UNIVERSITÀ
DEGLI STUDI
DI PADOVA

To the Department of Industrial Engineering
Ph.D. Course in Industrial Engineering
Curriculum Energy Engineering
XXXIV Cohort

The Indoor Environmental Quality (IEQ) and comfort in educational buildings

Coordinator: Ch.mo Prof. Giulio Rosati

Supervisor: Ch.ma Prof.ssa Francesca Cappelletti

Co-Supervisore: Ch.mo Prof. Andrea Gasparella

Ph.D Candidate: Arch. Ilaria Pittana

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Si sa che è effimera, fragile, si sa che è così spesso illusoria […], ma si sente anche che un essere che prova gioia si sta abbandonando, sta cedendo.
È a quel luogo tenero e delicato che si invia l’augurio: «Che la tua gioia possa durare».

Chandra Livia Candiani

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Summary

The present research deals with the assessment of the Indoor Environmental Quality (IEQ) in educational buildings by means of physical measurements (i.e., objective evaluation), questionnaire (i.e., subjective evaluation) and building model simulation and calibration. In particular, the work proposes different original methods for:

- the design of a standard subjective questionnaire consistent for the four comfort domains, i.e., the indoor air quality (IAQ), thermal, acoustic and visual environment (i);
- data collection, namely the monitoring of the main physical parameters related to the four comfort domains (ii) and the administration of the standard questionnaire (iii);
- data validation and analysis, namely the validation of the questionnaire (iv) and the correlation method between objective and subjective data (v);
- optimization-based calibration, using a multi-level multi-step approach.

Assessing the IEQ in school buildings is not a simple task. Differently from what occurs during laboratories studies, in educational buildings schools' occupants (i.e. students and teachers) are exposed at once to acoustical, thermal, visual, and air quality stimuli, and the effect of the indoor environment on students' perception and performance depends on their combined effects.

As highlighted in Chapter 1, students use to stay more than 30% of their daytime in classrooms, thus the importance of assessing and enhancing the indoor conditions of school buildings. The indoor conditions can be evaluated either through an objective evaluation, i.e. measurements of physical quantities related to the main IEQ domains, or by means of subjective evaluation, i.e. questionnaires' administration, which considers building occupants as a valuable source of information about IEQ. Chapter 2 presents an overview of the state of the art of the assessment of the indoor environmental quality (IEQ) by means of questionnaires and measurements.

Chapter 3 reports the innovative methodology developed during my doctoral program to assess the IEQ in educational buildings and to calibrate the energy model of a building. In the first part, the method for evaluating the indoor conditions of school buildings through objective and subjective evaluation, namely respectively in-field measurements and questionnaires, is presented. The second part includes the optimization-based procedure to calibrate the energy model of educational buildings. The method for the evaluation of the IEQ includes the questionnaire design, the procedure for data collection and for data validation and analysis. The method for building model simulation and calibration, i.e., multi-level multi-step calibration, explores the optimization-based procedure to calibrate the energy model of an educational building from short-term monitoring of a portion of a building in selected periods of the year.

Chapter 4 presents the case studies considered for the application of the methodologies defined in Chapter 3. The method for assessing the IEQ has been applied to 21 classrooms located in three different buildings in Italy, i.e. one classroom of the university building of the Free University of Bozen-Bolzano (UR1), eighteen classrooms of the high school Margherita Hack in Morlupo, Rome (MR1-MR18), and two classrooms located in two different building of IUAV University of Venice (VR1 and VR2). The multi-level multi-step optimization-based calibration has been implemented to a primary school located near Vicenza, in the north of Italy.

Chapter 5 reports the main outcomes of the application of the methodology presented in Chapter 3. The results are divided into three sections, namely the questionnaire validation (i), the correlation between objective and subjective data, (ii) and the multi-level multi-step optimization-based calibration (iii). The results coming from the questionnaire validation are divided into three subsections according to the three selected KPIs, i.e. effectiveness, efficiency and resolution. The outcomes of the correlation between the subjective survey and the objective data are split based on the different type of analysis, namely the single-domain approach that consists in analyzing the correlation between measured environmental conditions and the subjective response within the same comfort domain, and the multi-domain approach that aims to explore the combine effects of different comfort domains. The results of each analysis are presented by comfort domains, i.e. thermal environment, indoor air quality, visual and acoustic environment. Regression analysis and descriptive statistics (i.e. box plots) are used for presenting the results. The last paragraph presents the results of the multi-level multi-step optimization-based calibration method applied to two monitoring periods, namely Period 1 (i.e. unoccupied building with system off) and Period 2 (i.e. occupied building with system off). The outcomes include the results of the calibration and the validation of the building model in different periods with the same characteristics of the reference periods.

The last chapter reports the main conclusions of the work and future developments of the research.

Riassunto

Diversamente da quanto accade negli studi di laboratorio, negli edifici scolastici gli occupanti sono esposti contemporaneamente a stimoli acustici, termici, visivi e di qualità dell'aria e l'effetto dell'ambiente interno sulla percezione e sulle prestazioni degli studenti dipende dai loro effetti combinati. La presente ricerca si occupa della valutazione della qualità ambientale interna (IEQ) negli edifici scolastici mediante misurazioni fisiche (valutazione oggettiva), somministrazione di questionari (valutazione soggettiva) e simulazione e calibrazione di modelli energetici. Il lavoro propone diversi metodi originali per: la progettazione di un questionario soggettivo standard coerente per i quattro domini di comfort, ovvero IAQ, ambiente termico, acustico e visivo (i); raccolta dati (ii) e la somministrazione del questionario (iii); validazione e analisi dei dati, ovvero la validazione del questionario (iv) e il metodo di correlazione tra dati oggettivi e soggettivi (v); calibrazione basata sull'ottimizzazione, utilizzando un approccio *multi-level multi-step*. Come evidenziato nel Capitolo 1, gli studenti trascorrono più del 30% della loro giornata in classe, da qui l'importanza di valutare e migliorare le condizioni interne degli edifici scolastici. Le condizioni indoor possono essere valutate sia attraverso misure di grandezze fisiche relative ai principali domini sia tramite la somministrazione di questionari. Il capitolo 2 presenta una panoramica dello stato dell'arte della valutazione dell'IEQ mediante questionari e misurazioni. Il capitolo 3 riporta la metodologia innovativa sviluppata durante il mio programma di dottorato. Nella prima parte viene presentato il metodo per valutare le condizioni interne degli edifici scolastici attraverso valutazioni oggettive e soggettive, ovvero rispettivamente misurazioni in campo e questionari. La seconda parte include la procedura basata sull'ottimizzazione per calibrare il modello energetico degli edifici didattici, che esplora la procedura basata sull'ottimizzazione per calibrare il modello energetico di un edificio scolastico dal monitoraggio a breve termine di una porzione di un edificio in periodi selezionati. Il capitolo 4 presenta i casi di studio considerati per l'applicazione delle metodologie. I risultati riportati nel Capitolo 5 sono divisi in tre sezioni: la validazione del questionario (i), la correlazione tra dati oggettivi e soggettivi ´ (ii) e la calibrazione basata sull'ottimizzazione *multi-level multi-step* (iii). I risultati provenienti dalla validazione del questionario sono suddivisi in tre sottosezioni in base ai tre KPI selezionati, ovvero efficacia, efficienza e risoluzione. Gli esiti della correlazione tra l'indagine soggettiva e i dati oggettivi sono suddivisi in base al diverso tipo di analisi, ovvero *single-domain* che consiste nell'analizzare la correlazione tra le condizioni ambientali misurate e la risposta soggettiva all'interno dello stesso dominio di comfort, e *multi-domain* che mira a esplorare gli effetti combinati di diversi domini di comfort. L'ultimo paragrafo presenta i risultati del metodo di calibrazione basato sull'ottimizzazione multilivello multifase applicato a due periodi di monitoraggio, ovvero edificio non occupato con sistema spento e edificio occupato con sistema spento. L'ultimo capitolo riporta le principali conclusioni del lavoro e gli sviluppi futuri della ricerca. Il set di dati raccolto e i metodi rigorosi sviluppati dovrebbero essere considerati come parte di un approccio complesso e replicabile che può fungere da quadro concettuale di base per studi futuri incentrati sulla valutazione dell'IEQ degli edifici scolastici e di altri edifici complessi può essere utilizzato per ulteriori indagini su la valutazione dell'IEQ e del comfort negli edifici scolastici.

1. Introduction

1.1 The Indoor Environmental Quality (IEQ) in educational buildings

Inhabitants of industrialized areas spend most of their time inside buildings (85–96%) [1-3]. Among them, students use to stay more than 30% of the day in classrooms [2]. Thus, being in the spotlight due to the resumption of learning activities after the health emergency related to the COVID pandemic, school buildings need to enhance their indoor conditions. Moreover, in Europe, schools represent a significant portion of the entire building stock and they are responsible for a considerable amount of the total energy consumption [4]: only in Italy, the educational building stock consists of about 40 000 buildings and despite the recent retrofitting interventions, most of it barely satisfies the current energy performance requirements nor guarantees an adequate quality of the indoor conditions. [5].

Most of the energy consumption of educational buildings is used for providing an adequate Indoor Environmental Quality (IEQ) in terms of thermal, visual, acoustic comfort and indoor air quality. If healthy and comfortable indoor conditions result to be essential for any type of building, this is particularly relevant for schools. In fact, in this category of buildings a high level of IEQ is required not to hinder students' visual and acoustic performance [6], attention, concentration, learning, and to maximize the education performances.

Indeed, IEQ is important not only for students' and teachers' wellbeing during the school day, but it has to be considered that students' mental effort and performance are arguably influenced by the quality of the environment where they carry out their activities [3]. Moreover, indoor conditions have an influence also on students and teachers' adaptive behaviour [1], namely the set of actions to enhance their comfort inside the buildings. People's actions on a building may have two main implications: on the one hand occupants' behaviour might affect building energy performance, for example when people try to restore their comfort by actions, such as shadings opening or temperature adjustments, their actions could compromise the building standard operation, thus altering the building energy consumption. On the other hand, people behaviour can also operate in such a way that restoring one comfort aspect (e.g. thermal local discomfort such as drafts) could be detrimental for another one. For example, windows opening to provide fresh air might affect the indoor air temperature causing discomfort to other students.

For these reasons it would be fundamental to monitor constantly the indoor conditions of educational buildings in order to study how adequate indoor conditions can be obtained and maintained. Besides, it is equally important to extend the evaluation also to the building design phase for helping practitioners to take into account and predict the IEQ and occupants' comfort for future buildings.

1.2 The Assessment of the IEQ in educational buildings: main issues & research gaps

The indoor conditions can be evaluated either through an objective evaluation, i.e. measurements of physical quantities related to the main IEQ domains, namely air quality, and thermal, acoustic and visual environment, or by means of subjective evaluation, i.e. questionnaires' administration, which considers building occupants as a valuable source of information about IEQ [7].

1.2.1 Objective evaluation

The measuring of the indoor conditions for inspecting occupants' comfort is ruled by International Standards that mainly focus on thermal environment and IAQ, i.e. UNI EN ISO 10551:2019, EN 16798-1:2019, EN 16798-2:2019, ASHRAE Standard 55:2017, UNI EN ISO 7730:2006, UNI EN ISO 7726:2002 [8-12]. EN 12665:2018 and EN ISO 12464-1:2011 [13-14] focus on visual environment, while ISO 3382-2:2008 regulates the acoustic domain [15].

The above-mentioned standards provide guidelines for selecting the appropriate measuring equipment, their location in relation to the indoor space to monitor and to the position of the occupants, and suggest benchmarks for evaluating comfort ranges derived from monitored data. However, International Standards rarely mention literature reference supporting evidence for the provided benchmarks.

The objective evaluation of the IEQ includes both long-term and short-term measurements, which respectively could take several days or months or just hours. Based on these two different monitoring approaches, it is possible to assess the quality of the indoor environment by comparing the measured physical parameters with the benchmarks provided by international standard, or to calculate comfort indexes.

The objective evaluation of IEQ has some limitations. On the one hand, long-term monitoring of physical parameters could be costly (i) and time consuming (ii), on the other, a critical aspect regards the difficulty to choose representative space of the building to monitor (iii) along with the selection of representing periods (iv) for running the measures. Moreover, standards do not provide a univocal level of detail of measurements in order to collect the appropriate dataset for evaluating people's comfort ranges. Furthermore, standards do not suggest possible strategies to guarantee the adequate well-being of the building occupants (v).

The highlighted limitations increase if the buildings to monitor are schools. In fact, educational buildings include environment with different functions, e.g. classrooms, corridors, gyms, canteens, etc., where students carry out various activities, thus the appropriate representative spaces could be very challenging.

However, the monitoring of environmental conditions is fundamental for understanding the relationship between the physical quantities and people's comfort and satisfaction. Moreover, if the monitoring is extended to the four comfort domains is possible to inspect occupants' global comfort, i.e., neutral conditions in the four domains, and the possible interactions between different comfort domains, i.e., crossed or multi-domain effects.

1.2.2 Subjective evaluation

The other approach for evaluating occupants' well-being inside building is subjective evaluation that consists of the administration of questionnaires in order to directly inspect people's perception, comfort and satisfaction for the indoor environment. Besides these aspects, it is possible to investigate also people's behaviour and to study occupants' performance in relation to the indoor conditions to which they are exposed. Recently, occupancy surveys have been widely used either for evaluating the right-now responses of building occupants [18-62, 64-74] or for post-occupancy assessments [63,86], i.e. long-term surveys, with the aim to inspect the influence of environmental factors on people's well-being, their behaviour for facing discomfort [81-82] or for the definition of comfort ranges to be considered in the design phase of a building and in relation to environmental control strategies.

There are different international standards that provide guidelines for inspecting occupants' comfort by means of the subjective evaluation, namely ASHRAE Standard 55/2017 [10], EN ISO 10551:2019 [8], EN 15251: 2007 [16] and EN ISO 28802:2012 [17], but all of them refer to adult workers (i) in office building or living lab, i.e., controlled spaces. Moreover, standards focus mainly on thermal environment and IAQ (ii) and even if EN ISO 28802 and EN ISO 10551 consider also visual and acoustic environment, they do not suggest consistent questions for the different domains (iii). In particular, they use different wording of questions, and unlike numbers of points scales for the four comfort aspects. The consequence is that in literature, even if some works aim to evaluate the comprehensive people's response [18-22], i.e. global comfort, or the interactions between different comfort factors [23-24], i.e. cross-effects, there is no common approach to the problem. The lack of consistency among all the comfort aspects is detrimental to any attempt of assessing the contribution of each to the global comfort as well as of understanding interactions between them. In fact, when the objective of the questionnaire aims at detecting the judgment of people in all areas of comfort there is the need of making the survey as homogeneous as possible in all the comfort areas.

1.2.3 Building simulation

Being complementary to the objective evaluation, building model simulation is an important tool used also for assessing occupants' comfort. In fact, through the simulation is possible to extend virtually the dataset collected with the in-site monitoring, either in terms of the spatial distribution of the measurements (i), i.e. number of measuring points, and with regard to the spans of time that could be analyzed (ii), i.e. simulation of occupants' comfort in different periods. Moreover, the simulation allows the virtualization of the measurement of some physical parameters (iii). For example, thanks to simulation it is possible to argue the mean radiant temperature knowing the indoor temperature and other physics characteristics of the indoor space. Furthermore, energy model simulation allows to consider standard climatic conditions (iv), i.e. representative conditions, in order to simulate extreme conditions (v), i.e. critical conditions or to neutralize the effect of the climate comparing buildings in different conditions (vi). Finally, the simulation of the indoor environment makes possible to evaluate the impacts of different indoor conditions (vii), i.e.: the variations of the physical parameters due to the occupants' actions for facing discomfort. But, for being effective in terms of reliability and accuracy, the building model needs to be calibrated and validated, in order to find the set of model parameters that closely represents the behavior of the building [93].

Considering all the above-mentioned aspects, the main issues related to the assessment and simulation of the IEQ in educational buildings that this doctoral thesis wanted to highlight are:

- Long-term monitoring could be costly and time consuming;
- Choosing the representative periods and spaces of the building to monitor could be tricky;
- Standards do not suggest a standardized procedure to collect the appropriate dataset for evaluating people's comfort ranges;
- Standards do not suggest possible strategies to guarantee the adequate well-being of the building occupants;
- Including environments with different functions, the monitoring of school buildings could be challenging;
- International standards focused on subjective evaluation refer to adults, in office buildings or in laboratories;
- Most of the standards consider only thermal environment and those that inspect also other comfort domains do not provide a consistent structure of the questions nor a unique wording of questions and evaluation scales;
- The lack of consistency in the evaluation of the four comfort domains, i.e. IAQ, thermal, visual and acoustic environment, precludes to assess the contribution of each to the students' global comfort and to understand the interactions between the domains;
- In order to be reliable and accurate, building energy models need to be calibrated and validate.

An exhaustive overview of the state of the art on the assessment of the IEQ based on international standard and literature reviews is presented in chapter 2.

1.3 Purpose and Research questions

Considering the above-mentioned gaps, my doctoral research concerns the assessment of the IEQ in educational buildings by means of three tools:

a) the **objective evaluation**, i.e., the measurements of the physical parameters related to the four comfort domains;
b) the **subjective evaluation**, i.e., the collection of occupants' responses about their perception of the environment.

Moreover,

c) the **building energy model simulation**, i.e., the simulation of the indoor comfort based on different IEQ conditions

is considered.

The last tool has been regarded as a complementary instrument to support and extend in space and time the dataset collected through the objective evaluation in terms of physical parameters, comfort ranges and evaluation of possible retrofitting strategies.

The objectives of my doctoral research and the corresponding research questions are:

a) Is there a correlation between the measured physical parameters and occupants' sensation?
b) What are the neutral conditions for the four environmental aspects?
c) Is the neutral condition expressed by the sensation votes related to the preferred condition? Is sensation coherent with preference?
d) What is the global comfort and are there predominant environmental aspects affecting the global comfort?

To accomplish these purposes, different original methods have been designed, tested and validated. Firstly, a rigorous protocol for physical measurements based on the above-mentioned international standards has been set (i). Secondly, a standard questionnaire capturing the subjective sensation, preference, comfort, and satisfaction of students and teachers and inspecting all the comfort domains has been designed and validated (ii). In addition, an original method for the calibration and validation of school energy model has been tested and validated (iii). Moreover, in order to analyze the collected dataset, an original and replicable method has been defined for inspecting the correlation between objective and subjective data (iv) considering both single and multi-domains approaches (i.e., crossed effects approach) and for defining students' and teachers' global comfort. The results of my doctoral research are intended to assess the effectiveness of a comprehensive method for assessing the IEQ in complex buildings as the educational buildings are.

1.4 Significance of the study

This research will provide new insights into the indoor environmental quality assessment. In details, the significant contributions of this work that bring novelties with respect to the studies available in the literature are (i) to design and test a replicable questionnaire consistent in all the four environmental domains (i.e. indoor air quality, thermal, visual and acoustic) in terms of assessed psychological continua, questions, evaluation scales and wording for inspecting occupants' comfort and behaviour and to be administered while monitoring the indoor physical parameters; (ii) to test an innovative method for grouping the subjective responses collected with the survey based on the indoor environmental conditions to which subjects are exposed in order and (iii) to clarify the relationship between physical quantities and subjective response. This method allows to collect consistent data in terms of numerosity of the subjective responses and environmental conditions to compare with values that the standards indicate for the comfort of people. Moreover, a further useful achievement is the design and validation of a multi-step multi-level optimization-based approach for calibrating the school energy models (iv) starting from the short-term monitoring (objective evaluation) with the aim of set a calibrated and validate model ready to be used for simulating occupants' comfort. The most important novelty compared to the calibration method available in the literature is the possibility of monitoring only a small portion of the building considering specific period of the year, thus avoiding time consuming and expensive monitoring. The data allows to simulate and calibrate the portion of the building and then obtain the calibration of the whole building. These strict methods should be considered as part of one complex and replicable approach which can serve as a basic conceptual framework for future studies focusing on the assessment the IEQ of educational buildings and other complex buildings. Furthermore, the collected dataset and the results of this study can be used for further investigations on IEQ. The methodology is presented in detail in chapter 3, while the outcomes coming from the application of the method on real buildings is included in chapter 5.

2. Questionnaires application for IEQ and comfort assessment: state of the art

This chapter provides an overview of the state of the art of the assessment of the indoor environmental quality (IEQ) by means of questionnaires.

In the first paragraph, the main international standards focusing on the evaluation of the IEQ, i.e. EN 15251:2007 [16], ASHRAE Standard 55:2017 [10], EN ISO 10551:2019 [8] and EN ISO 28802:2012 [17] are reviewed, considering the following categories: *Title, Purpose, Focus, Target, Assessed environment(s), Type of evaluation, Type of questions and scales, Suggested evaluation periods/Period of the day, Administration frequency or sampling method, Administration method, Results presentation/interpretations, Output*. Moreover, a focus on the suggested questions and evaluation scales was included.

In the second paragraph, the researches focused on the evaluation of IEQ in educational buildings using both subjective (i.e. questionnaire) and objective evaluation (i.e. measurement of physical parameters) and reporting the whole questionnaire or a part of it were analyzed and reviewed. Papers were reviewed in three steps. First, they are analyzed using the following categories: *Year, School Level, Assessed Domain(s), Country, Season, Type of Sampling, Number of Subjects or Questionnaires and Psychological Continua*. Second, works are classified according to the assessed environment and the investigated psychological continua. Third, papers were classified based on the used questions and evaluation scales.

Finally, the main conclusions derived from the literature review are reported at the end of the chapter.

2.1 International Standards for the assessment of IEQ by means of questionnaires

The international standards providing guidelines for the evaluation of occupants' comfort by means of the subjective evaluation during in-field monitoring are (i) EN 15251:2007 [16]; (ii) ASHRAE Standard 55:2017 [10], which focus only on thermal environment and indoor air quality (IAQ), (iii) EN ISO 10551:2019 [8] and (iv) EN ISO 28802:2012 [17], which extend the evaluation also to the visual and acoustic domains. The above-mentioned standards are reviewed in Tables 1 to 4 (Appendix 1) using several categories, i.e.: *Title, Purpose, Focus, Target, Assessed environment(s), Type of evaluation, Type of questions and scales, Suggested evaluation periods/Period of the day, Administration frequency or sampling method, Administration method, Results presentation/interpretations, Output* if any, such as the space categories definitions in case of the EN 15251:2007.

