	LSAV	ASAV	TSV	LSV	ASV	PTILP	PLILP	PAILP
X^2	49.910	2.048	5.537	15.377	16.480	5.629	77.394	14.648	25.144
p-value	<0.001	0.152	0.019	<0.001	<0.001	0.018	<0.001	<0.001	<0.001

Table B4-6. Statistical information of regression between subjective and objective variables.

Input variables:		TSAV - T_{op}	LSAV – Lighting	ASAV- L_{Aeq}	PTILP - T_{op}	PLILP – Lighting	PAILP - L_{Aeq}
Spain	R^2	0.521	-	0.210	0.548	-	0.070
	p-value	0.047	-	0.183	0.050	-	0.432
	S.E.	0.730	-	0.506	0.478	-	0.510
	F	4.595	-	2.077	4.474	-	0.677
Portugal	R^2	0.110	0.274	0.192	0.263	0.293	0.094
	p-value	0.422	0.449	0.278	0.466	0.420	0.461
	S.E.	0.487	1.144	0.603	0.386	0.652	0.497
	F	0.744	0.942	1.424	0.892	1.038	0.619

Table B4-7. Statistical information of regression between subjective and overall responses.

Input variables:		OV1 - TSAV	OV1 - LSAV	OV1 - ASAV	OV2 - PTILP	OV2 - PLILP	OV2 - PAILP
Spain	R^2	0.699	0.654	0.047	0.699	0.467	0.129
	p-value	0.001	0.003	0.521	0.001	0.02	0.278
	S.E.	0.268	0.287	0.477	0.251	0.334	0.427
	F	20.906	16.982	0.447	20.899	7.897	1.335
Portugal	R^2	0.584	0.364	0.677	0.570	0.526	0.894
	p-value	0.027	0.113	0.012	0.030	0.042	<0.001
	S.E.	0.397	0.491	0.350	0.408	0.4286	0.199
	F	8.412	3.434	12.557	7.960	6.654	52.590

Table B4-8. Statistical information of regression between subjective and overall responses.

Input variables:		TSV -T_{op}
Spain	R^2	0.930
	p-value	<0.001
	S.E.	0.250
	F	118.819
Portugal	R^2	0.353
	p-value	0.121
	S.E.	0.361
	F	3.269

Table B4-9. Spearman correlation analysis between subjective and objective variables.

Input variables:		TSAV - T_{op}	LSAV - Lighting	ASAV- L_{Aeq}	PTILP - T_{op}	PLILP - Lighting	PAILP - L_{Aeq}
Spain	ρ	0.305	-0.019	-0.044	0.307	0.026	-0.024
	p-value	<0.001	0.777	0.515	<0.001	0.694	0.719
Portugal	ρ	0.030	0.114	-0.289	-0.049	0.030	-0.129
	p-value	0.659	0.094	<0.001	0.474	0.665	0.058

* ρ indicates Spearman's Rho coefficient

Table B4-10. Spearman correlation analysis between subjective variables and overall responses.

Input variables:		OV1 - TSAV	OV1 - LSAV	OV1 - ASAV	OV2 - PTILP	OV2 - PLILP	OV2 - PAILP
Spain	*ρ*	0.522	0.477	0.490	0.375	0.389	0.403
	p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Portugal	*ρ*	0.492	0.400	0.540	0.609	0.546	0.581
	p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

* *ρ* indicates Spearman's Rho coefficient

5. Analysis of Impact of Natural Ventilation Strategies in Ventilation Rates and Indoor Environmental Acoustics Using Sensor Measurement Data in Educational Buildings

The work in this chapter is based upon the following publication: de la Hoz-Torres, M. L., Aguilar, A. J., Ruiz, D. P., & Martínez-Aires, M. D. (2021). *Analysis of impact of natural ventilation strategies in ventilation rates and indoor environmental acoustics using sensor measurement data in educational buildings*. Sensors, 21(18), 6122. https://doi.org/10.3390/s21186122

5.1. Introduction

Since people spend more than 80% of their time in indoor environments [2], if the indoor conditions are deficient, the health and comfort of the occupants may be affected [164]. Building design and its characteristics are important factors of indoor conditions and, hence, the satisfaction levels of the occupants [165]. Indoor environmental quality (IEQ) is defined as an indication that relates the health and well-being of the occupants of interior spaces with the quality of the building's environment [3].

The IEQ is essential in educational buildings, which are typically designed for high occupancy for long periods of the day [24, 166]. In particular, a good indoor air quality (IAQ) is crucial to provide a healthy, safe, productive and comfortable environment [68]. Students, teachers and other school staff are vulnerable to the impact of poor IAQ in these spaces, where concentration and intellectual work is required. Indoor air pollutants (i.e., inorganic/organic gases and biological and non-biological particles) accumulate more easily in indoor environments as a result of the building envelopes which intentionally separate occupants from the outside [167]. Exposure to air pollutants may cause a risk of short- and long-term health problems, such as several respiratory diseases [20, 21], cardiovascular disease [22], irritated eyes or nose, blocked nose, headaches and so forth [23]. In addition, poor IAQ may affect the comfort, productivity and academic achievement of students [6,13,14]. Therefore, IAQ is of particular concern in teaching-learning spaces.

These circumstances determine that one of the most demanding challenges facing educational building administrators is IAQ managing [52]. An adequate ventilation rate (VR) is one of the key elements to avoid compromising the IAQ since providing outdoor air ventilation dilutes internally generated contaminants to levels that do not cause health and comfort problems [27]. The analysis of the VR based on measured studies and the adequately characterised ventilation design of buildings are critical for assessing and interpreting IAQ [168, 169]. Selecting an appropriate ventilation strategy is essential for meeting the requirements for good IAQ. International guidelines, standards and building codes state a minimum VR in buildings [29-32]. However, it should be noted that previous research suggests that in order to substantially decrease illness absence and therefore produce economic benefits, one of the measures that can be taken is to increase classroom VRs above the State standard [149].

This fact has been highlighted by the COVID-19 pandemic. According to the World Health Organization, as of 7 July 2021, there had been 3,997,640 deaths and 184,572,371 confirmed cases of COVID-19 reported globally [45]. Transmission of SARS-CoV-2 occurs when uninfected people are exposed to infectious respiratory fluids after contact with infected people [46]. Factors contributing to increased transmission include: loud speech volume; intense physical activity; lack of well-fitting face masks; large numbers of people in the same space; decreased interpersonal distance; increased emission and exposure time and poor indoor VR [47]. Moreover, recent research has shown that transmission can be aggravated in confined and poorly ventilated spaces. Indeed, Nishiura et al. [48] state that COVID-19 transmission can be up to 18.7 times higher in confined spaces than in open air spaces. Park et al. [49] suggested that cross-ventilation is more efficient compared to single-sided ventilation, and recommend cross-ventilation to minimise the possibility of infection in high-density public buildings. According to Dai and Zhao [170], for a classroom with a volume of 348 m^3 and for an exposure period of 2 h, to keep the probability of infection below 1%, a VR of two Air Changes per Hour (*ACH*) with masks and seven *ACH* without masks is necessary.

Since students and teachers spend long periods each day in classrooms, these indoor spaces are risk environments for the airborne transmission of SARS-CoV-2 [50]. Consequently, measures adopted by governments to minimise the possibility of contagion included the closure of educational buildings. As a result, nearly half of the world's students are still affected by this measure and more than 100 million additional children will fall below the minimum level of reading proficiency [51]. The United Nations Educational, Scientific and Cultural Organization (UNESCO) warns that it is crucial to prioritise education recovery in order to avoid a generational catastrophe [51]. Adopting effective mitigation strategies to control the risk of airborne infection and adapting educational-learning spaces are essential processes to mitigate the impact of educational building closures. The reopening of educational buildings has had many socio-economic implications in all countries, and therefore countries are taking actions to ensure that educational buildings are safe spaces. In this regard, the Spanish Government's prevention guidelines require the use of well-fitted facemasks (a surgical mask is a minimum), reducing the volume of the voice in conversation, increased interpersonal distance and reduced contact time (e.g., reducing the occupation of indoor spaces) and improved ventilation in indoor spaces. Ventilation strategies are a key aspect of indoor spaces management in this context. In the case of natural ventilation, cross-ventilation (opening doors and/or windows on opposite sides) is recommended [47]. For mechanical ventilation, attention should be paid to the configuration of the system, to reduce the recirculation of air and increase/maximise outside air. The VR is measured by ACH. The recommended VR in indoor spaces for good air quality is 12.5 litres/second per person (L/s/p), which corresponds to approximately 5-6 ACH.

However, while these ventilation strategies ensure an optimal concentration of CO_2 and other pollutants, they also have an impact on other important indoor variables in indoor environments. One of the most important in teaching-learning spaces is the indoor acoustic environment, which is influenced by the natural and/or mechanical ventilation strategy selected [171]. In recent years, perceived acoustic quality in indoor environments has gained momentum and recent research has focused on indoor soundscapes [172, 173] Acoustic design and strategies should include noise control and perceptual approach of the users in order to enhance people's health and well-being [174, 175]. In this sense, Tang [176] analysed available façade noise control strategies for introducing devices while improving natural ventilation in buildings. The findings of his study show that, in congested cities, protrusive devices such as balconies, lintels and fins are not effective noise screening devices for high-rise buildings (even with sound absorbers and/or reflectors). Active control installation and resonance-based devices often result in bulky systems, affecting the façade design and the effectiveness of natural ventilation strategies. Systems such as plenum windows and double-wall plenum structures are often useful as natural ventilation and noise control devices. In addition, research is being conducted on the development of new window devices. Fusaro et. al. [177, 178] proposed a new metacage window which allows natural ventilation and noise reduction based on the principle of Snell's Law. The used of this novel prototype showed an overall mean sound reduction of 15 dB within a bandwidth of 380 to 5000 Hz.

In this context, the management of natural ventilation strategies and their impact in the indoor acoustic environment is essential in the teaching-learning spaces. Poor acoustic environments in classrooms affect learning achievements [7, 8] as well as the academic, psychosocial and psychoeducational performance of students [6]. Moreover, these may cause voice problems [179] and physical stress in teachers [180], and have significant effects on word identification and intelligibility [9]. External noise sources to educational buildings as well as sources within the building (e.g., in facilities rooms, contiguous spaces, etc.) influence the background noise inside the teaching-learning spaces. In order to achieve an adequate acoustic comfort and speech intelligibility to ensure the quality of educational processes the background noise level should not exceed the sound level of 35 dBA [161, 181]. Therefore, acoustic comfort is critical in determining the quality of educational processes. This fact makes it necessary to evaluate the impact of the ventilation strategies on IEQ parameters such as IAQ and acoustic performance. This is the main general purpose of this research.

In this context, and given the 6 *ACH* values recommended in current Spanish public policies to prevent the transmission of COVID-19, the aim of this study was to characterise their impact on the variables conditioning IAQ and the indoor acoustic environment. The study assesses the need to define health protocols for ventilation in educational buildings that, in addition to identifying natural ventilation strategies with a VR value as close as possible to the required *ACH* value, take into account the background noise level. This will therefore ensure the quality of teaching and learning processes while maintaining the required ventilation protocols.

5.2. Methodology and Data Collection

With the aim of characterising the impact of natural ventilation strategies on the variables conditioning IAQ and the indoor acoustic environment, natural ventilation efficiency was checked in three ventilation scenarios with different window and door opening configurations. Background equivalent continuous sound pPressure level (Leq) in dBA was also calculated from sound pressure levels measured in the configuration that provided sufficient VR through natural ventilation according to the current regulatory limit. This value was compared with the background equivalent continuous sound pressure level, measured in the closed doors and windows scenario. This section describes the study area, the data-collection methodology and the sensors used in the process. Figure 5-1 shows an overview of the study's methodological approach.

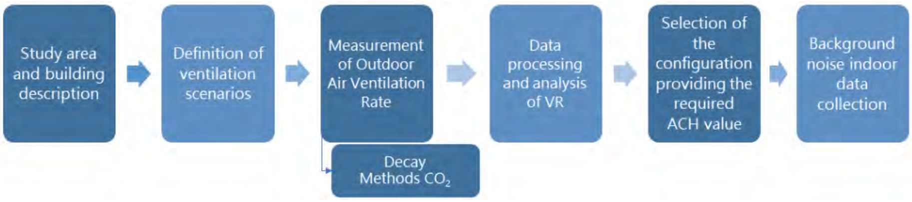


Figure 5-1. Diagram of the study's methodological approach.

5.2.1. Study Area and Building Description

The study comprises educational buildings from the Fuentenueva Campus of the University of Granada, located in Granada (Spain). The field measurements were conducted between March and April 2021 (spring season) in the Advanced Technical School for Building Engineering (built in 1972) and the Advanced Technical School for Civil Engineering (built in 2000) (Figure 5-2).

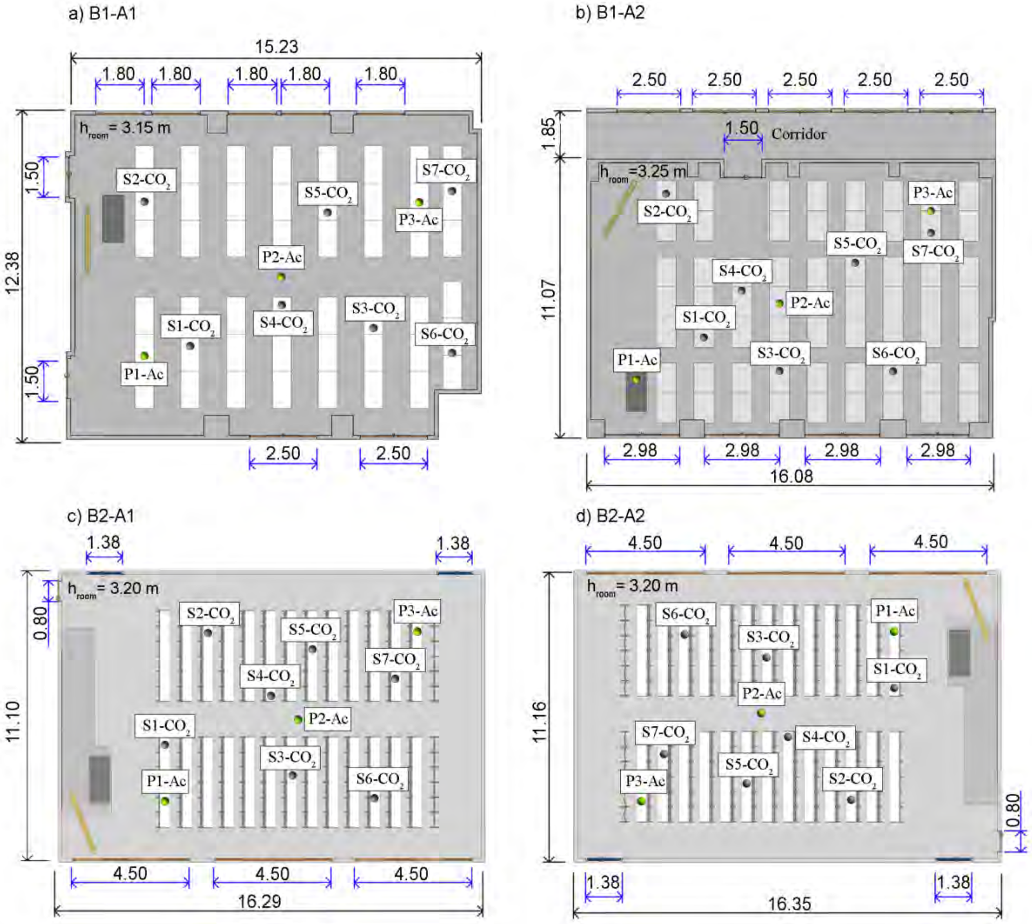


Figure 5-2. Location of the sensors during the experimental tests performed in each classroom; (a) B1-A1 classroom; (b) B1-A2 classroom; (c) B2-A1 classroom. (d) B2-A2 classroom; Blue dimensions indicate size of the openings; Black dimensions indicate sizes of the room; Green spheres indicate the position of the acoustic sensors; Grey spheres indicate the position of CO_2 sensors (dimensions in meters).

Face-to-face teaching was suspended at the University of Granada from October to January in response to COVID-19. The tests were carried out before the adaptation of the teaching spaces to the return to face-to-face teaching activities. For this purpose, ventilation and acoustic measurements were carried out in the newly adapted spaces. Granada is classified as a C3 zone by the Spanish Technical Building code CTE [182]. This zone is characterised by short, very hot and mostly clear summers and long, cold and partly cloudy winters. During the course of the year, the temperature generally varies from 0 °C to 34 °C and rarely drops below −4 °C or rises above 38 °C.

Two representative classrooms were selected for each building based on the data provided by the COVID-19 Action Plan developed by the University of Granada [120]. This plan defines institutional policies and guidance on occupational health and safety, which include: mandatory masks indoors, 50% occupancy, physical distancing (at least 1.5 m) and that indoor spaces must be ventilated naturally through open windows and doors. Within this framework, and in order to adapt the general measures established by the general action plan, the Academic Direction of each Technical School drew up an action plan adapted to their needs and to the characteristics of their spaces. The selection of these spaces took into account all the measures developed in this context.

Table 5-1 shows the characteristics of the classrooms. The process of characterisation and analysis starts with the selection of representative classrooms from the buildings of the campus. It should be noted that each selected classroom has a different orientation and that their geometry allows them to meet the requirements set out in the COVID-19 Action Plan. In addition, their different characteristics allow different ventilation strategies to be analysed: Classroom B1-A1 has windows on opposite sides, so natural cross-ventilation strategies can be assessed; Classroom B1-A2 is accessed through a corridor with windows, so cross-ventilation through corridors can be assessed; Classrooms B2–A1 and B2–A2 have identical geometries but are located on opposite sides of the building, such that ventilation strategies can be compared according to the location of the room.

Table 5-1. Characteristics of the classrooms.

Building	Id Class	Area [m^2]	Volume [m^3]	Orientation	Occupation Pre-Covid-19 [seats]	Occupation Ratio [m^2/student]	Occupation Covid-19 [seats]	Occupation Ratio [m^2/Student]
Building 1 (ETSIE)	B1-A1	175	524	East	96	1.82	48	3.27
	B1-A2	167	500	West	61	2.73	35	4.77
Building 2 (ETSICCP)	B2-A1	172	518	North	156	1.10	78	2.20
	B2-A2	174	522	South	156	1.12	78	2.24

5.2.2. Decay Method to Determine Air Change in Natural Ventilation in Classroom

The decay method can be used in unoccupied spaces using a tracer gas such as CO_2. The aim of this method is to determine the *ACH*. In fact, the decay method consists of increasing the CO_2 concentration by using a CO_2 generation source (e.g., dry ice) [79] in the classroom until a homogeneous and well-mixed mixture is reached [16,51,52]. Subsequently (without source and unoccupied) the rate of decrease of the CO_2 concentration under the different configurations is determined. The experimental test ends when the CO_2 level approaches 37% of its original peak concentration above the background [86, 87]. For this purpose, the CO_2 concentration is measured at known times and the *ACH* can be estimated using Equation (5-1):

$$ACH = \frac{-1 * \ln\left(\frac{C_{end} - C_{outdoor}}{C_{start} - C_{outdoor}}\right)}{t_{end} - t_{start}} \qquad (5\text{-}1)$$

where C_{end} is the measured CO_2 concentration at the end of the decay curve, t_{end} is the end time of the decay curve, C_{start} is the measured CO_2 concentration at the start of the decay curve, t_{start} is the end time of the decay curve and $C_{outdoor}$ is the measured CO_2 concentration outside the building.

Otherwise, in order to fit a solution to the decay concentration process using a regression or other means, a sequence of CO_2 concentrations over a portion of the decay period, C_t, is used as shown in Equation (5-2) [27]:

$$C_t = (C_{Start} - C_{outdoor})exp(-ACH * t) + C_{outdoor} \qquad (5\text{-}2)$$

where t is the measurement time in hours. In addition, Equation (2) can be rearranged to be linear in time as (Equation (5-3)):

$$ln(C_t - C_{outdoor}) = -ACH * t + ln(C_{Start} - C_{outdoor}) \qquad (5\text{-}3)$$

where C_{Start} is the steady-state CO_2 concentration at the start of the test. The estimated *ACH* is the slope of the regression of *ln*(C_t—$C_{outdoor}$) against time *t*.

In this study, this method was applied for the VR characterisation of three configurations for each classroom. The values obtained were used to compare the *ACH* provided by each configuration. In addition, and given that the re-opening guidelines [47] recommend a ventilation rate of 12.5 litres per second and person to achieve good air quality (corresponding to approximately 5-6 *ACH*), the configuration providing the required *ACH* value was selected.

5.2.3. Background Noise Indoor Data Collection

In order to characterise the indoor acoustic environment in different configurations of natural ventilation strategies, the sound pressure level of the background noise was measured in the different configurations. For this purpose, a two-phase methodology was followed: in the first phase, the background noise was measured in the classroom with all doors and windows closed. Subsequently, in phase two, the background noise was measured with the natural ventilation configuration selected based on the experimental results of the decay method previously obtained (i.e., the configuration that provided the required *ACH* value).

During the field measurement period, three acoustical measurements were made at three seat locations in the classroom (front, middle and back) in both phases, resulting in nine measurements in each phase. The locations were selected because they were typical listener positions inside the classroom. The measurements were recorded at least 1.2 m away from the ground, 0.7 m between measurement positions and at 0.5 m. away from any wall, ceiling or ground surface, in compliance with the UNE-ISO 1996-2:2020 [183] recommendations (details about the instrument and positions are shown in Section 5.2.4 and Figure 5-2). Each measurement consists of a binaural recordings signal, which contains background noise and has a duration above 15 min. This minimum measurement time interval was selected because previous studies have identified that activity background noise level measured for a long time (4 h) was not found to be statically different from the values obtained over 15 min [184, 185]. The measurements were recorded at the ear position using a head-torso manikin (height: 1.30 m) located in the listener positions previously selected. The manikin was stably fixed to perform the recordings in a stationary condition in order to avoid additional noise. The manikin's head was oriented towards the typical teacher's position in the classroom.

The continuous equivalent sound pressure level (Leq) of each acoustical measurement was calculated as the averaged equivalent-energy of the sound pressure levels from the left and right channels during the measuring time. Based on these measurements, an energy averaging of the acoustic measurement in each configuration was performed with the aim of obtaining a sound-level value (dBA) representative of each configuration.

The obtained values were then compared with the limits for the ambient noise level for teaching-learning spaces recommended by the World Human Organization (WHO) [161] and ANSI/ASA S12.60-2010/Part 1 [181]. Both organisations recommend sound-level values below 35 dBA.

5.2.4. Sensors and Data Collection

The HOBO® MX1102 logger was used to measure the CO_2 concentrations in the classroom. The instrument has a measurement range from 0 to 5000 ppm (accuracy ± 50 ppm ± 5% of reading at 25 °C, less than 90% RH non-condensing and 1.013 mbar). The sensing method is non-dispersive infrared (NDIR) absorption. Regarding the acoustical signals recordings, these were made using a Squadriga I recorder and BHS I headset/microphone unit. The sampling rate of the external microphones was 48 kHz. Maximum sound pressure level of 130 dB_{SPL} and frequency response of 4 Hz to 20 kHz.

Figure 5-2 shows the position of the sensors in the experimental tests for each classroom. Seven HOBO® MX1102 sensors were used during the decay method experimental tests, numbered in Figure 5-2 as sensor S1-CO_2 to sensor S7-CO_2. With regard to the acoustic measurements, they were performed in the locations P1-Ac, P2-Ac and P3-Ac (front, middle and back position in the audience respectively).

One of the fundamental requirements established in the COVID-19 Action Plan elaborated by the University of Granada was to establish natural ventilation through open windows and doors, even in adverse weather conditions [120].