(i) Standard EN 15251:2007 (Table 1) has been one of the main references for a consistent number of papers focusing on the evaluation of indoor environment using both the objective (i.e. measurements) and the subjective evaluation (i.e. surveys). In details, the standard specified methods for long-term evaluation of the indoor environment obtained with calculations or measurements, mentioning also educational buildings among the possible buildings to assess. Besides objective evaluation, the standard suggested also to inspect thermal comfort by asking the occupants to rate their state by using different questions, i.e.: *How do you rate your thermal sensation? / Do you want the room temperature to be…? / How do you perceive the temperature?* associated respectively to thermal sensation, preference and acceptance scale. Moreover, it reports additional questions for inspecting occupants' acceptance of the indoor air quality and odour intensity. But, both for the thermal environment and the IAQ, the significance of each sphere of judgment, i.e.: sensation, preference and acceptance, is not explained and the relation between questions and scales is not clear. EN 15251:2007 has recently been superseded by EN 16798-1:2019 [9a] and EN 16798-2:2019 [9b] which contain similar topics.

(ii) ASHRAE Standard 55:2017 (Table 2) suggest two type of surveys for measuring the percent of occupants that are "satisfied", and of who "accept" or feel "comfortable with the environment": from one hand *right-now* (point-in-time) surveys used for evaluating thermal sensations at a single point in time and to correlate thermal comfort with environmental factors (metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, humidity), thermal preference and acceptance; from the other hand *long-term* or satisfaction surveys (i.e. post occupancy evaluation) allows to evaluate occupants' satisfaction of the environment considering a longer span of time.

(iii) Standard EN ISO 28802:2012 (Table 3) provides questions for the assessment of the comfort and well-being of occupants in indoor and outdoor environments, considering all the environmental aspects, i.e thermal, acoustic, visual and IAQ. It considers both right-now surveys (preferable) and long-term surveys (to be avoided due to poor reliability where possible). This standard is the most comprehensive one in terms of types of environments considered, types of subjective state investigated and the related evaluation scales to use for the evaluation of all the environmental aspects, e.g. sensation, comfort, preference. Nevertheless, it does not provide consistent and homogeneous questions and evaluations scale for all the comfort domains.

(iv) Standard EN ISO 10551:2019 (Table 4) focuses on the construction and use of judgement scales. This standard considers both the instantaneous evaluation (right-now) and surveys extended over a period of time (long-term). Besides the thermal environment, the recent version of this standard (2019) gives some suggestion also for the other environmental aspects (i.e., air quality, acoustic and visual environment) taking as a reference the above-mentioned standard EN ISO 28802:2012. Moreover, it provides different type of questions based on the aim of the surveys suggesting a precise order: if the focus is the personal state of the occupants the questions should inspect first the perception, second the affecting evaluation (i.e. occupants' comfort) and third the preference, while if the survey aims to evaluate the indoor environment, the suggested questions are about the acceptance and tolerance of the indoor conditionst. The questions and scales are presented in the Annexes A to E of the standard (and further translated in several languages) as the ones commonly used in literature, without providing a strict and homogeneous method for constructing a whole questionnaire focused on the four domains. For example, the so-called evaluative judgment scale for evaluating occupants' comfort is presented only as regards thermal and visual environments. Moreover, regarding the acoustic environment, even if *loudness* is mentioned as the perceptual term for this domain, it is not treated in the standard because “it is not normally considered in assessment”, and the question about the *Intensity of odour*, i.e.: the perceptual term for inspecting IAQ according to this standard, is not presented in the related Annex but some references using this subjective term are suggested, e.g.: EN 15251:2007 (CEN 2007).

2.2 Papers on the assessment of IEQ in educational building using both subjective and objective evaluation

This section presents an overview of papers focusing on the assessment of occupants’ comfort by means of both subjective and objective evaluation in educational buildings. Papers were selected and analyzed with the aim of highlighting the state of the art on students’ subjective surveys and questions, evaluation scales and wording mostly used in the questionnaires.

Papers have been researched on the platform Scopus (https://www.scopus.com) using the following keywords: *Educational Building OR School OR Classroom AND Thermal comfort OR Acoustic comfort OR Visual comfort OR Indoor Air quality OR Indoor Environmental Quality OR Post-occupancy evaluation AND questionnaire OR survey.* Papers focusing only on health topics (e.g., Sick building syndrome) have been excluded from the analysis. Considering each paper once, 418 articles were found on Scopus database. In this work, the reviewed studies are limited to the 51 papers including the questionnaire in its whole or partial form, questions or evaluation scales (Table 5a). The selected researches present the results of the assessment of the IEQ and comfort in educational buildings (i.e. primary, secondary school and university) using both objective and subjective evaluation by inspecting (i) at least one comfort aspect (i.e. indoor air quality, thermal, visual or acoustic environment); the (ii) combination of two or more of them; (iii) students’ global comfort and satisfaction or (iv) the interactions of different comfort factors, i.e. cross-effects.

To provide an outline of the state of the art, the 51 papers have been analysed through three degrees of detail. First, studies were categorized and reviewed based on specific categories, i.e. *Year, Assessed Domaint(s), School Level, Country, Season, Type of Sampling, Number of Subjects or Questionnaires* and *Psychological Continua,* namely the sensory experiences based on environmental stimuli (Table 5a). Second, papers have been classified according to the assessed domain i.e. IAQ, thermal, acoustic and visual environment, and the investigated psychological continua, i.e. sensation, preference, comfort, satisfaction, personal acceptance and tolerance (Table 5b). Third, a focus on assessed environment and related questions and evaluation scales used in the papers is reported in Table 5c. In this table, papers have been classified considering the assessed domain and related psychological continua (e.g., sensation), reporting the evaluation scale used in the questionnaire in terms of type (i.e. one-pole or two-poles), number of degrees or labels (e.g., symmetrical 7-degrees two-poles scale) and wording of the degrees (e.g., hot, warm, slightly warm, neutral, slightly cool, cool, cold).

2.2.1 Papers adopting objective and subjective evaluation

During the last decades, several studies focused on the assessment of indoor conditions and occupants’ well-being inside built environments have combined in-field measurements (i.e.: objective evaluation) with occupants’ surveys (i.e.: subjective evaluation) highlighting the importance of the correlation between those two approaches. Most of those studies have investigated these aspects in office buildings or by means of laboratory studies. Furthermore, as highlighted in the previous paragraph, since no standardized questionnaire consistent in all the environmental aspects is available in international standards, the same occurs in the literature.

In recent years some researchers have applied objective and subjective evaluation also to educational buildings, thus extending the evaluation also to young people in real conditions. Indeed, differently from what occurs during laboratories studies, in educational buildings schools’ occupants (i.e. students and teachers) are exposed at once to acoustical, thermal, visual, and air quality stimuli so that the effect of the indoor environment on human perception and performance depends on their combined effects. Nevertheless, among the 51 reviewed works (Table 5a), most of the papers consider a single aspect rather than evaluating the four environmental aspects simultaneously.

Table 5a reports the list of the 51 reviewed papers adopting both objective and subjective evaluation for evaluating the IEQ and occupants’ comfort in educational buildings. Regarding the comfort domains, it can be seen that 49 researches assessed thermal environment [2, 6, 18-25, 26-27, 29, 31-44, 46, 48-69]. This may be due to the already largely consolidate literature tested on adult workers, the majority of them focused on thermal environment. Among them, 25 works inspect this domain singularly [6, 18, 20, 29, 31-33, 36, 38, 43, 46, 48, 50-52, 54-55, 57-60, 64, 66-67, 69], while the remaining papers tried to embrace a more holistic approach extending the assessment to other environmental domains aside from thermal environment, exploring or combining with the thermal sphere also IAQ [2, 19, 21-22, 24, 26-27, 34-35, 40-41, 49, 53, 56, 61-63, 65], acoustic environment [2, 21-22, 24, 27, 34, 37, 41, 44, 47, 61, 65] and visual environment [2, 21-22, 24, 27-28, 34, 41-42, 44, 61, 65]. Among them, very few works assumed a holistic approach investigating the global comfort [21-22, 68], i.e., neutral condition in all the four comfort domains, or the crossed effects of one domain to the others [22-24].

The researches presented in the reviewed papers cover different educational stages, thus considering groups of students with different ages, i.e. primary school, (students 7–11 years old), secondary or high school (12–17 years old), and university (18–28 years old) [4]. According to this classification criteria, primary school students have been interviewed in [2, 18-20, 26, 31-33, 42, 43-44, 47, 51, 54, 56-58, 60, 62 65-66], high school students have been considered in [6, 27, 32, 36, 41, 43, 49, 53, 55, 65, 67-69] and [6, 21-24, 28-29, 34-40, 46, 48, 59, 64] focused on university students and classrooms. Moreover, some studies involve kindergarten children [47, 50, 52].

The researches include in-field campaigns in different countries and continents. Data reveals that most of the studies were conducted in Europe: [2, 6, 22, 23, 27-28, 41, 44, 54-55, 64-65] were carried out in Italy; [18, 34] in Spain; [19, 40] in Slovakia, [24] in Romania; [34] in Poland; [35] in Czech Republic; [42, 61] in Greece; [47] in France; [49, 53] in Portugal; [56] in Denmark and [60] in the Netherlands, while other studies are carried out in England [20, 26, 51, 58, 62]. Some researches are conducted in Asia: [31] in Taiwan; [32] in China; [39] in Turkey; [52] in Korea; [57] in Iran; [67] in Singapore and [68] in Japan. The remaining campaigns were conducted in Africa [36, 38, 59], in Australia [43, 66], in India [29, 48] and South America [50, 69].

The monitoring periods of the field campaigns depend on the site and climate. In Europe the researches were conducted mainly during the heating season.

Regarding the type of sampling, 25 works carried out a transverse survey (i.e. to collect as many as possible subjective responses), 19 used a longitudinal survey (i.e. to interview the same group of people more than once), while the remaining works didn't mention the sampling method.

Concerning the psychological continua, most of the studies investigated the sensation [6, 18-20, 23, 26, 28-55, 57-60, 62, 64, 66-69] and the preference [6, 18, 20, 26, 29-33, 36, 38, 42-43, 46, 50-51, 53-54, 57-59, 64, 66-69]. Some works ask the occupants their comfort [21-22, 24, 26, 29-3236, 40, 52, 59, 61, 63, 68] and satisfaction [27, 32, 34-36, 63, 65], while other studies investigated the acceptance [29, 31, 33, 38, 41-42, 48, 53, 55, 64, 66-68] and tolerance [22].

Table 5a. List of papers adopting objective and subjective evaluation.

Ref.	Year	Assessed Domain(s)	Level	Country	Season	Type of sampling	n. subjects/ questionnaires	Psychological continua
[2]	2012	IAQ thermal Visual Acoustic	Primary school	Italy	spring	Longitudinal	61 questionnaires	N/A
[6]	2007	Thermal	High school University	Italy	Heating season	Longitudinal	427 questionnaires	Sensation Preference acceptance
[18]	2021	Thermal	Primary school	Spain	summer	Longitudinal	67 questionnaires	Sensation Preference
[19]	2018	IAQ thermal	Primary school	Slovakia	Autumn / spring	Transverse	48 subjects	Sensation
[20]	2012	thermal	Primary school	England	spring	Transverse	1314 (230 students)	Sensation Preference
[21]	2014	IAQ thermal Visual Acoustic Overall	University	Thailand	hot-rainy season / mild season	Transverse	704 questionnaires	Comfort
[22]	2014	IAQ thermal Visual Acoustic Overall	University	Italy	winter	Transverse	17 subjects	Comfort Tolerance

[23], [28]	2018	thermal Visual Acoustic	University	Italy	Spring / autumn	Longitudinal	928 questionnaires	Thermal sensation Acoustic sensation Intelligibility Light annoyance
[24]	2016	IAQ thermal Visual Acoustic	University	Romania	winter	Longitudinal	115	Comfort
[26]	2020	IAQ thermal	Primary school	England	Non-heating / Heating season	Transverse	1390 questionnaires, 805 (29 classrooms)	IAQ/thermal Sensation IAQ Preference IAQ comfort
[27]	2019	IAQ thermal Visual Acoustic	High school	Italy	Heating season	Transverse	123 students	Satisfaction
[29]	2018	thermal	University	India	Summer season	Transverse	900 students	Sensation Preference Comfort Acceptance
[31]	2017	thermal	Primary school	Taiwan	Summer season	Transverse	729 subjects	Sensation Preference Overall Comfort Acceptance
[32]	2017	Thermal	Primary and secondary	Northwestern China	winter	Longitudinal	763 questionnaires	Sensation Preference Comfort Satisfaction
[33]	2017	Thermal	Primary school	Chile	Winter and spring	Transverse	440 subjects	Sensation Preference Acceptance
[34]	2017	IAQ thermal Visual Acoustic	University	Poland and Spain	Heating season	Transverse	267	Sensation Satisfaction
[35]	2017	IAQ thermal	University	Czech Republic	Spring and autumn	N/A	25	Odour sensation Satisfaction
[36]	2017	Thermal	High school University	Madagascar	Dry and rainy season	Longitudinal	625 students	Sensation Satisfaction Preference Comfort
[37]	2017	Thermal Acoustic	University	Indonesia	N/A	Longitudinal	55	Sensation
[38]	2017	Thermal	University	Algeria	Autumn	Transverse	N/A	Sensation Acceptance Preference
[39]	2017	Thermal	University	Turkey	Heating season	Transverse	235	Sensation
[40]	2018	IAQ thermal	University	Slovakia	Winter / summer	N/A	N/A	Sensation Comfort
[41]	2016	Thermal IAQ Visual Acoustic	High school	Italy	Winter / summer	Transverse	290 questionnaires	Sensation Acceptance
[42]	2015	IAQ thermal Visual	Primary school	Athens, Greece	spring	Transverse	193 students / 665 questionnaires in 9 naturally ventilated schools	Sensation Preference Acceptance Satisfaction
[43]	2015	Thermal	primary and secondary schools	Australia	summer	Longitudinal	2850	sensation, preference
[44]	2015	Thermal Visual Acoustic	Primary school	Italy	Winter / spring	Transverse	N/A	Sensation Discomfort
[46]	2015	Thermal	University	Romania	Winter	N/A	N/A	Sensation Preference

[47]	2015	Acoustic	Pre-school and primary school	France	Heating season	N/A	155	Sensation
[48]	2015	Thermal	University	India	N/A	Transverse	50	Sensation Acceptance
[49]	2015	IAQ thermal	High school	Portugal	N/A	N/A	N/A	Sensation
[50]	2014	Thermal	Kindergarten	Colombia	autumn	Transverse	N/A	Sensation Preference
[51]	2014	Thermal	primary school	England	Spring	Transverse	2990 questionnaires	Sensation Preference
[52]	2014	Thermal	preschool	Korea	spring	Transverse	119 students	Sensation Comfort
[53]	2014	Thermal IAQ	High school	Portugal	spring	Longitudinal	45 questionnaires	Acceptance Sensation Preference
[54]	2013	Thermal	primary school	Italy	Heating season	Transverse	20 students	Sensation Preference
[55]	2013	Thermal	High school	Italy	Winter / summer	Transverse	4416 questionnaires	Sensation Acceptance
[56]	2013	Thermal IAQ	primary school	Denmark	Late summer and winter	Transverse	380 students	N/A
[57]	2012	thermal	primary school	Iran	N/A	Transverse	80 pilot applicants	sensation, preference
[58]	2012	thermal	primary school	England	Spring /summer	Longitudinal	1314 responses (230 pupils in 8 classrooms	sensation, preference
[59]	2011	thermal	University	La Reunion	Hot season	Transverse	1749 questionnaire	Sensation Preference comfort
[60]	2011	thermal	primary school	The Netherlands	Winter / spring / summer	Longitudinal	79 questionnaires	Sensation
[61]	2010	Thermal IAQ Visual Acoustic	vary	Greece	3-years period	Longitudinal	N/A	Comfort
[62]	2010	Thermal IAQ	Primary	England	Winter / summer	Longitudinal	62 questionnaires	Sensation (post-occupancy)
[63]	2010	Thermal IAQ	vary	Canada	Winter / summer	Longitudinal	N/A	Comfort Satisfaction (post-occupancy)
[64a]	2009	Thermal	University	Italy	Winter / spring	Longitudinal	959	Sensation Preference Acceptance
[64b]	2016	Thermal	University	Italy	Winter / spring	Transverse	1106	Sensation Preference
[65]	2008	Thermal IAQ Visual Acoustic	High school	Italy	Winter	Longitudinal	1006	Satisfaction
[66]	2007	Thermal	Primary and secondary school	Australia	2 years spring	Longitudinal	3356 questionnaires (2012) 2850 questionnaires (2012)	Sensation Preference Acceptance
[67]	2006	Thermal	High school	Singapore	Cool /hot season	Transverse	506 (493 students and 13 teachers)	Sensation, comfort, preference, Acceptance
[68]	2003	Thermal Overall	High school	Japan	Summer / winter	Longitudinal	74 questionnaires	Sensation Preference Comfort Acceptance
[69]	2000	Thermal	High school	Brazil	N/A	N/A	N/A	Sensation Preference

2.2.2 Classification of papers according to the assessed environment and the psychological continua investigated

In Table 5b papers are classified based on the assessed domain and the psychological continua investigated with the questionnaire. The outcomes of the review are reported below divided according to the four comfort domains, i.e. thermal, indoor air quality, visual and acoustic environment.

Thermal Environment. Regarding papers focused on thermal environment, most of them explore thermal sensation [2, 19-20, 23, 28-29, 32-34, 36-41, 43-44, 46, 48-49, 51-52, 54, 59-60, 64a, 64b, 66, 69], preference [20, 24, 29, 32-33, 36, 43, 46, 53, 64, 66, 69] and comfort [20-21, 24, 29, 32, 37, 40, 52-53, 59], while few works consider satisfaction [27, 31-32, 34-36, 63], Acceptance [29, 39, 40-41, 48, 64, 66] and tolerance [22].

Indoor Air Quality. Among the papers inspecting IAQ, most of the studies explored indoor air sensation [26, 34-35, 40-41, 49, 70], some other inspect comfort [21, 24, 26, 40], satisfaction [27, 34, 35] and Acceptance [19, 35, 41], while preference is explored by [26] and [22] ask students to rate their tolerance.

Visual Environment. The review highlighted that the visual domain is inspect through sensation [23, 28, 41], comfort [21, 24, 28, 31, 63], satisfaction [27, 34, 42] and annoyance [23, 28], while visual preference was not considered.

Acoustic Environment. Regarding acoustic domain, the reviewed studies inspected sensation [23, 28, 37, 45, 47], annoyance [23, 28, 47], comfort [21, 23-24, 28, 37, 63], satisfaction [27, 34, 37, 47] and personal tolerance [22]. As in the case of visual environment preference was not considered.

Table 5b. Classification of papers according to the assessed environment and the psychological continua investigated.

Assessed domain	Psychological continua	References
Thermal	Sensation	[41], [54], [2], [32], [33], [34], [19], [29], [36], [38], [39], [40], [46], [43], [48], [49], [51], [69], [52], [20], [59], [28], [23], [37], [38], [44], [60], [64], [66]
	Preference	[66], [32], [33], [29], [36], [46], [43], [69], [53], [20], [64]
	Comfort	[32], [37], [40], [21], [52], [53], [20], [59], [24], [29]
	Satisfaction	[31], [34], [35], [36], [63], [27], [32]
	Personal Acceptance	[41], [66], [39], [48], [29], [40], [64]
	Personal tolerance	[22]
IAQ	Sensation	[41], [40], [49], [70], [26], [34], [35]
	Preference	[26]
	Comfort	[21], [40], [24], [26]
	Satisfaction	[34], [35], [27]
	Personal Acceptance	[41], [19], [35]
	Personal tolerance	[22]
Visual	Sensation	[28], [23], [41]
	Comfort	[28], [31], [21], [63], [24]
	Satisfaction	[34], [27], [42]
	Annoyance	[23], [28]
Acoustic	Sensation	[47], [37], [28], [23], [45]

	Annoyance	[47], [23], [28]
	Comfort	[37], [21], [23], [28], [63], [24]
	Satisfaction	[34], [37], [47], [27]
	Personal tolerance	[22]
Overall/Global	Comfort	[21], [22]

2.2.3 Classification of papers according to the evaluation scales

Table 5c reports the classification of papers according to the evaluation scales with a focus on the type of scale and wording for the evaluation of the psychological continua adopted for investigating the different comfort domains. The outcomes are reported below divided according to the four comfort domains, i.e., thermal, indoor air quality, visual and acoustic environment.

Thermal Environment. A considerable number of reviewed papers focus on thermal environment [2, 4, 6, 26, 29, 33-41, 43, 49-52, 54-64, 66-69, 71] that is assessed mainly through questions about the sensation and preference taking as a reference the Thermal sensation scale and Thermal preference scale suggested by Standards EN ISO 15251:2007 (CEN, 2007) [16], ASHRAE 55 [10] and EN ISO 10551 (CEN 2019) [8]. In these works, the subjective responses are compared with the PMV (Predict Mean Vote) and PPD (Percent of Dissatisfied People) [74] derived from in-filed measurements.