For this reason, different scenarios of window and door opening combinations were selected to generate each configuration. Three types of configurations were defined for each of the four selected classrooms (Table 5-2). Experimental tests were carried out in order to evaluate the configuration that provides sufficient ventilation according to the COVID-19 standards. In addition, the impact of the selected configuration on the acoustic comfort was evaluated.

Table 5-2. Configurations for natural ventilation strategic tests.

Classroom	Configuration	Doors and Windows Opening Combinations
B1-A1	C-1	All windows opened and main door opened.
	C-2	End windows opened and main door opened.
	C-3	Only windows at the end in west façade opened, the centre windows in east façade opened (”Y” configuration) and the main door opened.
B1-A2	C-1	All windows opened, main door opened and the corridor windows opened.
	C-2	All windows opened, main door opened and the corridor windows closed.
	C-3	Only the windows at the end opened and main door opened, and the corridor windows opened.
B2-A1	C-1	All windows opened and two doors opened.
	C-2	All windows opened and main door opened.
	C-3	Only windows at the end opened and main door opened.
B2-A2	C-1	All windows opened and the two doors opened.
	C-2	All windows opened and the main door opened.
	C-3	Only windows at the end and the main door opened.

5.3. Results

In the next sections, results are presented for the three configuration scenarios of the four classrooms previously described. Firstly, each section shows the data obtained from the experimental tests of the decay method and the average *ACH* results. Subsequently, the background noise sound pressure levels Leq obtained in two different ventilation scenarios are shown: (1) doors and windows closed; and (2) the natural ventilation configuration that provides the *ACH* value required (based on the decay method experimental results previously obtained).

5.3.1. Building 1—Classroom A-1 (B1-A1): Windows-Based Natural Cross-Ventilation Strategies—East Orientation

Figure 5-3 shows the decay methods results obtained for the three different configurations selected for the classroom B1-A1. In addition, the regression of ln(C1-CR) against time t is shown in Table C5-3 in Appendix C. Differences between the data recorded by each sensor are observed for the three tested scenarios. These are mainly due to the different relative positions of the sensors from the windows and doors, and may also derive from the indoor air currents. This fact is applicable also to all the tested natural ventilation scenarios shown in the following sections.

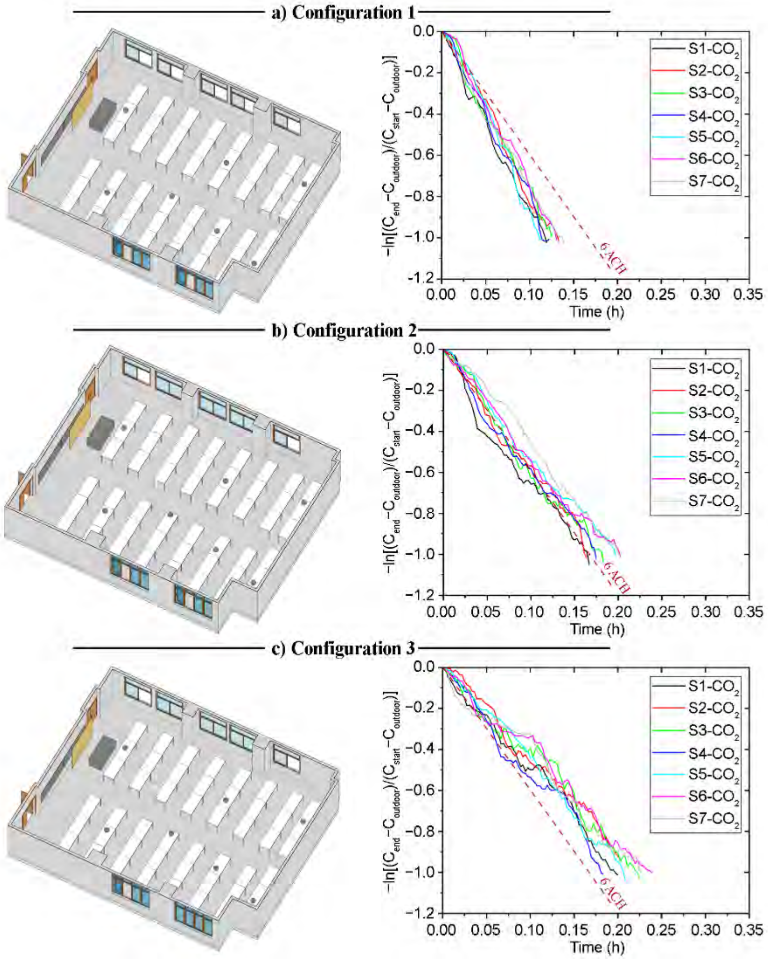


Figure 5-3. Configuration schemes and decay curves in Classroom B1-A1; (a) Configuration 1; (b) Configuration 2; (c) Configuration 3.

Based on the values shown in Table C5-3, the slope value obtained in the fitting curve of each case indicates the *ACH* value for the configuration measured at each point. As can be seen in Figure 5-4, which shows the *ACH* obtained in each configuration, the ACH values obtained are homogeneous. It should be noted that C-1 configuration is the one that provides the highest number of ACH. The *ACH* values in C-1 varied from 7.4 to 9.4 with a mean of 8.3 ± 0.6 per hour, whereas configuration C-3 shows the lowest ventilation rates, from 4.3 to 5.1 with a mean of 4.6 ± 0.3 per hour. Following the recommendations of the Spanish Ministry of Health [47], the recommended ventilation rate for indoor spaces (such as classrooms) is a minimum of 6 ACH. As we can see in Figure 5-4, the configuration that satisfies this premise is configuration C-1 (all windows opened and main door opened), in which the ventilation rate is higher than the 6 *ACH* value for all sensors.

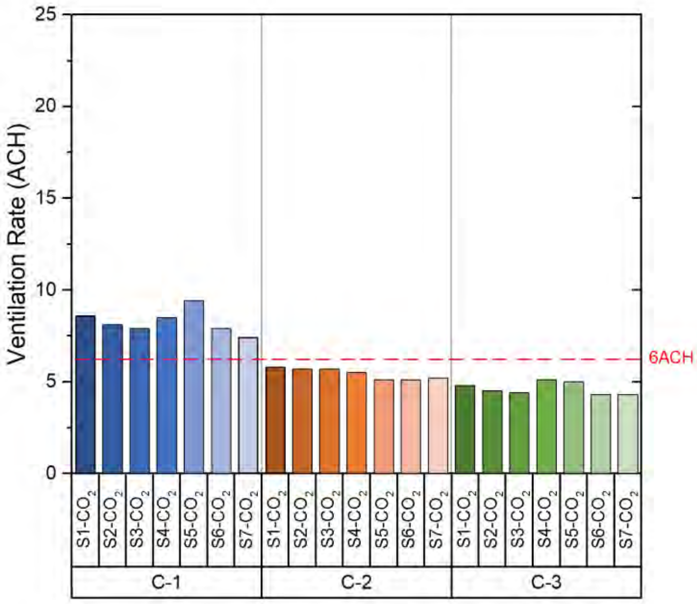


Figure 5-4. Ventilation rate (ACH) in Classroom B1-A1.

Since configuration C-1 provides an *ACH* value above 6, it was selected in order to evaluate the background noise in this scenario. Hence, the background noise was measured in the following two configurations: (1) windows and door closed and (2) configuration C-1. As shown in Figure 5-5, the background Leq in the C-1 configuration is 12 dBA above the Leq measured in the same classroom with windows and door closed.

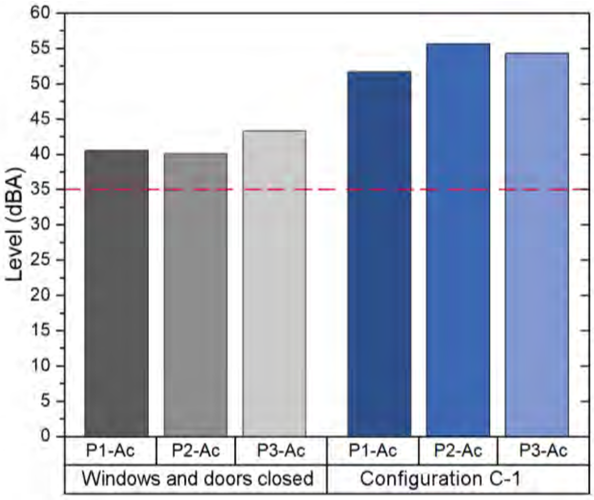


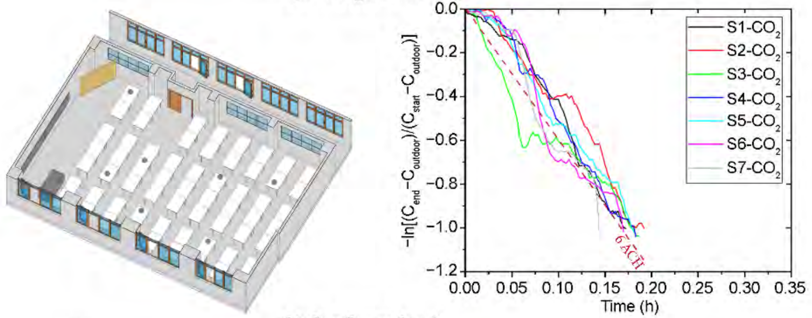
Figure 5-5. Background noise levels in classroom B1-A1.

The background noise Leq for the C-1 was 54.1 dBA. This value is above the background noise Leq with windows and door closed (41.5 dBA) and the value recommended by WHO (35dBA). Exposure to traffic noise is the main problem in this classroom, since it is located in the east façade of building 1, close to the main street of this district. The traffic noise has a high impact on the background noise of the classroom, since in order to achieve an adequate VR it is necessary to open all windows and the main door.

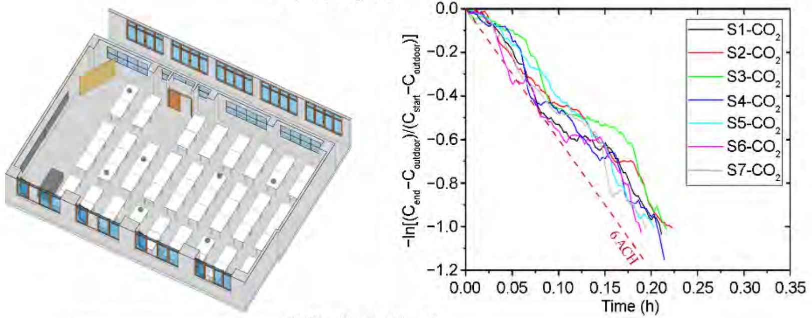
5.3.2. Building 1—Classroom A-2 (B1-A2): Cross-Ventilation through Corridors Strategies—West Orientation

The experimental results obtained in the tests performed in the classroom B1-A2 are shown in this section. This classroom is characterised by the fact that it can only generate natural ventilation through the windows located on its west side and the main door on its east side. In this respect, the different natural ventilation strategies have been analysed, taking into account scenarios with different opening configurations of these windows, the opening of the door and the possibility of opening the corridor windows. The decay methods results for the three configurations are shown in Figure 5-6. In addition, the data are analysed by fitting a curve using linear regression, as shown in Table C5-4 in Appendix C.

a) Configuration 1



b) Configuration 2



c) Configuration 3

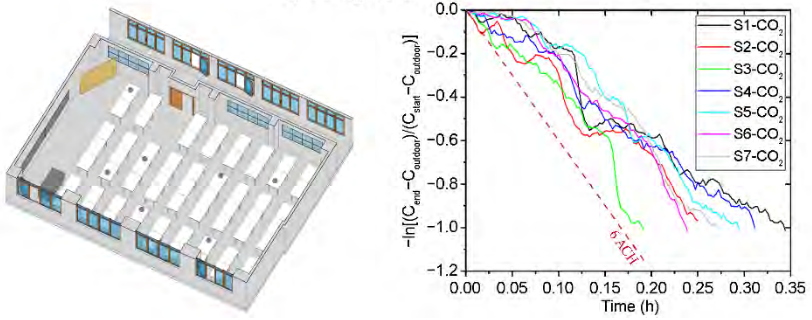


Figure 5-6. Configuration schemes and decay curves in Classroom B1-A2. ; (a) Configuration 1; (b) Configuration 2; (c) Configuration 3.

The *ACH* values obtained from each sensor are shown in Figure 5-7. As was seen in the case of the classroom B1-A1, the *ACH* values are homogeneous between the sensors in each configuration. If the data obtained for each configuration are compared, it is possible to appreciate that the *ACH* is higher in configuration C-1. The values obtained in both configuration C-2 and configuration C-3 are similar. However, configuration C-2 and C-3 provide *ACH* values below the recommended *ACH* limits stated in the legislation related to COVID-19.

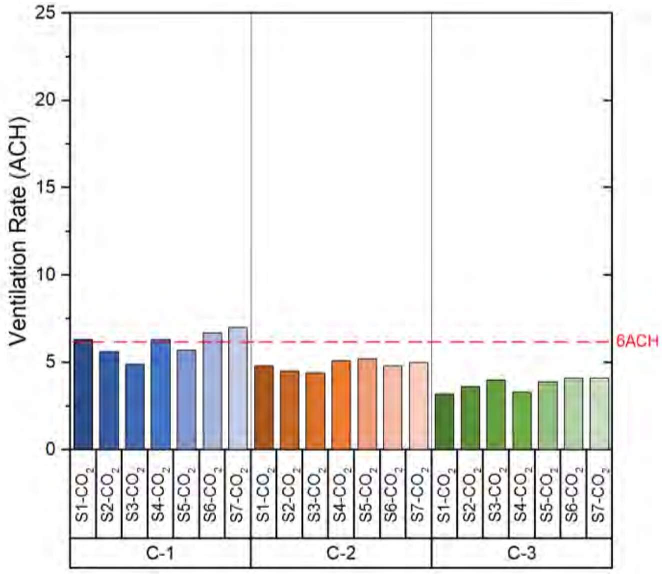


Figure 5-7. Ventilation rate (ACH) in Classroom B1-A2.

In addition, the results obtained from the field acoustic measurement are shown in Figure 5-8. Since the C-1 configuration (i.e., all windows opened, main door opened and the corridor windows opened) provides an *ACH* higher than the recommendation set by the ministry guidelines (6 ACH), the background Leq was analysed first in the scenario with closed windows and door, and then in the scenario of configuration C-1. The average Leq value obtained in configuration C-1 was 44.5 dBA, 6.4 dBA above the Leq in the configuration of closed windows and door and also above the value recommended by the WHO (35 dBA).

In contrast to the classroom B1-A1, classroom B1-A2 is orientated towards a green zone in the opposite façade and a corridor. In this case, the dominant source of background noise is the noise generated by the students themselves when interacting with university activities.

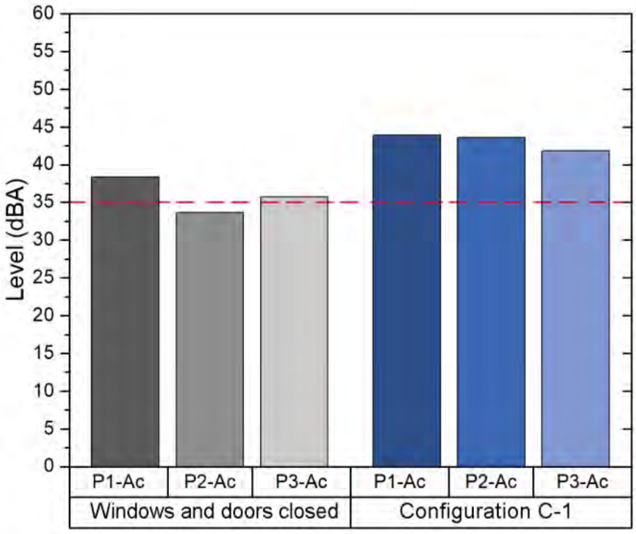
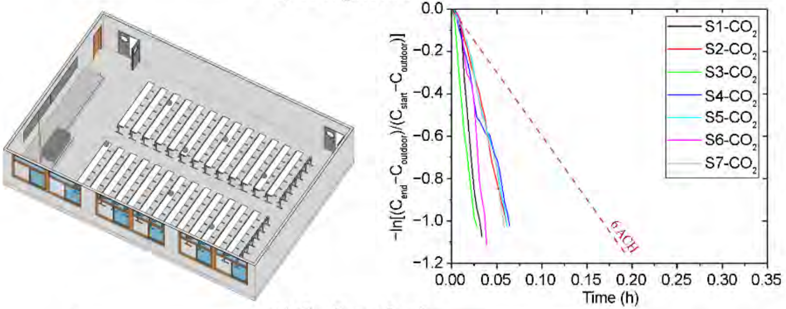


Figure 5-8. Background noise levels in classroom B1-A2.

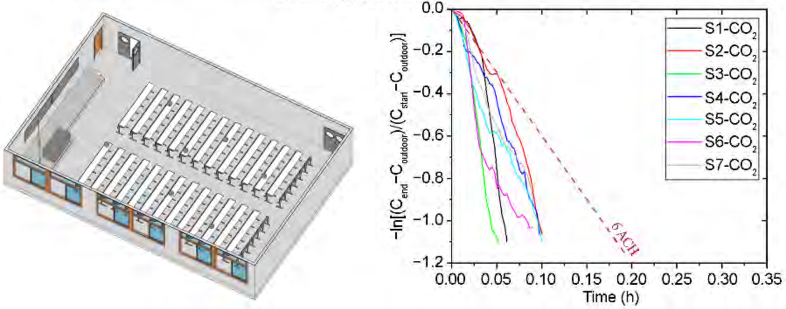
5.3.3. Building 2—Classroom A1 (B2-A1): Natural Cross-Ventilation Strategies—North Orientation

Classroom B2-A1 is characterised by two doors located at the ends of one of its side walls. This wall is parallel to the side west wall, which contains the only windows in the room. These characteristics have been taken into account in the analysis of the different natural ventilation strategies. The field measurements were used to analyse the *ACH* in each configuration. The data obtained are shown in Figure 5-9 and Table C5-5 in Appendix C.

a) Configuration 1



b) Configuration 2



c) Configuration 3

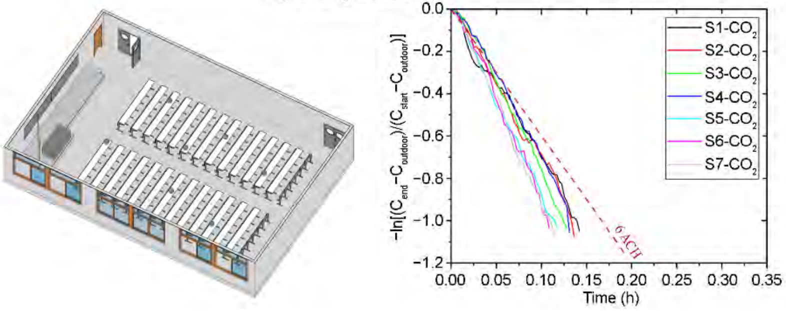


Figure 5-9. Configuration schemes and decay curves in Classroom B2-A1. ; (a) Configuration 1; (b) Configuration 2; (c) Configuration 3.

Figure 5-10 shows the *ACH* value obtained from the sensors for each of the configurations. Configuration C-1 provides *ACH* values far above the other configurations. The range of values obtained depends on the relative location of the sensors within the room. In this case, all configurations provide an *ACH* above the minimum set by the ministry's guideline recommendations. However, the decay rate of the CO_2 concentration in the case of configuration C-1 is caused by the air currents when opening the windows and doors. While such a high *ACH* is very safe, a high airflow through the windows may affect the comfort of the users. A configuration such as C-3 is preferable, which provides an *ACH* higher than the minimum set out in the guidelines, ensuring that ventilation will not impact on the performance and comfort of the students.

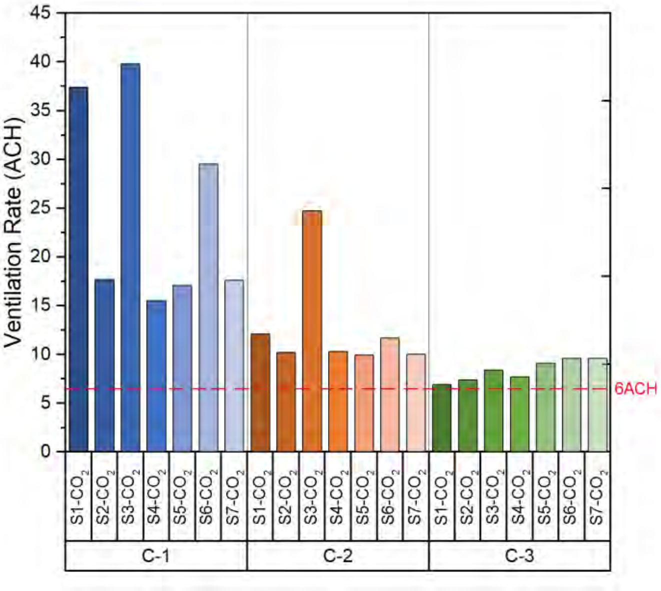


Figure 5-10. Ventilation rates (ACH) in Classroom B2-A1.

In addition, the values obtained from the acoustic field measurements are shown in Figure 5-11. These values were measured in two scenarios: first closed windows and door, and then in the scenario with the configuration C-3 (i.e., only windows at the end opened and main door opened). The average background Leq value obtained in the measurement of the configuration C-3 is 43.7 dBA, 7.2 dBA higher than the value obtained in the measurement where the windows and doors were closed.

This classroom is orientated to other areas of the university campus and, as well as the B1-A2 classroom, the dominant source of background noise is the sound from university facilities. In this case, it is the only classroom studied in which it is not necessary to open all the windows to achieve the recommended VR (only windows at the end). This is reflected in the result obtained from monitoring the middle position, where the background noise is lower compared to the front and back positions.

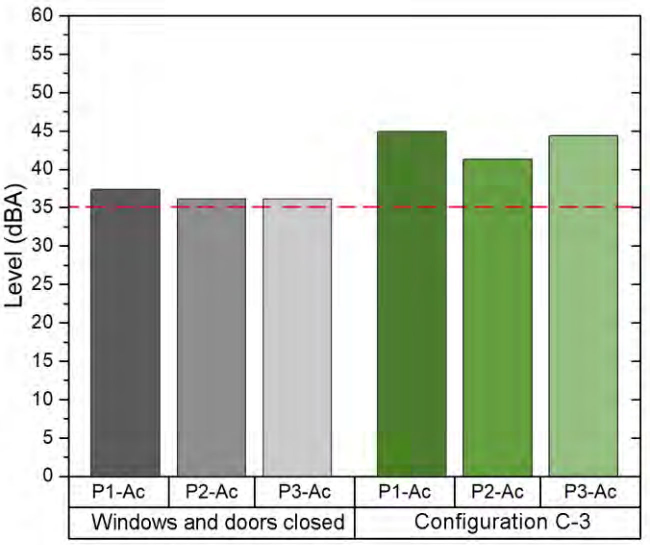
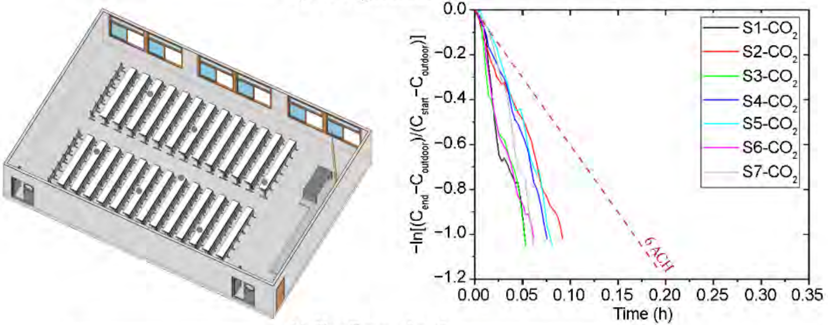


Figure 5-11. Background noise level in Classroom B2-A1.