Regarding *Thermal sensation*, even though most of the papers use the 7-points scale, i.e. from cold to hot with 0 as the neutral condition, suggested by the above-mentioned standards, there is inhomogeneities regarding the wording of the question: if the majority of them use the thermal sensation question in the form "*How do you feel, at this moment?*" [41], [19], [39], [40], [43], [48], [52], [53], [20], [69], [49] [23] [28] other papers draw the focus on room temperature as suggested by the EN ISO 15251:2007 (CEN, 2007), e.g. *How do you perceive/feel (about) the temperature?* [32-33, 41, 64]. Consequently, some of these studies present also two more questions, one referring to the sensation about air movements or draughts [36, 64, 29, 40] and students' perception about the humidity [29, 34, 36, 38, 40]. The reason of this change of the thermal sensation question is maybe due to the will to compare the measurement of the physical parameters, i.e. the room air temperature, the air velocity and the relative humidity, thus misunderstanding the real meaning of thermal sensation as the combination of multiple thermal aspects [74]. Other papers change a bit the wording of the 7-points scale, using "comfort" [49] or "OK" [33], [69] instead of "neutral", or the labels of the degree using "a bit" instead of "slightly" [46]. Some other works used a symmetrical 5-degrees two-poles scale, avoiding the "slightly" degree [34,37], a symmetrical 3-degrees two-poles scale [66]. Moreover, some papers make an effort for tailoring the evaluation scales to children, changing a bit the wording [54] or using faces instead of the labels [32]. Finally [23], [28] and [64] use also a 13-degrees scales adding (−2.5, −1.5, −0.5, +0.5, +1.5, +2.5) for rating thermal sensation, in order to give the possibility of voting intermediate feelings and compare them with the PMV.

Thermal preference is inspected by using the 3-points two-poles scale presented in the standards [66, 43] which suggest the following wording of the labels: cooler and warmer at the extreme (poles) and no change/without change as point of indifference; the 7-points scale [20, 33, 69] or 5-points scale [36]. Moreover, some papers make an effort for tailoring the evaluation scales to children, changing a bit the wording [20] or using faces instead of the words [32].

Some other papers also introduce the *Thermal comfort* question, i.e. affective evaluation question as it is called in the standard EN ISO 10551 (CEN 2019). Generally, the comfort evaluation scale is the one-pole with 4-points evaluation scale with some slightly different wording of the question [21,40], monopolar with 5-points evaluation scale from 1= very uncomfortable to 5= very comfortable [21] or the direct answer yes/no or comfortable/uncomfortable [20,52].

Other works also inspect the *Thermal acceptance*, as suggested by EN ISO 10551 (CEN 2019), requiring a direct answer yes/no or acceptable/unacceptable [39] or using the unipolar scale, from clearly acceptable to clearly not acceptable [41, 48]. Nevertheless, some papers change the question focusing on the room temperature [41] instead of inspecting the overall thermal environment, giving again a misleading the sense of the question Some papers also evaluate students' *Thermal tolerance* [22] using a 5-points and finally, some papers inspect also the *Thermal satisfaction* using the direct yes/no answer or satisfied/not satisfied [31], a symmetrical 5-degree two-poles scale [34-36], or a 13-degrees scales, i.e. 1=unsatisfied, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7= Satisfied [63], introduced by ASHRAE 55 (2017) for long-term or post-occupancy evaluation and normally in a one-pole 7-degrees form.

Indoor Air Quality. Besides of evaluating the thermal environment, some papers also inspect students' perception of the IAQ [21-22, 26, 34-35, 40-41, 49, 53, 70]. These works evaluate students' *indoor air sensation* with the question suggested by EN 15251:2007 (CEN 2007), i.e.: *How do you perceive the indoor air quality?* Using a symmetrical two poles 7-degrees scale, such as "Very used, used, slightly used, NEITHER NOR, slightly fresh, fresh, very fresh" [41]; a symmetrical 6-degrees scale with no point of indifference [49,52], or using the labels "bad, good, very good" [19]. Other papers use the symmetrical 6-degrees scale, such as "Terrible, bad, slightly bad, slightly good, good, exceptional" [49, 52]; a one-pole 6-points from 0=fresh to 6= stale [42]; a symmetrical two-poles 5-degrees scale "Very fresh, Fresh, OK, Stuffy, Very Stuffy [26] or " Very nice, nice, NEUTRAL, bad, very bad " [34] and finally a one-pole 3-points "bad, good, very good" [70]. Moreover, some works inspect also students' *perception of odour* inside classrooms as source of discomfort, as suggested by EN ISO 28802:2012 and EN ISO 10551:2019 using the one-pole 6-points scale "No odour, weak odour, moderate odour, strong odour, very strong odour, overpowering odour" as an additional sensation question [19, 35, 60] and one-pole 6-points from 0=odorless to 6= smells bad [42] with the possibility to compare the sensation votes to olf and decipol [82-83]. Furthermore, [26] inspect ask students also to rate their Preference for the indoor air my means of a one-pole 2-points from 1=Fresher, 2=As it is.

Other papers ask to rate students' *indoor air comfort* using a one-pole 4-points scale, i.e. COMFORT, slightly discomfort, discomfort, very discomfort [40] or a one-pole 5-degrees scale from "1= very uncomfortable, 5= very comfortable" [21]. The *indoor air satisfaction* is inspected with a symmetrical scale from very dissatisfied to very satisfied [34-35] while the *indoor air acceptance* with using a one-pole scale from clearly acceptable to clearly not acceptable [23, 28, 41]. Finally, the *indoor air tolerance* is inspected with one-pole 4-points [22].

Visual Environment. Among the reviewed papers, a few included the subjective evaluation of the visual environment [23, 28, 30, 84]. [23] and [28] ask to evaluate the *quantity of light* entering the room or reaching the desk using a 10-degrees one-pole scale from 1=inadequate to 10=suitable and *Visual comfort* using a 10-degrees one-pole scale with 0 as very bad and 10 as excellent, while [41] inspects visual sensation by means of the symmetrical 7-degrees two-poles scale "Too bright, very bright, slightly bright, Just right, Slightly dark, very dark, too dark". *Visual comfort* is inspected through a one-pole 5-degrees from 1= very uncomfortable, 5= very comfortable [21], 10-degrees one-pole scale from 0 as very bad and 10 as excellent [23, 28] and with one pole scale from to 100 [24]. Moreover, [23] and [28] include some questions about *Visual discomfort* or *annoyance* asking to students if they perceive any sources of glare and ask to rate how many times they are annoyed by artificial lights or natural light through the windows. Moreover, [34] ask students to rate their satisfaction for the visual environment with a symmetrical 5-degree two-poles scale and [22] includes the tolerance using a one-pole 4-degrees.

Acoustic Environment. Concerning the investigation of the acoustic environment, [47] inspect students' *Acoustic sensation* is by means of a two-poles 7-points scale (i.e. Very quiet, Quiet, rather quiet, Neither noisy nor quiet, Rather noisy, Noisy, Very noisy), while [37] use a two-poles 5-points scale that use the term Comfort instead of neutral, i.e.: Too silence, silence, COMFORT, noisy, too noisy. Moreover, [47] include also the evaluation of the *Annoyance* with a two-poles 7-points scale. *Acoustic comfort* is evaluated using different evaluation scales, such as a 10-degrees one-pole scale with 0 as very bad and 10 as excellent [23, 28], a one-pole 5-degrees from 1= very uncomfortable, 5= very comfortable [21] and [24] uses a one pole scale from to 100. *Satisfaction* for the acoustic environment is inspected with a symmetrical 5-degree two-poles scale [34] and the *Personal Tolerance* with the one-pole 4-degrees "unbearable, hardly tolerable, not completely tolerable, satisfactory" [22].

Global comfort. Among the reviewed works, very few included the subjective evaluation of global or overall comfort: [21] inspect Global comfort using a one-pole 5-degrees from 1= very uncomfortable, 5= very comfortable, while [22] uses a one-pole 4-degrees from 0= Satisfactory (the activities can be properly performed); 1= Not completely Tolerable; 2= Hardly Tolerable; 3= Unbearable".

Crossed effects or multi-domain approach. Most of the reviewed studies assed the IEQ in educational buildings considering each comfort domain as independent factor. However, some studies put an effort towards the multi-domain approach. Fassio et al. [22] used linear and logistical regression to predict overall comfort starting from comfort questions related to each comfort aspect, i.e. IAQ, thermal, visual and acoustic environment. Nevertheless, any consistent weightings of the contributing factors were found [25]. Buratti et al. [23] combined the results referred to thermal, acoustic and visual comfort for getting a comprehensive comfort index highlighting that a change in one factor can have an impact on occupants' sensation or comfort for other aspects. In this work, thermal and acoustic aspects had about the same weight (i.e. 0.35), while visual domain had a lower weight (i.e. 0.3). Finally, Mihai and Iordache [24] used a similar approach including also the indoor air quality. Even in this case, the different weighting factors used for building the unique comfort index were quite similar to each other, i.e. 0.251 for thermal environment, 0.241 for acoustics, 0.244 for visual environemnt and 0.263 for IAQ.

Table 5c. Classification of papers according to the evaluation scales.

Psychological continua	Degree	wording	Ref.
Thermal Environment			
Sensation	Symmetrical 7-degrees two-poles scale	Hot, Warm, slightly warm, NEUTRAL, slightly cool, cool, cold	[41], [19], [39], [40], [43], [48], [52], [53], [20], [69], [49] [23] [28], [29], [32], [36], [42], [44], [46], [57], [66], [68]
		Very cold/cold; cool, slightly cool, COMFORTABLE, slightly warm, warm, very warm/hot	[49]
		Very cold; cold, a bit cold, OK, a bit hot, Hot, Very hot	[33], [69]
		A lot colder, colder, a bit colder, NO CHANGE, a bit warmer, warmer, a lot warmer	[46]
	Children oriented	☹ 😐 ☺	[32]
	Symmetrical 5-degrees two-poles scale	too hot, warm, OK, cold, too cold	[34]
		very cold, cold, COMFORT, hot, very hot	[37]
	Child oriented	FREESING COLD (-2) COLD (-1) LUKEWARM (0) WARM (+1) HOT (+2) SIZZLING HOT (+3)	[54]
	4-degrees	cold, cool, warm, hot	[51]
	Symmetrical 3-degrees two-poles scale	cool; neutral; hot	[66]
	3-degrees unique-pole scale	Very hot, hot, adequate	[25]
	13-degrees	- 3, - 2.5, -2, – 1.5, -1, − 0.5 , 0, + 0.5, + 1, +1.5, + 2, + 2.5, + 3	[23], [28], [64a], [64b]
Preference	Symmetrical 7-degree two-poles scale	much colder/colder/a bit colder/ ANY CHANGE/a bit warmer/ hotter / much hotter	[33]
		A lot colder, Colder, A bit colder, No change, A bit warmer, warmer, a lot warmer	[46]
		I wish it was a lot colder/colder/a bit colder/ I DONT'T WANT ANY CHANGE, /a bit warmer, warmer/ a lot warmer	[20]

		Much warmer, warmer, slightly warmer, in this way (neither warmer nor cooler), slightly cooler, cooler, much cooler	[69]
	Symmetrical 5-degree two-pole scale	cooler, slightly cooler, NO CHANGE, slightly warmer, warmer	[36]
	Children oriented	☹ 😐 ☺	[32]
	Symmetrical 3-degree two-pole scale	Colder (cooler), no change, warmer	[32], [43], [42], [66]
Comfort	Symmetrical 5-degree two-pole scale	Very uncomfortable, Uncomfortable, Comfortable, Slightly comfortable, very comfortable	[29]
	One pole, 4-degrees	very uncomfortable, uncomfortable, COMFORTABLE, very comfortable	[36]
	One pole, 4-degrees	COMFORT, slightly discomfort, discomfort, very discomfort	[40]
	One pole, 5-degrees	1= very uncomfortable, 5= very comfortable	[21]
	One pole, 5-degrees	Comfortable, a little discomfort, uncomfortable, more uncomfortable, most uncomfortable	[32]
	One pole	From 1 to 100	[24]
	binary	Yes / No	[20], [52]
Satisfaction	binary	satisfied; not satisfied	[31]
	Symmetrical 5-degree two-poles scale	Very dissatisfied, dissatisfied, acceptable/no opinion, satisfied, very satisfied	[32], [34]
	Symmetrical 5-degree two-poles scale	dissatisfied, slightly dissatisfied, SATISFIED, slightly satisfied, very satisfied	[35], [36]
	13-degrees	1=unsatisfied, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7= Satisfied	[63]
Personal Acceptance	One pole, 4-degrees	clearly acceptable, just acceptable, just unacceptable, clearly acceptable	[41]
		highly acceptable, just acceptable, just unacceptable, highly unacceptable	[48]
	binary	not acceptable, acceptable	[29], [39]
Personal tolerance	One pole, 4-degrees	unbearable, hardly tolerable, not completely tolerable, satisfactory (the activity can be properly performed)	[22]
Indoor Air Quality			
Sensation	Symmetrical 7-degrees two-poles scale	Very used, used, slightly used, NEITHER NOR, slightly fresh, fresh, very fresh	[41]
	Symmetrical 6-degrees two-poles scale with no point of indifference	Terrible, bad, slightly bad, slightly good, good, exceptional	[49], [52]

	one-pole 6-points	From 0=fresh to 6= stale	[42]
	Symmetrical 5-degrees two-poles scale	Very fresh, Fresh, OK, Stuffy, Very Stuffy	[26]
	Symmetrical 5-degrees two-poles scale	Very nice, nice, NEUTRAL, bad, very bad	[34]
	one-pole 3-points	bad, good, very good	[70]
Odour	one-pole 6-points	No odour, weak odour, moderate odour, strong odour, very strong odour, overpowering odour	[19], [35]. [40]
	one-pole 6-points	From 0=odorless to 6= smells bad	[42]
Preference	one-pole 2-points	1=Fresher, 2=As it is	[26]
Comfort	one-pole 4-points	COMFORT, slightly discomfort, discomfort, very discomfort	[40]
	one-pole 5-degrees	1= very uncomfortable, 5= very comfortable	[21]
	one-pole 3-points	I am comfortable, I am a little comfortable, I am not comfortable	[26]
	One pole	From 1 to 100	[24]
Satisfaction	Symmetrical 5-degree two-poles scale	Very dissatisfied, dissatisfied, no opinion, glad, very glad	[34]
	Symmetrical 6-degree two-poles scale with no point of indifference	Very dissatisfied (-3) Very satisfied (+3)	[35], [42]
Personal Acceptance	one-pole 4-points	clearly acceptable, just acceptable, just unacceptable, clearly acceptable	[41]
		from completely unacceptable to perfectly acceptable (Air movement)	[23], [28]
Personal tolerance	one-pole 4-points	unbearable, hardly tolerable, not completely tolerable, satisfactory	[22]
Visual Environment			
Sensation	10-degrees one-pole scale	1 = INADEQUATE - 10 = SUITABLE	[23], [28]
	Symmetrical 7-degrees two-poles scale	Too bright, very bright, slightly bright, Just right, Slightly dark, very dark, too dark	[41]
Comfort	one-pole 5-degrees	1= very uncomfortable, 5= very comfortable	[21]
	10-degrees one-pole scale	0 as very bad and 10 as excellent	[23], [28]
	One pole	From 1 to 100	[24]
Satisfaction	Symmetrical 5-degree two-poles scale	Very dissatisfied, dissatisfied, no opinion, glad, very glad	[34]
	Symmetrical 6-degree two-poles scale with no point of indifference	Very dissatisfied (-3) Very satisfied (+3)	[42]
Personal tolerance	one-pole 4-degrees	unbearable, hardly tolerable, not completely tolerable, satisfactory	[22]
Acoustic Environment			
Sensation	two-poles 7-points scale	Very quiet, quiet, rather quiet, neither noisy nor quiet, rather noisy, noisy, very noisy	[47]
	two-poles 5-points scale	too silence, silence, COMFORT, noisy, too noisy	[37]

Annoyance	two-poles 7-points scale	not heard, not at all annoyed, slightly annoyed, moderately annoyed, strongly annoyed, extremely annoyed	[47]
Comfort	one-pole 5-degrees	1= very uncomfortable, 5= very comfortable	[21]
	10-degrees one-pole scale	0 as very bad and 10 as excellent	[23], [28]
	One pole	From 1 to 100	[24]
Satisfaction	Symmetrical 5-degree two-poles scale	Very dissatisfied, dissatisfied, no opinion, glad, very glad	[34]
Personal tolerance	one-pole 5-degrees	unbearable, hardly tolerable, not completely tolerable, satisfactory	[22]
Overall/Global Comfort			
Comfort	one-pole 5-degrees	1= very uncomfortable, 5= very comfortable	[21]
	one-pole 4-degrees	0= Satisfactory (the activities can be properly performed); 1= Not completely Tolerable; 2= Hardly Tolerable; 3= Unbearable"	[22]

2.3 Conclusions

To sum up, the main outcomes of the review of international standards are the following:

- all the above-mentioned standards refer to adult workers without given any suggestion for tailoring the question based on the different age of the occupants;
- EN 15251:2007 and ASHRAE Standard 55:2017 refer only to the thermal environment and IAQ;
- in EN 15251: 2007 the significance of each sphere of judgment, i.e.: sensation, preference and acceptance, is not explained and the relation between questions and scales is not clear. Moreover, this standard has been recently superseded by EN 16798-1:2019 [9a] and EN 16798-2:2019 [9b] which do not give more specifications about questionnaires;
- ASHRAE 55: 2017 separates right-now surveys focused on occupants' comfort from long-terms questionnaires (satisfaction surveys) centered on the environment, suggesting different type of questions based on the different surveys;
- both EN ISO 28802:2012 and EN ISO 10551:2019 consider all the environmental aspects, i.e., thermal, acoustic, visual and indoor air quality, but they do not suggest questions consistent for all these aspects. Moreover, they do not provide the complete wording of the questions or univocal evaluation scales. Finally, they do not report a unique definition of sensation, preference, satisfaction, comfort or annoyance, nor indicate a method for the analysis and interpretation of the subjective responses, such as the consistency between different subjective aspects (e.g. sensation/preference vs satisfaction).

The main outcomes from the paper review are resumed below:

- no standardized questionnaire consistent in all the environmental aspects is available in the literature;
- besides the studies on thermal environment, there is still the need for research to inspect the correlation between measured parameters and subjective responses concerning other comfort domains, i.e.: IAQ, visual and acoustic environment;
- after thermal environment, IAQ results to be the most explored domain compared with visual and acoustic environment;
- further investigation is needed in order to highlight the indoor conditions in the four comfort domains that ensure students' global comfort, i.e. neutral conditions;
- according to the literature review the crossed effects approach is still a little-explored field, especially regarding in field monitoring in educational buildings. On this topic, a review by Tang et al. [25], reported some papers focused on office buildings that highlighted the interactions

between different comfort domains. In details, Fang et al. [81] found out that IAQ acceptance is influenced by air temperature and humidity; Tiller et al. [30] highlighted a slight impact of sound pressure on thermal comfort, with a decrease of thermal acceptance when the sound pressure level increase; finally, a study by Yang and Moon highlighted that illuminance from 150 lx to 1000 lx seems don’t have impact on thermal sensation [79].

3. Methodology

This chapter describes the innovative methodology developed during my doctoral program to assess the IEQ in educational buildings and to calibrate the energy model of a building. In the first part, the method for evaluating the indoor conditions of school buildings through objective and subjective evaluation, namely respectively in-field measurements and questionnaires, is presented. The second part includes the optimization-based procedure to calibrate the energy model of educational buildings.

The method for the evaluation of the IEQ is divided into three main parts: (i) the questionnaire design, (ii) data collection procedure and (iii) data validation and analysis method. The questionnaire design includes the description of the psychological continua considered in the questionnaire, the structure of the survey and the wording adopted for questions and evaluation scales. The data collection part comprehends the procedure for the monitoring of the physical parameters related to the four environmental aspects (i.e. IAQ, thermal, visual and acoustic environment) and the administration method of the questionnaire. Finally, the paragraph focused on the data validation and analysis, includes from one hand, the validation of the questions of the survey based on specific KPIs (i.e. efficiency, effectiveness and resolution) and the procedure for correlate the objective data derived from the in-field monitoring with the subjective responses collected through the questionnaires.

The last paragraph, namely 3.4 Building thermal model simulation: multi-level multi-step method for calibration, explores the optimization-based procedure to calibrate the energy model of an educational building from short-term monitoring of a portion of a building in selected periods. The methodology includes the setting of the energy model and the calibration workflow.

3.1 Assessment of the Indoor Environmental Quality: subjective questionnaire design

In order to correlate the measurements to the subjective perception of the occupants, a questionnaire considering all the comfort domains should be administered to students simultaneously to the experimental campaign. For this purpose, a standard questionnaire has been designed and validated. The questionnaire, designed within my doctoral research, aims to collect subjective responses in educational buildings for understanding how people perceive the environmental stimuli, and how much they are satisfied with them not only singularly, i.e., single-domain approach, but also globally and for highlighting possible interaction between different comfort areas, i.e., multi-domain approach. To assess people global comfort inside a building, it is necessary investigating their feeling or perception, preference, comfort and satisfaction considering their thermal, olfactory, visual and acoustic experience. To understand these experiences in a homogeneous way, similar psychological continua are investigated through the designed questionnaire using equivalent questions for each domain.

3.1.1 Psychological continua considered in this research

The psychological continua considered in this research are the sensation, the preference, the comfort and the satisfaction for each comfort domain. In International Standards there is no definition of them, even though they are widely used in the scientific literature. In the following, a definition for each psychological continua has been developed.

Sensation is what the subjects feel by means of their senses (touch, smell, sight and hearing) in relation to one or more stimuli received from the environment. For some of the aspects the human body has specific receptors that can be directly implied in sensation (i.e., heat/cold) and in general with presence or absence of comfort, while in other cases receptors are mainly playing a sensorial role (light, noise, odour) and sensation is produced by complex interactions. Nevertheless, it seems that sensation is the first subjective response to the physical environment [84] and that it has to be reported excluding any mediation by rational or irrational evaluations. For this reason, sensation votes allow a correlation between subjective evaluation and objective environmental measurements, providing an understanding on which are the environmental conditions that affect sensation. Sensation votes themselves are often not sufficient to determine comfort and satisfaction. That is justified by the fact that sensation votes other than “0” (i.e., neutral) might indicate a preferred condition. For instance, one might feel slightly warm or slightly cold and still prefer no change; in this case, “no change will indicate a form of acceptability and satisfaction” [17].