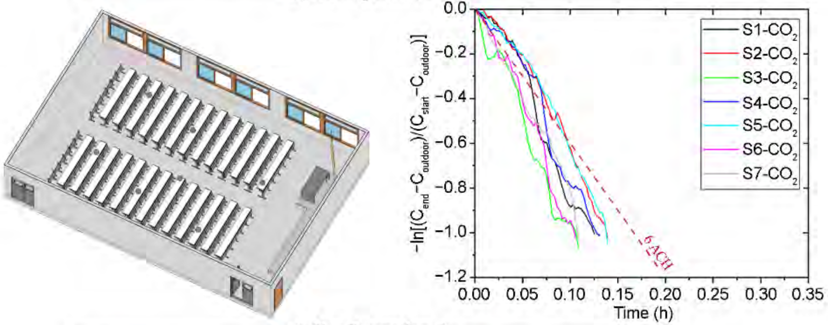
5.3.4. Building 2—Classroom A2 (B2-A2): Natural Cross-Ventilation Strategies—South Orientation

The architectural characteristics of classroom B2-A2 are similar to those of classroom B2-A1. Both classrooms are located on the second floor of the ETSICCP building, but on opposite sides. Therefore, the only difference is the orientation of the room and its location in the building. In this case, classroom B2-A2 has the windows located on the west side, which is the opposite of the location of the windows in classroom B2-A1. The configurations selected for the natural ventilation strategy tests were the same as in classroom B2-A1 (see Table 5-2). The results obtained are shown in Figure 5-12 and Table C5-6 in Appendix C.

a) Configuration 1



b) Configuration 2



c) Configuration 3

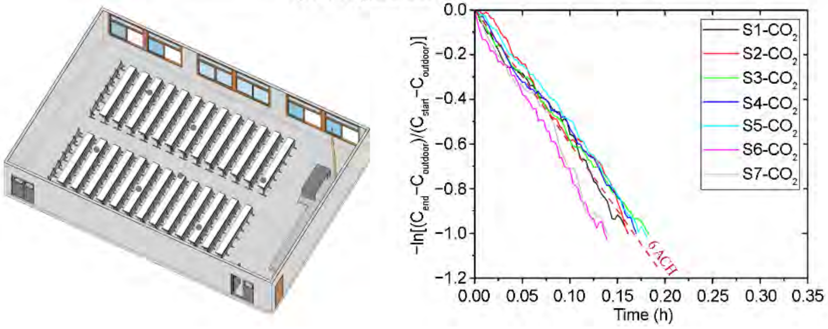


Figure 5-12. Configuration schemes and decay curves in Classroom B2-A2. ; (a) Configuration 1; (b) Configuration 2; (c) Configuration 3.

The *ACH* values obtained from the field measurements are shown in Figure 5-13. As in the case of class B2-A1, all three natural ventilation configurations provide *ACH* above the minimum set in the standard recommendation. However, the *ACH* values obtained in configuration C-1 are lower than those obtained in room B2-A1 with the same configuration. This is due to the orientation of the room, as the air currents are higher on the west façade of the building where room B2-A1 is located.

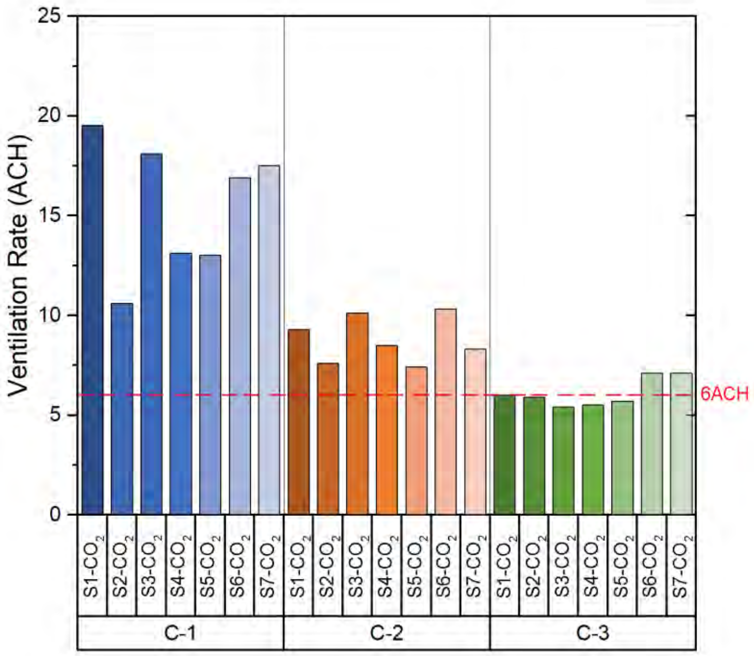


Figure 5-13. Ventilation rate (ACH) in Classroom B2-A2.

Regarding the background noise sound pressure level values, these were measured first with the windows and doors closed, and secondly with configuration C-2 (i.e., all windows opened and the main door opened). The average Leq value obtained with configuration C-2 (44.5 dBA) is above that obtained with windows and doors closed (6.4 dBA). Figure 5-14 shows the results.

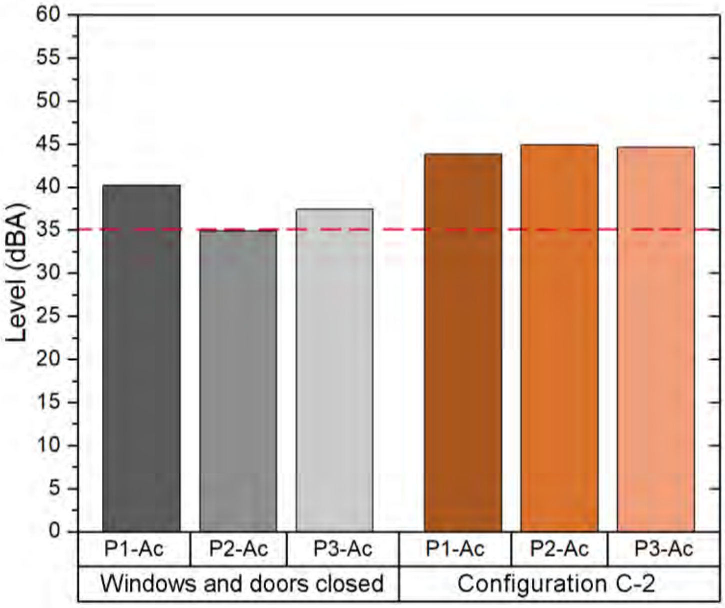


Figure 5-14. Background noise level in Classroom B2-A2.

This classroom is similar in both geometry and predominant background noise to the classroom analysed in Section 3.3 (classroom B2-A1). In this sense, although both classrooms are in the same building, since their orientations are opposite the ventilation strategies to achieve the required VR are different for each of them. Thus, since in this classroom it is necessary to open all the windows (unlike B2-A1, where only windows at the end had to be opened), the background noise is slightly higher.

5.4. Discussion

The classrooms selected in this study are representative of the classrooms' typology in Building 1 (Building Engineering School) and Building 2 (Civil Engineering School) of the University of Granada during return to teaching activity. For this purpose, field measurements were carried out to test three different configurations in the four selected classrooms.

The results obtained from the experimental tests in Building 1 showed that, in classroom B1-A1, the configuration that provides the lowest average *ACH* value is configuration C-3 (4.6) and the highest average value is configuration C-1 (8.3). In the case of the classroom B1-A2, the configurations providing the lowest and highest average value of *ACH* are configuration C-3 (3.7) and C-1 (6.1) respectively. With regard to the results obtained from the experimental analysis in Building 2, in the case of classroom B2-A1, configuration C-3 provides the lowest mean *ACH* value (8.4) and configuration C-1 provides the highest mean *ACH* value (24.9). In the case of classroom B2-A2, the configuration providing the lowest average *ACH* value is configuration C-3 (6.1) and the highest average *ACH* value is configuration C-1 (15.5).

As can be seen, the VR depends on the local and particular conditions of each indoor space. In this context, the configuration chosen among the three analysed in each classroom was the one that meets the minimum ventilation requirements. The configurations selected for classrooms B1-A1, B1-A2, B2-A1 and B2-A2 were configurations C-1 (all windows opened and main door opened), C-1 (all windows opened, main door opened and the corridor windows opened), C-3 (only windows at the end opened and main door opened) and C-2 (all windows opened and the main door opened) respectively. This decision is based on ensuring that the *ACH* value is sufficient to guarantee that the space is safe, although there may be variability in the *ACH* value due to possible variations in environmental conditions.

Once the natural ventilation configuration was selected for each classroom, an acoustic study was carried out to compare the normal classroom scenario (windows and door closed) with the chosen configuration of natural ventilation. As can be seen from the results obtained, since the background noise level should not exceed 35 dBA for good speech intelligibility, none of the classrooms met this acoustic quality recommendation. With regard to the comparison between the scenario of closed doors and windows and the natural ventilation configuration selected, it was identified that the natural ventilation configuration causes an increase of between 6.4 dBA and 12.6 dBA in the background noise level of the classrooms analysed. The background noise is an important factor that affects the acoustic clarity and quality of teaching and learning process [186].

Background noise is closely related to the signal-to-noise ratio (SNR). In this sense, a high level of background noise can cause a low or negative SNR. Therefore, a poor SNR causes, on the one hand, difficulties for students having to understand the message. On the other hand, it also causes a higher vocal effort among teachers, as the speaker's speech level has to be higher than the background noise level.

In fact, background noise becomes a problem that has a major impact on the current situation. Since the classrooms used for the return to campus are larger, and to ensure physical distance between students the distribution of students occupies all rows of seats, many students are in positions far away from the teacher. As a result, the signal-noise ratio is very low in the rear positions, causing significant effects on reducing word identification and intelligibility.

The location and orientation of the classroom also influences the impact of the natural ventilation configuration on classroom background noise. This is evident in the results obtained for classroom B1-A1, which is oriented towards a dense traffic area and the background noise level was 54.1 dBA. Therefore, more factors than room size and ventilation strategy should be taken into account when choosing the classroom. The location and orientation of the classroom should be considered in order to reduce the impact of background noise on the teaching-learning process. Consequently, the practical implications of the findings show that ventilation strategies management in educational buildings should consider the following design and operation guidelines:

- The classroom selection must take into account both the health recommendations and the impact of background noise. Priority should be given to selecting those indoor spaces that: 1) meet the health requirements (minimum distances, VR, etc.) and 2) (due to their location and orientation) have a background noise level that does not interfere with the teaching-learning activities.
- In those cases where it is not possible to meet the criterion stated in the previous point, an adaptation intervention must be carried out (i.e., installation of passive, active, automation-based or hybrid noise control devices). Noise control solutions for natural ventilation openings must ensure the required VR while also ensuring the background noise does not interfere with the performance of students and teachers.

The limitations presented in the study stem from the effect of indoor and outdoor environmental conditions (the local and particular conditions of each indoor spaces as well as the wind speed and outdoor temperatures). Additionally, this study follows the protocols stated by the Spanish Government and University of Granada prevention guidelines. One of this protocols is the IAQ management of both buildings is to ventilate (for at least 1 h before and after each class) by opening all windows. This procedure achieves indoor temperature and relative humidity levels similar to those outside, so the effect of these factors should be taken into account if different conditions would apply.

5.5. Conclusions

The aim of this study was to analyse the natural ventilation strategies through the configuration of window and door openings, in accordance with the recommendations established in the COVID Action Plan of the University of Granada, which complies with the recommendations while maintaining the maximum degree of comfort for the user. To this end, the impact of these measures on the acoustic environment of the classroom was analysed, so that both students and teaching staff maintain safe levels of protection against the transmission of SARSCOV-2 without affecting their teaching-learning activities.

The results obtained show that a correct choice of configuration can satisfy the VR needs while ensuring that the indoor space is safe for the occupants. The measurements were carried out in four different classrooms with an occupancy per area ranging from 2.20 m^2/student to 4.77 m^2/student. These spaces were selected according to the COVID-19 contingency plan set up at the beginning of the 2020/2021 academic year in each university centre. The natural ventilation configuration that met the required *ACH* was chosen to assess the impact on background noise inside the classroom. The main results obtained were:

- Natural cross-ventilation is an effective strategy to achieve the *ACH* levels required to ensure that the indoor spaces meet the guideline recommendations for a safe return to campus.
- There are differences in the specific natural ventilation strategy depending on the configuration of classrooms and building orientation. Thus, for the classrooms in building B1 the configuration of all windows opened and main door opened should be selected no matter the type of possible ventilation (natural ventilation through windows or cross-ventilation through corridors). On the other hand, in B2 the specific configuration depends on the classroom type, i.e., all windows opened and main door opened in the case of south-orientated classroom, or only windows at the end opened and main door opened in the case of the case of north-orientated classroom achieve better results due to the different orientation of the building. This fact highlights the needs of performing specific studies to select the best strategy to implement natural cross-ventilation.
- The average VR value provided by the selected configuration for each classroom was 8.3 ACH, 6.1 ACH, 8.4 *ACH* and 8.8 *ACH* for classrooms B1-A1, B1-A2, B2-A1 and B2-A2, respectively. Therefore, the average *ACH* value is above 6 *ACH* in all the selected natural ventilation configurations.
- The background noise level is strongly affected by the selected natural ventilation configuration. The background noise levels with the selected natural ventilation configuration were between 43.2 and 54.1 dBA. As can be seen, all classrooms exceed the recommended 35 dBA background noise level limit for background noise in teaching spaces. Consequently, the teaching activity management has to take into account not only the ACH, but also its impact on the indoor environmental conditions such as the acoustic environment. Since a high value of background noise level can interfere with the teaching and learning process and even interfere with the performance of students and teachers, educational building administrators need to consider this issue. In those cases where in order to achieve a natural ventilation strategy that provides the required VR, the background noise level

exceeds 35 dbA, building managers should make intervening adaptations (i.e., installation of passive, active, automation-based or hybrid noise control devices).

Since this research proves that the best strategies to achieve a VR value that complies with the standard imply a significant impact in other indoor environmental variables such as indoor noise levels, some actions to improve the indoor acoustic behaviour of classrooms are recommended. For example, the need of electroacoustic support to increase speech intelligibility, improving the acoustic conditioning of classrooms, increasing noise insulation with other classrooms and other common areas, and reinforcing the compliance of outdoor noise levels achieving the acoustic quality criteria prescribed for sensitive acoustic areas such as the educational ones. Therefore, the management, organization and planning for indoor spaces of educational buildings must not only ensure occupants' safety, but also not influence the performance of teaching activities. Action plans are required that allow buildings' administrators to achieve adequate natural ventilation strategies and implement effective noise reduction measures in indoor spaces.

Finally, future studies should focus on the environmental conditions of natural ventilation with occupancy in the classrooms, in order to evaluate not only the objective variables of the IEQ factors, but also the subjective variables associated with the perception and comfort of occupants with regard to the window and door opening configurations established.

5.6. Appendix C

Table C5-3. Decay curves in Classroom B1-A1.

Sensor	Configuration 1 (C-1)			Configuration 2 (C-2)			Configuration 3 (C-3)		
	Regression	R^2	ACH	Regression	R^2	ACH	Regression	R^2	ACH
Sensor 1	y = −8.5562x − 0.0116	0.99	8.6	y = −5.8032x − 0.0643	0.97	5.8	y = −4.8164x − 0.013	0.99	4.8
Sensor 2	y = −8,1303x + 0.032	0.99	8.1	y = −5.6655x − 0.0146	0.99	5.7	y = −4.5337x + 0.0213	0.99	4.5
Sensor 3	y = −7.8861x + 0.0128	0.99	7.9	y = −5.6654x − 0.0067	0.98	5.7	y = −4.4275x + 0.0039	0.98	4.4
Sensor 4	y = −8.4811x + 0.0253	0.99	8.5	y = −5.4554x − 0.0361	0.98	5.5	y = −5.0707x − 0.0076	0.97	5.1
Sensor 5	y = −9.4362x + 0.0788	0.99	9.4	y = −5.1062x − 0.0007	0.99	5.1	y = −4.9633x + 0.0372	0.99	5.0
Sensor 6	y = −7.8993x + 0.0444	0.99	7.9	y = −5.0867x − 0.0127	0.99	5.1	y = −4.2515x + 0.0065	0.98	4.3
Sensor 7	y = −7.3562x − 0.0178	0.99	7.4	y = −5.2405x + 0.0546	0.99	5.2	y = −4.3029x − 0.0154	0.97	4.3

Table C5-4. Decay curves in Classroom B1-A2.

Sensor	Configuration 1 (C-1)			Configuration 2 (C-2)			Configuration 3 (C-3)		
	Regression	R^2	ACH	Regression	R^2	ACH	Regression	R^2	ACH
Sensor 1	y = −6.337x + 0.1217	0.96	6.3	y = −4.7516x + 0.0131	0.97	4.8	y = −3.2131x + 0.0578	0.96	3.2
Sensor 2	y = −5.5545x + 0.1072	0.96	5.6	y = −4.4593x + 0.0234	0.98	4.5	y = −3.6485x + 0.0048	0.96	3.6
Sensor 3	y = −4.9443x + 0.1088	0.92	4.9	y = −4.3944x + 0.062	0.95	4.4	y = −3.997x + 0.0927	0.97	4.0
Sensor 4	y = −6.314x + 0.1222	0.98	6.3	y = −5.0606x + 0.0484	0.98	5.1	y = −3.2628x + 0.0311	0.99	3.3
Sensor 5	y = −5.7117x + 0.0777	0.99	5.7	y = −5.1964x + 0.0938	0.98	5.2	y = −3.8595x + 0.1546	0.96	3.9
Sensor 6	y = −6.6585x + 0.1135	0.93	6.7	y = −4.7563x − 0.0159	0.95	4.8	y = −4.1027x + 0.1336	0.95	4.1
Sensor 7	y = −6.9932x + 0.1164	0.94	7.0	y = −5.0269x + 0.0316	0.97	5.0	y = −4.0927x + 0.1599	0.96	4.1

Table C5-5. Decay curves in Classroom B2-A1.

Sensor	Configuration 1 (C-1)			Configuration 2 (C-2)			Configuration 3 (C-3)		
	Regression	R^2	ACH	Regression	R^2	ACH	Regression	R^2	ACH
Sensor 1	y = −37.373x + 0.3503	0.97	37.4	y = −12.071x − 0.1136	0.95	12.1	y = −6.9297x − 0.0104	0.99	6.9
Sensor 2	y = −17.728x + 0.0923	0.99	17.7	y = −10.227x + 0.1121	0.96	10.2	y = −7.4124x + 0.0203	0.99	7.4
Sensor 3	y = −39.807x + 0.0103	0.99	39.8	y = −24.743x + 0.1323	0.97	24.7	y = −8.431x + 0.0709	0.99	8.4
Sensor 4	y = −15.465x + 0.008	0.98	15.5	y = −10.332x + 0.0293	0.99	10.3	y = −7.6596x + 0.0606	0.99	7.7
Sensor 5	y = −17.138x + 0.0901	0.99	17.1	y = −9.9033x − 0.0758	0.97	9.9	y = −9.0858x + 0.0245	0.99	9.1
Sensor 6	y = −29.454x + 0.1544	0.94	29.5	y = −11.694x − 0.1097	0.96	11.7	y = −9.5583x + 0.049	0.99	9.6
Sensor 7	y = −17.66x + 0.0902	0.98	17.6	y = −9.9647x − 0.0078	0.98	10.0	y = −9.58x + 0.0345	0.99	9.6

Table C5-6. Decay curves in Classroom B2-A2.

Sensor	Configuration 1 (C-1)			Configuration 2 (C-2)			Configuration 3 (C-3)		
	Regression	R^2	ACH	Regression	R^2	ACH	Regression	R^2	ACH
Sensor 1	$y = -19.547x - 0.0038$	0.94	19.5	$y = -9.2905x + 0.1220$	0.97	9.3	$y = -5.9718x + 0.0009$	0.98	6.0
Sensor 2	$y = -10.564x - 0.015$	0.99	10.6	$y = -7.6267x + 0.1165$	0.97	7.6	$y = -5.9458x + 0.0431$	0.99	5.9
Sensor 3	$y = -18.071x - 0.0384$	0.96	18.1	$y = -10.101x + 0.0051$	0.97	10.1	$y = -5.3937x - 0.0211$	0.99	5.4
Sensor 4	$y = -13.097x + 0.0481$	0.99	13.1	$y = -8.4722x + 0.1049$	0.96	8.5	$y = -5.5117x - 0.0074$	0.99	5.5
Sensor 5	$y = -12.97x + 0.0908$	0.98	13.0	$y = -7.3876x + 0.1053$	0.97	7.4	$y = -5.7052x + 0.0387$	0.99	5.7
Sensor 6	$y = -16.88x - 0.0424$	0.97	16.9	$y = -10.316x + 0.0732$	0.98	10.3	$y = -7.0921x - 0.0266$	0.99	7.1
Sensor 7	$y = -17.514x + 0.1204$	0.97	17.5	$y = -8.3386x + 0.0169$	0.98	8.3	$y = -7.0636x + 0.0025$	0.98	7.1

6. Thermal Perception in Naturally Ventilated University Buildings in Spain during the cold season

The work in this chapter is based upon the following publication: Aguilar, A. J., de la Hoz-Torres, M. L., Martínez-Aires, M. D., & Ruiz, D. P. (2022). *Thermal perception in naturally ventilated university buildings in Spain during the cold season*. Buildings, 12(7), 890. https://doi.org/10.3390/buildings12070890

6.1. Introduction

The indoor environmental quality (IEQ) is one of the many factors that influence occupants' satisfaction. A good value of IEQ is crucial, as it not only affects the building's energy efficiency and energy consumption [187-189], but also the health and emotions of the building' occupants [190]. This is of particular importance in educational buildings, where students, teachers and other staff spend long periods of the day. Previous studies have highlighted that students' concentration and learning abilities may be negatively affected by a poor IEQ [191-193], and health problems may even be created or worsened [194]. However, the management of indoor environmental conditions in educational buildings in Europe is different from other types of buildings (e.g. offices or residential buildings) due to their characteristics: for example, the high occupant density in classrooms (three to four times higher than in residential or commercial buildings [195]), and the fact that indoor air is renewed by natural ventilation [28].

An unsatisfactory indoor thermal environment can negatively influence the students' learning and performance [67]. Thermal comfort is defined as "that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" [1, 121]. Thermal comfort is therefore a subjective variable, and has received attention from researchers in recent years. Previous research conducted in different climate regions has analysed indoor thermal conditions and students' subjective thermal perception in educational buildings. For instance, Jowkar et al. [124] conducted a study in university buildings in Scotland and England, and found evidence of the influence of students' acclimatisation (students from Edinburgh reported higher values of neutral mean thermal sensation votes (TSVs) than Coventry students). In addition, Stazi et al. [42] conducted a measurement campaign over several years in a school buildings in Italy, and concluded that students tended to suffer from poor air quality during the heating season, as the students placed a high priority on satisfying thermal perceptions. Stazi found that indoor and outdoor temperatures were the main factors driving window-opening behaviours, while CO_2 concentration was not a stimulus. Similar conclusions were reported in research by Duarte et al. [43] on Portuguese educational buildings, where it was reported that manual opening of windows provided adequate ventilation for average outdoor temperatures above 19°C. However, it was also found that when average outdoor temperatures were below 16°C, manual window opening was inadequate, and for average outdoor temperatures of 16–19°C, manual window opening depended on the indoor air temperature. In the same vein, Heracleous and Michael [44] evaluated the thermal comfort and indoor air quality conditions in a typical classroom with natural ventilation, in a secondary school in Cyprus. They also concluded that window-opening behaviour was highly influenced by the outdoor temperature, and that windows were closed when outdoor temperatures were lower than 15°C. Papadopoulos et al. [196] reported in transition season in classrooms (free-running) there is a correlation between operative temperature with mean outdoor temperature. Another research study performed by Korsavi et al. [40, 41] found that 55% of all CO_2 measurements were above 1000 ppm, as ventilation was higher during the warm season than the cold season. They also concluded that indoor air quality was strongly affected by the adaptive behaviours of the occupants. Kim and de Dear [197] conducted a study in secondary school buildings located across temperate and subtropical climate regions in New South Wales and concluded that the students' 80% acceptability zone was wider than the suggested by PMV model. Hamzah et al. [198] found that the students' neutral temperature obtained using the PMV model was lower than the value of neutral temperature obtained from the actual TSV. It is worth noting that, according with the adaptive thermal model, neutral temperature in warm climates is higher than the neutral temperature in cold climates [199]. Previous studies concluded that students feel comfortable on cooler side of the thermal sensation scale [18, 200].

In addition, previous studies have analysed thermal perception in other types of buildings, such as Ozarisoy and Altan [201], who explored the determinant factors on the development of adaptive thermal comfort of households through a field study conducted in flats in Cyprus. Their results reported that 80% of the participants were slightly comfortable in a temperature ranging from 28.5 °C to 31.50 °C. These findings suggest that in hot and dry climates in which thermally uncomfortable indoor environments occurs, occupants of residential buildings appear to tolerate a warmer conditions than at other climate regions, particularly in summer.

Indoor environmental conditions inside educational buildings have also been affected by the protocols implemented as a consequence of the COVID-19 outbreaks. Reopening college and university campuses after the COVID-19 Lockdown posed a challenge worldwide. Ensure proper ventilation with outside air to reduce the concentration of airborne contaminants required the implementation of new ventilation protocols. International organisations have issued guidelines with the aim of minimising the transmission of the SARS-CoV-2 virus [70], and governments of countries around the world have taken measures to prevent and control its spread. In the case of Spain, these measures included increasing the ventilation rate in classrooms (to at least 6 air changes per hour) through continuous natural ventilation (i.e. windows and doors remain continuously open during the class lecture), increasing social distancing (to at least 1.5 m), and requiring hand washing and the use of facemasks indoors [47]. Regarding to the EU guidelines for ventilation, the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) has recommended using CO_2 concentration as an indicator of good indoor air quality, and has suggested a traffic light indicator for effective ventilation, where concentration values of below 800 ppm indicate good ventilation (green light), values between 800 and 1000 ppm represent acceptable ventilation (orange light), and values above 1000 ppm indicate unacceptable ventilation (red light) [70]. Consequently, the normal use of classrooms was modified and new protocols and ventilation strategies were implemented, resulting in alterations to the classroom's indoor environmental conditions [118, 125, 127, 202].

Furthermore, it should be noted that students' freedom to apply adaptive behaviours has been limited as a result of these new pandemic protocols. Prior to the COVID-19 pandemic, students in higher education buildings had the freedom to choose appropriate adaptive behaviours, both personal (e.g. changing where they were sitting during the teaching-learning process) and environmental (e.g. closing or opening classroom windows, using blinds, etc.) [203, 204]. However, as the situation now stands, students must not close windows and doors due to the ventilation protocols (i.e. continuous natural ventilation). Moreover, as social distancing must be maintained at all times (at least 1.5 m), students cannot freely choose their positions within the class.

As students' thermal perception can be influenced by the level of control possibilities within a space and the available adaptive behaviours, it is necessary to evaluate these new indoor environmental conditions, since the alterations in the thermal quality of the learning environment affects students' learning achievements and physical and psychological health. Given that the studies mentioned previously were conducted before the implementation of the COVID-19 protocols, this study aims to evaluate students' thermal perception in higher educational buildings in southern Spain after the implementation of pandemic protocols. For this purpose, a questionnaire survey ~~field survey~~ was conducted simultaneously with a sensor monitoring campaign during university lectures in the first semester of the academic year 2021–2022 (i.e. November 2021 to January 2022, corresponding to the cold season).

6.2. Materials and Methods

The methodology used in this field study included measurements of both objective parameters (through a sensor monitoring campaign) and subjective variables (through a questionnaire survey) to evaluate the indoor thermal perception of students. The following sections describe the characteristics of the buildings and lecture classrooms assessed, the sensors and survey applied, and the procedure followed during the measurement campaign. Figure 6-1 shows the methodological workflow developed for the study.

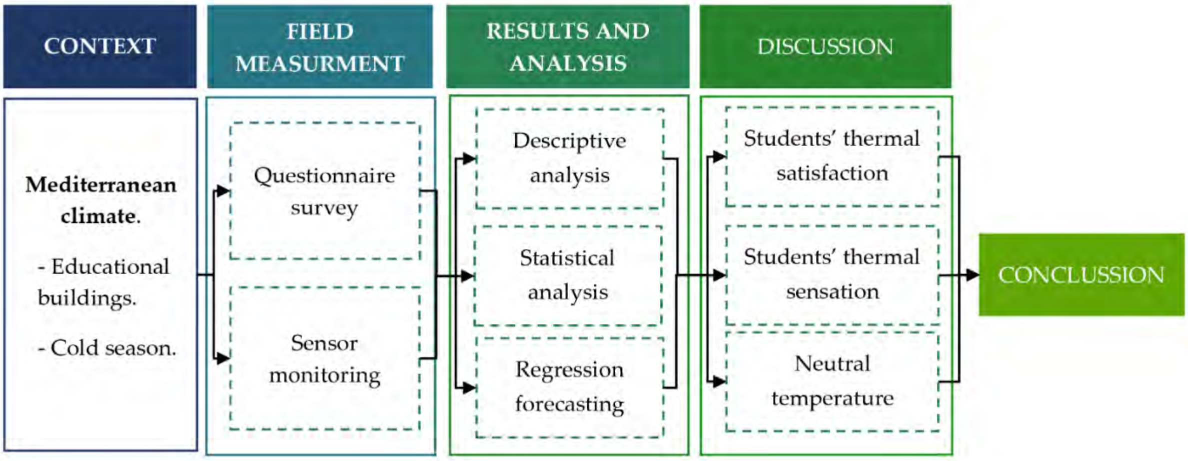


Figure 6-1. Methodological flow diagram.

6.2.1. Descriptions of the buildings and classrooms

Data collection took place in lecture rooms in the educational buildings of Fuentenueva Campus of the University of Granada. This campus is located in Granada, a city in Andalusia (in the southern region of Spain), which is characterised by a climate classified as Csa according to the Köppen-Geiger climate classification. The temperature is generally in the range 0–34°C, and rarely rises above 38°C or drops below −4°C during the course of the year. All the buildings in which the field study was conducted were naturally ventilated. A summary of the characteristics of the investigated buildings is shown in Table 6-1. The selected classrooms were a representative sample of the typical classrooms in each building, and the study was conducted in classrooms where the lecturers gave consent and the teaching-learning activities were comparable (i.e. the lecture lasted at least one hour and students remained seated throughout).

Table 6-1. Summary of the characteristics of the investigated buildings.

Building	Finishing materials	Type of windows	Average area (m^2)	No. of surveyed rooms	Ave. occupancy ratio (m^2/person)
1	Wall: Gypsum plaster Floor: Terrazzo Ceiling: Registrable suspended ceiling	Aluminium glazed windows (tilt and turn)	144 ± 44	6	2.0 ± 0.6
2	Wall: Gypsum plaster Floor: Terrazzo Ceiling: Registrable suspended ceiling	Aluminium glazed windows (sliding)	173 ± 53	8	1.7 ± 0.9
3	Wall: Gypsum plaster Floor: Terrazzo Ceiling: Registrable suspended ceiling	Aluminium glazed windows (tilt and turn)	92 ± 12	10	1.2 ± 0.2

Figure 6-2. (a) Investigated buildings' location. (b) Building 1. (c) Building 2. (d) Building 3.

6.2.2. Environmental evaluation

Ambient parameters can affect the heat balance of the human body and thus the thermal comfort of the occupants of buildings [205]. In this study, the indoor environmental variables recorded during field measurements were the air temperature (°C), mean radiant temperature (°C), air velocity (m/s), relative humidity (RH) (%) and CO_2 concentration (ppm). The variables were recorded at a sampling interval of 1 min. The characteristics of the sensors are summarised in Table 6-2. The sensors were positioned 10 min before the lecture started, and were evenly distributed in the classroom at 0.6 m above floor level, following the recommendations in ISO 7726:1998. An example of the layout of the sensors' locations is shown in Figure 6-3. The layout was similar in all classrooms.

Table 6-2. Characteristics of the sensors used in the field measurement campaign

Sensor	Model	Parameter	Range	Accuracy
CO_2 analyser HOBO®	MX1102	CO_2 concentration	0 to 5.000 ppm	±50 ppm ±5% reading accuracy
AHLBORN air temperature sensor	FHAD 46-C41A	Air temperature meter	−20 to +80 °C	Typical ±0.2 K at 5 to 60°C maximum ±0.4 K at 5 to 60°C maximum ±0.7 K at −20 to +80°C
AHLBORN RH sensor	FHAD 46-C41A	RH	0 to 98% RH	±2.0% RH in the range 10–90% RH ±4.0% RH in the range 5–98% RH
Delta OHM hotwire air speed transmitter	HD403TS2	Air speed	0.1–5 m/s	± 0.2 m/s + 3% f.s.
AHLBORN black ball thermometer	FPA805GTS	Mean radiant temperature	−50 to 200 °C	0.1°C

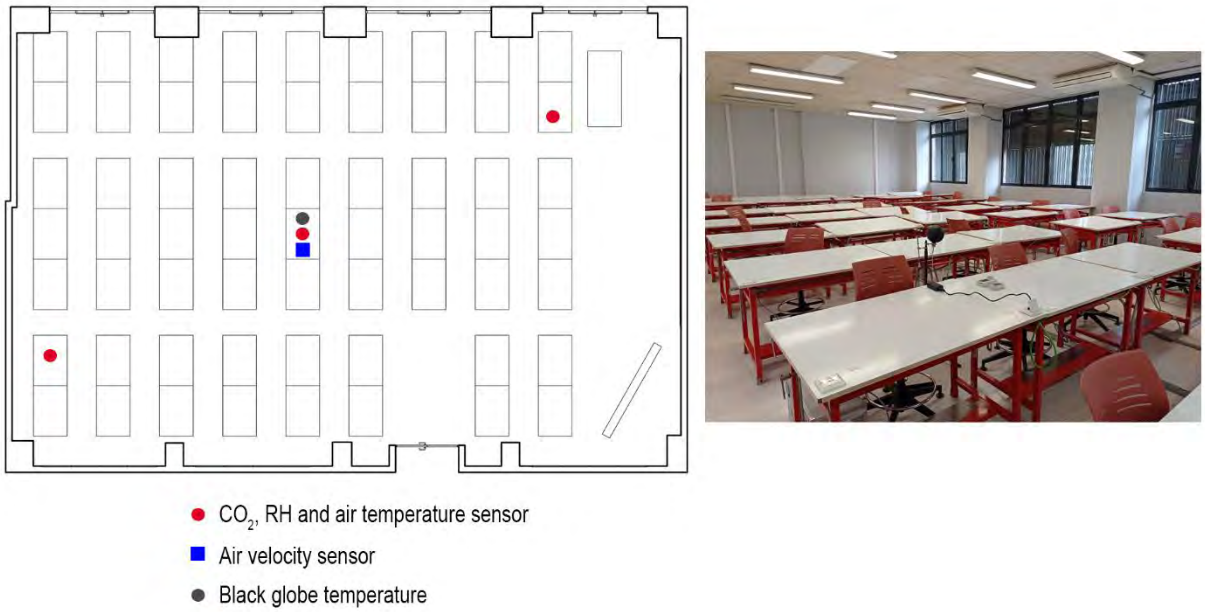


Figure 6-3. Example of the layout of the sensor locations during field measurements.

The parameters of the outdoor thermal environment (air temperature, RH and air velocity) were obtained from the state meteorological agency AEMET [119], whose meteorological station was located in Cartuja Campus, close to the study area.

6.2.3. Thermal perception survey

The thermal perceptions of the higher education students were evaluated using a questionnaire survey during regular lectures. The questionnaire was based on the UNE–CEN/TR 16798-2:2019 Standard recommendations for evaluation of the indoor environmental quality, and included items related to personal information (gender, age and clothing and type of masks worn by students during the survey) and thermal perception (thermal satisfaction vote (TSaV), TSV and thermal interference with the students' performance (TIP)). TSaV, TSV and TIP were examined based on a seven-point Likert scale. Table 6-3 shows the scale used in the questionnaire survey. The questionnaires were filled out by the students during the final minutes of the lecture. The clothing insulation values have been calculated based on the clothing selected by the students and using the guidelines stated in ISO 7730.

Table 6-3. Scales used in the questionnaire survey

Index	Level	Scale
TSaV	Very dissatisfied, dissatisfied, slightly dissatisfied, neutral, slightly satisfied, satisfied, very satisfied	(-3),(-2),(-1),(0),(1),(2),(3)
TSV	Cold, cool, slightly cool, neutral, slightly warm, warm, hot	(-3),(-2),(-1),(0),(1),(2),(3)
TIP	Interfere a lot, interfere, slightly interfere, neutral, slightly enhance, enhance, enhance a lot	(-3),(-2),(-1),(0),(1),(2),(3)

*TSaV: thermal satisfaction vote; TSV: thermal sensation vote, TIP: thermal interference in the students' performance.

The collected subjective data were analysed and the significant differences between the responses were evaluated. For this purpose, the normality of the data was checked using a Kolmogorov-Smirnov test. A t-test was then used to examine the significant differences from normally distributed data, and a non-parametric Mann-Whitney U test was used to examine non-normally distributed data. Spearman's correlation test was used to determine the relationship between the variables. Linear fits were used to assess the relationship between TSVs and T_{op}. The neutral temperature (T_n) was calculated based on these linear fits. An exponential fit was used to explore the relationship between CO_2 concentration inside the classroom and the total open area (m^2) and the occupation density (m^2/student). The statistical analysis was conducted using SPSS (v. 23.0) software.

6.3. Results

6.3.1. Indoor and outdoor environments

The average, standard deviation, minimum and maximum values obtained from measurements of the indoor and outdoor environmental parameters are shown in Table 6-4. It can be seen that there were significant differences between the indoor and outdoor parameters. The indoor air was renewed by continuous natural ventilation through opening of the doors and windows, and the indoor environmental variables were therefore influenced by this ventilation protocol. The results obtained for the indoor operating temperature and RH show a wide range of variation (14.6–28.2°C and 19.6–50.1%, respectively).

Table 6-4. Summary of values obtained from the sensor monitoring campaign

Type	Outdoor			Indoor			
	Air temperature (°C)	RH (%)	Air velocity (m/s)	Operative temperature (T_{op}) (°C)	RH (%)	Air velocity (m/s)	CO_2 concentration (ppm)
Average	13.1	58.4	5.07	20.6	37.9	0.03	566.4
STD*	7.5	21.2	5.48	3.9	7.3	0.04	118.2
Max	30.4	94.0	23.00	28.2	50.1	0.19	897.3
Min	2.1	16.0	<0.01	14.6	19.6	<0.01	410.0

*STD: standard deviation value

6.3.2. Students' thermal perceptions

A total of 1100 questionnaires were collected in this field study, of which 989 were valid (111 were discarded as incomplete). Table 6-5 shows the distributions of the general information on the respondents. An approximately equal number of male and female subjects participated in this study (with only 8% more males than females). In addition, 84% of the participants were aged between 18 and 24, a figure that rose to 91% when participants aged 25–30 were included. These values were as expected, since the statistical data published in the annual report for the academic year 2020/2021 by the University of Granada indicated that 95% of the students enrolled in university degrees were aged between 18 and 30 [206]. In terms of the masks worn by students, the type most frequently used was a surgical mask (75%), followed by an FFP2 mask (16%). Only 8% of the students who participated in this study wore different types of mask.

Table 6-5. Characteristics of the sensors used in the field measurement campaign

Variable	Number of respondents, N (%)	
Gender	Male	539 (54%)
	Female	450 (46%)
Age	n/a	31 (3%)
	18–24	829 (84%)
	25–30	107 (11%)
	+30	22 (2%)
Type of mask	FFP2	163 (16%)
	Surgical	742 (75%)
	Cloth	60 (6%)
	n/a	24 (2%)

The clothing insulation value was calculated on the basis of the clothing worn by each student, following the conventional clo table defined in ISO 7730 [122]. The distribution of the clothing insulation values is shown in Figure 6-4. The median clothing insulation value was 0.60 clo for males and 0.77 clo for females. Although previous research on the effect of clothing on people's perception of the thermal environment has found that differences in clothing insulation between males and females were negligible for the cold seasons [207], the results obtained in this study show significant differences (*p*<0.001).

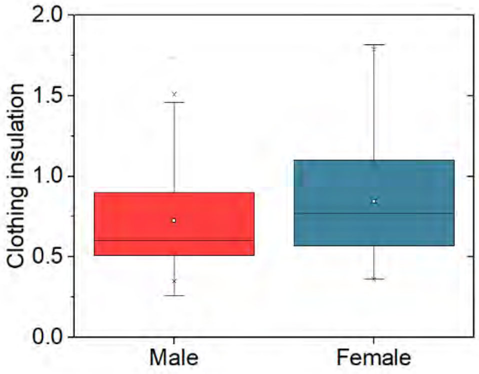


Figure 6-4. Distribution of clothing insulation values by gender.

Figure 6-5 shows the subjective thermal perception data collected through the questionnaires, including the percentage distributions of TSaV (Figure 6-5a), TSV (Figure 6-5b) and TIP (Figure 6-5c). The collected data were divided into two groups based on gender, and significant differences were found for these three subjective variables between the votes reported by female and male students (*p* < 0.001). With respect to the TSaV, the predominant responses of students of both genders were 'very dissatisfied', 'dissatisfied' or 'slightly dissatisfied' with the indoor thermal conditions (accounting for a total response of 47% for males and 64% for females). Only 11% of females and 18% of males reported a 'neutral' response. It should be noted that the percentage of females reporting satisfaction with the temperature was lower than the percentage of males. For the TSV, 55% of the female students' votes and 63% of the males' were in the comfort range (i.e. between 'slightly cool' (−1) and 'slightly warm' according to [1]). Of the TSVs that were outside the comfort range, the percentage of students who considered the environment 'cold' or 'cool' (40% of females and 28% of males) was higher than those that considered it to be 'warm' or 'hot' (5% and 9% of females and males, respectively).

About 47% of the male and 66% of the female occupants reported that the indoor thermal conditions interfered with their academic performance (based on the total responses of 'interfere a lot', 'interfere' and 'slightly interfere'). However, only 21% of males and 17% of females indicated that the indoor thermal conditions enhanced learning (based on the total responses of 'slightly enhance', 'enhance' and 'enhance a lot'). It was notable that only 17% of the female students gave a neutral response to this question, a much lower value than for the males (32%). In view of these results, it is possible to conclude that the percentage of female students who reported that the indoor thermal conditions interfered with their academic performance was much higher than for the male students.

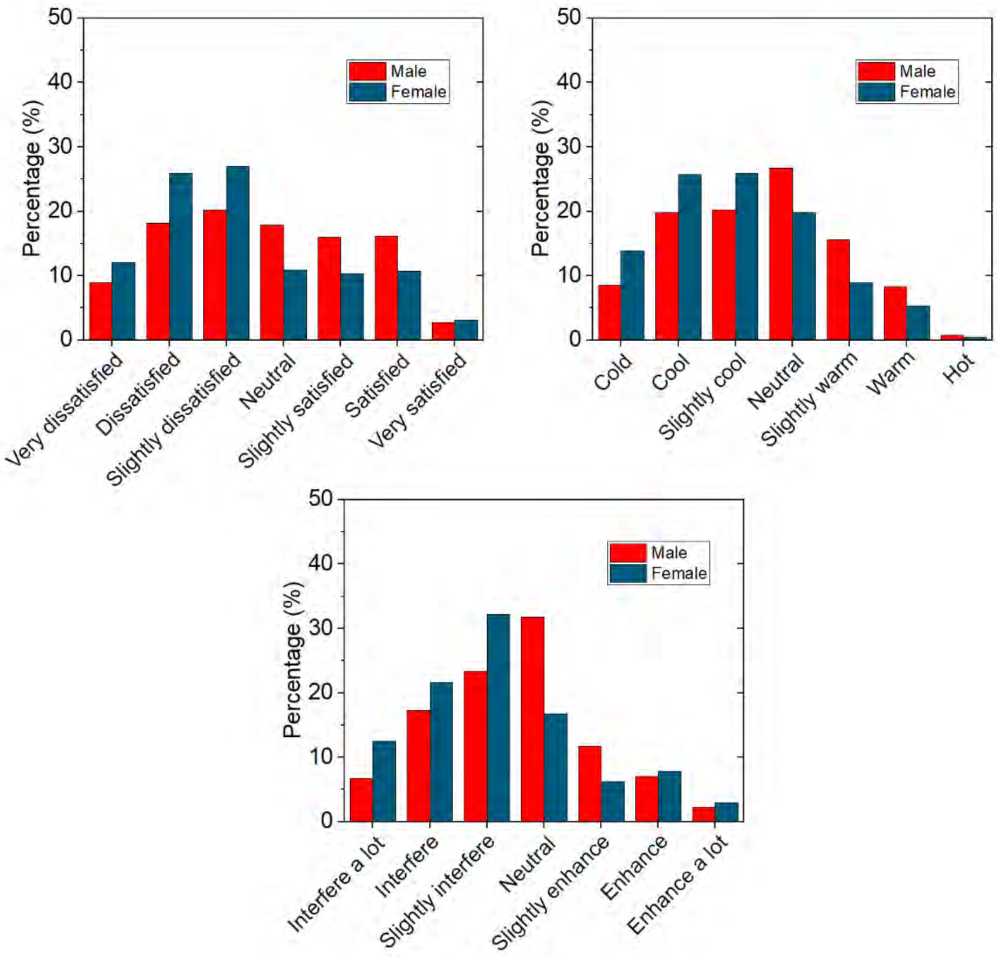


Figure 6-5. Distribution of responses obtained for (a) TSaV; (b) TSV; (c) TIP.

The relationships between the subjective variables were also examined, and the distributions of the values of TSaV and TIP reported by the students in relation to the TSV values are shown in Figure 6-6. Between 95% and 100% of the students who voted that the indoor thermal conditions were cold or cool were also dissatisfied, and reported that these conditions interfered with their academic performance.

Of the students who reported that the temperature was within a comfortable range (between 'slightly cool' and slightly 'warm'), both male and female students indicated that a slightly warm indoor environment was more satisfactory and enhanced their academic work. In the case of female students who reported a 'slightly cool' TSV, a higher percentage of dissatisfaction was observed (80%) than for male students (64%). Similar results were found with regard to interference in academic performance.

In contrast, of those students who reported a 'warm' TSV, lower percentages were dissatisfied (13% of male students and 21% of female students) or indicated that the thermal conditions interfered with their academic performance (16% and 21% of male and female students, respectively). These results evidence a preference for a warmer indoor environment during cold season.