Preference indicates how people would like to be in relation to the actual conditions they experience when answering the questions. In this sense, preference allows determining how the issues could be fixed and the extent to which the actions required can correlate to the amount of perceived discomfort. The preference vote is generally cast on an evaluation scale, correlating closely to comfort/satisfaction [58, 86]. Nevertheless, in the suggested approach we consider preference questions to assess single specific needs, in relation with the sensation question, leaving comfort questions to sum up different contributions and including specific annoyance factors. Moreover, preference for non-neutral sensation is common and often not symmetrical around neutrality [6, 87]. The correlation between sensation and preference becomes then a relevant topic to investigate as preference votes provide the direction towards which we should modify the environmental characteristics to reach users’ comfort.

Comfort is the third psychological continuum useful to collect a comprehensive subjective response. *Thermal comfort* is defined as the “condition of mind that expresses satisfaction with the thermal environment” [10-11]. *Visual comfort* is defined as “a subjective condition of visual well-being induced by the visual environment” [13]. While thermal and visual comfort are defined with standardized definitions, acoustic comfort and the expression of comfort concerning IAQ are of much less common use [3]. In this research, the definitions provided above are transferred to the other domains of comfort in order to give consistency to the questionnaire. Moreover, as said previously, comfort question is intended to include the impact of specific discomfort factors. In the case of thermal comfort for instance, while preference could refer to “global comfort” (and thus relate to global thermal balance), comfort questions could include the evaluation of local discomfort aspects.

Satisfaction. Despite occupants’ comfort is said to express satisfaction with the environment, occupants are also asked to evaluate their satisfaction towards the environment. As explained in the ASHRAE 55 standard, satisfaction surveys are used “to evaluate thermal comfort response of the building occupants in a certain span of time". Thus, occupants' satisfaction refers to a longer span of time than comfort and it could depend on several factors such as the task, the individual expectations, relevance ascribed for the environmental aspects. That means, instead of retrieving information on satisfaction from thermal sensation votes, that are expressed point-in-time, the satisfaction scale allows researchers to directly compute the overall satisfaction that individual perceive related to the environment.

3.1.2 Structure of the questionnaire.

The questionnaire is divided into 7 different parts (Table 7). The first part contains general questions, personal and anthropometric data (i.e., age, weight, height, gender identity, nationality, mother tongue, etc.), along with some questions about school life. The second part contains information related to the specific moment in which respondents are asked to fill the questionnaire: clothes worn, activity carried out during the previous hour, position inside the classroom, a self-evaluation of the health state and the alertness. The four central sections focus on the subjective experience regarding four environmental aspects: thermal, visual, acoustic and IAQ environments. In these sections, the order of the questions is maintained the same as follow:

- Sensation,
- Preference,
- Sources of discomfort and related annoyance level,
- Comfort,
- Effects on productivity
- Satisfaction.

To avoid biases (e.g., fatigue) the order of these four sections were randomized within the questionnaires.

The last part of the questionnaire aims to inspect the global experience of students' and teachers and contains the following questions:

- Global comfort,
- Relevance of each domain of comfort in the evaluation of global comfort (right-now)
- Global satisfaction (over the last hour).

Table 7. Questionnaire Sections

#	Section	Composition of questions
1	General Information	Age, height, weight, gender, nationality, mothertongue, smoker, use of glasses/lenses, use of hearing devices, satisfaction related to classroom, school, relation with teacher, relation with classmates.
2	Information related to the moment	Activity carried out in the past 30 min, clothing items worn, how students take notes, alertness, health.
3-6	Thermal/acoustic/IAQ/visual domain	Sensation, preference, sources of discomfort and related annoyance rating, comfort, performance, satisfaction.
7	Global comfort	Global comfort, relevance score attributed to each domain, global satisfaction.

3.1.3 Wording and graduation

The questions wording and the scales for the answers were chosen in accordance with EN ISO 10551 [8] and EN 28802 [12]. For thermal, visual, and some acoustic features, symmetrical 7-degree two-pole scales were used, the point of indifference corresponding to the vote "0" and the degrees of intensity ranging from {-3; -2; -1} to {1; 2; 3}. For acoustics and IAQ, 4-degree one-pole scales were chosen to characterize sensation; the vote "0" represents the absence of the effect and the degrees of intensity range between {1; 2; 3}. The format of preference scales was chosen in agreement with the format of sensation scales. For evaluation scales (comfort, satisfaction), 4-degree one-pole scales were chosen, the vote "0" being intended as "absence of discomfort/dissatisfaction". In the visual, IAQ and acoustic domains, more than one sensation question was formulated. Indeed, while the question related to the thermal sensation has a standardized formulation, widely used in the literature and incorporated by all relevant standards [11,9,10,17], the same does not occur for the other domains. Sensation of indoor air quality was investigated by using two questions, related to the air freshness [88] and to the air smelliness [17]. Visual sensation was inspected by asking a rating on the brightness of the visual environment [17, 89]. Two additional questions regard the sensation of the illuminance on the desk and on the blackboard/whiteboard. As concerns acoustics sensation, the attributes quantified are the following: the noisiness of the environment [17, 88], the loudness and the clarity of the teacher voice, and room reverberation [65, 28, 79]. The preference questions considered in the questionnaire relate only to the main sensation questions, labelled as S1 in the table. The sensation questions are summarized in Table 8 and the entire questionnaire reporting all the questions and evaluation scales is presented in Appendix 2.

Table 8. Sensation Scales Used to Evaluate the Four Comfort Domains

Environment	Code	Attribute Characterized	Scale
Thermal	S1	Thermal environment	-3 (cold) to 3 (hot)
IAQ	S1	Air freshness	0 (fresh) to 3 (stuffy)
	S2	Air smelliness	0 (odourless) to 3 (very odorous)
Visual	S1	Visual environment	-3 (very dark) to 3 (very bright)
	S2	Desk	-3 (very dark) to 3 (very bright)
	S3	Whiteboard/blackboard	-3 (very dark) to 3 (very bright)
Acoustic	S1	Acoustic environment	0 (quiet) to 3 (loud)
	S2	Loudness of the teacher's voice	-3 (very loud) to 3 (very soft)
	S3	Clarity of the teacher's voice	0 (clear) to 3 (very unclear)
	S4	Reverberation of the room (sounds)	-3 (very dry) to 3 (very reverberated)

3.1.4 Regarding the age of the subjects

When dealing with educational buildings, an important aspect to consider in the questionnaire design phase is the age of subjects to whom the questionnaire will be administered. In order to ease the comprehension of the survey and thus avoiding errors in completing the questionnaire that can compromise the goodness of the data, the type of questions, the wording of the questions or the labels of the evaluation scales could be tailored according to the different educational stage of the students (e.g.: primary school, secondary school or university).

In the design of the present survey two different targets were considered, namely high school and university students. In order to obtain a questionnaire as standard as possible, it was decided to maintain the same structure and wording both for high school and university students, choosing to add to the questionnaire for high school students an appendix with a detailed explanation of the different sections and the wording of questions and evaluation scales and thus simplifying the comprehension.

3.2 Assessment of the Indoor Environmental Quality: Data collection

3.2.1 The environmental monitoring for the objective evaluation

In order to assess the indoor conditions of a building and to simulate and calibrate its behavior it is necessary to monitor some important physical parameters related to the four environmental aspects, i.e. IAQ, thermal, visual and acoustic environment. There are two types of monitoring, namely *long-term monitoring* that is scheduled over a wide span of time (e.g., weeks, months, seasons or years) and it is useful for recording the behavior of the building for simulating, calibrating and validating its energy model, and *short-term monitoring*, that lasts less time and it is usually run in conjunction with subjective surveys.

Long-term monitoring. In order to monitor the behavior of the building is necessary to select a reasonable amount of reference rooms where locating the sensors. Moreover, to get information about the boundary conditions also the adjacent spaces need to be equipped with sensors. Within my doctoral research the physical parameters monitored during the long-term field-campaigns were the indoor air temperature and relative humidity of the room, the surface temperature of radiators' and heat generator's supply and return pipes, the CO_2 concentration and illuminance level. Environmental parameters related to the IEQ were recorded at 10-muntes intervals. The details of the installed sensors are reported in table 9a.

The installation of the sensors needs to be performed in order to avoid interference from external sources, which could affect and falsify the measurements. Therefore, the below-mentioned best practices for the installation were followed:

- all sensors have been installed approximately at the same height and in order not to be accessible by the occupants;

- the sensors have been positioned so as not to be affected by solar beam radiation;
- the sensors have been installed far from eventual air fluxes due to window or door openings.

After equipping the rooms with the monitoring infrastructure, every one or two months the sensors have been downloaded and during these surveys, the presence of the students has been logged by reading of the classroom registers. In order to evaluate user's behavior and its impact on building performance, interviews have been conducted and when possible, students compiled specific excel files related to classrooms conditions (i.e. windows and door open/closed, shadings up/down, artificial lightings on/off, radiators on/off) and their behavior during to face any situations of discomfort during regular classrooms. Although the planimetry of the building has been available, further surveys have been performed in order to verify the correspondence between project data and real building shape.

Table 9a. Long-term monitoring: instruments and physical parameters

S.No	Instrument	Parameter(s)	Accuracy
1	Sensor Data Logger HOBO® U12-U13	Ambient Temperature Relative Humidity	Temperature: Max. Range: -20◦C-70◦C; Accuracy: ±0.35◦C in the interval from 0◦C to 50◦C; Resolution (12 bit): 0.03◦C at 25◦C RH: Range: 5%-95%RH; Accuracy: ± 2.5%, max. 3.5% from 10% to 90% RH; Resolution (10 bit): 0.03 % RH
2	Sensor Data Logger HOBO® MX1102A	CO_2 Ambient Temperature Relative Humidity	CO_2: Range: 0 ÷ 5000ppm ±50 ppm; Accuracy: ±5% at 25°C Temperature: Measurement Range: 0°C ÷ +50°C Accuracy: ± 0.2°C RH: Range: 1% ÷ 90% Rh; Accuracy ±2%RH
3	Sensor Data Logger HOBO® U12-012	Ambient Temperature Relative Humidity Light intensity	Temperature: Range: -20◦C-70◦C; Accuracy: ±0.35◦C in the interval from 0◦C to 50◦C; Resolution (12 bit): 0.03◦C at 25◦C RH: Range: 5%-95%RH; Accuracy: ± 2.5%, max. 3.5% from 10% to 90% RH; Resolution (10 bit): 0.03 % RH Light intensity: Range: 1 to 3000 footcandles (lumens/ft^2); Accuracy: Designed for indoor measurement of relative light levels, see Plot B for light wavelength response. External input channel: ± 2 mV ± 2.5% of absolute reading.

Short-term monitoring. Environmental parameters related to IEQ were recorded at 1-minute intervals, during regular classes, starting from the beginning of the lecture until the students had completed the questionnaires. Thermohygrometric parameters were recorded by means of the Microclimatic Station DeltaOhm HD32.1 located in the center of the classrooms, away from heat sources (e.g., projectors), and also away from sun patches at a height of 1.1 m as recommended by the Standard EN ISO 7726 [14]. TVOC, CO_2, CO, T, RH were measured with the IAQ Meter Graywolf Wolfpack (IQ-610). The sensor was located on the teacher's desk. The horizontal illuminance level was measured at all the students' desk inside the classrooms with the illuminance meter Konika Minolta T-10A. The A-weighted L_{eq} sound level ($L_{A,eq}$) was measured with B&K 2270 Sound level meter. The sensor was located in the center of the classroom near the Microclimatic Station. During these field-campaigns classrooms conditions (i.e. windows and door open/closed, shadings up/down, artificial lightings on/off, radiators on/off) were jotted down by researchers. The same installation best practices followed for the long-term monitoring were pursued. Specifications of the sensors are reported in Table 9b.

Table 9b. Short-term monitoring: instruments and physical parameters

S.No	Instrument	Parameter(s)	Accuracy
3	DeltaOhm HD32.1	Globe Temperature Ambient Temperature Relative Humidity Air Velocity	Temperature: Pt100 Accuracy ±0.01°C in the range ±199.99°C, ± 0.1°C outside this range RH: Accuracy ±0.1%RH Velocity: ±0.2m/s (0…0.99 m/s), ±0.4 m/s (1.00…9.99 m/s)
4	Graywolf Wolfpack (IQ-610)	TVOC, CO_2, CO, T, RH	CO: Accuracy ±2ppm <50ppm, 3%rdg >50 ppm CO_2: Accuracy ±3%rdg ±50 ppm VOC: Resolution 1ppb, L.O.D. <5ppb RH: Accuracy ±2%RH <80%RH (±3%RH>80%RH) Temperature: Accuracy ± 0.3°C
5	Konika Minolta T-10A	Illuminance (lx)	Linearity: ± 2% ± 1 digit of displayed value
6	B&K 2270	$L_{A,eq}$ (dB)	Free-field ½ " Microphone: Nominal Open-circuit Sensitivity: 50mV/Pa 1.5bB; Capacitance: 14pF at 250 Hz Microphone Preamplifier: Nominal Preamplier Attenuation: 0.25 dB

3.2.2 The survey for the subjective evaluation

The standard questionnaire was administered in a pseudonymized form to students and teachers during the experimental campaigns (short-term monitoring) considering both heating and cooling seasons. During the questionnaire administration, ongoing and point-in-time measurements were carried out to investigate the possible correlation between students' responses and the measured physical parameters related to the four environmental aspects, i.e., thermal, visual, acoustic and indoor air quality. Students and teachers are asked to fill the questionnaire during the last 10-15 minutes of a regular class, while sitting at their desk, after being exposed to the same indoor conditions for at least 30-40 minutes. After data collection, responses by people with cognitive or acoustic impairment were removed.

3.3 Data validation and analysis

3.3.1 Validation of the standard questionnaire

Establishing the goodness of a questionnaire means (i) demonstrating its capability of discriminating different subjective responses in different environmental conditions (**effectiveness**), (ii) checking if questions are sufficient to understand which environmental and contextual factors affect comfort and to understand how occupants express comfort (**efficiency**) and (iii) able to capture the different level of judgement on each question (**resolution**). The questionnaire effectiveness is evaluated by analyzing the mean sensation, preference, and comfort votes expressed in each panel, and relating these votes to a physical parameter that was deemed representative of the environmental conditions of each domain. The questionnaire efficiency is tested by performing a multilinear regression analysis in which individual sensation votes are predictors and comfort votes are the response variables, by checking the significance level of the variables. The questionnaire resolution is investigated by means of a qualitative analysis of the distribution of the votes expressed in the sensation and preference scales, in the four domains. For the validation of the questionnaire the subjective responses collected during several infield campaigns were used (for details see chapter 4 Application of the methodology to case studies). The results have been published in a conference paper (Appendix 3).

3.3.2 Methodology for data analysis

In order to correlate the objective data collected through the in-field measurements with the subjective votes gathered with questionnaires inspecting students' comfort in different environmental conditions, it is necessary to analyze sufficiently representative data. On the one hand, the raw measurements need to be pre-processed in order to identify different indoor conditions in terms of indoor air quality, thermal, visual and acoustic environment. On the other hand, it appears necessary to group the panels (i.e. groups of students exposed at the same conditions) based on the environmental conditions in order to treat a consistent number of responses.

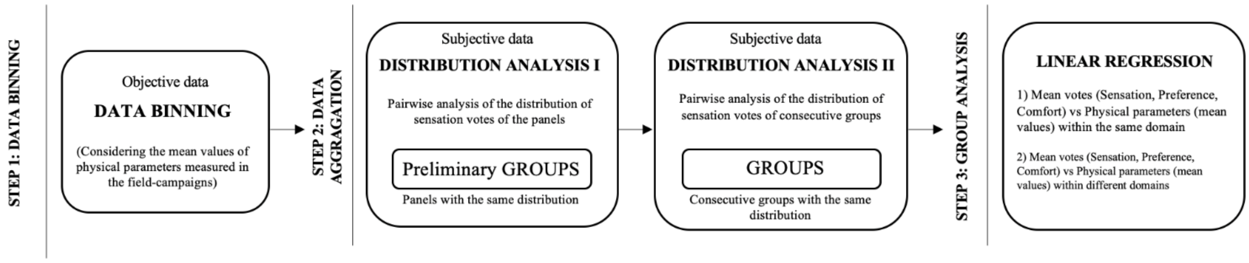


Figure 1. The main steps of the method for analysing the dataset collected for the four environmental

For aggregating different panels according to specific physical parameters ranges or bins, representing the different indoor conditions to which subjects have been exposed, the time averaged value of the physical parameters measured inside each classroom, i.e., indoor air temperature, CO_2 content, the illuminance level and $L_{A,eq}$, need to be calculated. Regarding the visual environment, the illuminance level has been calculated as the spatial mean value of the horizontal illuminance level measured at all the desks inside the classroom. The process for grouping the panels can be divided into three main steps (Figure 1). First, the panels have been binned considering specific ranges of the measured physical parameters (Data binning). In this way, subjects of panels exposed to similar indoor conditions in terms of indoor air temperature, CO_2 content, illuminance level and sound pressure level were aggregated into preliminary groups. The preliminary groups were then checked by analyzing the distribution of sensation votes of each group by means of statistical tests: panels with the same distribution of sensation votes within a specific bin were aggregated (Preliminary Data aggregation). Secondly, the same statistical tests were used for verifying the groups (Definition of the groups). Finally, the correlation between measured parameters and the subjective responses of the final groups has been inspected (Analysis of the groups). This methodology has been validated using the database collected during several infields campaigns and published in a conference paper (Appendix 3). The detailed steps are presented below.

Data Binning. The environmental conditions of each panel have been binned for each of the main physical parameters related to each of the four environmental aspects separately, i.e. the indoor air temperature, the CO_2 concentration, the illuminance level and the A-weighted equivalent sound level L_{Aeq}. In more detail, for the indoor air temperature the intervals of 0,6 °C have been considered [14]; for the CO_2 average levels have been binned according to the categories defined by EN 16798-3 [9], i.e. 500 ppm, 800 ppm, 1100 ppm and 1400 ppm; regarding the visual environment the data have been binned according to the recommended steps of illuminance defined by EN ISO 12464-1 [14], i.e. 20, 30, 50, 100, 200, 300, 500, 1000 lx finally for the Acoustic data the step of 1 dB has been used as tentative range.

Preliminary Data Aggregation (Statistical Analyis I). In order to verify the possibility to aggregate more panels into the same group, the distribution in each panel of the sensation votes expressed by subjects about one comfort aspect at a time, have been analyzed by means of non-parametric statistical test, namely the pairwise Mann Whitney U-test. All the panels inside a specific bin have been compared pairwise. The results of the statistical analysis have been interpretated as follow: (a) if the distributions of sensation votes of two panel within the same bin are the same, it is possible to combine the panels and thus form a preliminary group; (b) if not, it is not possible to combine the panels, so the most selective panel (i.e. the panel with the fewest matches) is not considered in the analysis.

Definition of the groups (Statistical Analyis II). In order to confirm the preliminary groups a second pairwise Mann Whitney U-test has been carried out considering the newborn groups. The results of the statistical analysis have been interpretated as follow: (a) if the distributions of sensation votes of two groups referring to subsequent bins are the same, it is possible to aggregate forming a broader group; (b) conversely if they had different distributions they were considered as separate groups.

Analysis of the groups: single-domain. To analyze the correlation between measured environmental conditions and the subjective response within the same comfort domain, the mean value of the physical parameters referring to a specific environment domain was compared with the mean sensation, preference and comfort votes referring to the same domain (regression models).

Analysis of the groups: multi-domain. In order to explore the combine effects of different comfort domains, the multi-domain approach analysis has been set starting from the groups formed within the step *Definition of the groups*. The multi-domain analysis is conducted with two different approaches, namely subjective and objective approach. The *subjective approach* aims to investigate if the main physical parameter related to a domain (the same parameter used in the data binning phase in order to form the groups) have an impact also on the sensation votes expressed for the other comfort areas by the same homogeneous group of students. In this analysis the mean value of the physical parameters referring to a specific environment is correlated to the mean sensation votes express for the other domains. The purpose of the *objective approach* is to explore if the sensation vote expressed for a comfort area by the same homogeneous group of students is influenced also by the physical parameters related to the other domains. In this analysis the mean sensation vote expressed for a specific domain is correlated to the distribution of physical parameters related to the other domains.

3.4 Building thermal model simulation: multi-level multi-step method for calibration

Over the recent decades, an increasing amount of works focused on the application of building simulation procedures for the optimization and application of predictive methods for building system control in existing buildings [99] or for retrofitting strategies. In order to obtain a reliable representation of the building and energy systems behaviour, accurate simulation models for energy diagnoses of buildings are required and generally, expensive and long-term monitoring of some building performance variables (e.g. energy consumption, air temperature, etc.) are needed. A calibration process, by changing uncertain building parameters until the output matches measured values is often adopted to improve the model. However, when the complexity of the building is high, the number of descriptive parameters is typically too high to rely on a calibration method based on an iterative manual procedure and it requires a time-consuming trial-and-error process [101]. Moreover, it potentially leads to results which are still far from reflecting the real building data, due to compensation effects as highlighted by Coakley et al. [93]. To make the process easier, the proposed methodology divides the calibration process can be divided into different steps in order to limit the number of model parameters to calibrate at each step, considering their different impact in different reference periods. In addition, the monitoring phase can be less expensive by choosing a small representative portion of building to monitor and calibrate the values of some specific quantities to be extended to the whole-building model. This method allows to calibrate fewer parameters when considering the model of the entire building and reduces the possibility of overfitting.