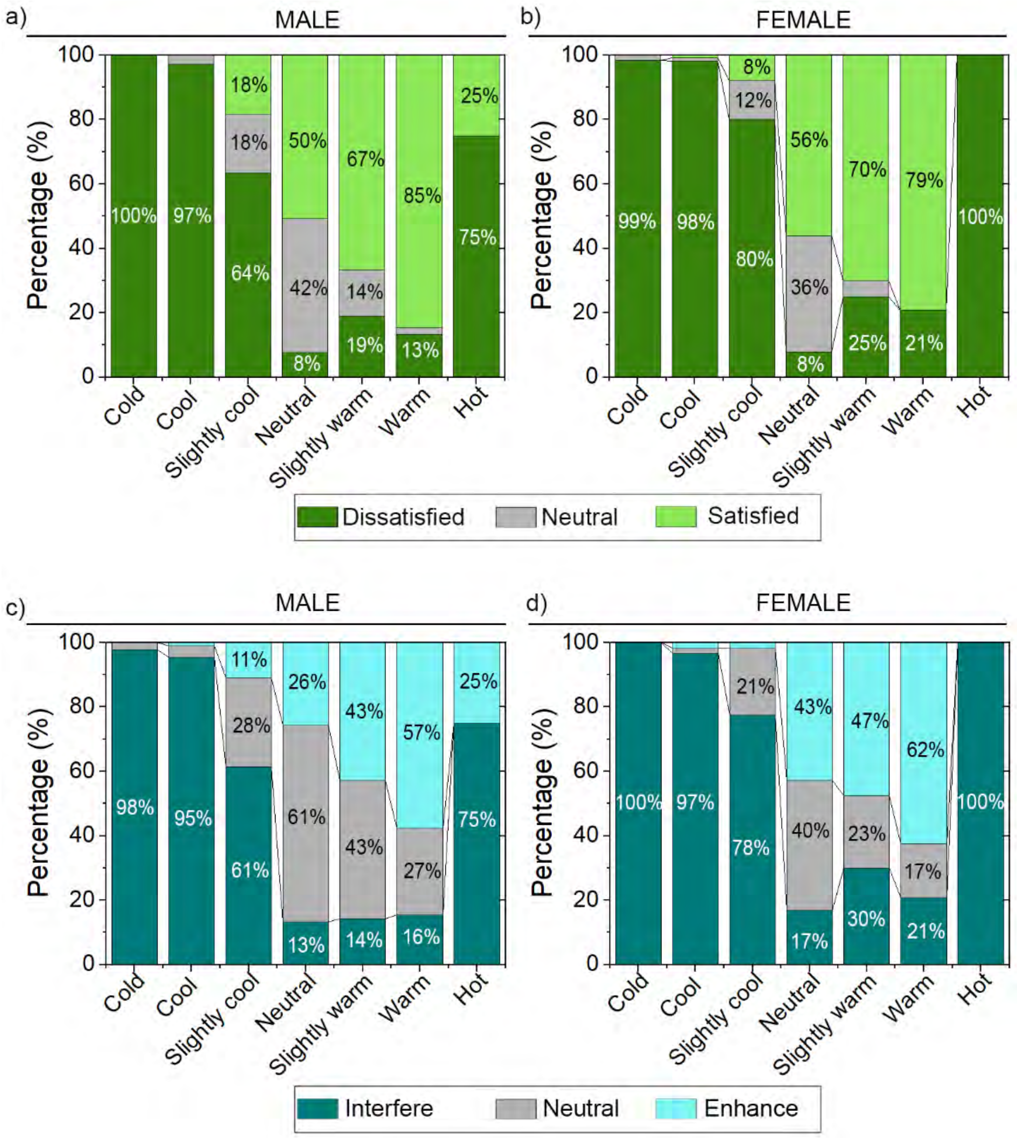


Figure 6-6. (a) Distributions of TSaV versus TSV results for male and female students; (b) distributions of TIP versus TSV results for male and female students.

To illustrate the relationship between the objective and subjective variables, Figure 6-7 shows the values of TSV against the T_{op}. A linear regression was used to analyse the thermal neutrality (T_n), and the fitting equations obtained in this way are shown in Table 6-6. Since significant differences were found between the TSVs reported by male and female students, the data were evaluated separately. The overall total T_n was 23.8°C, with values of 23.2°C for males and 24.2°C for females.

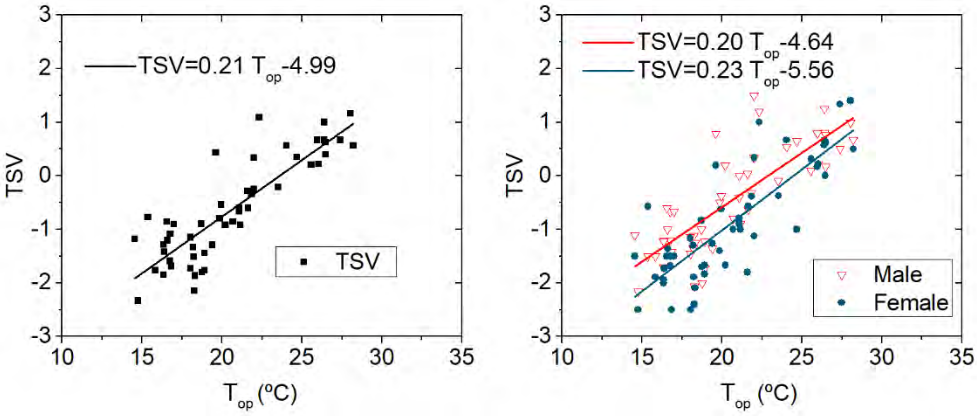


Figure 6-7. (a) TSV values reported by students versus T_{op}; (b) values of TSV reported by female and male students versus T_{op}.

Table 6-6. Fitting equations of TSV against t_{op}

	Fitting	p-value	R^2
Total	$TSV = 0.21\ t_{op} - 4.99$	$p < 0.001$	0.74
Male	$TSV = 0.20\ t_{op} - 4.64$	$p < 0.001$	0.65
Female	$TSV = 0.23\ t_{op} - 5.56$	$p < 0.001$	0.68

The difference between the values of T_n obtained for the male and female students shows that the female students had a preference for warmer temperatures. This finding is also reflected in Figure 6-8, which shows the relationships between the difference between T_{op} and T_n (i.e. DT) and the percentages of dissatisfied students (Figure 6-8a) and those reporting learning interference (Figure 6-8b). These results indicate a lower percentage of dissatisfied students (≤20%) when DT ranges from −2 to 4°C.

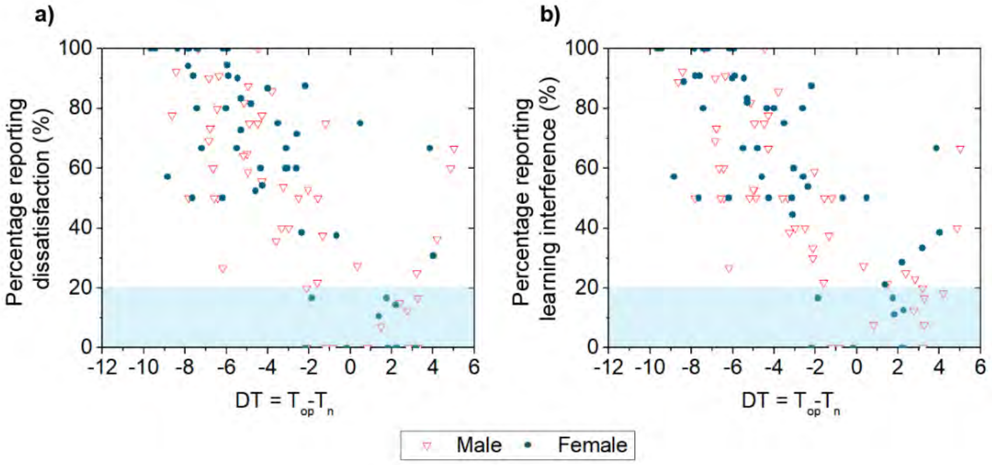


Figure 6-8. (a) Percentage of dissatisfied students versus DT; (b) percentage reporting learning interference versus TSV.

6.3.3. Continuous natural ventilation and the indoor thermal and air quality environment

Figure 6-9a shows the relationship between the total open area (m^2) of windows and doors, used to provide continuous natural ventilation, and the CO_2 concentration inside the classrooms. If the recommendations for ventilation efficiency given in the REHVA guidelines are considered, we see that 90% of the lectures in which measurements were conducted had values lower than 800 ppm, meaning that the ventilation strategy provided enough air renovation according to these guidelines. Figure 6-9b shows the occupation density (m^2/student) against CO_2 concentration. As expected, the lower the area per occupant, the higher the CO_2 concentration in the classroom. The fitting equations are shown in Table 6-7. In addition, the relationship was examined by Spearman correlation test. The results showed a moderate relationship between CO2 concentration and the total open area ($\rho = -0.515$, $p < 0.01$). Regarding the CO_2 concentration and occupation, a moderate-low relationship has been obtained ($\rho = -0.451$, $p < 0.01$).

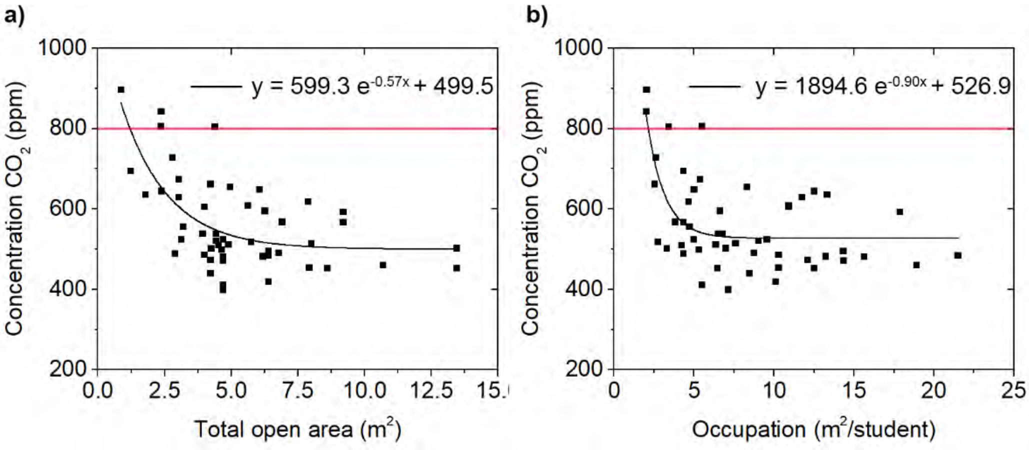


Figure 6-9. (a) CO_2 concentration versus total open area (m^2); (b) CO_2 concentration versus occupation density (m^2/student). Red line indicates the REHVA CO2 concentration limit recommendation.

Table 6-7. Fitting equations

Variables	Fitting	p-value	R^2
CO_2 concentration/total open area (m^2)	$CO_2 = 599.3\ e^{-0.57x} + 499.5$	$p < 0.001$	0.42
CO_2 concentration (ppm)/occupation (m^2/student)	$CO_2 = 1894.6\ e^{-0.90x} + 526.9$	$p < 0.001$	0.40

Although the CO_2 concentrations remained below 800 ppm in most of the analysed scenarios, these ventilation strategies also affected the indoor environmental conditions. In fact, the results presented in the previous section indicate that a high percentage of students were dissatisfied with the indoor thermal conditions, and considered that the indoor environment was 'cold', 'cool' or 'slightly cool' (49.2%). This was due to the influence of the outside temperature on the indoor thermal conditions, from the open windows. This is evident in

Figure 6-10, which shows the total percentage of students who were dissatisfied with the indoor thermal conditions as a function of the outdoor temperature and the total area of open windows.

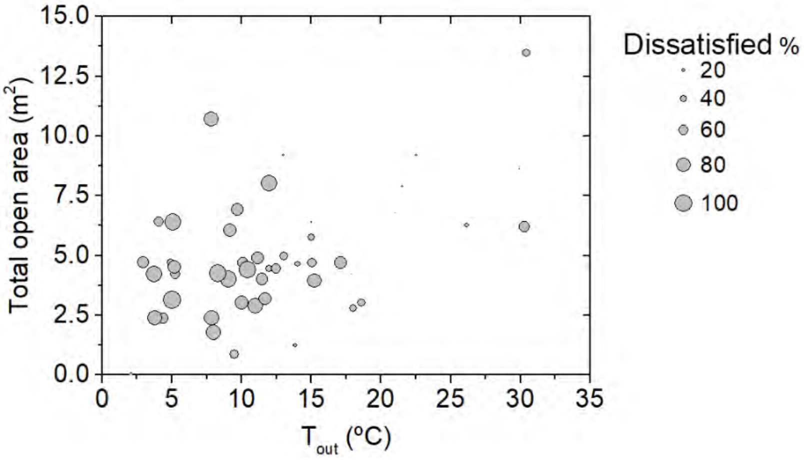


Figure 6-10. Relationship between the percentage of dissatisfied students, outdoor temperature and total area of open windows.

6.4. Discussion

The results obtained in this study represent the students' perceptions of the indoor thermal environment during the cold season in a naturally ventilated higher education building. The reopening of educational buildings for the academic year 2021/2022 posed a challenge to building managers, and the need to ensure that indoor spaces were healthy and safe for students and teachers led to the implementation of ventilation protocols to ensure effective air renewal.

The results presented here show that a strategy of continuous natural ventilation was able to provide effective air renewal and kept the CO_2 concentration below 800 ppm in more than 90% of the classrooms (Figure 6-9). However, this protocol also influenced the indoor thermal conditions of these spaces. The average indoor temperature was 20.5°C, below the lower limit given in the Regulation on Building Heating Installations (RITE) (which states that the indoor operative temperature should be in the range 21.0–23.0°C during the winter season) [90]. Only the 18% of the evaluated classrooms were in this range, which was reflected in the high percentage of dissatisfied students. Our findings are similar to those reported by Monge-Barrio et al. [208], who conducted a study to evaluate the use of natural ventilation to improve IAQ in educational buildings in northern Spain. They found that although natural ventilation helped to improve IAQ (with lower CO_2 concentrations), this resulted in lower temperatures inside the classroom, especially on the coldest days of the winter season.

The values obtained for T_n (23.2°C for males and 24.2°C for females) were slightly above the range given in the RITE standard. It was observed that students preferred a warmer environment during the cold season. The percentage of dissatisfied students was lower when the difference between T_n and T_{op} was between −2 and 4°C (see Figure 6-8). Lower values of TSV were detected for female students than male students, and significant differences between the overall votes of males and females were detected. This effect has been also found in previous research conducted in cold regions [209]. Similar results were reported by Jowkar et al. [124], who conducted a study of higher educational buildings in Coventry and Edinburgh and concluded that women tended to have statistically higher thermal preferences and lower thermal TSVs than men. Although the clothing insulation value for females was higher than for males, female students assessed the indoor environment as cooler and preferred warmer thermal conditions.

If these results are compared with those reported by other studies carried out in educational buildings in different climatic regions, it is found that the T_n in cold climates is lower than the T_n in warmer climates [199]. Regarding the analysis of students' thermal comfort in regions located in the Tropics, Hamzah et al. [198] carried out a study in the tropical city of Makassar and found that the T_n were 29.0 °C and 28.5 °C for TSV and TCV, respectively, with an average clothing insulation of 0.69 clo. Kim and Dear [197] conducted a study in secondary school buildings located across temperate and subtropical climate regions in New South Wales and investigated the students' perception of classroom thermal environment in relation to adaptive comfort guidelines. They found a neutral temperature of 24.4 °C with an average clothing insulation of 0.48 clo. In contrast, the study conducted by Liu et al. [199] in rural school classrooms in Northwestern China reported a neutral temperature of 15 °C. Nevertheless, this study reported that the students' average clothing insulation was found to be 1.6 clo, which is much higher than that found in studies in warmer regions.

Considering studies conducted in other types of buildings, the T_n also differs from the T_n obtained in the presents study. As an example, Ozarisoy [201] conducted a study during summer in multi-family social-housing units in Cyprus and found a T_n of 28.5 °C. However, it should be noted that households' freedom to apply adaptive behaviours has not been limited due to the COVID-19 pandemic, as in the case of students in educational buildings.

It should be also noted that significant differences were found between the clothing insulation values for female and male students, with the median value for female students being 0.17 clo above the value for the male students. It should be also be borne in mind that the adaptive behaviour of students during lectures was limited due to the pandemic protocols; it is possible that students came to class expecting different indoor environmental conditions, and did not dress appropriately for this new scenario. As a result, their indoor thermal comfort may have been compromised. This is evidenced in Figure 6-8, which shows the percentage of dissatisfied students as a function of outdoor temperature and the total area of open windows. In a study of thermal comfort in university classrooms of south-west Spain during mid-season (spring), Miranda et al. [125] also reported that different natural ventilation strategies are recommended when the outdoor temperature is below 12°C (i.e. limiting the number of open windows) in order to minimise the number of dissatisfied students.

In view of the fact that the implemented protocols affected the students' perception of the thermal environment, not only resulting in a high percentage of students who were dissatisfied with the indoor thermal conditions, but with 56% stating that these thermal conditions negatively affected their academic performance, we conclude that these new protocols need to be adapted.

6.5. Limitations

Unlike other types of buildings (i.e. commercial, industrial or residential buildings, etc.), educational buildings should provide a conducive environment to enhance the teaching and learning process [24]. The specific characteristics of educational buildings are especially important in the analysis of the thermal environment and the thermal perception of students. The reopening of university campuses after lockdown due to the COVID-19 pandemic and the implementation of new ventilation protocols has resulted in limiting students' freedom to apply adaptive behaviour. In this context, this study aims to assess the thermal perception of students in educational buildings and, therefore, the obtained results should not be extrapolated to other populations without prior considerations.

6.6. Conclusions

The indoor thermal environmental conditions were significantly affected by the new ventilation protocols resulting from the COVID pandemic during the cold season. Adaptive behaviours by students were limited, as they were prevented from opening or closing windows, and the results reflect the high number of dissatisfied students. Although our results show that continuous natural ventilation allowed these spaces to be safe and healthy, its effect on thermal conditions must be taken into account, as it had a strong impact on student satisfaction and performance.

Amongst our other findings, we observed statistically significant differences between the TSav, TSV and TIP values reported by male and female students. Female students reported a value for T_n that was 1°C higher than men, showing a preference for warmer temperatures for comfort. It is worth noting that even though the clothing insulation values were higher for females than for males, there were significant differences in the results, and females indicated a preference for warmer thermal conditions.

Finally, we recommend that the findings obtained in this study are taken into account and the protocols modified to ensure that indoor thermal conditions do not negatively affect student satisfaction and academic performance. From the results obtained in this study, we conclude that the maximum range of deviation in the temperature from T_n is −2°C to 4°C, so that the percentage of dissatisfied students does not exceed 20%. Consequently, additional measures should be considered to adapt these protocols during the cold-mid season, in order to contribute to keeping spaces safe while minimising the negative impact on students' academic performance.

7. Monitoring and Assessment of Indoor Environmental Conditions in Educational Building Using Building Information Modelling Methodology

The work in this chapter is based upon the following publication: Aguilar, A. J., de la Hoz-Torres, M. L., Ruiz, D. P. & Martínez-Aires, M. D. (2022). *Monitoring and Assessment of Indoor Environmental Conditions in Educational Building Using Building Information Modelling Methodology*. International Journal of Environmental Research and Public Health. https://doi.org/10.3390/ijerph192113756

7.1. Introduction

Nowadays, one of the goals of contemporary society is to achieve sustainable development and performance of the built environment [210]. Buildings have to not only meet the required standards for an indoor environment but also meet the occupants' needs and ensure their satisfaction (including social, economic and environmental aspects) [211]. Since people are always surrounded by a physical environment, maintaining comfort, wellbeing and health poses a great challenge [212]. The role of indoor environmental conditions in buildings is essential, since people tend to spend 90% of their time indoors [1]. Such is its importance that previous research has even stated that indoor environmental quality (IEQ) is key in determining the success or failure of buildings [213]. Building occupants interact with their surrounding environments, and their feedback, as building users, helps determine the requirements for a comfortable IEQ [214]. Accordingly, if the indoor environment ensures up to 80% satisfaction of the occupants, the built environment can be assumed to be performing well [1, 215].

However, buildings do not always meet the required indoor environmental conditions, which has a negative impact on their users [216]. These circumstances are critical in educational buildings, where students, teachers and staff spend long periods of the day. Primary and secondary school students spend more time at school than any other building except at home [217]; some studies claim that they spend around one-third of their day inside school [191]. In contrast, university students spend less time in classrooms (at least 3 h a day) compared to the two other educational stages [217]. Thermal, acoustic and lighting sensations are influenced by physical variables such as temperature, sound pressure level (SPL) and lighting, and therefore, overall satisfaction is also influenced. Previous studies have shown that poor IEQ in educational buildings is common and adversely influences the attendance, performance and health of students [67, 218]. In addition, the recent events caused by the COVID-19 pandemic highlighted that a suitable IEQ is essential in educational buildings. Minimising the transmission of the SARS-CoV-2 virus led governments to implement measures to ensure that students could use spaces safely. For example, the measures introduced by the Spanish government included reducing contact time, distance social distancing and using facemasks in educational buildings. Furthermore, the ventilation rate (VR) inside the classroom had to be increased by continuous ventilation [47]. However, since most educational buildings in European countries are naturally ventilated, achieving high values of VRs (e.g., 6–10 ACH) is hard through a natural ventilation strategy [70]. In this context, several researchers have assessed if the VR required by governments for educational buildings could be achieved through natural ventilation strategies during the pre-pandemic scenario [40, 114, 215] and during the post-pandemic scenario [111, 158, 202, 208, 219]. Although the results presented by these studies showed that a continuous natural ventilation strategy could provide effective air renewal, they also showed that other indoor environmental variables were influenced. Wind speed and outdoor temperatures are critical variables that significantly affect the indoor environmental conditions if doors and windows are continuously opened. In addition, students who are seated close to windows are more exposed to drafts. Moreover, indoor acoustic quality can be affected by outdoor noise [127]. As a result, students' comfort, health and productivity could contribute to a poor IEQ [67].

This situation poses a challenge to building facility managers who have to analyse and manage operation strategies to ensure that indoor spaces are safe for students and to guarantee a suitable IEQ. The Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) recommended installing CO_2 sensors to evaluate the effectiveness of ventilation [70]. However, the calculation of the individual COVID-19 infection risk depends on more variables, including the ACH, type of activity conducted during the class, time of exposure, and size and occupancy of the room. Managing this information in a non-centralised database is complex and t

Nevertheless, new methodologies are emerging in the architecture, engineering, construction and operation (AECO) sector as building information modelling (BIM). BIM is a methodology that offers new challenges and opportunities in the process of design, construction and maintenance of buildings [220, 221]. BIM covers all phases of the building life cycle, and previous studies have shown its potential application during the building operation phase. Marzouk and Abdelaty [59] proposed the use of BIM to monitor IEQ in subway stations. Cheung et al. [60] developed a system to integrate a hazardous gas sensor network into BIM methodology. Nojedehi et al. [61] defined a methodology to integrate maintenance management systems and BIM to improve building management. Alavi et al. [62] proposed a probabilistic approach to evaluate occupants' comfort using BIM. Artan et al. [63] defined a BIM-integrated post-occupancy evaluation system for office buildings. In this sense, this study starts from the premise that the integration of data obtained from indoor environmental monitoring into the BIM model could facilitate the process of data collection and subsequent analysis. However, to the best of our knowledge, no previous study has developed a framework for integrating occupants' feedback in order to conduct the assessment of the individual airborne virus transmission risk and IEQ. This study aims to fill this research gap. In this context, the main objective of this study is to develop a framework based on BIM methodology for integrating the assessment of the IEQ and airborne virus transmission risk in higher educational buildings. To achieve this objective, a methodology has been defined to obtain the occupants' feedback and integrate it into the BIM model. Subsequently, a BIM-based framework has been developed as a platform that can be used to support decision making by building managers and improve operational strategies. Finally, the proposed framework has been applied to a university building case study.

7.2. Material and Methods

7.2.1. Research Approach

The proposed framework is based on four main phases: (1) obtaining occupants' feedback on IEQ; (2) monitoring of the building's IEQ variables; (3) integration of the data obtained in phases 1 and 2 into the BIM model and performing the evaluation; and (4) visualising the results in the BIM software interface and generating reports. Figure 7-1 shows the automation process of integrating the indoor environmental assessment and occupants' feedback into BIM. The following subsections show the materials and methods used in each of the phases.

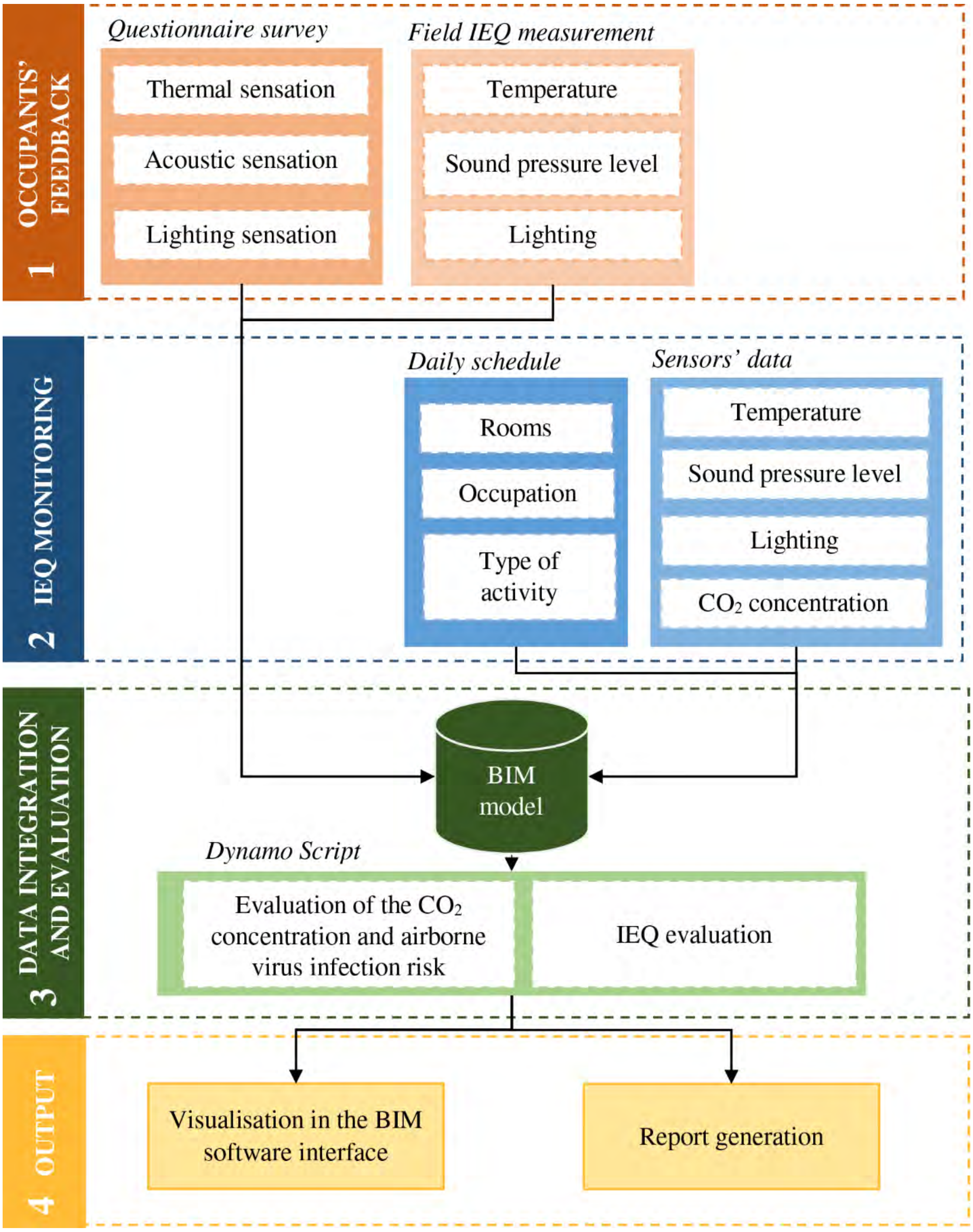


Figure 7-1. Automation process of integrating indoor environmental assessment and occupants' feedback into BIM.

Phase 1: occupants' feedback. The occupant comfort in existing buildings is directly determined from indoor environmental measurements and the responses of occupants through a questionnaire survey. The questionnaire used in this study was divided into two parts and was based on the recommendations for the evaluation of indoor environmental quality stated in UNE-CEN/TR 16798-2:2019 and UNE-EN ISO 28802:2012 standards [121, 222]. The first part of the questionnaire was related to personal information (age, gender and clothing), while the second part contained questions related to physical environmental parameters. A 7-point Likert scale was used to evaluate the occupants' indoor environmental perception: the thermal sensation vote (TSV, from −3 for 'cold' to 3 for 'hot'), the acoustic sensation vote (ASV, from −3 for 'very noisy' to 3 for 'very quiet') and the lighting sensation vote (LSV, from −3 for 'very bright' to 3 for 'very dark'). In addition, occupants were asked whether they were satisfied with the indoor thermal, acoustic and lighting environment, with a scale ranging from −3 ('very dissatisfied') to 3 ('very satisfied'), with 0 being neutral.

Simultaneously with the survey, the measurement of indoor environmental variables was carried out. For this purpose, sensors were placed to record the radiant temperature, air temperature, air velocity, lighting, relative humidity (RH), CO_2 concentration and SPL. Table A1 in Appendix A shows the sensors used to measure the indoor environmental conditions in the classrooms.

Phase 2: IEQ monitoring. In this phase, the indoor environmental conditions in classrooms are monitored during teaching activities. The indoor environmental variables are monitored continuously at 1 min logging intervals. The sensors should be placed in the middle of the classroom at 0.6 m above floor level, following the recommendations in ISO 7726:1998. Figure D7-10 in Appendix D shows an example of the layout of the sensor location. The sensors indicated in Table D7-8 in Appendix D were used for this purpose. In addition, the occupation and the type of activity conducted in the classrooms are considered. These parameters are taken into account due to their impact on the occupants' IEQ perception and the airborne virus infection risk.

Phase 3: IEQ assessment and evaluation of airborne virus infection risk. The data obtained in phases 1 and 2 and the geometric data contained in the BIM model are used as inputs in this phase. Subsequently, the evaluation process is divided into two parts.

Firstly, the evaluation of the airborne virus infection risk is carried out. In this regard, the measures implemented by governments to contain COVID-19 virus transmission in public buildings during the pandemic period are considered [47]. The probability of infection (P) due to the SARS-CoV-2 virus during teaching activities in educational buildings is calculated using the Wells–Riley airborne disease transmission model (see Equation (7-1)) [94].

$$P = \frac{C_i}{C_s} = 1 - e^{\left(-I\,q\,p\,t/\mathrm{ACH}\right)} \qquad (7\text{-}1)$$

where C_i is the number of occupants who develop an infection, C_s is the number of susceptible occupants, I is the number of infectors, q is the quantum generation rate (h−1), p is the pulmonary VR of susceptible people, t is the exposure time (h), and ACH is the air changes per hour (h−1). This model assumes a steady-state infectious particle concentration that varies with the VR and a well-mixed room air. Therefore, the ventilation of indoor spaces is a key factor to control the airborne virus transmission.

One of the parameters used to monitor the VR and indoor air quality in the classroom is the CO2 concentration. The methods using CO2 as a tracer gas to estimate VRs are based on a fully mixed mass balance model (Equation (7-2)):

$$V\frac{dC}{dt} = E + Q \cdot C_{outdoor} - Q \cdot C \tag{7-2}$$

where V is the volume of the indoor space under study, E is the CO_2 emission rate of the occupants per hour, Q is the outdoor air flow rate, $C_{outdoor}$ is the CO_2 concentration in the outdoor air, and C is the CO_2 concentration in the indoor space.

The approach proposed in this study relies on the assessment of the probability of airborne virus infection and the effectiveness of ventilation based on the ACH assessment for each scenario. For this purpose, the build-up VR technique is used. This technique uses the series of measurements of CO_2 concentration over time with a solution to the fully mixed model (Equation (7-3)):

$$C_t = (C_S - C_{outdoor})(1 - e^{-ACH\,t}) + C_{outdoor} \tag{7-3}$$

Equation (4) may be linearised as the following expression (Equation (7-4)):

$$\ln(C_S - C_t) = -ACH\,t + \ln(C_S - C_{outdoor}) \tag{7-4}$$

Therefore, the ACH can be calculated as the slope of the $\ln(C_S - C_t)$ versus time t. The ACH derived using this method assumes that the VR is constant over a specific time period, and it is applied only to a single and fully mixed zone. For this purpose, the CO_2 measurement sequence over time is required, from which the ACH is calculated by minimising the squared residuals. The build-up method has been used by previous studies to obtain the VR in an occupied classroom [27, 223, 224].

Secondly, the IEQ evaluation is conducted. For this purpose, the feedback obtained from the first phase is used to determine if the students are satisfied with the indoor environmental parameters. To this end, the indoor variables measured during the teaching activity in the classroom are compared with the values indicated as suitable by the occupants (in this case, the students).

Phase 4: output generation. The results obtained in phase 3 are shown to the facility managers in two different formats: (1) the results are shown in the same interface as the BIM software and (2) a report. The first one is shown automatically in the BIM software interface after the application of the framework. This format shows the results in two different charts (the first one shows the assessment of IEQ for each lecture, and the second one shows the probability of infection). In addition, the report is automatically generated in .csv format. It contains all the data obtained from the evaluation.

7.2.2. Case Study

The polytechnic building of the University of Granada was used as a case study to evaluate the proposed BIM framework (Figure D7-11 in Appendix D). The building is located at the Fuentenueva campus, in the urban area of the city of Granada. Granada is characterised by a climate classified as Csa according to the Köppen–Geiger climate classification. The temperature is generally in the range 0–34 °C and rarely rises above 38 °C or drops below −4 °C during the course of the year.

The polytechnic building was built in 2000 and has seven floors with a concrete structure (waffle slab), concrete wall and flat roof with a sloping section. Classrooms are naturally ventilated and have heating systems (radiators). Table 7-1 shows the main characteristics of the classrooms.

Table 7-1. Characteristics of the classrooms in the polytechnic building.

Finishing Materials	Type of Windows	Mean Area (m^2)	Mean Occupancy Ratio (m^2/Person)
Wall: Gypsum plaster/Ceramic tile Floor: Natural stone Ceiling: Registrable suspended ceiling	Aluminium glazed windows (sliding)	170 ± 40.5	1.6 ± 0.9

The occupants' feedback survey was conducted during the academic year 2021–2022 (four times a month, 10 months from September 2021 to June 2022). The questionnaires were filled out by students in middle morning or middle afternoon, during the last fifteen minutes of the lecture class. This decision was intended to minimise the lecture disturbance and to maximize the exposure of the students to the indoor environmental conditions (students had been sitting for at least 1 h in the classroom). This field study followed the recommendations stated in UNE-CEN/TR16798-2:2019 and ISO 10551:2019 [121, 225]. A total of 930 responses were obtained.

7.2.3. Statistical Analysis

A statistical analysis was carried out with the data obtained from the field measurement campaign. The subjective data collected in combination with the objective data obtained from the sensors' field measurements were used to relate the occupants' perception to the indoor environmental conditions of the buildings. To evaluate the IEQ affecting the building occupants, regression methods were applied to the related objective and subjective results obtained. SPSS software (v.23.0) was used to perform this analysis.

7.3. Integration of the Proposed Methodology into BIM

As indicated in the previous section, a framework was developed to integrate the occupants' feedback and the data obtained from the sensor monitoring into the BIM model. In this study, the software BIM Revit® (v. 2023) and its open-source visual programming language Dynamo (v. 2.13) were used. Figure 7-2 shows the workflow of the system developed in the BIM. Firstly, a BIM model of the building under study was required to implement the developed framework. This model had to incorporate all the geometric and non-geometric information of the building. Therefore, a BIM level of detail (LOD) 300, as the minimum, was required to run the assessment process.

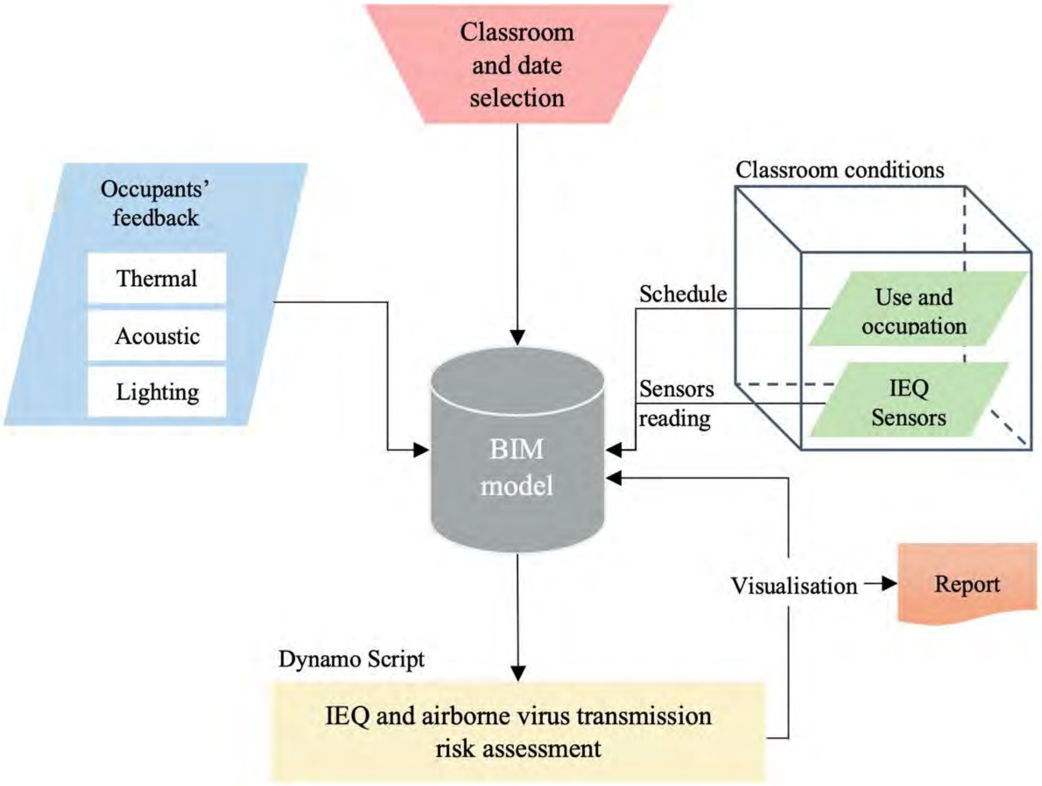


Figure 7-2. Workflow of the system developed in BIM

In addition, several shared parameters needed to be defined during the design of the BIM model (Table 7-2). These parameters were used to store and communicate information about the components of the BIM model.

Table 7-2. Shared parameters used in the model.

Parameter	Definition	Parameter Type	Category
Classroom_Id	Name of the classroom	String	Room
Max_occup	Maximum number of occupants	Number	Room
ID_Sensors	Identifier number of each sensor located in the classroom	String	Room

The proposed system developed in BIM included six main Dynamo packages or scripts, which are classified as follows (Figure 7-3):

- Scripts-1: Inputs.
- Scripts-2: Building data extraction.
- Scripts-3: Data extraction from sensors and schedule database.
- Scripts-4: Virus transmission risk assessment.
- Scripts-5: IEQ assessment.
- Scripts-6: Data visualisation and report.

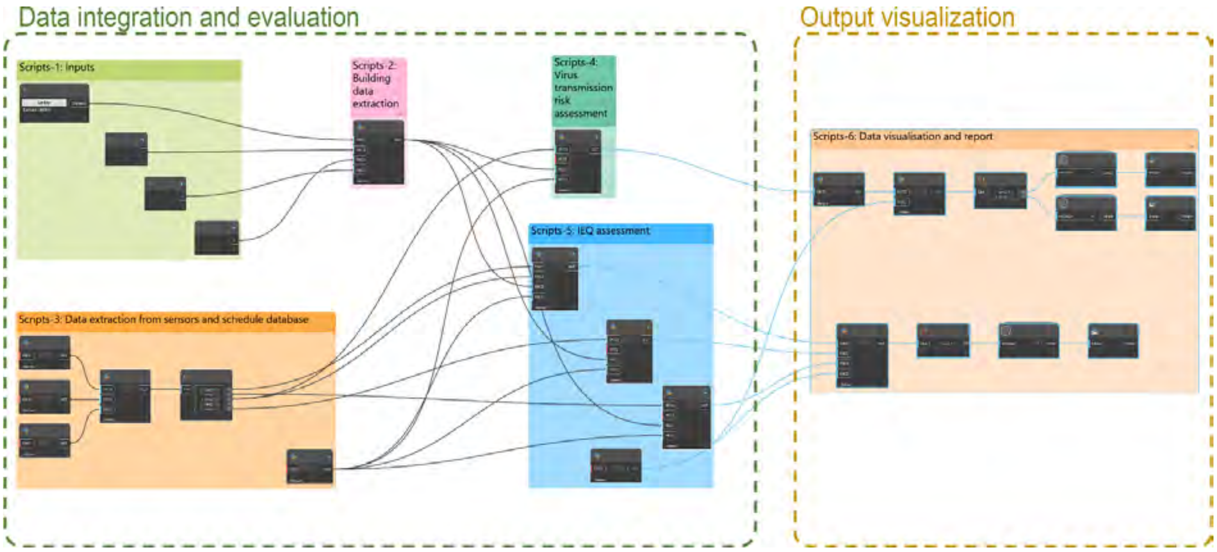


Figure 7-3. Overview of the diagram of the scripts developed using Dynamo.

The set of Scripts-1 Inputs allowed the selection of the classroom under study as well as the date considered for the evaluation. This information was used to identify the indoor environmental conditions of the selected classroom during the period under study. The classroom was selected directly in the BIM model. Subsequently, the period of analysis (start and end date) was entered through a string.

Scripts-2 Building data extraction obtained the geometric data (dimensions, volume and area) and the non-geometric data (Classroom_Id, Max_occup and ID_sensors) of the selected classroom.

The next set, Scripts-3 Data extraction from sensors and schedule database, connected and imported the data obtained from the sensors placed in the classroom (temperature, lighting, SPL and CO2 concentration) for the period under study. The parameter ID_sensors was used to link the sensor located in each classroom with the virtual model of the building. In addition, this process also imported the schedule of teaching activities that were conducted in the classroom during the selected period. The information imported for each teaching activity is shown in Table 7-3.

Table 7-3. Characteristics of teaching activities.

Element	Definition	Data-Type	Element
Classroom_Id	Name of the classroom where the teaching activity is carried out	String	Classroom_Id
Subject	Name of the subject	String	Subject
Start time	Day and time when the class starts	Date	Start time
End time	Day and time when the class ends	Date	End time
Type	Type of teaching learning activity (e.g., lecture, laboratory class, etc.)	String	Type
Occupation	Number of students attending the class	Integer	Occupation

Subsequently, based on the information incorporated by the previous sets of scripts, the assessment of the virus transmission risk was carried out in Scripts-4. For this purpose, the methodology defined in Section 7.2 was applied, and the probability of infection due to the SARS-CoV-2 virus was calculated using the Wells–Riley airborne disease transmission model (Equation (1)). According to the type of activity carried out during the teaching activity, the breathing rate of the students and professors (*p*) was selected: lectures where students were seated (*p* = 0.50 m3/h), laboratory activities where students were carrying out experiments (*p* = 0.65 m3/h), etc. These breathing rate values were obtained from REHVA COVID-19 guidance [70].

In addition, since the probability of transmission of the SARS-CoV-2 virus (Omicron variant) was considered in this study, two possible scenarios were evaluated when selecting the quanta emission: (1) q = 4.0 quanta/h, assuming that there is an infected student (C_i = 1), and (2) q = 10.8 quanta/h, assuming that the infected person is the professor (C_i= 1) [226]. However, if another variant or airborne virus transmission is assessed, the model will have to be modified and the appropriate quanta emission rate selected. The number of susceptible occupants (C_s) was equal to the classroom's occupation minus the number of infected occupants. The pulmonary VR was assumed as 0.54 m^3/h for students and 0.65 m^3/h for the professor [226]. The exposure time (*t*) was equal to the duration of each lecture. This script automatically evaluated, as a function of the occupation pattern obtained from the schedule database and the CO_2 time series measured by the sensors, the VRs during each class (ACH). Equation (4) (shown in Section 7.2) was used for this purpose. The ACH obtained value was used to calculate the probability of airborne virus transmission during each class.

Parallel to this process, the set of Scripts-5 assessed the indoor environmental conditions. The occupants' feedback obtained from the field survey (TSV, ASV and LSV) was analysed alongside the indoor environmental variables measured simultaneously (temperature, SPL and lighting), and the comfort zones were identified for each variable. In the case of thermal comfort, the ANSI/ASHRAE 55-2020 and the ISO 7730 standards [1, 122] were followed according to the comfort zone method. These standards state that, to maintain a percentage of dissatisfied occupants below 10%, the TSV should be between +0.5 and −0.5, while to maintain it below 20%, the TSV should be between +1 and −1. Therefore, three thermal comfort ranges were established (Equation (7-5)) [1]:

$$\begin{array}{lll} a. & -0.5 < TSV < 0.5 & Optimum \\ b. & -1.0 < TSV < 1.0 & Acceptable \\ c. & TSV < -1.0 \ or \ TSV > 1.0 & Unacceptable \end{array} \qquad (7\text{-}5)$$

The same strategy was assumed for the indoor light quality (Equation (7-6)):

$$\begin{array}{lll} a. & -0.5 < LSV < 0.5 & Optimum \\ b. & -1.0 < LSV < 1.0 & Acceptable \\ c. & LSV < -1.0 \ or \ LSV > 1.0 & Unacceptable \end{array} \qquad (7\text{-}6)$$

However, regarding the indoor acoustic quality, this study evaluated the indoor background noise to conduct the assessment. In this case, since the objective was to keep the background noise SPL at a level that did not interfere with the teaching learning activity, the three ranges were assumed as follows (Equation (7-7)):

$$\begin{array}{lll} a. & 0.5 < ASV & Optimum \\ b. & 0 < ASV < 0.5 & Acceptable \\ c. & ASV < 0 & Unacceptable \end{array} \tag{7-7}$$

The final step of the system generated in Dynamo was Scripts-6 Data visualization and report. This set of nodes made it possible to visualise the data obtained from the assessment process in the same BIM software, as well as to export a report of these data in a .csv format file. With respect to the IEQ assessment, the data are displayed in a stacked bar chart with the results obtained. The diagram shows the comfort zone and, for each time slot of the classroom under study, the thermal, lighting and acoustic conditions. The python library matplotlib is used for this purpose. In addition, with respect to the results obtained from the virus transmission risk assessment, a percentage of probability of infection is plotted using a range of colours depending on the value obtained.

7.4. Results: Case Study

7.4.1. Occupants' Feedback Survey

The occupants' feedback survey and IEQ measurement were carried out simultaneously during the 2021/2022 academic year. A total of 930 questionnaires were collected in this study, of which 908 were valid (22 were incomplete). Therefore, the feedback from 908 students was analysed and subsequently incorporate into the BIM model. The participants (university students) were sitting and listening to the lecturers during the field measurements. Figure 7-4 shows the distribution of the respondents' general information.

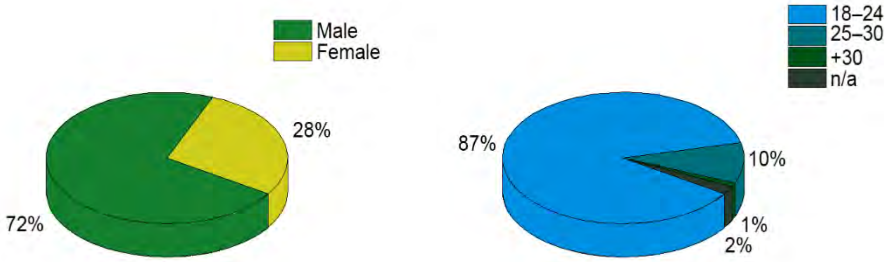


Figure 7-4. Gender and age of the surveyed students.

Regarding the participants' characteristics, 87% were aged between 18 and 24, a figure that rose to 97% when participants aged between 25 and 30 were included. The results obtained from the sensor monitoring are summarised in Table 7-4.

Table 7-4. Results obtained from the field measurements during heating season (HS) and non-heating season (NHS).