Setting the building model: The dynamic simulation model of the school building has been implemented with the simulation code TRNSYS v.18 [100]. The 3D geometry model of the building has been described using the TRNSYS plugin and Google Sketch-up v.8, while the building thermo-physical characteristics have been set in TRNBuild. The Air Flow Network has been implemented with the tool TRNFLOW, the integration of the multizone air flow model COMIS into the thermal building module of TRNSYS, Type 56-TRNflow. A simulation time-step of 10 minutes has been selected. For the periods in which the building is occupied, in order to consider students' interaction with the windows, (i.e. windows opening), a Logistic regression model have been used. The windows status (open or closed) is due to either random events (students or teacher interaction with the window during lessons) or scheduled events as the opening of the windows during break-time or cleaning time and the closing during the night. While an opening or closing schedule was set for the scheduled events, a logistic regression model had to be implemented for the period of occupation in which students are also present and attending the lessons. Using the logistic regression model, it is possible to obtain the probability for each classroom of finding at least an open window or all closed windows given a set of parameters. In this model we have chosen to use only one variable, the internal temperature, since as highlighted by Stazi et al. [98] it is the best predictor for both opening and closing probability in classrooms. Below is reported the equation to calculate according to the regression model the probability of finding at least one window open.

$$p = \frac{exp^{(\beta_0+\beta_1 * x)}}{1+exp^{(\beta_0+\beta_1 * x)}} \qquad (1)$$

In equation 1 the coefficients β0 and β1, are constants estimated by the regression analysis through maximum likelihood estimation and x is the environmental parameter, namely the indoor air temperature. Given the need to calibrate the regression model as well, it was necessary to transform the model from probabilistic to deterministic. This was done by imposing two parameters that determine the probability threshold beyond which the windows status is changed to open or closed.

$$p > T_{open} \qquad (2)$$

$$(1-p) > T_{closed} \qquad (3)$$

Moreover, additional parameters related to the AFN have been considered in the model, i.e. wind velocity coefficient and the discharge coefficients of the windows, and calibrated.

Calibration method. The proposed approach is based on the selection of representative spaces in the buildings, and the identification of multiple monitoring periods during which only a subset of building parameters needs to be calibrated at a time. The calibration method considers four selected periods (un-occupied and system off; un-occupied system on; occupied and system off; occupied system on) to calibrate different parameters, and with a multi-level methodology that extends the parameters calibrated for the partial model to the whole building (Figure 2). The monitoring considers the four periods and includes the air temperature and relative humidity into reference rooms and their surrounding rooms (i.e. monitored zones) in order to provide the required boundary conditions. The calibration method proposed is based on the monitoring of the air temperature and the relative humidity of a portion of a building such as one or two reference rooms along with all. The purpose is to minimize the differences between the simulation output and the monitoring data. The calibration phase is split into two main levels: (i) the calibration of a limited portion of the building (i.e. partial-building calibration) and (ii) the afterwards calibration of the whole-building model (i.e. whole-building calibration). Since the first level considers only a portion of the building, the calibration is set on the indoor conditions (i.e the indoor air temperature and relative humidity), while the building energy consumptions are considered for the annual validation of the whole-building calibrated model. According to this method, a model of the reference rooms needs to be set-up and calibrated. To avoid compensation effects during the automated calibration process, the unknown building parameters are separated into subsets and the partial-building model is progressively calibrated during different periods of the year. These periods are selected to be representative of different seasons and building operation modes in relation to human presence (occupied/unoccupied) and HVAC system operation (on/off). In each period, different sets of building parameters are consequently calibrated (e.g.: physical characteristics of the building envelope and infiltration, heating system characteristics, shading level and ventilation rate due to occupants' presence and behavior). Then, the already calibrated parameters are used to the following periods and to the whole-building model, while the remaining unknown quantities are calibrated for the entire building, considering again the different periods already defined. The result of this approach is a multi-stage multi-level calibration of a building model. The simulation output to calibrate is the indoor air temperature trend in the reference rooms in the first level (i.e. partial building calibration) and the air temperature of all the monitored rooms in the second level (i.e. whole-building calibration).

The calibration process is performed following an optimization-based approach simultaneously minimizing the differences between the simulated and monitored indoor air temperatures of the selected reference rooms in the partial-building calibration and of all the monitored rooms in the whole-building model calibration. Among the calibration performance indexes reviewed in [93] for representing the cumulative differences between measured and simulated air temperatures, we selected the Coefficient of Variation of the Root Mean Square Difference CV(RMSD) (Equation 4 and 5), widely used in the literature [92].

$$CV_{\mathrm{J}}(RMSD_J) = \frac{RMSD_J}{\bar{m}_j} \qquad (4)$$

$$RMSD_{\mathrm{J}} = \sqrt{\frac{\sum_{i=1}^{n}(m_{ij} - s_{ij})^2}{n}} \qquad (5)$$

where $\boldsymbol{m_{ij}}$ is the measured indoor air temperature; $\boldsymbol{s_{ij}}$ is the simulated indoor air temperature; $\boldsymbol{n}$ is the number of the simulation time steps and $\bar{m}_j$ is the measured mean temperature; *i* is the time step index and *j* is the number of monitored rooms utilized for the calibration process. In addition, in order to avoid overfitting issues, the cost function of the optimization-based calibration is defined combining the CV(RMSD) with the regression coefficient R^2, since the latter adds complementary information about the quality of the model. The determination coefficient R^2 (Equation 6) is used for describing the proportion of the variance in measured data according with the model [94]:

$$\mathrm{R^2{}_J} = \left(\frac{\mathrm{n} \sum_{\mathrm{i}} \mathrm{m_{ij}} \mathrm{s_{ij}} - \sum_{\mathrm{i}} \mathrm{m_{ij}} \mathrm{s_{ij}}}{\sqrt{\left(\mathrm{n} \sum_{\mathrm{i}} \mathrm{m^2{}_{ij}} - \left(\sum_{\mathrm{i}} \mathrm{m_{ij}}\right)^2\right) * \left(\mathrm{n} \sum_{\mathrm{i}} \mathrm{s^2{}_{ij}} - \left(\sum_{\mathrm{i}} \mathrm{s_{ij}}\right)^2\right)}} \right)^2 \qquad (6)$$

For calibration purpose, different weighting factors have been assigned to the statistical indexes [98-99] with the aim to prioritize the minimizing of the CV (RMSD. Hence a value of 0.7 for the CV(RMSD) weighting factor and a value of 0.3 for R^2. For each monitored zone, the cost functions f_{j} are defined (Equation 7) and the overall cost function f_{tot} is calculated as their summation (Equation 8).

$$f_{\text{J}} = 0.7CV_j\left(RMSD_j\right) + 0.3\left(1 - {R_j}^2\right) \qquad (7)$$

The overall cost function f_{tot} is calculated as their summation (Equation 8).

$$f_{\text{tot}} = \sum\nolimits_j f_j \qquad (8)$$

Calibration workflow and calibrated parameters: Several buildings' thermophysical properties, the windows thermal and solar transmittance, the shading coefficient, the convective airflows between the stories and to assess the airtightness of the building, three parameters related to the Air Flow Network (AFN) have been calibrated in a partial-building model considering the first period (un-occupied, system off) and then used for calibrating the entire school building in period 2. Other specific building parameters (i.e. the single-glazed windows thermal and solar transmittance, the crack value of the single-glazed window and the pressure drops of the stairwells, the thickness of the ground floor hollow slab and the shading coefficients of the boundary rooms) need to be calibrated in the whole-building model in the first period and used for building the whole model in Period 2 (unoccupied, system off). In this period other building parameters were calibrated to capture human presence and interaction with the building (i.e. windows and doors opening). The same procedure is adopted for period 3 and 4 (occupied building). In these periods, the system is simulated through TRNSYS subroutines Types 869 and 362. The characteristics of the radiators calibrated during Period 3 (unoccupied building, system on) in the two-zone calibration, the heating system operation schedule and the radiators' supply temperature collected in the same period is determined: one during working days, based on a scheduled heating time and a climatic control of the water supply temperature, and a setback mode, when the building is unoccupied for a long period. During the scheduled heating time, the system is turned on from 6 am to 12 pm and a climatic adjustment of the radiator supply temperature, $T_{supply,0}$, is assumed as in the following equations:

$$\text{If} \quad T_{ext} < 10°C; \quad T_{supply,0} = (a \cdot T_{ext} + b) \qquad (9)$$

$$\text{If} \quad T_{ext} > 10°C; \quad T_{supply,0} = c \qquad (10)$$

where T_{ext} is the outdoor air temperature and *a, b, c* are the multiplying coefficients of the supply temperature of the radiators. Outside the scheduled heating time, the heating system is switched on only when the indoor temperature falls below 14°C. For this period the supply temperature $T_{supply,0}$ assumes a constant value, *d*

$$\text{if} \quad T_{indoor} < 14°C; \quad T_{supply,0} = d \qquad (11)$$

Moreover, a decremental factor is applied to $T_{supply,0}$ to take into account the thermal losses due to the distribution system, as follows:

$$T_{supply,1} = T_{supply,0} - \Delta T_1 \cdot (20 - T_{ext}) / (20 - T_{ext,0}) \qquad (12)$$

$$T_{supply,2} = T_{supply,0} - \Delta T_2 \cdot (20 - T_{ext}) / (20 - T_{ext,0}) \qquad (13)$$

where ΔT_1 and ΔT_2 are respectively the thermal loss between the basement and ground floor and between the basement and the first floor, calculated at a design external temperature ($T_{ext,0}$) equal to -10°C. Firstly, the whole-building initial model is built using the multiplying coefficients of the radiators *a, b, c* and *d* calibrated during the partial calibration while ΔT_1 and ΔT_2 are set as tentative values. Secondly, *a, b, c* and *d* together with ΔT_1 and ΔT_2 are calibrated. For all coefficients, a variation range of ±20% of the tentative values was determined. The calibration needs to be validated by simulating the building model in a similar period (unoccupied building, passive mode). The multi-level methodology was tested in previous work [96-97], while the results of the application of the whole methodology (i.e. multi-level, multi-stage) have been published into two conference papers (Appendix 4) [95].

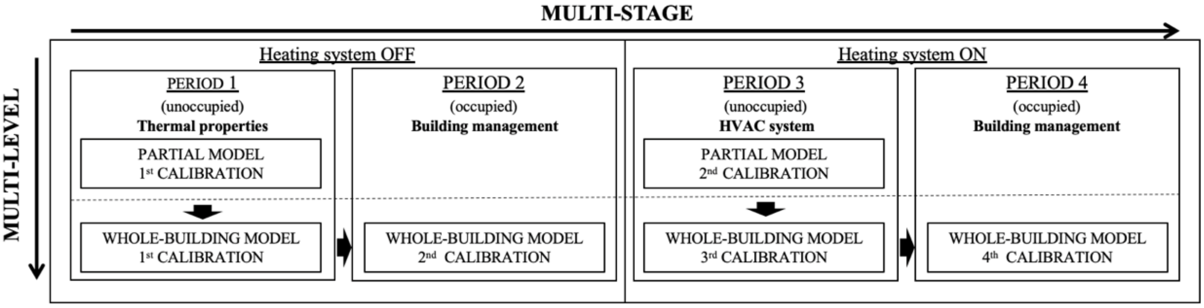


Figure 2. Scheme of the multi-stage multi-level calibration procedure

4. Application of the methodology to Case Studies

This chapter presents the case studies considered for the application of the methodologies defined in the previous chapter (i.e. Methodology). In details, the sections 4.1 and 4.2, respectively Questionnaire administration and Experimental campaign, consider the 21 classrooms monitored classroom located in three different buildings in Italy: one classroom of the university building of the Free University of Bozen-Bolzano (UR1), eighteen classrooms of the high school Margherita Hack in Morlupo, Rome (MR1-MR18), and two classrooms located in two different building of IUAV University of Venice (VR1 and VR2). The buildings have been chosen in order to assess different climate locations, while the choice of the classrooms was due for assessing rooms with different characteristics, i.e., exposure, volume, crowd, windows surface, location inside the building, and thus monitoring different indoor conditions. Figure 3 reported some pictures of the investigated classrooms for experimental and subjective analysis located in Morlupo, Rome, while the planimetries of the most representative classrooms are shown in figure 4. The characteristics of the buildings and classrooms, i.e., *location, climate, school level, type of building system, type of ventilation, code of monitored classrooms, floor area, type of heating terminals, number of heating terminals, number of windows, type of electric lighting, number of lighting sources, shading system*, are reported in Table 10a. Moreover, Tables 10b presents the monitoring conditions and number of interviewed subjects, while the mean value of the physical parameters recorded during the experimental campaigns is reported in Table 11.

Finally, section 4.3, i.e. Building Model Simulation and calibration: multi-level multi-step approach, presents the optimization-based calibration method applied to a primary school located near Vicenza, in the north of Italy. The calibration workflow is presented in figure 5 while the planimetries of the building are reported in figures 6a-b and 7a while figure 7b shown the location of the sensors inside the 9 monitored rooms.

4.1 Questionnaire administration

The subjective survey consisted of a questionnaire, filled during regular classes, simultaneously with the measurements of the physical parameters. The four comfort aspects, i.e. thermal, visual, acoustic and indoor air quality (IAQ), along with the global comfort and satisfaction have been included in the questionnaire. Considering all the experimental campaigns, namely Bolzano, Rome and Venice, a number of 55 panels, i.e. groups of students interviewed in the same moment in the same classroom, have been interviewed, for a total of 949 questionnaires which have been analyzed in this work. The votes about sensation, preference and comfort expressed by students in each panel have been aggregated in clusters and then analyzed. The aggregation method and the analysis of the dataset is presented further on. The number of interviewed subjects, the mean age of the panels and the mean age of all the interviewed subjects are shown in Table 10b. The mean age of panels interviewed in Bolzano ranges from 22 to 25 years, questionnaires in Morlupo were administered to subjects old between 13 and 18, while the mean age of students interviewed in Venice is 21 years. In the analysis method presented in the following chapter (Methodology) the difference in the students' age was not considered but this aspect will be explored in future works.

The questionnaire is reported in the Appendix 2.

4.2 Experimental campaign

The entire experimental campaign took place from winter 2019 to spring 2021. In details, the monitoring of the classroom UR1 at the Free University of Bozen-Bolzano took place from November to December 2019; the monitoring of the classrooms of the high school Margherita Hack in Rome (MR1-MR18) lasted from February 2020 to May 2021, and in Venice one classroom was monitored in December 2019 and the other in May 2021. The monitoring conditions recorded by researchers and panel characteristics are reported in Table 10. Environmental parameters related to IEQ, i.e. indoor air quality, thermal and acoustic environments, were recorded at 1-minute intervals, during regular classes, starting from the beginning of the lecture until the students had completed the questionnaires. The plan illuminance has been measured at each desk during the administration of the questionnaire. The mean value of the physical parameters monitored during the field campaigns are summarized in Table 11. The plans of the classrooms and the sensors' location are shown in Figures 3-5.

Data quality and assurance. According to the survey method, the questionnaires were administered ensuring that the students had spent in the classroom enough time to reach an adequate balance with the thermal environment, being exposed for a suitable period of time to the environmental conditions. Before the administration, the questionnaire is explained in all its parts to the students by the researchers, answering all the students' clarification requests. Moreover, it was ensured that students had all the time they needed for filling the questionnaires, neither the teacher nor the researcher hurried them to answer. To avoid bias due to tiredness, the order of sections of the questionnaire related to the four environmental aspects has been randomized for each student. Collected responses underwent a quality verification by identifying and removing irrational or inconsistent answers. Responses by people with some learning, language, or acoustic impairment were removed. Questionnaires with up to one missing answer about one of the perception aspects, i.e. sensation, preference and comfort, or satisfaction were used anyhow for the analysis of the other questions not to reduce too much the number of surveys per classroom. Regarding the objective evaluation, all the right-now measurements have been carried out during regular classes between 8 a.m. and 3 p.m., starting at the beginning of the lecture and lasting until the end of the filling of the questionnaires. For this work measurements carried out before (at least 30-35 minute before giving them the questionnaire) and during the filling of the questionnaire have been considered. Thermal measurements underwent a quality check by verifying their stationarity according to the Standard EN ISO 7726 (CEN, 2001).

Table 10a. Building and classrooms characteristics

Location	Climate	Level	Type of building system	Type of ventilation	Room cod.	Floor area [m^2]	Type of heating terminals	n. of heating terminals	n. of windows	Type of electric lighting	n. of lighting sources	Shading system
Bolzano, Italy	E, Dfb	University	HVAC	Mechanical	UR1	53	Radiators	2	2	fluorescent lamp	4	vertical electric blinds
Rome, Italy	D, Csa	High school	Heating system	Natural	MR1	100	Radiators	4	5	fluorescent lamp	12	vertical blinds
					MR2	44		3	3		6	
					MR3	43		4	3		6	
					MR4	61		4	3		8	
					MR5	57		4	3		8	
					MR6	69		3	3		6	
					MR7	52		3	3		6	
					MR8	149		6	6		15	Internal curtains
					MR9	52		3	3		6	vertical blinds
					MR10	49		3	3		6	
					MR11	44		3	3		6	
					MR12	57		3	3		6	
					MR13	58		2	3		9	
					MR14	61		4	3		8	
					MR15	44		3	3		6	
					MR16	49		3	3		6	
					MR17	44		3	3		6	
					MR18	43		4	3		6	
Venice, Italy	E, Cfb	University	HVAC	Mechanical	VR1	216	Fan coil	/	6	fluorescent lamp	xx	external curtains
					VR2	174	Fan coil	/	3		32	

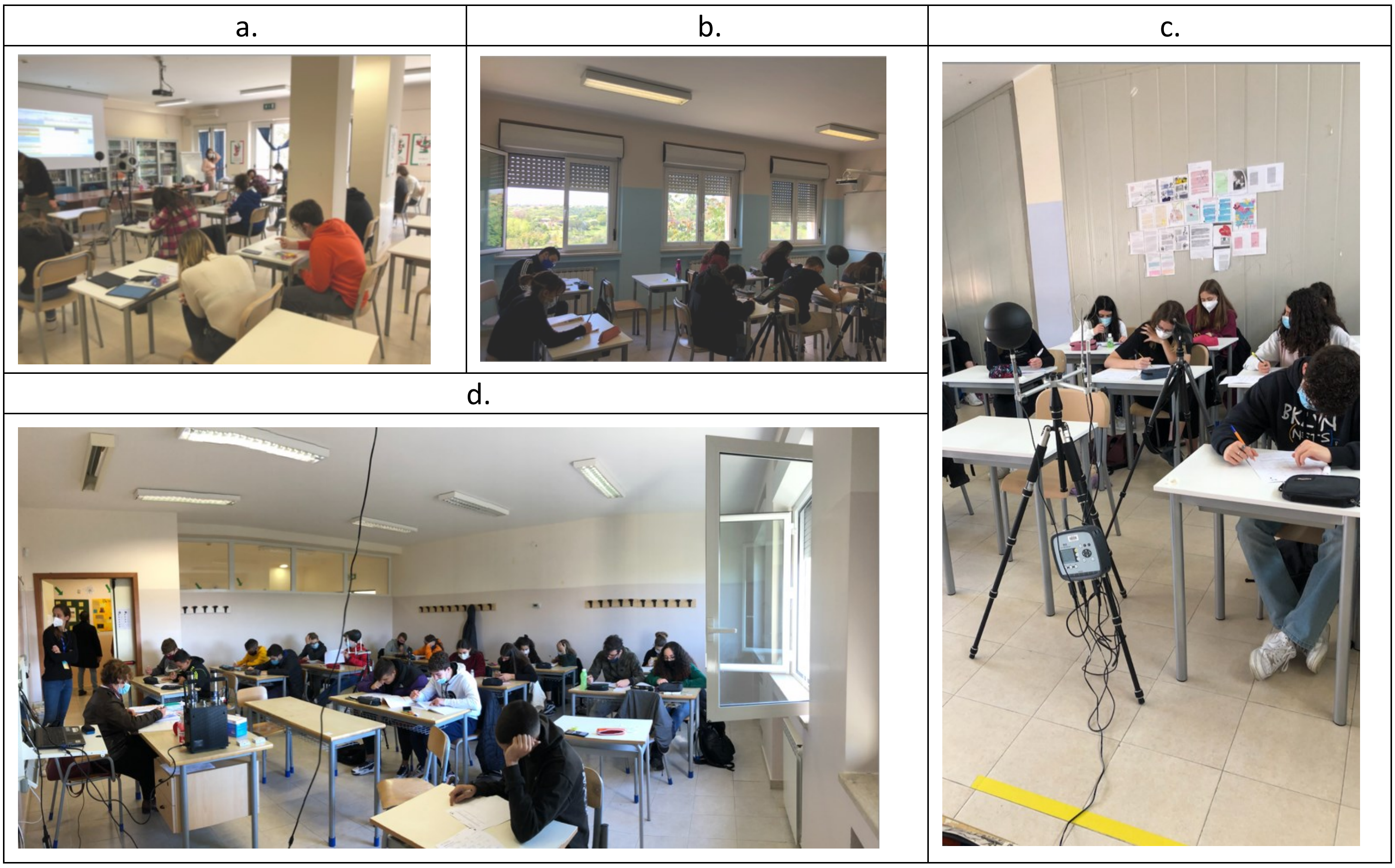
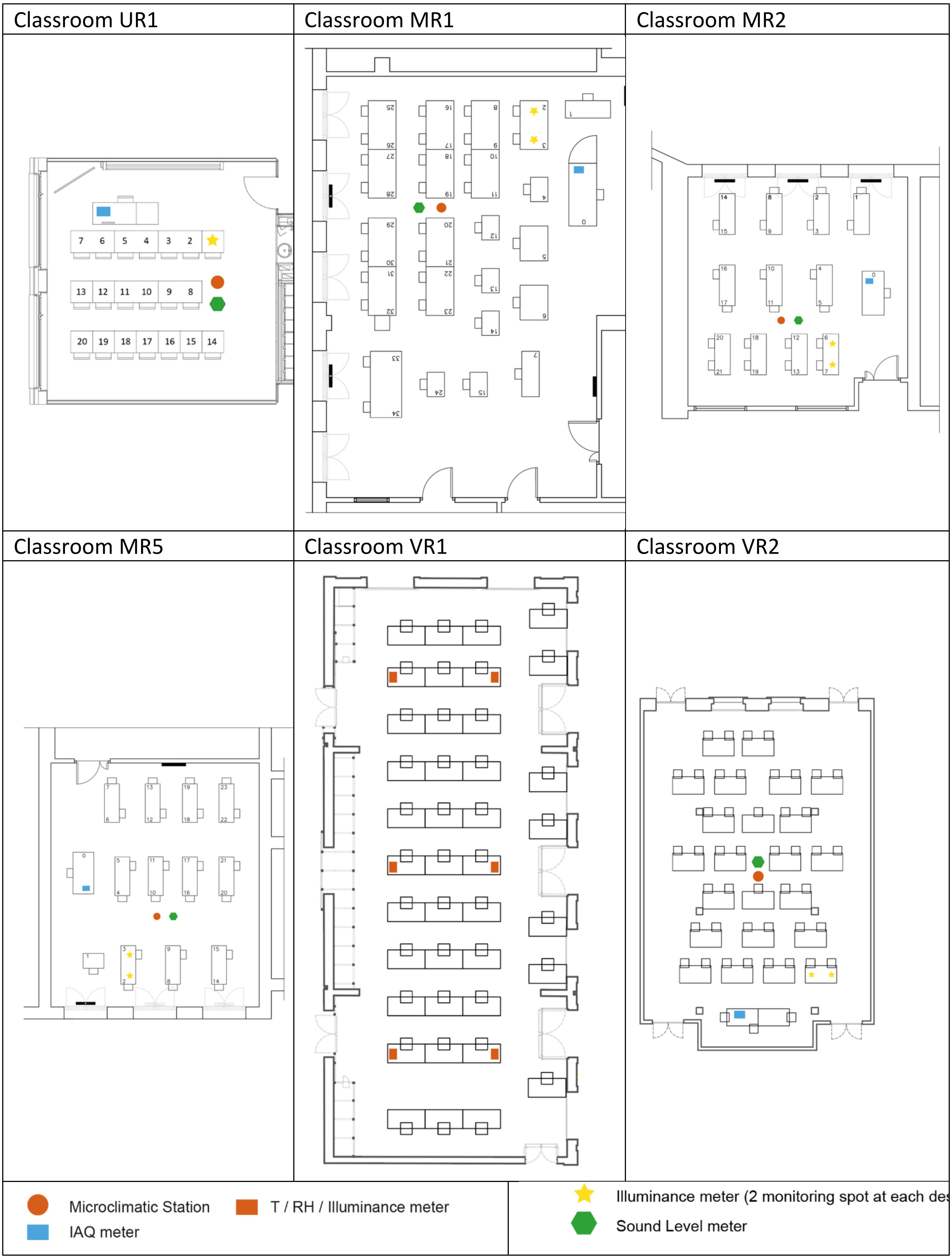


Figure 3: Some pictures of the investigated classrooms for experimental and subjective analysis (a = classroom MR8; b = classroom MR16; c = classroom MR6; d = classroom MR3.


Classroom UR1

Classroom MR1

Classroom MR2

Classroom MR5

Classroom VR1

Classroom VR2

Figure 4: Planimetries of the most representative monitored classrooms: thermo-hygrometric, indoor air quality, lighting and acoustic sensors' positions.

Table 10b. Monitoring conditions and number of interviewed subjects.

Location	Period	COVID-19 pandemic	Panel cod.	Room cod.	Heating system	Windows	Lighting	Shading system	no. of subjects	Mean age
Bolzano, Italy	November 2019	Before	U1	UR1	ON	Closed	OFF	Up	11	23
			U2		ON	Closed	ON	Up	8	24
			U3		ON	Closed	ON	Up	6	24
			U4		ON	Closed	ON	Up	14	22
			U5		ON	Closed	ON	Up	10	24
			U6		ON	Closed	ON	Up	7	24
			U7		ON	Closed	ON	Up	15	22
			U8		ON	Closed	ON	Up	14	22
	December 2019	Before	U9		ON	Closed	OFF	Up	6	23
			U10		ON	Closed	OFF	Up	12	24
			U11		ON	Closed	ON	Up	8	24
			U12		ON	Closed	ON	Up	12	22
			U13		ON	Closed	ON	Up	9	25
Venice, Italy	December 2019	Before	V1	VR1	ON	Closed	ON	Up	79	21
Rome, Italy	February 2020	Before	M1	MR1	ON	Closed	ON	Down	20	16
			M2	MR2	ON	Closed	ON	Down	17	16
			M3	MR3	ON	Closed	ON	Up	17	17
			M4	MR5	ON	Closed	ON	Down	18	17
			M5	MR4	ON	Closed	ON	Down	14	16
			M6	MR2	ON	Closed	ON	Up	15	16
			M7	MR3	ON	Closed	ON	Down	17	17
			M8	MR1	ON	Closed	ON	Down	18	16
	November 2020	During (no mandatory mask)	M10	MR1	ON	Closed	ON	Down	24	17
			M11	MR5	ON	Closed	ON	Down	21	13
			M12	MR2	ON	Closed	ON	Down	14	18
			M13	MR3	ON	Closed	ON	Down	18	16
			M14	MR4	ON	Open	ON	Down	19	15
			M15	MR2	ON	Closed	ON	Down	15	17
			M16	MR5	ON	Closed	ON	Up	7	16
			M17	MR4	ON	Closed	ON	Up	12	14
			M18	MR3	ON	Closed	ON	Up	18	18
			M19	MR6	ON	Open	OFF	Up	21	14
	February 2021	During (mandatory mask)	M20	MR5	ON	Closed	ON	Up	17	14
			M21	MR4	ON	Closed	ON	Up	18	18
			M22	MR7	ON	Closed	ON	Up	16	16
			M23	MR8	ON	Closed	ON	Down	23	18
			M24	MR9	ON	Closed	OFF	Up	17	17
			M25	MR2	ON	Open	ON	Up	17	18
			M26	MR10	ON	Closed	ON	Up	20	14
			M27	MR11	ON	Open	ON	Down	19	18
			M28	MR3	ON	Closed	ON	Down	19	18
			M29	MR12	ON	Closed	OFF	Down	21	14
			M30	MR13	ON	Closed	OFF	Up	23	14
			M31	MR8	ON	Closed	ON	Up	15	17
			M32	MR8	ON	Closed	ON	Up	13	17
			M33	MR8	ON	Closed	ON	Up	16	16
	May 2021	During (mandatory mask)	M40	MR14	OFF	Open	OFF	Up	20	16
			M41	MR15	OFF	Open	OFF	Up	18	15
			M42	MR16	OFF	Closed	ON	Down	12	17
			M43	MR11	OFF	Open	OFF	Up	22	17
			M44	MR3	OFF	Closed	ON	Down	21	16
			M45	MR6	OFF	Open	OFF	Up	23	15
			M46	MR17	OFF	Open	OFF	Down	15	17
			M47	MR18	OFF	Open	OFF	Up	18	17
Venice, Italy	May 2021	During (mandatory mask)	V2	VR2	OFF	Open	ON	Up	30	21
	Total interviewed subjects								**949**	**18**

Table 11. Mean value of the physical parameters recorded during the experimental campaigns.

	Tair [°C]	Pr [hPa]	RH [%]	va [m/s]	Tmr [°C]	CO_2 [ppm]	Illuminance [lx]	LAeq [dBA]
U1	24,5	978	28,0	0,00	24,0	751	329	61,0
U2	22,4	966	33,1	0,00	22,4	622	421	57,0
U3	23,4	979	31,6	0,00	23,2	680	233	62,2
U4	24,2	983	35,8	0,01	23,8	965	467	61,6
U5	24,4	976	35,7	0,00	24,2	799	370	57,8
U6	22,8	973	36,1	0,02	23,2	544	696	58,5
U7	24,7	975	33,4	0,00	24,5	853	697	60,8
U8	22,5	971	39,0	0,00	22,4	912	433	68
U9	24,3	980	30,2	0,00	24,0	701	314	68
U10	22,6	970	26,4	0,01	22,5	911	19	63,7
U11	22,2	968	19,6	0,00	22,0	754	358	61,8
U12	23,6	985	26,9	0,00	23,5	842	449	57,9
U13	22,2	983	34,7	0,00	22,1	736	368	60,1
M1	22,7	993	39,7	0,00	22,6	1339	488	67
M2	23,4	992	33,7	0,00	23,7	897	983	66,8
M3	24,4	991	35,2	0,00	24,6	1464	767	69
M4	20,4	989	47,8	0,00	20,4	1181	549	63,3
M5	20,5	990	45,8	0,00	20,8	695	849	72,3
M6	23,8	989	42,8	0,01	23,8	1423	459	69,5
M7	21,9	989	45,2	0,00	21,9	1281	482	67,5
M8	23,0	988	43,5	0,00	23,0	1443	348	64
M10	19,6	989	58,2	0,02	20,1	486	548	66
M11	20,0	989	60,7	0,01	20,2	737	517	69,5
M12	19,7	989	61,7	0,00	19,6	685	419	60,4
M13	19,7	988	59,8	0,17	19,9	502	499	74,3
M14	21,0	987	58,4	0,00	20,8	767	476	75,4
M15	19,6	987	67,7	0,00	19,5	885	353	69,7
M16	19,5	987	65,8	0,00	19,5	902	465	64,3
M17	20,2	987	65,6	0,00	20,1	769	522	74,4
M18	19,8	987	66,0	0,01	19,9	691	365	67
M19	20,2	986	65,4	0,03	20,1	804	500	64,7
M20	21,2	982	47,5	0,02	21,7	682	578	66,7
M21	23,0	982	45,7	0,00	22,5	907	529	66,7
M22	20,2	982	53,6	0,01	20,3	976	461	63,3
M23	21,3	983	51,5	0,00	21,0	1154	322	63,2
M24	20,8	982	54,8	0,01	20,7	1081	334	66,2
M25	22,5	981	45,7	0,02	23,0	828	654	70,9
M26	20,9	983	55,7	0,01	20,8	1401	430	62,6
M27	21,1	983	47,8	0,00	21,4	527	501	64,8
M28	22,8	983	45,8	0,01	23,5	579	352	71,5
M29	21,1	983	51,3	0,02	21,3	769	419	61,8
M30	22,0	982	52,6	0,00	21,9	1007	295	63,8
M31	22,5	993	42,3	0,01	22,1	592	692	60,2
M32	20,4	993	42,5	0,00	20,9	411	490	59
M33	21,7	991	42,3	0,00	21,8	479	501	60,3
M40	22,2	980	45,1	0,02	22,6	836	406	65,0
M41	22,5	980	41,0	0,01	22,8	710	67	67,2

M42	22,5	981	40,7	0,00	22,7	764	285	66
M43	23,8	980	33,7	0,04	24,1	565	239	64,7
M44	22,5	978	62,4	0,00	22,4	994	71	75,9
M45	23,3	978	58,3	0,01	23,6	870	360	69,9
M46	22,3	977	60,0	0,02	22,8	551	225	66,2
M47	23,0	977	57,6	0,00	23,2	686	159	65,8
V1	22,5	-	37,8	-	-	-	132	-
V2	23,2	1014	51,8	0,00	23,3	718	515	58,6

4.3 Building Model Simulation and calibration: multi-level multi-step approach

In order to test and illustrate the abovementioned calibration method, a school building has been calibrated and presented in this work as case study. In particular, the focus is on the implementation of the entire calibration method, from the partial model to the entire building, considering only the passive performance. The calibration is conducted on two periods, the first one with unoccupied building, and the second one with the building regularly occupied. Moreover, two levels are considered in the first period, starting from two representative classrooms and extending the calibration to the whole-building. The calibrated parameters have been used in the second period. In order to test their effectiveness, the calibrated models have been validated in other periods with the same characteristics, respectively unoccupied and building with the system off. The calibration procedure considered in my thesis is reported in Figure 5.

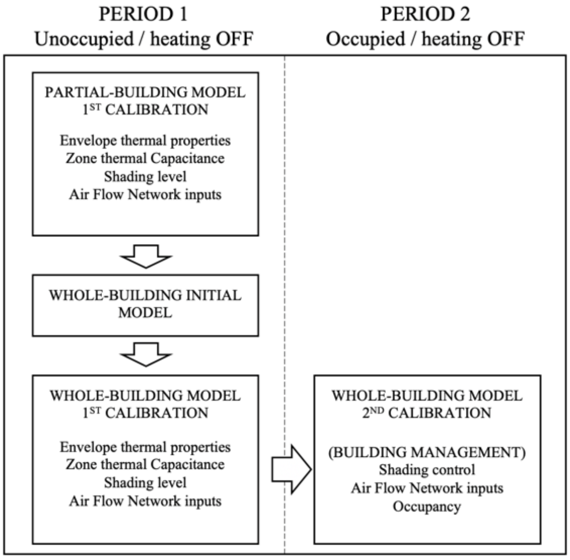


Figure 5: Scheme of the applied calibration procedure: from partial-building to the whole-building calibration. Period 1 (non-occupied building, passive mode) and Period 2 (occupied building, passive mode).

a

b

Figure 6: Case study. a) planimetry and b) entrance façade of the primary school San Benedetto Primary School (Italy).

Monitoring of the case study. The case study selected for testing the proposed method is a primary school located in Schio, a municipality in the North-East of Italy (Fig. 6a-b and 7a-b). The building complex was realized at the beginning of the 1950s and considerably extended by the middle of the 1960s.The building has three stories: the basement and two upper floors, where the classrooms are located. Two overlying classrooms, R1 and R2, located respectively on the first and second floor of the school, have been chosen as the reference rooms (Fig. 7b) and used for testing the first level of the calibration in period 1. For this reason, measuring instruments were located in the reference rooms and in all the adjacent spaces, having different uses: the canteen located in the basement level (B1), two ground floor classrooms (B2 and B3), the library and a classroom located at the first floor (B5 and B6) and the corridors, B4 and B7, located respectively on the ground floor and on the first floor. which comprise. As a result, the indoor air temperature of 9 rooms have been monitored (Fig. 7b). The measurement setup includes data loggers (HOBO® U-12 and U-13) to measure indoor air temperature (accuracy ±0.35°C), relative humidity (accuracy ±2.5%) and supply and return radiator pipe temperatures at small intervals (10 minutes). In the first level of this approach, also explored in Penna et al. (2015a) and Penna et al. (2015b), i.e. the partial-building calibration (or two-zone calibration), the monitored temperatures of the spaces adjacent to the reference rooms are used as boundary conditions for the model of the two reference classrooms. Afterwards, in the second level, the so called whole-building calibration (or multi-zone calibration), all the 9 monitored zones are used as reference in the calibration process. Regarding the outdoor conditions, the weather data file has been implemented through the hourly weather recordings from the weather station of the municipality of Malo (10 km far away from school site) The recordings refer to school year 2013-2014.

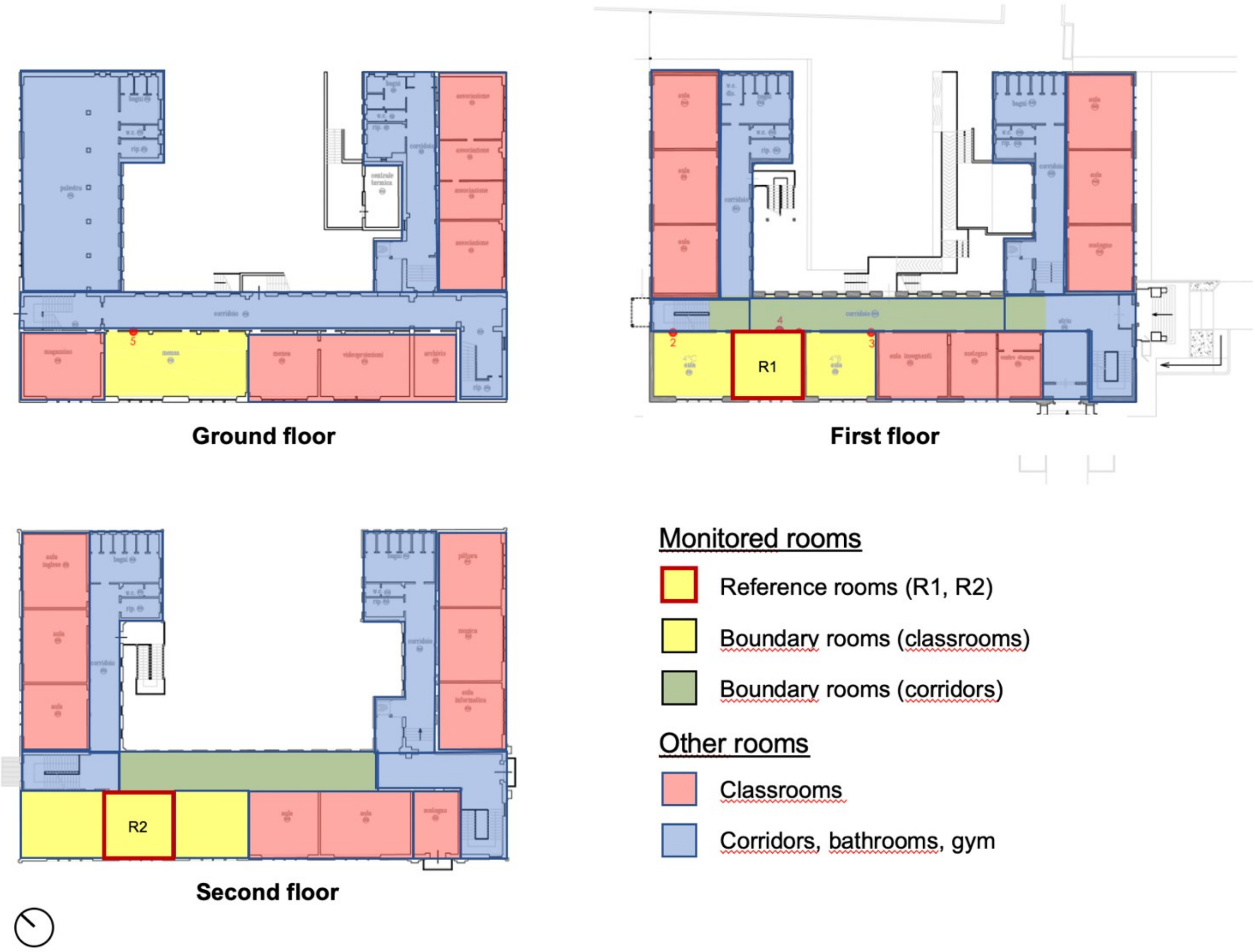


Figure 7a: Planimetries of the building: monitored and boundary rooms and intended uses of other rooms.

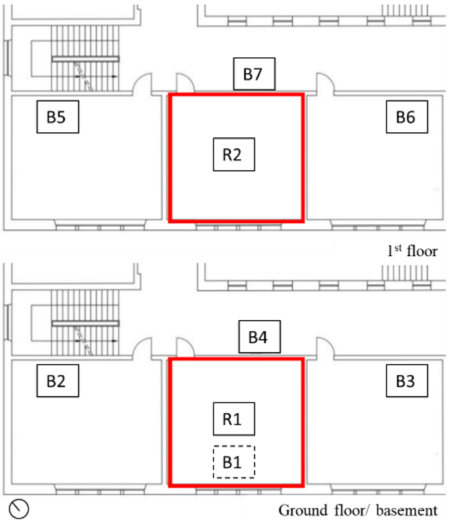


Figure 7b: Sensors inside the 9 monitored rooms. Letters R and B before sensor numbering indicate respectively Reference room and Boundary room.

5. Results

This chapter reports the main outcomes of the application of the methodology presented in Chapter 3. The results are divided into three sections, namely the questionnaire validation (i), the correlation between objective and subjective data (ii) and the multi-level multi-step optimization-based calibration (iii). The results coming from the questionnaire validation are divided into three subsections according to the three selected KPIs, i.e. effectiveness, efficiency and resolution. The outcomes of the correlation between the subjective survey and the objective data are split based on the different type of analysis, namely the single-domain that consists in analyzing the correlation between measured environmental conditions and the subjective response within the same comfort domain, and the multi-domain that aims to explore the combine effects of different comfort domains. The results of each analysis are presented by comfort domains, i.e. thermal environment, indoor air quality, visual and acoustic environment. Regression analysis and descriptive statistics (i.e. box plots) are used for presenting the results. The last paragraph presents the results of the multi-level multi-step optimization-based calibration method applied to two monitoring periods, namely Period 1 (i.e. unoccupied building with system off) and Period 2 (i.e. occupied building with system off). The outcomes include the results of the calibration and the validation of the building model in different periods with the same characteristics of the reference periods.

5.1 Questionnaire evaluation and validation

Establishing the goodness of a questionnaire means evaluating (i) its capability of discriminating different subjective responses under different environmental conditions (effectiveness), (ii) the ability to identify all environmental and contextual factors affecting comfort and the way occupants express it (efficiency) and (iii) the ability of capturing the different level of judgement on each question (resolution). The questionnaire effectiveness can be evaluated by analysing the mean sensation, preference, and comfort votes expressed by different panels of subjects, in relation to the physical parameter deemed to be representative of the environmental conditions in each domain. The questionnaire efficiency can be tested by performing a multilinear regression analysis in which individual sensation votes are predictors and comfort votes are the response variables, thus checking the significance level of the sensation variables. The questionnaire resolution can be investigated by means of a qualitative analysis of the distribution of the votes expressed in the sensation and preference scales, in the four domains. To achieve this aim the questionnaire was administered in a pseudonymized form to students and teachers during several experimental campaigns carried out in three educational buildings located in Bolzano and Rome during the heating season. During the questionnaire administration, ongoing and point-in-time measurements were carried out to investigate the possible correlation between students' responses and the measured physical parameters related to the four environmental aspects, i.e. thermal, visual, acoustic and indoor air quality. For the questionnaire validation the subjective responses collected from 45 panels in two school building were considered. Table 12 reports the number of panels and subjects analyzed.

Table 12. Questionnaire validation: panels and subjects analyzed.