Type	Operative Temperature (T_{op}) (°C)		RH (%)		Air Velocity (m/s)		CO_2 Concentration (ppm)	Lighting (lux)	SPL (dBA)
	HS	NHS	NS	NHS	HS	NSH			
Max	26.3	28.3	49.4	50.1	0.15	0.22	1676	594	52.2
Min	14.5	19.1	26.9	21.3	0.01	0.01	400	110	30.0
Mean	18.4	23.6	38.3	37.7	0.04	0.04	592	409	44.6
Median	16.9	22.9	39.4	38.2	0.02	0.02	511	420	44.1
SD	3.3	3.0	6.5	7.8	0.05	0.05	233	101	4.3

Figure 7-5 shows the relationships between the sensation vote values and satisfaction vote values. In terms of indoor thermal quality during heating season (Figure 7-5a), the values obtained show that between 98% and 100% of the students who voted that the indoor thermal conditions were cold/cool or hot were dissatisfied. The values obtained of indoor thermal quality during the non-heating season (Figure 7-5b) show that between 92% and 100% of the students who voted that the indoor thermal conditions were cold/cool or hot were also dissatisfied, while dissatisfaction dropped to 70% for warm TSVs. These values may indicate a greater adaptation to warm environments than to cold environments. Figure 5c shows the relationship of student acoustic satisfaction and ASV. These values reveal that for a 'very noisy'/'noisy' ASV, 100–97% of students were dissatisfied, while for a 'slightly noisy' ASV, the percentage of dissatisfied students dropped to 46%. With respect to the indoor lighting quality (Figure 5d), about 63–64% of students who indicated dissatisfaction also indicated a 'very bright' or 'very dark' LSV. In fact, it was the less well-lit environments that caused the most dissatisfaction among students.

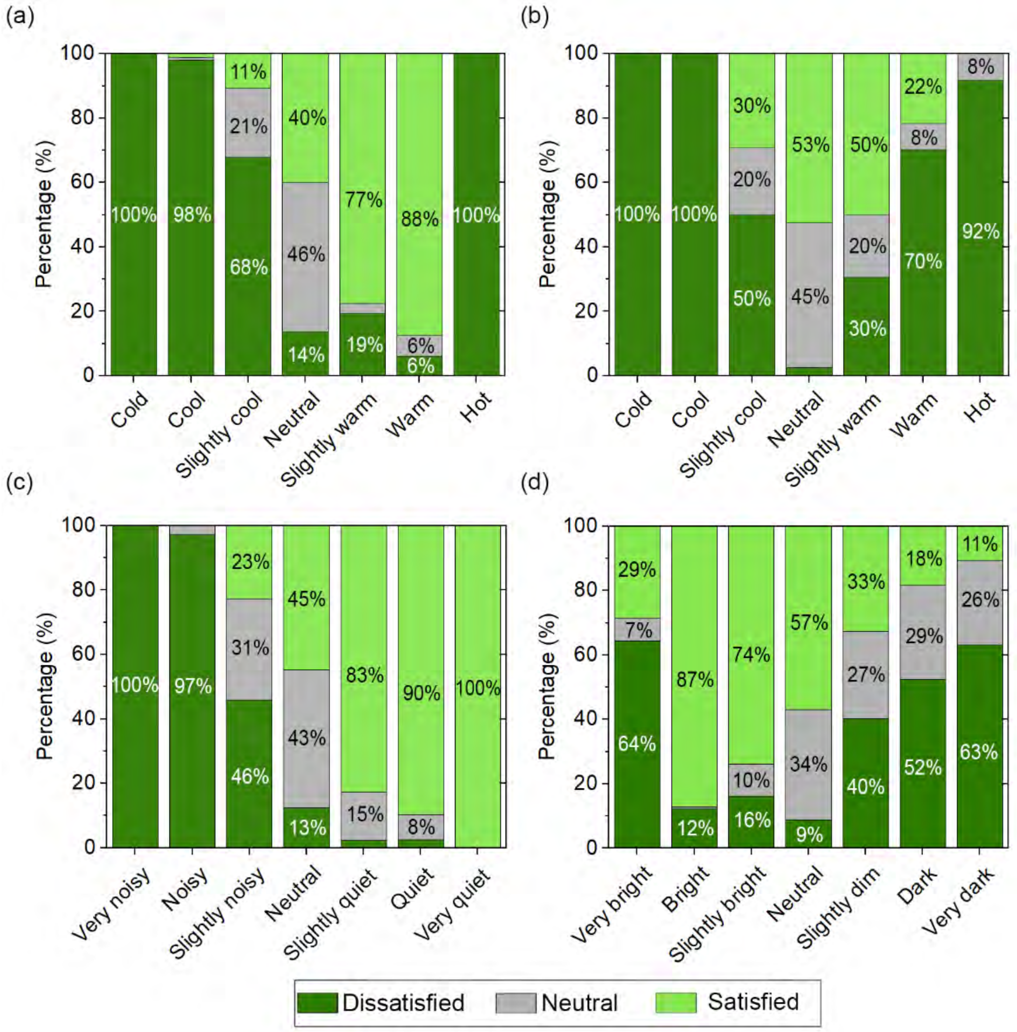


Figure 7-5. Sensation votes and satisfaction votes: (a) thermal (heating season), (b) thermal (non-heating season), (c) acoustic, (d) lighting.

Moreover, with respect to the relationship between the objective variables and sensation votes for each of the environmental factors studied, the results obtained are shown in Figure 7-6. Since the thermal adaptation and clothing level affect TSV, the relationship between the temperature and the subjective thermal perception of students was analysed separately for the winter and summer seasons. Figure 7-6a, b show the results obtained for the heating season ($R^2 = 0.85$, $p < 0.001$) and non-heating season ($R^2 = 0.84$, $p < 0.001$), respectively. It was found that the neutral temperature was 22.2 °C for the winter season and 23.5 °C for the summer season. Figure 7-6c shows the relationship between the LSV and the lighting values ($R^2 = 0.44$, $p < 0.001$). In addition, Figure 6d shows the relationship between the ASV and the background noise measured in the classrooms ($R^2 = 0.40$, $p < 0.001$). Based on the equation obtained from this regression analysis, the comfort zone was defined (Table 7-5). The sensation votes equal to '−1', '−0.5', '0', '0.5' and '1' were calculated for each environmental factor.

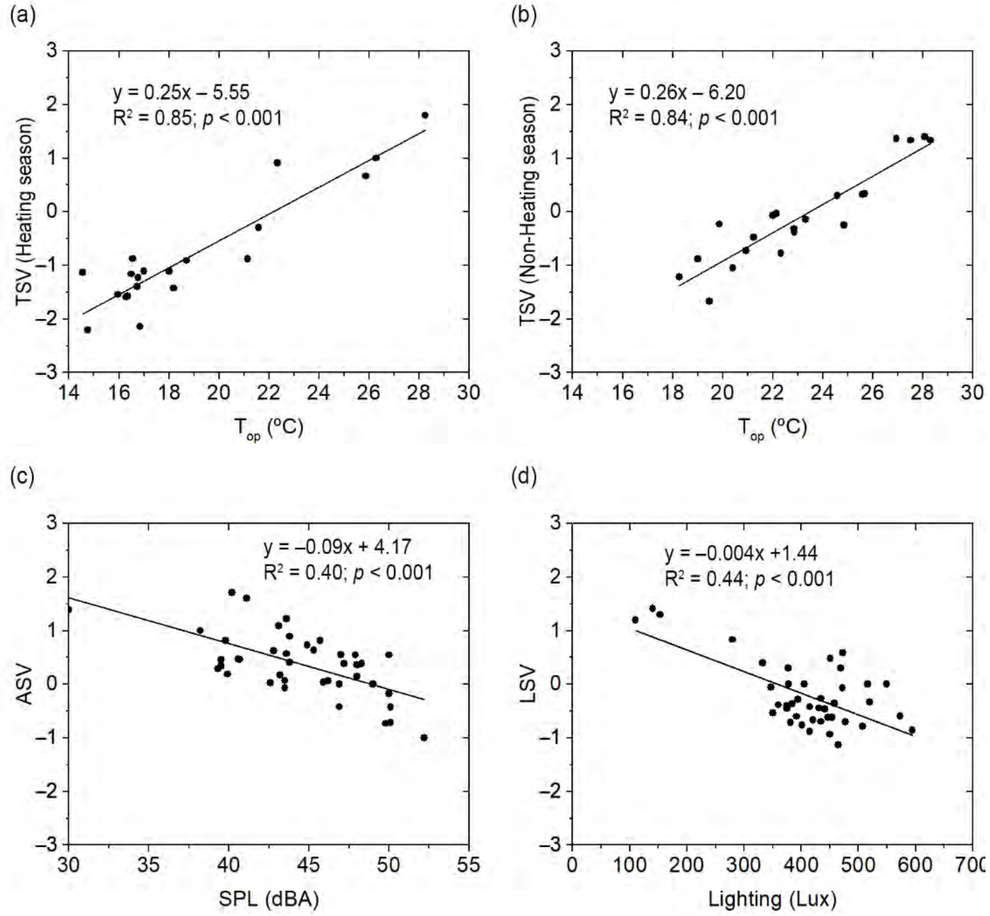


Figure 7-6. (a) TSV vs. Top winter season; (b) TSV vs. Top summer season, (c) ASV vs. SPL, (d) LSV vs. lighting.

Table 7-5. Values calculated for the comfort zones based on the sensation votes.

Parameter	Sensation Votes				
Values	−1	−0.5	0	+0.5	+1
Thermal (winter)	18.2 °C	20.2 °C	22.2 °C	24.2 °C	26.2 °C
Thermal (summer)	19.7 °C	21.6 °C	23.5 °C	25.4 °C	27.3 °C
Lighting	611 lux	486 lux	361 lux	236 lux	111 lux
Acoustic	-	-	48.9	43.0 dBA	37.2 dBA

7.4.2. Implementation in the BIM Model

This section shows an example of the application of the system developed in BIM to one of the classrooms of the building under study. Classroom 110 was selected on 30 May 2022 (non-heating season), whose teaching activity time schedule is shown in Table 7-6. Figure 7-7 shows the classroom selected.

Table 7-6. Schedule of the teaching activities in classroom 110.

Date	Time	Subject	Type of Activity	Occupation
30 May 2022	09:30–11:30	Sanitary Engineering (Group A)	Lecture	28
30 May 2022	11:30–12:30	Sanitary Engineering (Group B)	Lecture	30
30 May 2022	13:30–14:30	Structural analysis	Lecture	40

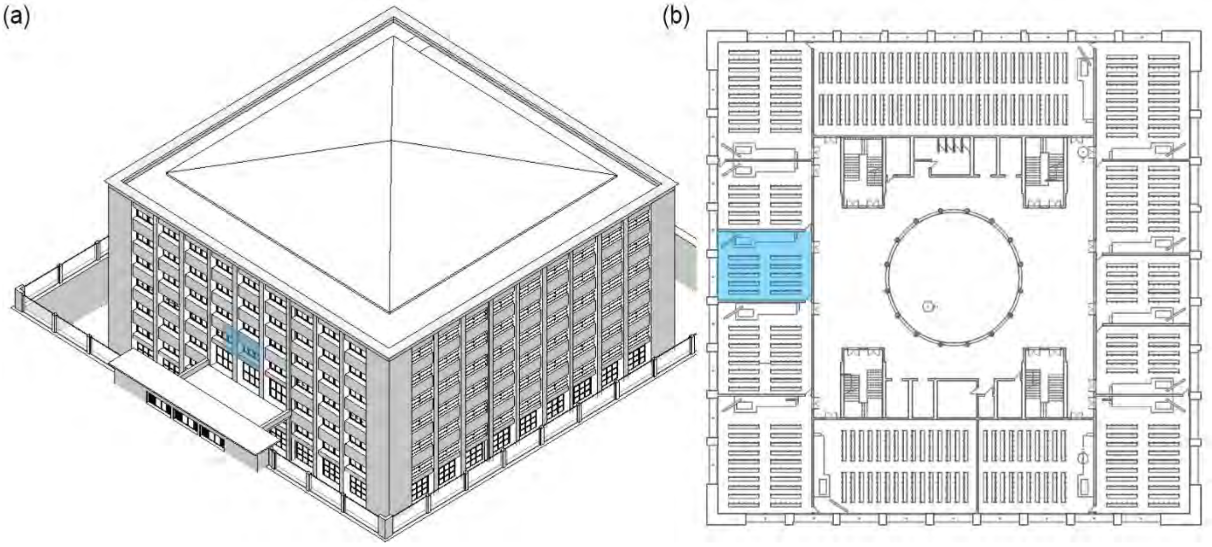


Figure 7-7. (a) BIM model of polytechnic building. (b) Plan of the first floor. Blue colour indicates classroom 110.

Protocols in this educational building include that classes must end ten minutes before the scheduled time to provide a rest interval for students and renew the air in the classroom. The results obtained from the IEQ evaluation in classroom 110 are shown in Figure 7-8 and Table 7-7. Green, blue and red colours indicate that the variables are in the optimum, acceptable and unacceptable ranges, respectively.

Figure 7-8. IEQ evaluation results of classroom 110.

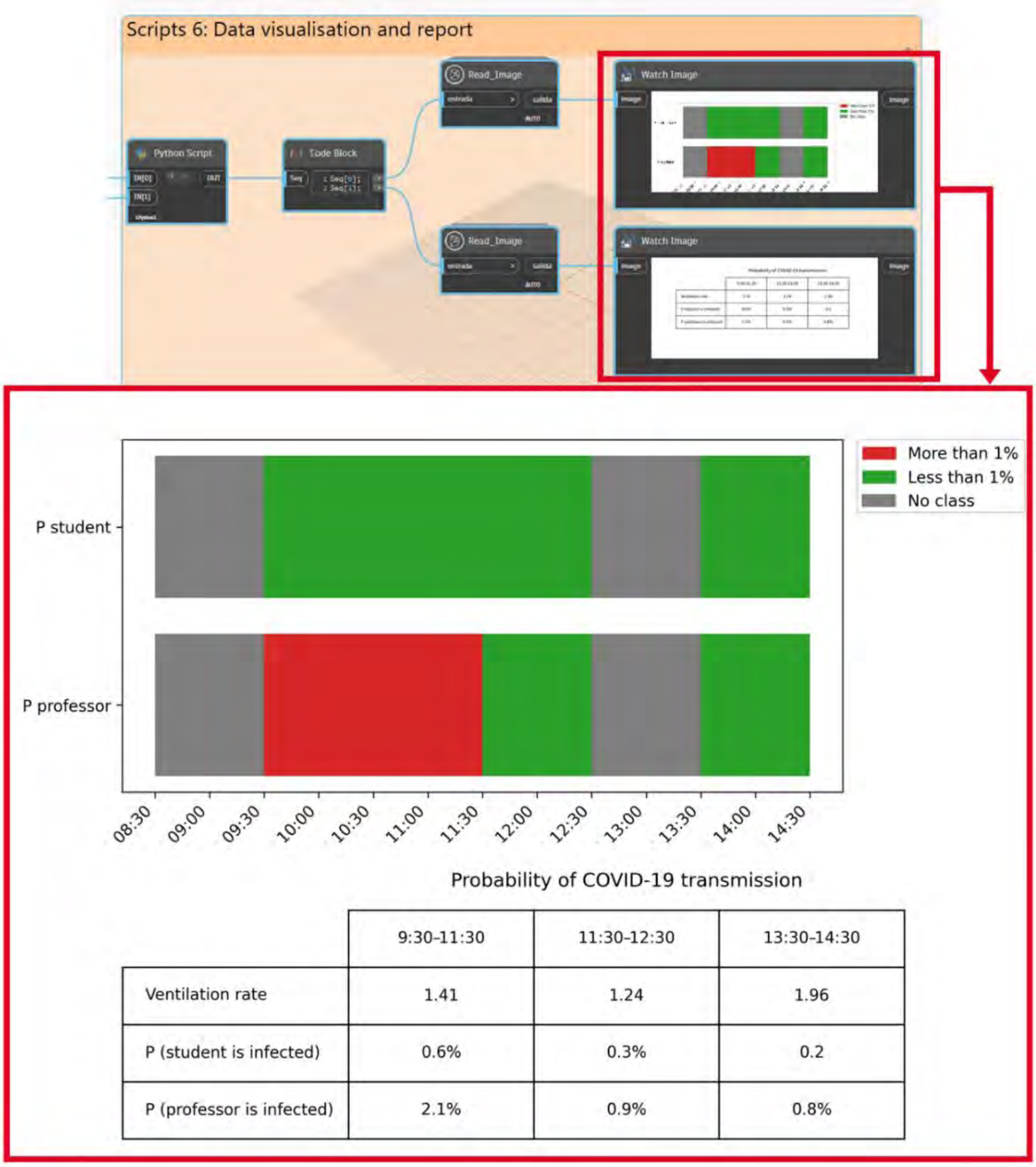
Table 7-7. Mean values of indoor environmental conditions.

Time	8:30–9:30	09:30–11:30	11:30–12:30	12:30–13:30	13:30–14:30
Temperature (°C)	24.1	24.9	25.2	25.6	27.8
Lighting (lux)	249	368	447	434	408
SPL (dBA)	40.3	44.5	50.1	44.3	49.5

In the analysed case, the indoor thermal conditions were acceptable during the first two lectures (the mean indoor temperature was 24.9 °C and 25.2 °C during Sanitary Engineering Group A and B lectures, respectively) and unacceptable during Structural analysis (27.8 °C, higher than the 26.2 °C limit value of the acceptable comfort zone). It should be noted that the last lecture took place during the warmest hours of the day, which, together with the fact that it was the most occupied lecture class, resulted in a higher indoor temperature.

Regarding indoor acoustic conditions, these were unacceptable during Sanitary Engineering (Group B) and structural analysis, and acceptable during Sanitary Engineering (Group A). Since this building is located in the urban area of Granada, natural ventilation strategies affect the indoor environmental conditions: outside urban noise (e.g., disturbing traffic noises such as sirens, trucks, etc.) and people talking in common areas (e.g., corridors) affect the acoustic conditions. In contrast, the indoor lighting conditions were optimal during all the lectures (all the mean values were in the optimum range).

In addition, the VRs inside classroom 110 during the teaching activities were calculated, and the probability of COVID-19 virus transmission was estimated assuming two scenarios: (1) a student was infected, and (2) the professor was infected. In addition, Figure 7-9 is plotted in the Dynamo environment. The results obtained for this case indicated that the probability exceeded 1% only during the first lecture (9:30–11:30) and assuming the scenario where the infected person was a professor. This lecture had the longest exposure time (2 h) and the second lowest ventilation rate. These conditions, together with the fact that the professor's quantum generation rate was higher (they talked more during the lecture), determine that the probability of COVID-19 infection is higher in this scenario (above 1%) than during the rest of the lectures.



	9:30-11:30	11:30-12:30	13:30-14:30
Ventilation rate	1.41	1.24	1.96
P (student is infected)	0.6%	0.3%	0.2
P (professor is infected)	2.1%	0.9%	0.8%

Figure 7-9. Assessment of the probability of airborne virus transmission in classroom 110.

7.5. Discussion

7.5.1. Field Measurement Campaign

In relation to the occupants' feedback survey, since the statistics published by the University of Granada in the report for the academic year 2020/2021 indicated that 95% of students on university degrees were aged between 18 and 30 [206], the values shown in Figure 4 were to be expected. With regard to the operative temperature during the heating season, the measured values ranged from 14.5 °C to 26.3 °C, and the RH ranged from 26.9% to 49.4%. In contrast, during the non-heating season, the operative temperature ranged from 19.1 °C to 28.3 °C, and the RH ranged from 21.3% to 50.1%. Regarding air velocity, this variable ranged between 0.01 and 0.15 m/s and 0.01 and 0.22 m/s during the heating and non-heating seasons, respectively. These environmental factors were influenced by the continuous natural ventilation through the opening of doors and windows [120]. Both operative temperature and RH reached values that were out of the ranges defined by the Spanish state regulation [90] (21–23 °C and 40–50% in heating season, and 23–25 °C and 45–60% in the non-heating season). These obtained results from the field measurement campaign were similar to those found in other studies conducted during the pandemic scenario. In fact, other studies conducted in Spain found that there was a significant period with out-of-range temperature conditions in natural ventilated classrooms during the COVID-19 pandemic [125, 158]. Regarding CO_2 concentration, values between 400 ppm and 1676 ppm were recorded. Some of these concentration values were above the limits indicated by the Spanish regulations (900 ppm), as well as exceeding the REVHA recommendations for educational buildings for indoor climate during the COVID-19 pandemic (800 ppm). Similar CO_2 concentration values were reported by studies conducted in classrooms where natural ventilation strategies were implemented [118, 125]. With regard to the indoor acoustic quality, values between 30.0 dBA and 52.2 dBA SPL were observed. Since background noise is an essential factor in educational buildings due to its effects on the quality of the learning process, previous research considered that the level of 35 dBA should not be exceeded in order to guarantee good speech intelligibility [186]. In this sense, the natural ventilation protocols implemented because of the COVID-19 pandemic have also influenced the indoor acoustic quality inside classrooms, increasing the background SPL [127]. The opening of doors and windows can increase the background noise level in the classroom, as it decreases sound insulation with neighbouring spaces (traffic noise, people talking in neighbouring areas, etc.). In the case of lighting, the measured values ranged from 110 to 594 lux. The UNE-EN 16798-1:2020 standard [72] recommends an illumination of 500 lux for classrooms. Therefore, the low lighting values observed may affect students' academic performance.

7.5.2. BIM-Based Framework

The obtained results from the case study evidence that the proposed framework can be used to assess the IEQ comfort requirements and the individual airborne transmission risk of COVID-19 in the BIM methodology. One of the advantages of the proposed framework that was identified is that the use of the BIM model of existing buildings together with its linkage to IEQ data allows the generation of a centralised database of the building characteristics. Therefore, the barrier to collecting the different information required is eliminated. The proposed methodology encourages the use of BIM models, which are currently mainly used in the design phase and throughout the whole of the building operation phase. In fact, the feedback obtained from groups of building occupants can be used by facility managers to evaluate indoor environmental conditions. The proposed methodology provides key information for post-occupancy IEQ evaluation and strategies for the control of ventilation. The framework automatically estimates the acoustic, lighting and thermal comfort of occupants based on the reading of sensor data. The results are shown in the software BIM interface, reducing the data processing time. The fact that all the information is available in a single database provides building managers with the necessary tool to analyse the facilities for any given period of time. This process provides valuable information for the building management and planning of the different subjects and classrooms. As a result, facility managers can use these results to support decision-making processes and improve building performance.

Moreover, the evaluation is based on occupant feedback, and the results therefore show real problems of occupants' dissatisfaction. Facility managers can make decisions based on this information from an occupant-centric point of view. In fact, the proposed framework can be applied to other type of spaces (e.g., offices, library, labs, etc.) as long as the subjective responses of the occupants of the spaces under evaluation are obtained. Therefore, the building manager can choose the room to be analysed with the proposed framework and use the generated output to support the building management decision-making process. Furthermore, the methodology presented in this study not only provides information to assess whether indoor spaces are safe for occupants (by assessing the risk of airborne virus infection), but also assesses whether the protocols implemented result in poor indoor environmental conditions. Therefore, the obtained results also show the potential use of the proposed framework and BIM methodology. This fact is in line with the conclusions provided by previous studies applying BIM and field environmental measurement data during the operational phase of the building. For example, Chang et al. [64] developed a BIM-based platform using Dynamo to visualize sensor data in BIM and help in making energy-saving management decision. Valinejadshoubi et al. [227] evaluated the applicability of BIM for an efficient sensor failure management system during the operational phase of a building and concluded that the information within BIM allows better and more effective decision making for building facility managers. In addition, Desogus et al. [65] tested the integrated use of BIM methodology and IoT systems using Dynamo, and concluded that the BIM model allows the management of useful information about the building, which is key for effective and accurate building management.