Location	Panels	Subjects
Bolzano	U1-U13	132
Rome	M1-M33	562
Tot	**45**	**694**

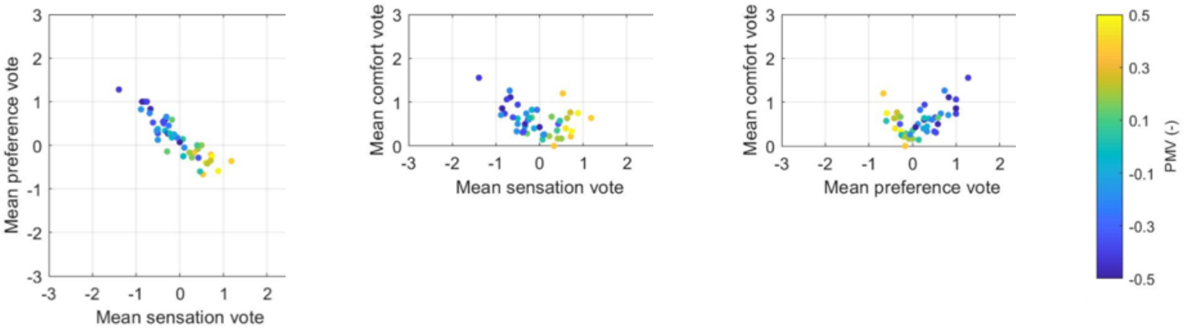
Questionnaire Effectiveness

Figure 8 reports the scatter plots of the mean votes of sensation, preference, comfort for each of the four investigated domains for the 45 panels monitored. Each of the three charts can be interpreted as the 2-dimensional projection of the 3-dimensional plot representing the votes expressed in the sensation/preference/comfort space. The colors of the points relate to the environmental parameter measured during the lecture, that is here considered representative of the investigated domain. For the thermal environment, the environmental conditions were summarized in an equivalent Predicted Mean Vote (PMV) calculated from the mean air temperature, relative humidity, air velocity and mean radiant temperature monitored during the lecture, and considering a uniform clothing level of 0.9 and a metabolic rate of 1.2 met. For the IAQ, visual and acoustic domain, measures of CO_2 concentration, desk illuminance and A-weighted equivalent sound pressure level were used to describe the environmental conditions.

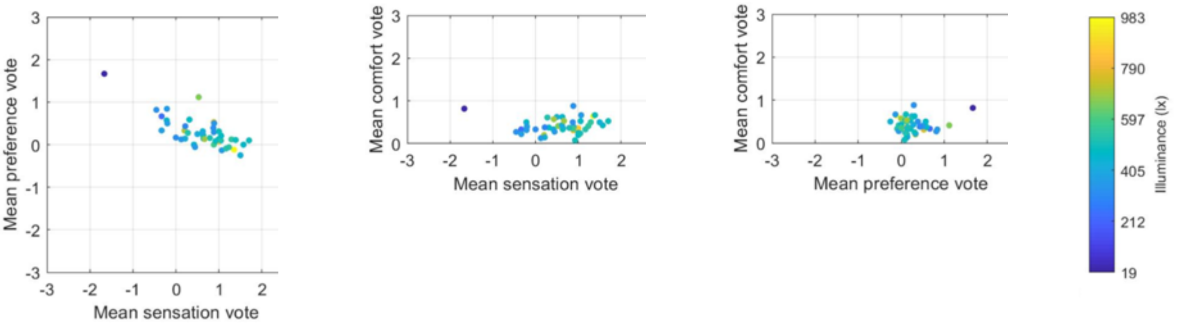
Thermal environment. Figure 8a shows a clear correlation between mean sensation and preference votes, slightly flattened in the 4th quadrant (neutral preference for slightly warm conditions). Most of the mean sensation and mean preference votes concentrate in the [-1; 1] interval; considerations regarding values beyond these limits might suffer from limited availability of data. The preference-comfort diagram shows an almost symmetrical distribution of votes around neutrality. Similar considerations hold for the sensation-comfort scatter plot, thanks to the fairly good linear relation between sensation and preference votes. The PMV computed for each panel, visualized through the color scale, matches well the votes expressed: negative PMV are associated to negative sensation votes and positive preference votes, and vice versa.

Visual environment. In the visual domain, the sensation/preference relation is not diagonal: for positive sensation votes (bright environment), a flattening of the scattered data is observed (bright environment does not imply wanting it darker). This is confirmed in the sensation-comfort plot: all mean sensation votes, ranging [-2; +2] are associated to a comfort vote between "0" (comfortable) and "1" (slightly uncomfortable). The correlation between mean votes and desk illuminance suggests the existence of a threshold beyond which sensation votes are almost invariant to the environmental stimuli.

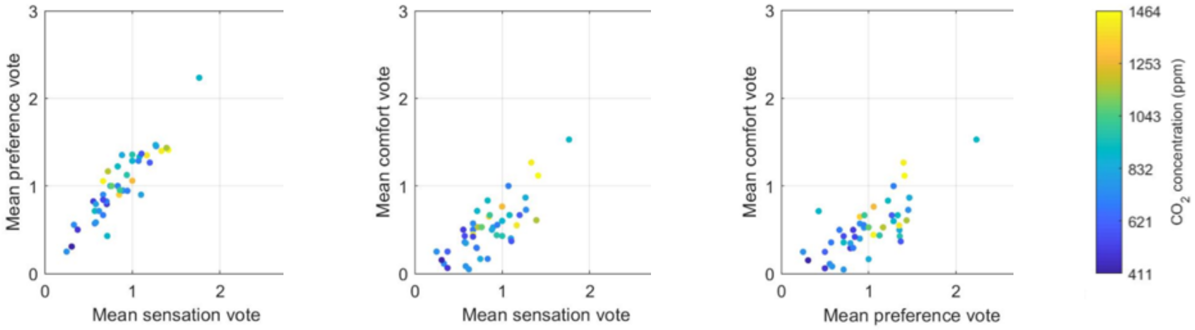
Indoor air quality. The sensation-preference scatter plot displays a clear correlation between the variables. Mean votes extend significantly towards the extremes of the scales compared to other domains, indicating a greater occurrence of high values. The preference-comfort relation has an angular coefficient lower than one, meaning that preference does not have that much hold on the evaluation of comfort: expressing a preference of “1” (slightly fresher preference) does not necessarily have a negative meaning in terms of comfort. The same holds for sensation votes. Correlations with experimental data of CO_2 concentration show that, in general, lower CO_2 concentration identifies comfort conditions, while higher CO_2 concentrations relates to higher discomfort. Anyway, boundaries in this qualitative analysis are much blurred.



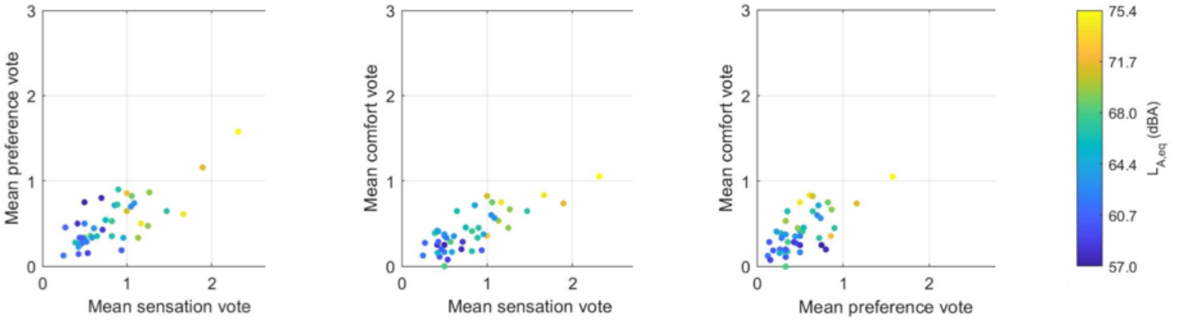
a) Thermal environment



b) Visual environment



c) Indoor air quality



d) Acoustic environment

Figure 8 Scatter plots of mean sensation, preference, and comfort votes of each panel in the four comfort domains: a) thermal, b) visual, c) indoor air quality and d) acoustic environment. The color of the dots matches the relevant experimental conditions collected during the questionnaire administered to the 45 panels.

Acoustic environment. Though the acoustic domain is characterized by the same scales used in the IAQ analysis, the dispersion of sensation-preference mean votes is much larger. The sensation-preference diagram highlights the presence of many points with sensation greater than zero and preference "0" (slightly noisy/noisy environment, but I would not prefer it quieter). This reflects on the sensation-comfort relation; comfort votes tend to vary less than the variation in the sensation votes. Votes correlate well with the sound pressure level measured in the classrooms; the degree of acceptability of quite noisy environment is a feature that will deserve further investigation.

Questionnaire Efficiency

As previously discussed, multiple questions regarding sensation were proposed in this work (Table 12). It is therefore necessary to understand whether all the proposed sensation questions reported are necessary for the evaluation of comfort. The results of the multilinear regression analysis are presented in Table 12.

Sensation questions were formulated using either unipolar or bipolar scales. As a preliminary analysis, the input data for the linear regression were the actual value for unipolar scales and the absolute value of bipolar scales, in the attempt to correlate them to the comfort unipolar scales. Further investigation on the dependencies and relations between the scales will be carried out in future work. As it concerns the thermal environment, the sensation question is significant at the 5 % significance level. In the visual environment, the question labelled S1 is not significant at the 5 % significance level, given the other terms considered in the model. The only significant questions are S2 and S3 (brightness/darkness of the desk and of the whiteboard/blackboard). The estimated coefficient related to the S2 variable is anyway quite low, showing a weak dependence. Both questions regarding IAQ (air freshness and air smelliness) are significant at the 5 % significance level.

Table 12. Regression Analysis of Sensation Votes using Comfort as Response Variable

Environment	Code	Estimate	Standard Error	p-value
Thermal	|S1|	0.505	0.032	2.43e-49
IAQ	S1	0.486	0.028	6.39e-56
	S2	0.174	0.028	5.65e-10
Visual	|S1|	-0.012	0.030	0.695
	|S2|	-0.026	0.021	0.391
	|S3|	0.128	0.030	1.71e-05
Acoustic	S1	0.270	0.036	2.28e-13
	|S2|	0.078	0.038	0.038
	S3	0.298	0.053	3.56e-08
	|S4|	0.061	0.032	0.058

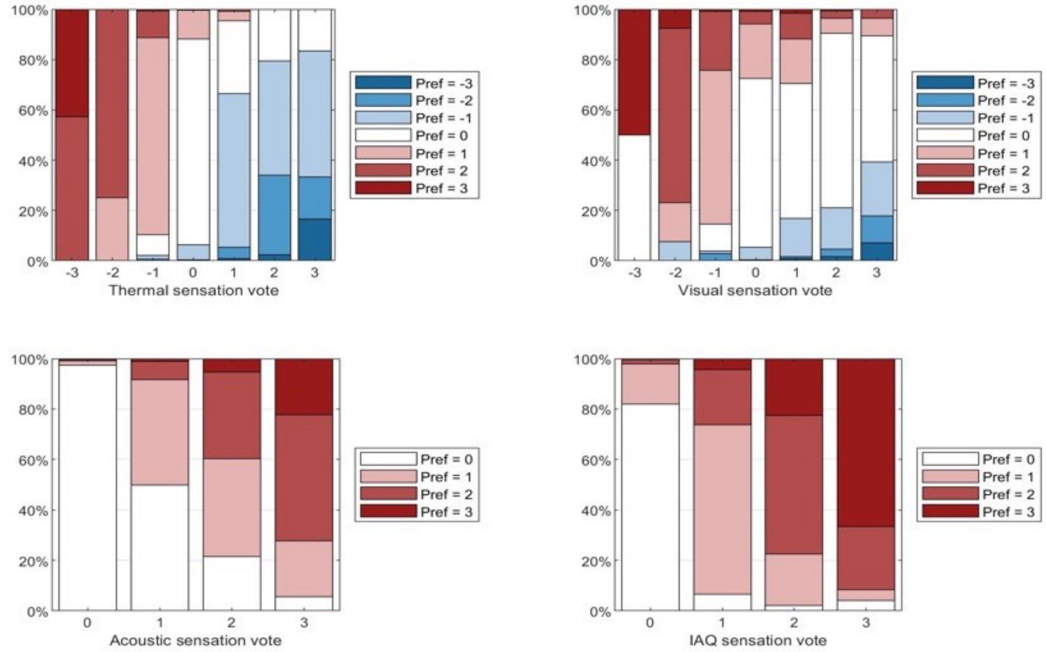


Figure 9 Distribution of preference votes based on the sensation votes in the four comfort domains.

As concerns the acoustic environment, the only question that is not significant at the 5 % significance level is S4 (room reverberation). Moreover, the regression coefficients attributed to S2 (loudness of teacher's voice) has a low value. For those domains in which sensation questions alone are not sufficient to determine comfort conditions, a deeper insight concerning the modelling of comfort votes based on other ordinal and categorical variables is required in the future.

Questionnaire Resolution

The study of the resolution of the scales would allow to understand the relation between the scales, and hypothesize possible transformations. Figure 9 shows the distribution of preference votes that individuals expressed for each of the sensation votes. The thermal environment shows a significant share of neutral preference (no change) votes for higher (+1, +2, +3) sensation votes, while this does not occur for lower (-1,-2,-3) sensation votes. This asymmetrical behaviour was also highlighted in previous analysis on mean sensation and preference votes. In the visual environment, neutral preference (no change) is expressed as the most common vote in all sensation categories, indicating that bright sensation of the visual environment is preferred. The distribution of votes in the unipolar scales, used in the acoustic and air quality environments, is similar. In both charts, there is a clear predominance of "0" preference votes (no change) associated to "0" sensation votes. In the IAQ environment, votes equal to "1" (slightly stuffy) correspond to preference votes centred on "1" (slightly fresher). Similarly, sensation "2" correspond, in the vast majority of the cases, to a preference of "2". In the acoustic environment, a significant shift is found when considering sensation votes of "1" (slightly noisy), that are almost equally split between preference "0" (no change) and "1" (prefer slightly quieter), and sensation equals "2" (noisy), that splits preference votes between "1" and "2". In this analysis, the limited availability of votes at the extremes of the scale should be considered.

Conclusion and further development. This work presents the analysis of an experimental campaign which gathered subjective and objective evaluations on global comfort in classrooms. With the aim of validating the questionnaire developed to investigate the four domains of comfort by evaluating its effectiveness, efficiency and resolution. Some of the most relevant findings are summarized below. The correlation between mean sensation/preference/comfort votes in relation to environmental parameters generally showed a good agreement. For the environments in which this correlation is weaker, future work will be needed to evaluate if this mismatch is due to a problem in the formulation of the questions, or to a difficulty of the occupants to discriminate or evaluate different environmental conditions, as it seems the case with CO_2 concentration and IAQ. The regression analysis on sensation questions to predict comfort showed that not all questions are significant. It will be necessary to assess whether, using alternative analysis techniques or additional inputs, these variables gain significance. Sensation questions will then be reformulated accordingly. The analysis of the distribution of preference votes based on sensation votes is regarded as a preliminary step towards the investigation of the resolution of the scales and their relations. The analysis on single votes confirmed the observations derived from the analysis of mean votes. Non-symmetrical distributions of neutral preference votes were observed in the thermal and in the visual environments. In the IAQ environment, a clear correspondence was found between sensation and preference scales, while in the acoustic domain, the distribution of neutral preference votes encompassed sensation votes related to noisier conditions. Though the four domains were investigated using different scales, the different behaviours highlighted by this analysis demonstrated the ability of the questions to characterize students' perception.

5.2 Correlation between objective and subjective data

The collected data have been analysed to investigate the correlation between the measured environmental characteristics of the monitored classrooms and the subjective response obtained by means of the validated questionnaire. The mean sensation, preference and comfort votes have been compared with the peculiar characteristics of each environmental aspect. To achieve this goal responses and measurements under different exposure conditions in educational buildings have been collected and analysed by means of statistical indices. The final result of this research is the identification of students' preferred environmental conditions (i.e. neutral condition) and the identification of possible influences of environmental conditions on the sensation of a different domain (i.e. thermal sensation vs CO_2 concentration, desk illuminance, sound pressure level).

In the following analysis the subjective responses collected from 52 panels in three school building were considered. Table 13 reports the panels and number of subjects analyzed.

Table 13. Questionnaire validation: panels and subjects analyzed.

Location	Panels	Subjects
Bolzano	U1-U13	132
Venice	V1-V2	109
Rome	M1-M47	711
Tot	**55**	**949**

The data aggregation method led to the constitution of 5 groups for the thermal environment (776 subjects), 4 groups for IAQ (592 subjects), 4 groups the visual environment (773 subjects) and 5 groups (692 subjects) for the acoustic environment.

5.2.1 Single-domain analysis

Thermal Environment. Table 14 reports the environmental conditions (i.e. the mean indoor air temperature) and the subjective mean votes (mean observed votes) along with the number of subjects of each group. In Figures 10a, b and c the mean observed votes (red dots) obtained using the questions about sensation (TSV_{mean}), preference (TPV_{mean}) and comfort (TCV_{mean}) is plotted against the mean value of the indoor air temperature. In the same plot the distribution of all the subjective votes have been also reported by means of boxplots representing the maximum, the minimum, the median and the 1st and 3rd quartiles of the votes. The dependence of the sensation and preference mean votes on the air temperature is represented in the graphs by the linear regression line and its slope. Within the considered range of indoor temperature (20,4-25,5 °C), the mean thermal sensation vote increases linearly with the temperature. Both the mean sensation vote and the preference vote resulted significantly correlated with the indoor air temperature, with the coefficient of determination R^2 respectively equal to 0.91 and 0.83. According to the analysis, the neutral conditions, namely the environmental conditions under which the sensation vote is equal to 0, occur when the indoor temperature is about 22,5 °C.

As it can be seen the TCV_{mean} of the five groups have a quadratic correlation with the temperature, with the higher discomfort level (TCV_{mean} = 0,7) around 20,5°C.

Table 14. Thermal Environment: environmental conditions and subjective mean votes of the groups

Group	Subjects	Tair [°C]	TSV_{mean}	TPV_{mean}	TCV_{mean}
T1	248	20,4	-0,5	0,5	0,7
T2	237	22,3	-0,2	0,4	0,6
T3	183	23,0	0,2	-0,1	0,4
T4	57	24,0	0,4	-0,4	0,5
T5	53	25,5	0,8	-0,4	0,5

Indoor Air Quality. Table 15 reports the mean CO_2 level, the subjective mean votes along with the number of subjects of each group related to the Indoor Air Quality. The mean observed votes obtained using the IAQ perceptual questions about sensation ($IAQSV_{mean}$), preference ($IAQPV_{mean}$) and comfort ($IAQCV_{mean}$), along with those gathered with the question related to the odour perception. i.e. IAQ $(odour)_{mean}$, have been correlated with the mean value of the CO_2 level of each group (Figures 11a, b and c). The x axis reports the mean value of CO_2 level while the y axis reports the average votes expressed by sensation (from 0 = fresh air to 3 = very stuffy), preference (from 0 = no change to 3 = much fresher), odour perception (form 0 = absent to 3 = intense) and comfort scales (from 0 = comfortable to 3 = very uncomfortable). Even though all the coefficients of determination range between 0.70 and 0.79, the sensitivity is quite low, highlighting that the CO_2 level is not a good indicator for the subjective sensation about air quality and the correlation with some other IAQ parameters should be analyzed. In details, with the increasing of the CO_2 content the mean votes get close to 1 which means the sensation of slightly stuffy air, the preference of slightly fresher air, the perception of “weak” odour and “slightly uncomfortable” in case of comfort vote. Moreover, when the CO_2 is equal to 500 ppm the IAQ sensation vote is equal to 0,6. It would mean that the neutral conditions, with the sensation vote tending to 0, correspond to CO_2 much lower than 500 ppm.

Table 15. Indoor Air Quality: environmental conditions and subjective mean votes of the groups

Group	Subjects	CO_2 [ppm]	$IAQSV_{mean}$	$IAQPV_{mean}$	$IAQ(odour)_{mean}$	$IAQCV_{mean}$
IAQ1	142	500	0,6	0,7	0,6	0,3
IAQ2	269	800	0,9	1,1	0,6	0,6
IAQ3	109	1100	0,9	1,1	0,9	0,5
IAQ4	72	1400	1,1	1,2	0,9	0,8

Visual Environment. Table 16 reports the illuminance level, the subjective mean votes and the number of subjects of each group related to the visual environment. The mean observed vote obtained through the questions about sensation (VSV_{mean}, VSV-$desk_{mean}$ and VSV-$blackboard_{mean}$), preference (VPV_{mean}) and comfort (VCV_{mean}) have been correlated with the mean value of the illuminance level of each group (Figures 12a, b and c). The x axis reports the mean value of illuminance while the y axis reports the votes expressed by sensation (from -3 = very dark to 3 = very bright), preference (from – 3 = much brighter to 3 = much darker, 0 = no change) and comfort scales (from 0 = comfortable to 3 = very uncomfortable). Contrary to the thermal and IAQ aspects, in this case the visual sensation, preference and comfort votes do not have a linear dependency on the main environmental parameter, i.e. illuminance. With the increasing of the illuminance level from 20 lx to 300 lx the mean sensation vote increases as well, but, after that threshold and reaching the 500 lx, the sensation seem to be less correlated to the increasing of the illuminance, because the sensation does not change much between 300 lx and 500 lx. The preference is much more explanatory: in average people do not want to change when they are exposed from 300 lx still 500 lx. In summary, according to the analysis, the neutral conditions, namely the environmental conditions under which the sensation vote is equal to 0, occur when the illuminance is 300 lx, according to the sensation vote. Preference indeed is stably around 0 change from 150 to 500 lx while looking at comfort it can be seen that the higher discomfort level ($0,8 < VCV_{mean} < 0,6$) corresponds to an illuminance level ranging between 20 and 150 lx.