It should be highlighted that managing IEQ data has become critical in the aftermath of the COVID-19 pandemic, and ensuring the good ventilation of educational spaces is a challenge today. In this sense, this framework provides an analysis of data obtained from CO2 sensors and estimates the VR of each classroom. These data are used to assess the probability of infection by different airborne viruses, such as the SARS-CoV-2 virus. Regarding the probability infection results obtained from the case study, it should be noted that although Sanitary Engineering (Group A, 9:30–11:30) was the lecture that had the second lowest ventilation rate, it also had the longest exposure time (2 h), and the professor's quantum generation rate was higher than that of the students (as professors spend more time talking during lectures). In fact, Equation (1) of the Wells–Riley model shows this relationship: infection rate increases as the exposure time increases, while infection rate decreases as ventilation rate increases. In contrast, the results obtained from the last lecture show the highest ventilation rate and a probability of infection of less than 1%. However, the outdoor environmental conditions and surrounding spaces have a greater influence on the indoor environmental conditions of the classroom (acoustic and thermal conditions are outside the range of acceptable zone values for both variables). In addition, the threshold for the probability of infection was fixed at 1% because previous studies that analysed natural ventilation strategies and COVID-19 transmission considered 1% as a reference value of infection probability [49]. Nevertheless, this percentage can be modified in the framework at the discretion of the building manager.

Finally, the long-term application of the proposed methodology could provide data that can support the evaluation of the ventilation and management strategies implemented in buildings. This information is crucial for redesigning protocols and minimising the impact of poor IEQ conditions on building occupants.

7.6. Conclusions

This research has developed a framework to assess IEQ and the risk of infection by airborne viruses integrated into the BIM environment. The proposed system has been applied to an educational building of the University of Granada for validation. The main contributions of this study are as follows:

- The framework allows the integration of IEQ parameters and models to evaluate thermal, light and acoustic comfort into the BIM model.
- The system automatically calculates the thermal, acoustic and light sensation values for each of the classes in the selected period. It also avoids the possibility of information losses and errors in the process of assessment. Furthermore, the results are visualised in the same interface of the BIM software, facilitating the identification and detection of possible problems in the classrooms.
- The proposed system is an effective tool for building managers to manage IEQ and control airborne virus transmission. Its implementation supports decision making by providing useful information for the continuous assessment of the building. In addition, it is worth noting that it allows the building to be evaluated continuously over time and can be applied at any time as long as the time series measured by the sensors are available, as well as the evaluation and preventive diagnosis of buildings.
- The results presented in the case study showed that the proposed framework is a useful tool for building managers. The framework allows the identification of indoor environmental conditions out of the comfort range, such as thermal conditions (during "Structural Analysis") and acoustic conditions (during "Sanitary Engineering Group B" and "Structural Analysis"). It can also identify and visualise the risk of infection as shown in the scenario of an infected professor (with a probability of 2.1%).

7.7. Appendix D

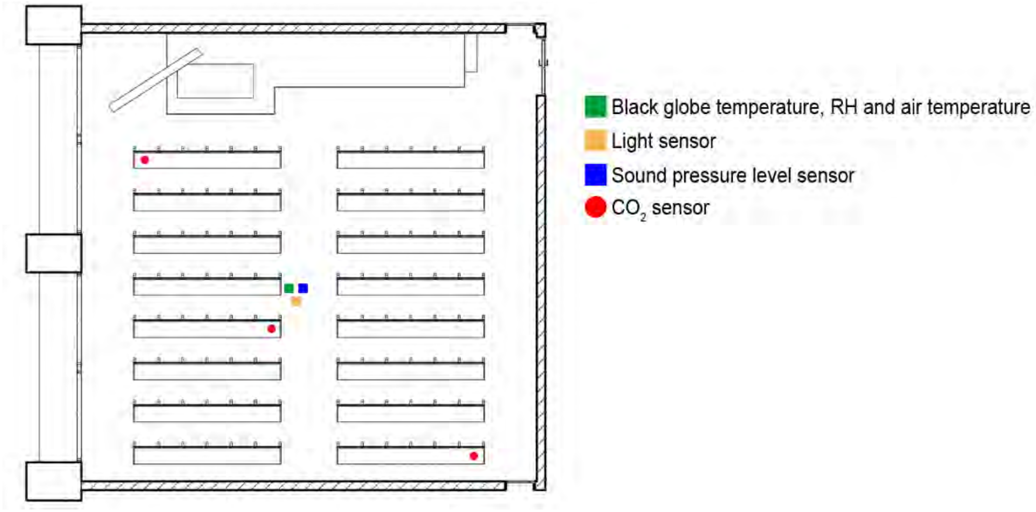


Figure D7-10. Layout of the sensor location in classroom

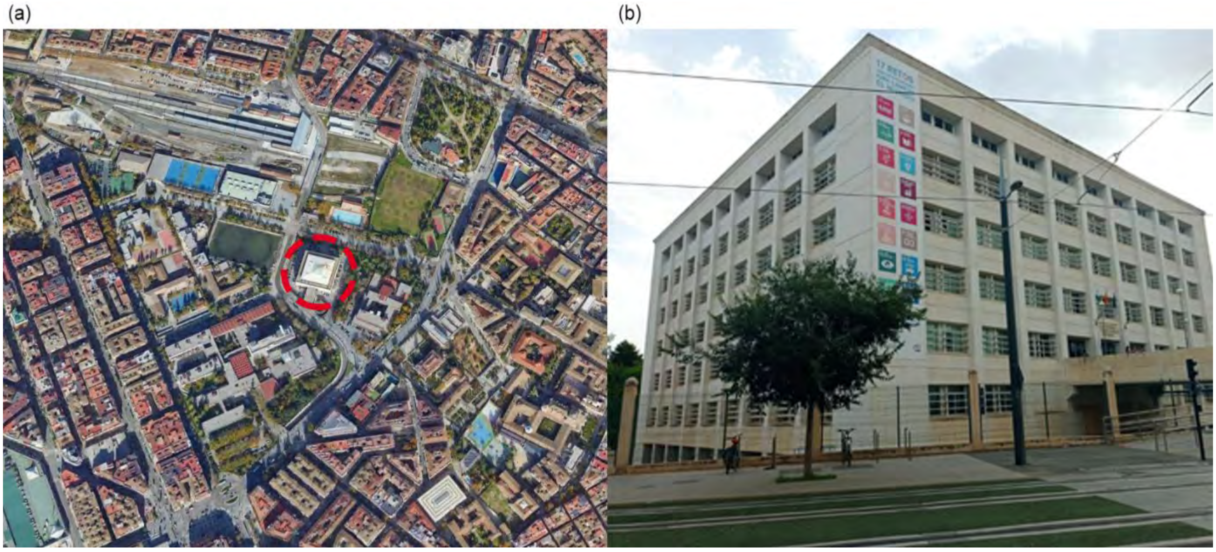


Figure D7-11. Polytechnic building of University of Granada: (a) location, (b) façade. Red dotted line indicates the location of the polytechnic building.

Table D7-8. Characteristics of the sensors used to measure the indoor environmental parameters.

Variable	Sensor	Range	Accuracy
Air temperature	FHAD 46-C41A AHLBORN	−20 to +80 °C	Typical ±0.2 K at 5 to 60 °C Maximum ±0.4 K at 5 to 60 °C Maximum ±0.7 K at −20 to +80 °C
Mean radiant temperature	FPA805GTS AHLBORN	–50 to 200 °C	0.1℃
Air velocity	HD403TS2 Delta OHM®	0.1 to 5 m/s	±0.2 m/s + 3% f.s
RH	FHAD 46-C41A AHLBORN	0 to 98% RH	±2.0% RH in range from 10 to 90% RH
CO_2 concentration	HOBO® MX1102	0 to 5000 ppm	±50 ppm ±5% of reading
Lighting	HOBO® MX1104	0 to 167,731 lux	±10% typical for direct sunlight
SPL	Imperum-R TECNITAX® Ingeniería	35 to 115 dBA	±1 dBA

8. CONCLUSIONES Y FUTURAS LÍNEAS DE INVESTIGACIÓN

8.1. Conclusiones

El Objetivo General de la investigación presentada en la presente Memoria de Tesis Doctoral es desarrollar una metodología para la integración de la evaluación de los factores de calidad ambiental interiores en el modelado de información de construcción (Building Information Modelling o BIM). Con este propósito, se han desarrollado campañas de medición en varios centros docentes universitarios de España y Portugal, que han permitido obtener información clave para proponer modelos integrados en un marco de trabajo, diseñado en un entorno BIM, para la monitorización, evaluación y gestión de la calidad ambiental interior en edificios docentes.

La consecución de este Objetivo General ha conllevado el desarrollo de un amplio trabajo de investigación y ha resultado en las siguientes aportaciones:

Para dar alcance al **O1**, en el **Capítulo 2**, se realizó una campaña de medición en edificios universitarios en Granada (España) y Guimarães (Portugal) con la finalidad de analizar diferentes estrategias de ventilación en ambas ubicaciones. Basado en los resultados obtenidos, se comprobó que la selección de una combinación adecuada de apertura de puertas y ventanas puede proporcionar una renovación de aire suficiente para cumplir las exigencias definidas en las normativas, así como las recomendaciones establecidas por las autoridades sanitarias como consecuencia de la pandemia COVID-19.

En cuanto a las estrategias de ventilación natural se obtuvieron valores que oscilaron entre 2.0 y 20.1 h^{-1}. Con respecto a la ventilación mecánica, el valor de tasa de ventilación obtenido en las aulas osciló entre 1.8 y 3.5 h^{-1}, siendo valores inferiores a los recomendados. En relación a la simulación y evaluación de la concentración de CO_2 se observó una amplia dispersión de los valores obtenidos entre las aulas y los diferentes escenarios de ventilación. Los resultados obtenidos para una ocupación normal de las aulas oscilaron entre 534 y 3903 ppm, mientras que para la ocupación recomendada durante la pandemia COVID-19 (50% de ocupación) oscilaron entre 475 y 2201 ppm. Para una ocupación de funcionamiento normal del aula, se encontraron valores superiores a los recomendados por la OMS, mientras que para una ocupación del 50% se obtuvo una reducción entre el 11 y el 44% en las concentraciones. En cuanto al riesgo de infección, sólo fue superior al 1% en cuatro de los escenarios estudiados, los cuales se correspondían con aulas con una superficie inferior a 70 m^2 y con una estrategia de ventilación unilateral. En este sentido cabe destacar que la tasa de infección aumenta a medida que aumenta el tiempo de exposición, mientras que la tasa disminuye a medida que aumenta la tasa de ventilación; por lo que para mantener el porcentaje inferior al 1%, las aulas con mayor volumen y menor densidad de ocupación van a requerir una tasa de ventilación menor que las aulas con un volumen inferior y misma densidad de ocupación. El análisis de los resultados ha puesto de manifiesto que, aunque el nivel de CO_2 estimado sea superior al recomendado por la REHVA, no implica necesariamente que el riesgo de infección sea mayor, ya que este está relacionado con el tiempo de exposición y la tasa de ventilación, que a su vez está condicionada por otras variables como el diseño de la sala, número de ventanas y puertas abiertas, condiciones climáticas exteriores, etc.

Para dar respuesta al **O2**, en el **Capítulo 3**, se ha desarrollado una campaña de medición de variables objetivas y subjetivas de las condiciones ambientales interiores en edificios universitarios de la Universidad de Granada (España) tras implementar los protocolos COVID-19. Aunque los resultados obtenidos mostraron que las estrategias de ventilación natural han proporcionado una renovación eficaz del aire, es evidente que también han alterado las condiciones ambientales interiores de las aulas. Si bien se encontraron valores bajos de concentraciones de CO_2 (397 – 668 ppm), también se detectaron valores de temperatura y humedad relativa (RH) fuera del rango recomendado por la normativa estatal (15.6 – 29.3 °C y 24.5 – 62.6%, respectivamente). En el caso del ambiente acústico interior se encontraron valores entre 49.8 – 64.3 dBA.

La ventilación natural continua mediante la apertura de puertas y ventanas ha condicionado la temperatura interior del aula, resultando en amplios rangos de temperatura tanto en el periodo de estación fría (periodo que requeriría uso de calefacción) (P1) como en la estación cálida (periodo que requeriría uso de refrigeración) (P2). Esto se evidencia en un mayor porcentaje de estudiantes insatisfechos en ambos periodos en relación con las condiciones térmicas interiores (53% en P1 y 17% en P2). Además, a partir de los resultados obtenidos, se observó que los estudiantes estaban más satisfechos con un entorno ligeramente cálido frente a un entorno más fresco. A partir de los resultados obtenidos es posible concluir que la ventilación natural puede mejorar la satisfacción térmica en las estaciones intermedias, cuando el flujo de aire del exterior puede reducir el sobrecalentamiento del aula. Por otro lado, el alto porcentaje de alumnos insatisfechos en P1 puede estar influenciado por varios factores: (1) el aislamiento de la ropa que vestían los estudiantes era inferior al requerido y (2) la temperatura dentro del aula era más baja como resultado de los protocolos de ventilación COVID- 19.

En relación a las condiciones acústicas interiores, éstas fueron la segunda condición ambiental con mayor porcentaje de estudiantes insatisfechos. En este sentido, existe una relación entre el protocolo implementado para garantizar la ventilación efectiva y el nivel de ruido equivalente de fondo L_{Aeq} dentro del aula. Las fuentes de ruido externas contribuyen a aumentar los niveles de ruido en mayor medida que en condiciones pre-pandémicas (ventanas y puertas cerradas). Este hecho está condicionado por la ubicación del campus universitario en el centro de la zona urbana de Granada.

Además, cabe destacar que los resultados del análisis estadístico han mostrado una relación moderada-alta entre la satisfacción general de los estudiantes con la satisfacción acústica y con la satisfacción térmica (ρ= 0,64; $p < 0,001$ y ρ= 0,51; $p < 0,001$, respectivamente). Estos valores muestran que las condiciones acústicas y térmicas han sido las que más han influido en la satisfacción del estudiante.

El **Capítulo 4** muestra la ampliación de la campaña de medición a edificios docentes universitarios de Guimarães (Portugal), contribuyendo al alcance del **O2**. Este estudio evaluó las condiciones ambientales interiores durante la reapertura de edificios educativos en el escenario post-epidémico del curso académico 2021/2022 tras la aplicación de las medidas estratégicas de "nueva normalidad" en España y Portugal. Aunque los protocolos post-epidémicos han proporcionado una renovación efectiva del aire y los niveles medios de concentración de CO_2 se han mantenido por debajo de 900 ppm en ambas localizaciones, los resultados sugieren que su aplicación tiene un impacto significativo en el grado de satisfacción de los estudiantes. Los resultados del estudio mostraron diferencias significativas entre las causas de insatisfacción tras comparar los datos obtenidos en ambos campus. La calidad acústica interior y la iluminación interior fueron las variables ambientales con las que los estudiantes portugueses se mostraron más insatisfechos. Por el contrario, los estudiantes españoles indicaron que estaban más insatisfechos con el ambiente térmico interior. De hecho, se observó una fuerte relación entre la satisfacción general y la satisfacción acústica en el conjunto de datos obtenido de los estudiantes portugueses (ρ= 0,540; p < 0,001). Mientras que, en el caso de los estudiantes españoles, la prueba de correlación de Spearman reveló una fuerte relación entre la satisfacción general y la satisfacción térmica (ρ= 0,522; p < 0,001). Además, siendo las condiciones acústicas y térmicas las variables que generaron mayor interferencia en el rendimiento del aprendizaje de los estudiantes portugueses y españoles, respectivamente.

La principal causa de insatisfacción relacionada con las condiciones térmicas interiores indicada por los estudiantes españoles fue "las corrientes de aire". Por el contrario, los estudiantes portugueses informaron de que su principal causa de insatisfacción eran las condiciones acústicas interiores debido a "la gente que habla en las zonas vecinas". Además, se encontraron diferencias estadísticamente significativas entre las preferencias de los estudiantes del campus de Fuentenueva y del campus de Azurém: los estudiantes españoles indicaron una preferencia más cálida (temperatura neutra = 23.3 °C) que los portugueses (temperatura neutra = 20,7 °C).

En los **Capítulos 5 y 6** se describe la realización de trabajo de campo necesario para alcanzar el objetivo **O4**. En el **Capítulo 5** se han estudiado las estrategias de ventilación natural (configuración de apertura de ventanas y puertas) que cumplan con las recomendaciones sanitarias del plan de acción COVID-19 a la vez que minimizan la influencia de las condiciones acústicas interiores en la satisfacción de los estudiantes. Entre las principales conclusiones se destaca que la ventilación natural cruzada es la estrategia más eficaz para alcanzar los niveles de ventilación requeridos que garanticen que los espacios cumplen con los requisitos para un regreso seguro a la docencia presencial. Se ha comprobado que existen diferencias entre las estrategias de ventilación natural según la configuración y características de las aulas. Así, por ejemplo, los niveles de ruido de fondo medidos en este estudio oscilaron entre 43,2 y 54,1 dBA, y como puede observarse, todas las aulas superan el límite de nivel de ruido de fondo de 35,0 dBA recomendado para los espacios de enseñanza por la OMS. Se constata que la ubicación y la orientación del aula influyen en la configuración de la ventilación natural y en el ruido de fondo en la misma, lo cual es evidente en los resultados obtenidos para el aula orientada hacia una zona de tráfico denso, en la que el nivel de ruido de fondo era de 54,1 dBA.

Se hace evidente a la luz de los datos anteriores que elevados niveles de ruido de fondo en espacios docentes generan interferencia en las actividades de enseñanza aprendizaje. Por un lado, provocan dificultades en la comprensión del mensaje por parte de los estudiantes. Por otro, requieren que el profesor realice un mayor esfuerzo vocal ya que el nivel de habla vocal tiene que ser mayor. Este hecho determina que el ruido de fondo se convierta en un problema que tiene una gran repercusión en la situación actual. Dado que las aulas utilizadas para el regreso al campus son las más grandes y los estudiantes se distribuyen en toda su superficie para garantizar una mínima distancia física (ocupando todas las filas), muchos alumnos se encuentran en posiciones alejadas del profesor. En consecuencia, la relación señal-ruido es muy baja en las posiciones traseras, lo que provoca efectos significativos en la reducción de la identificación e inteligibilidad de las palabras.

Por lo tanto, una de las principales conclusiones obtenidas de esta investigación es que la gestión, organización y planificación de los espacios interiores de los edificios educativos no sólo debe garantizar la seguridad de los ocupantes, sino también no influir en el desarrollo de las actividades docentes. La selección de aulas debe tener en cuenta más factores que únicamente el tamaño de la misma y la estrategia de ventilación. Se necesitan planes de acción que permitan a los administradores de los edificios conseguir estrategias adecuadas de ventilación natural y aplicar medidas eficaces de reducción del ruido en los espacios interiores.

En el **Capítulo 6** se ha llevado a cabo una campaña de monitorización para analizar la percepción térmica de los estudiantes durante las clases universitarias del primer semestre del curso 2021-2022 (estación fría). Los resultados obtenidos evidenciaron que las condiciones térmicas interiores se vieron significativamente afectadas durante esta estación por los nuevos protocolos de ventilación resultantes de los planes de acción de la COVID-19.

Los resultados mostraron que la ventilación continua permitía que las aulas fueran seguras, aunque con un elevado impacto en las condiciones térmicas en relación a la satisfacción y el rendimiento de los estudiantes. En este sentido, sólo el 18% de las aulas evaluadas estaban en el rango de confort térmico establecido por la normativa, lo que se reflejó en el alto porcentaje de estudiantes insatisfechos. Del análisis de los datos también se observó que los estudiantes preferían un ambiente más cálido durante la estación fría. Asimismo, se observaron diferencias estadísticamente significativas entre los valores de satisfacción, sensación e interferencia entre los votos de los hombres y mujeres (la Temperatura neutral obtenida fue 23,2 °C para los hombres y 24,2 °C para las mujeres). El porcentaje de estudiantes insatisfechos fue menor cuando la diferencia entre la temperatura neutral y la temperatura operativa estaba entre -2.0 y 4.0 °C. Las alumnas evaluaron el ambiente interior como más frío y preferían condiciones térmicas más cálidas. También cabe señalar que se han encontrado diferencias significativas entre los valores de aislamiento de la ropa de los alumnos y las alumnas, siendo el valor medio de las alumnas 0,17 clo superior al de los alumnos.

En cuanto al objetivo **O4**, se le da respuesta en el **Capítulo 7** donde se presenta un marco de trabajo integrado en BIM para evaluar los factores de IEQ y el riesgo de contagio de virus de transmisión aérea. Entre las principales contribuciones de este estudio se encuentran:

- El marco de trabajo permite la incorporación de información relativa a la calidad ambiental térmica, acústica y lumínica en el modelo BIM. Además, permite la integración de modelos IEQ para la evaluación de estos parámetros. La utilización de una única base de datos (modelo BIM) permite eliminar la recopilación de información requerida por distintas bases de datos, ahorrando tiempo y evitando la posibilidad de pérdidas de información y errores en el proceso de evaluación y valoración.
- El sistema calcula automáticamente los valores de sensación térmica, acústica y lumínica para cada una de las clases en el periodo seleccionado. Además, los resultados se visualizan en la misma interfaz del software BIM, facilitando la identificación y detección de posibles problemas en las aulas. Además el marco de trabajo es flexible, es decir, permite incorporar nuevos modelos y/o rangos de acuerdo con la normativa de los diferentes países o espacios.
- El marco de trabajo generado se constituye como una herramienta que proporciona información clave para el apoyo durante la toma de decisiones en fase de uso y mantenimiento de edificios de distintos usos. Esta propuesta contribuye a ampliar el uso de la metodología BIM más allá de la fase de diseño. Además, cabe destacar que permite la evaluación continua del edificio a lo largo del tiempo y puede aplicarse en cualquier momento siempre que se disponga de las series temporales medidas por los sensores, así como de la evaluación y el diagnóstico preventivo de los edificios.

Por último, es necesario señalar que la consecución con éxito del Objetivo General de la presente Memoria de Tesis Doctoral ha sido posible a partir de las aportaciones generadas durante el proceso de investigación, proporcionando a su vez perspectivas de futuras líneas de trabajo que se describen a continuación.

8.2. Futuras líneas de investigación

La investigación presentada en esta Memoria de Tesis Doctoral ha generado futuras líneas de trabajo entre las que destacan:

- Desarrollo de nuevos algoritmos basados en aprendizaje automático para la evaluación de los factores IEQ desde fase de diseño hasta la fase de mantenimiento y operación de los edificios (redes neuronales, redes bayesianas, algoritmos genéticos, etc.).
- Integración de los algoritmos basados en aprendizaje automático en la metodología BIM. Si bien BIM permite la recopilación, el intercambio y la vinculación de información a lo largo del ciclo de vida del edificio, se plantea ampliar su funcionalidad a través de la integración de algoritmos de Inteligencia Artificial y Aprendizaje Automático o "Machine Learning" con el objetivo de realizar simulaciones y evaluaciones. Este proceso proporcionará información clave a los profesionales de la AIC (como diseñadores, gerentes de proyectos, inspectores y propietarios) para la toma de decisiones efectivas. El desarrollo de esta línea permitirá valorar el enfoque del aprendizaje automático integrado en BIM para la gestión de las IEQ en los edificios, en línea con la transformación digital que está sufriendo el sector de la construcción.
- Implementación de los algoritmos desarrollados en sensores o dispositivos de Internet de las cosas (IoT) e interconexión con modelos BIM. Los futuros estudios de investigación deberían abordar el desarrollo de sistemas y dispositivos combinados con protocolos de seguridad rediseñados que garanticen no sólo la seguridad de los espacios interiores, sino también el mantenimiento de niveles aceptables de satisfacción en relación con la IEQ. Esta línea está acorde a las nuevas tendencias en el sector de la AIC como son el desarrollo de los Gemelos Digitales.

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