Table 16. Visual Environment: environmental conditions and subjective mean votes of the groups

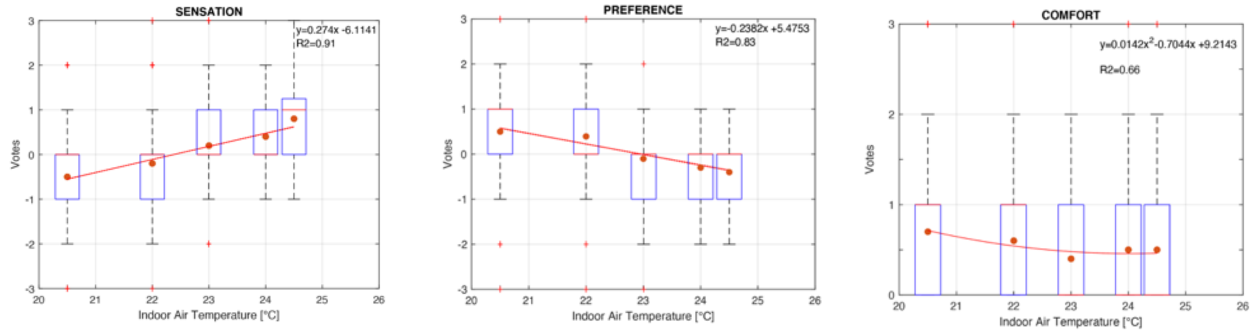
Group	Subjects	Illuminance [lx]	VSV_{mean}	VPV_{mean}	$VSV(desk)_{mean}$	$VSV(backboard)_{mean}$	VCV_{mean}
V1	12	20	-1,7	1,7	1,2	-1,0	0,8
V2	157	150	0,1	0,3	-0,3	-0,3	0,6
V3	125	300	0,6	0,3	0,2	0,2	0,4
V4	439	500	1,0	0,2	0,4	0,4	0,4

Acoustic Environment. Table 17 reports the A-weighted equivalent sound pressure level, L_{Aeq}, the subjective mean votes and the number of subjects of each group related to the acoustic environment. The mean observed vote obtained using the three acoustic perceptual questions about sensation (ASV_{mean}, ASV- $voice_{mean}$, ASV- voice $clarity_{mean}$), preference (APV_{mean}) and comfort (ACV_{mean}) has been compared with the mean value of the L_{Aeq} of each group. Figures 13a, b and c show the correlation. The x axis reports the mean value of L_{Aeq} while the y axis reports the votes expressed by sensation (from 0 = quiet to 3 = very noisy), sensation of the teacher's voice (from -3 = too soft to 3 = too loud), voice clarity (from 0 = clear to 3 = very unclear), preference (from 0 = no change to 3 = very quieter) and comfort scales (from 0 = comfortable to 3 = very uncomfortable). While in case of the sensation related to the teacher's voice and the voice clarity the correlation is very weak, sensation, preference and comfort show a linear correlation with the L_{Aeq} with the coefficient of determination R^2 respectively 0.93, 0.92 and 0.88. Within the considered range of L_{Aeq} (61-75 dB(A)), the mean acoustic sensation vote increases linearly with the L_{Aeq}. The lower sensation votes ($ASV_{mean} = 0,5$) is for 61 dB(A) highlighting that the acoustic neutral condition ($ASV_{mean} = 0$) corresponds to a $L_{Aeq\ lower}$ than this threshold. Looking at the preference it can be notice that between 66 and 70 dB(A) the mean preference votes does not noticeably vary ($0,5 < APV_{mean} < 0,7$), while in correspondence of 75 dB(A) the preference is equal to 1 = slightly quieter. The same occurs to the mean comfort vote that reach the value of 1 = slightly in discomfort under the same indoor conditions.

Table 17. **Acoustic Environment: environmental conditions and subjective mean votes of the groups**

Group	Subjects	L_{Aeq} [dBA]	$\mathrm{ASV_{mean}}$	$\mathrm{APV_{mean}}$	$\mathrm{ASV(voice)_{mean}}$	$\mathrm{A(clarity)_{mean}}$	$\mathrm{ACV_{mean}}$
A1	273	61	0,5	0,4	0,2	0,1	0,3
A2	190	66	0,9	0,5	0,0	0,3	0,4
A3	37	68	0,7	0,4	0,1	0,0	0,3
A4	122	70	1,2	0,7	0,1	0,3	0,6
A5	70	75	1,7	1,0	-0,1	0,5	0,9

Thermal Environment



(-3) = cold; (-2) = cool; (-1) = slightly cool; 0 = nor cold/warm; 1 = slightly warm; 2 = warm; 3 = hot

a.

(-3) = much cooler (-2) = cooler; (-1) = slightly cooler; 0 = no change; 1 = slightly warmer; 2 = warmer; 3 = much warmer

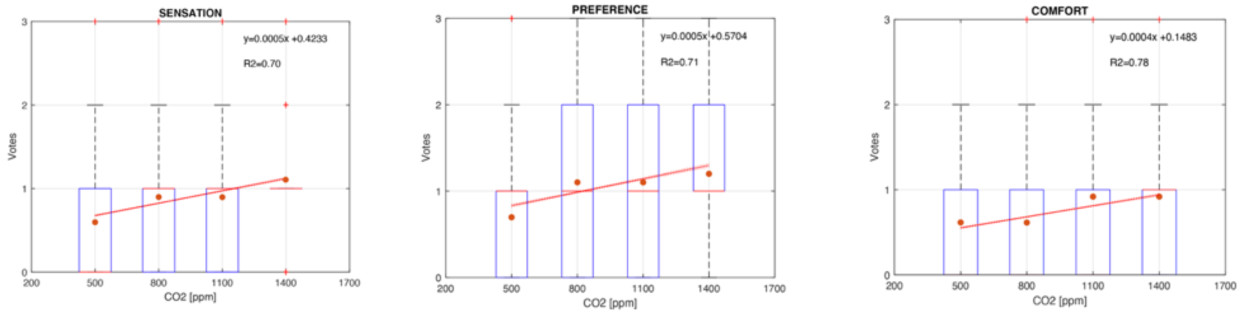
b.

0 = comfortable; 1 = slightly uncomfortable; 2 = uncomfortable; 3 = very uncomfortable

c.

Figure 10. Correlation between the mean thermal sensation (a), preference (b) and comfort (c) votes with the indoor air temperature.

Indoor Air Quality



0 = fresh; 1 = slightly stuffy; 2= stuffy; 3= very stuffy

a.

0 = no change; 1 = fresher stuffy; 2= fresher; 3= very fresher

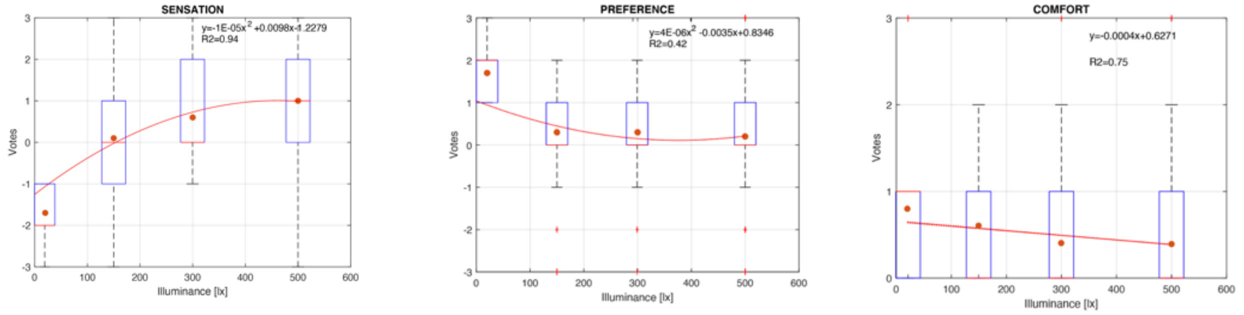
b.

0 = comfortable; 1 = slightly uncomfortable; 2 = uncomfortable; 3 = very uncomfortable

c.

Figure 11. Correlation between the mean thermal sensation (a), preference (b) and comfort (c) votes with the CO_2 level.

Visual Environment



(-3) = very dark; (-2) = dark; (-1) = slightly dark; 0 = nor dark/bright; 1 = slightly bright; 2 = bright; 3 = very bright

a.

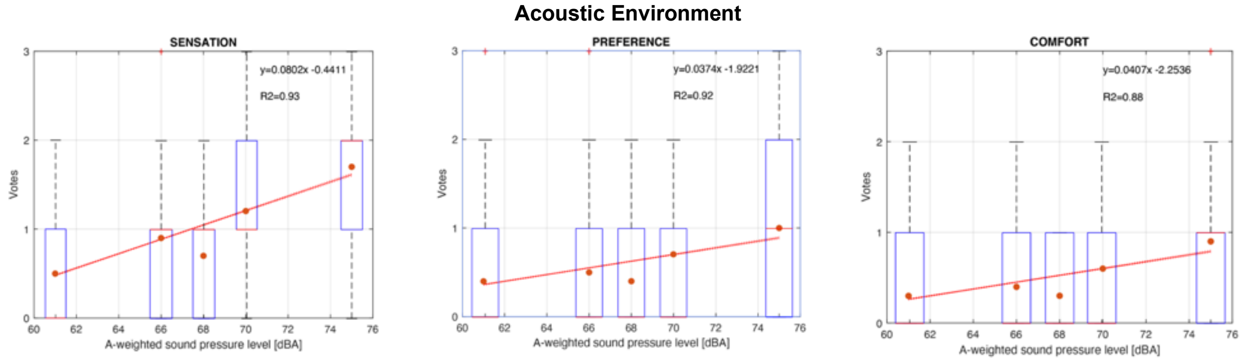
(-3) = much dark; (-2) = darker; (-1) = slightly darker; 0 = no change; 1 = slightly brighter; 2 = brighter; 3 = much brighter

b.

0 = comfortable; 1 = slightly uncomfortable; 2 = uncomfortable; 3 = very uncomfortable

c.

Figure 12. Correlation between the mean thermal sensation (a), preference (b) and comfort (c) votes with the illuminance level.



0 = quiet; 1 = slightly noisy; 2= noisy; 3= very noisy

0 = no change; 1 = slightly quieter; 2= quieter; 3= very quieter

0 = comfortable; 1 = slightly uncomfortable; 2 = uncomfortable; 3 = very uncomfortable

a. b. c.

Figure 13. Correlation between the mean thermal sensation (a), preference (b) and comfort (c) votes with the A-weighted sound pressure level.

5.2.2 Multi-domain analysis

To explore the possible cross effects between different comfort domains, the groups formed with the data aggregation have been analysed also using a multi-domain approach. Firstly, I have investigated if the main physical parameter of each domain has an effect also on the subjective responses related to another domain. Secondly, it has been investigated if the sensation vote expressed for a comfort area by the same homogeneous group of students is influenced also by the physical parameters related to the other domains (objective approach).

Multi-domain analysis: subjective approach

The main findings of the subjective multi-domain analysis are divided according to the four different comfort domains and reported in Figures 14-17 and Tables 18-21.

Thermal Environment. The results regarding the thermal environment are reported in Figures 14a, b and c and table 18. The sensation votes and the mean sensation votes for the IAQ, visual and acoustic environment expressed by the thermal groups are plotted against the mean value of the indoor air temperature related to the thermal groups. Those graphs allow to inspect if the temperature may affect students' sensation in other domains. In the boxplots in each box, the red dot is the mean sensation vote, the central mark is the median, the box limits denote 25th and 75th percentiles, and the whiskers are the minimum and maximum sensation votes.

Figure 14a shows the boxplot of IAQSV at each condition of temperature and the linear regression curve obtained considering the $IAQSV_{mean}$. Looking at the extreme values of the temperature, respectively 20.5 and 24.5 °C, both from the boxplots and from the linear regression line it can be noticed that cooler air temperature is perceived as fresher ($IAQSV_{mean}$ = 0.8), while warmer air is perceived stuffier ($IAQSV_{mean}$ = 1.3). However, within the temperature range between 22.0 and 24.0 °C there is no appreciable variation on the IAQ sensation votes. Considering a linear regression between data, the coefficient of determination is 0.73, and the slope is such that the neutral condition, namely the environmental condition under which the IAQ sensation vote is equal to 0 = fresh air, would occur when the indoor temperature is much lower than 20.5 °C.

Figure 14b shows the boxplot of VSV at each condition of temperature and the linear regression curve obtained considering the VSV_{mean}. The graph in figure 14b shows the variation of the VSV_{mean} on the temperature increasing: it is possible to see a decreasing trend of the vote with the temperature, but both the boxplots and the slope of the linear regression does not highlight a clear correlation between the visual sensation votes and the air temperature. Indeed, even if the VSV_{mean} at the extreme values of the temperature (20.5 - 24.5 °C) are respectively equal to 1 = slightly bright and almost equal to 0 (neither bright nor dark), within the temperature range 22.0-24.5 °C the medians are the same showing that the visual sensation votes may not be sensitive to the variation of the air temperature. According to the analysis, the neutral conditions (VSV_{mean} equal to 0 = neither bright nor dark, may occur when the indoor temperature is almost 25 °C.

Figure 14c shows the boxplot of ASV_{mean} at each condition of temperature and the linear regression curve obtained considering the ASV_{mean}. The boxplots show that the distribution of the acoustic sensation votes is the same at each value of indoor temperature, with a median equal to 1 = slightly noisy. Considering a linear regression between data, it is possible to see a decreasing trend of the votes as the temperature increases with a linear correlation coefficient R^2 equal to 0.75. However, the slope of the regression line is almost null, so the effect of temperature on the acoustic sensation seems to be negligible.

Table 18. Thermal Environment: environmental conditions, thermal sensation votes and sensation mean votes for the other comfort domains, i.e. IAQ, visual and acoustic environment

Group	Subjects	Tair [°C]	TSV_{mean}	$IAQSV_{mean}$	VSV_{mean}	ASV_{mean}
T1	248	20,4	-0,5	0,8	1,0	1,0
T2	237	22,3	-0,2	0,9	0,3	1,0
T3	183	23,0	0,2	0,9	0,6	0,9
T4	57	24,0	0,4	1,0	0,5	0,8
T5	53	25,5	0,8	1,3	0,2	0,7

Indoor Air Quality. The results regarding the indoor air quality are reported in Figures 15a, b and c and table 19. The sensation votes and the mean sensation votes for the thermal, visual and acoustic environment expressed by the IAQ groups are plotted against the mean value of the CO_2 concentration related to the IAQ groups. Those graphs allow to inspect if the CO_2 concentration may affect students' sensation in other domains. In the boxplots in each box, the dot is the mean sensation vote, the central mark is the median, the box limits denote 25th and 75th percentiles, and the whiskers are the minimum and maximum sensation votes.

Figure 15a shows the boxplot of TSV at each condition of CO_2 and the linear regression curve obtained considering the TSV_{mean}. The boxplots show that the thermal sensation votes have the same distribution for CO_2 equal to 500, 800 and 1100 ppm, while the distribution is different in correspondence of 1400 ppm. Looking at the linear regression of the TSV_{mean} over the CO_2, it is possible to see an increasing trend of the vote as the CO_2 increases with a linear correlation coefficient R^2 equal to 0.75, but the slope of the regression line is almost null. The same occurs in case of the visual and acoustic sensation votes (figures 15b and c) so the effect of CO_2 on the thermal, visual and acoustic sensation seems to be negligible.

Table 19. Indoor Air Quality: environmental conditions, IAQ sensation votes and sensation mean votes for the other comfort domains, i.e. thermal, visual and acoustic environment

Group	Subjects	CO_2 [ppm]	$IAQSV_{mean}$	TSV_{mean}	VSV_{mean}	ASV_{mean}
IAQ1	142	500	0,6	-0,2	0,9	0,8
IAQ2	269	800	0,9	-0,1	0,7	1,0
IAQ3	109	1100	0,9	-0,1	0,5	0,7
IAQ4	72	1400	1,1	0,1	1,2	1,0

Visual Environment. The results regarding the visual environment are reported in Figures 16a, b and c and table 20. The sensation votes and the mean sensation votes for the thermal, IAQ and acoustic environment expressed by the visual groups are plotted against the mean value of the illuminance related to the visual groups. Those graphs allow to inspect if the illuminance level may affect students' sensation in other domains. In the boxplots in each box, the dot is the mean sensation vote, the central mark is the median, the box limits denote 25th and 75th percentiles, and the whiskers are the minimum and maximum sensation votes.

Figure 16a shows the boxplot of TSV for each illuminance level and the linear regression curve of the TSV_{mean}. The boxplots show that the thermal sensation votes have the same distribution for illuminance equal to 150, 300 and 500 lx, except for illuminance level equal to 20 lx. The linear regression curve shows that the TSV_{mean} is near 0 (i.e. neither hot nor cold) at each illuminance bins, i.e. 20, 150, 300, 500 lx, showing that the effect of the illuminance level does not have any influence on the thermal sensation expressed by those groups of students.

Figure 16b shows the boxplot of IAQSV for each illuminance level and the linear regression curve of the $IAQSV_{mean}$. Looking at the extreme values of illuminance, respectively 20 and 500 lx, both from the boxplots and from the linear regression line it can be noticed that a darker room is perceived as slightly stuffy

($IAQSV_{mean}$ = 1,1), while a brighter environment is perceived as fresher ($IAQSV_{mean}$ = 0,8). According to the analysis, the linear correlation coefficient R^2 is equal to 0.96 and the neutral condition, namely the environmental condition under which the IAQ sensation vote is equal to 0 = fresh air, may occur for illuminance level much higher than 500 lx. Although this, the slope is almost equal to zero.

Figure 16c shows the boxplot of ASV for each illuminance level and the linear regression curve of the ASV_{mean}. Looking at the boxplots it can be noticed that for illuminance equal to 20 lx the acoustic sensation votes are between 0, i.e. quiet, and 1, i.e. slightly noisy with the median at zero, for illuminance equal to 150 lx the acoustic sensation votes are between i.e. 1 and 2 noisy with the median at 1 and the extreme values at 0 and 3 = very noisy, finally both for illuminance the acoustic sensation votes are between 0 and 1, with the median value at 1 and maximum value at 2. According to the results of the linear regression it is not possible to highlight a correlation between the $ASV_{mean\ with}$ and the variation of the illuminance level.

Table 20. Visual Environment: environmental conditions, visual sensation votes and sensation mean votes for the other comfort domains, i.e. thermal, IAQ and acoustic environment

Group	Subjects	Illuminance [lx]	$IAQSV_{mean}$	TSV_{mean}	$IAQSV_{mean}$	ASV_{mean}
V1	12	20	0,6	0,1	1,1	0,4
V2	157	150	0,9	0,0	1,1	1,2
V3	125	300	0,9	-0,3	0,9	0,7
V4	439	500	1,1	-0,2	0,8	0,9

Acoustic Environment. The results regarding the acoustic environment are reported in Figures 17a, b and c and table 21. The sensation votes and the mean sensation votes for the thermal, visual and acoustic environment expressed by the acoustic groups are plotted against the mean value of the A-weighted sound pressure level related to the acoustic groups (L_{Aeq}). Those graphs allow to inspect if the L_{Aeq} may affect students' sensation in other domains. In the boxplots in each box, the dot is the mean sensation vote, the central mark is the median, the box limits denote 25th and 75th percentiles, and the whiskers are the minimum and maximum sensation votes.

Figure 17a shows the boxplot of TSV_{mean} against the A-weighted sound pressure level and the TSV_{mean} to the A-weighted sound pressure level linear relationship. Even if the distribution of thermal sensation votes vary at each value of L_{Aeq}, the linear regression does not detect a significant relationship between the TSV_{mean} and the variation of A-weighted sound pressure level.

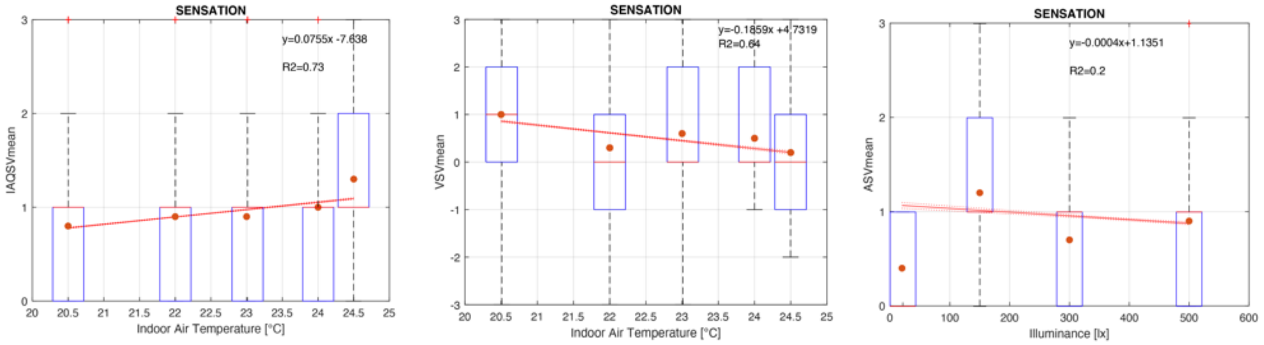
Figure 17b shows the boxplot of $IAQSV_{mean}$ against the A-weighted sound pressure level and the $IAQSV_{mean}$ to the A-weighted sound pressure level linear relationship. Looking the boxplots, it can be seen that the distribution of the IAQ sensation votes are the same at each value of A-weighted sound pressure level, highlighting that the effect of this physical parameters on the IAQ sensation is negligible. This result is confirmed also by the linear regression.

Figure 17c shows the boxplot of VSV_{mean} against the A-weighted sound pressure level and the VSV_{mean} to the A-weighted sound pressure level linear relationship. According to the graph there is an increasing trend of the vote with the A-weighted sound pressure level. In details, looking the extreme values it is possible to see that in correspondence of 61 dBA the visual sensation vote is near zero, i.e. neither dark nor bright, while for L_{Aeq} almost equal to 1, i.e. slightly bright.

Table 21. Acoustic Environment: environmental conditions, acoustic sensation votes and sensation mean votes for the other comfort domains, i.e. thermal, IAQ and visual environment

Group	Subjects	L_{Aeq} [dBA]	ASV_{mean}	TSV_{mean}	$IAQSV_{mean}$	VSV_{mean}
A1	273	61	0,5	0,0	0,8	0,4
A2	190	66	0,9	-0,2	0,8	0,8
A3	37	68	0,7	0,0	0,8	0,2
A4	122	70	1,2	0,0	1,0	1,1
A5	70	75	1,7	-0,4	0,8	0,9

Thermal Environment



0 = fresh; 1 = slightly stuffy; 2= stuffy; 3= very stuffy

a.

(-3) = very dark; (-2) = dark; (-1) = slightly dark; 0 = nor dark/bright; 1 = slightly bright; 2 = bright; 3 = very bright

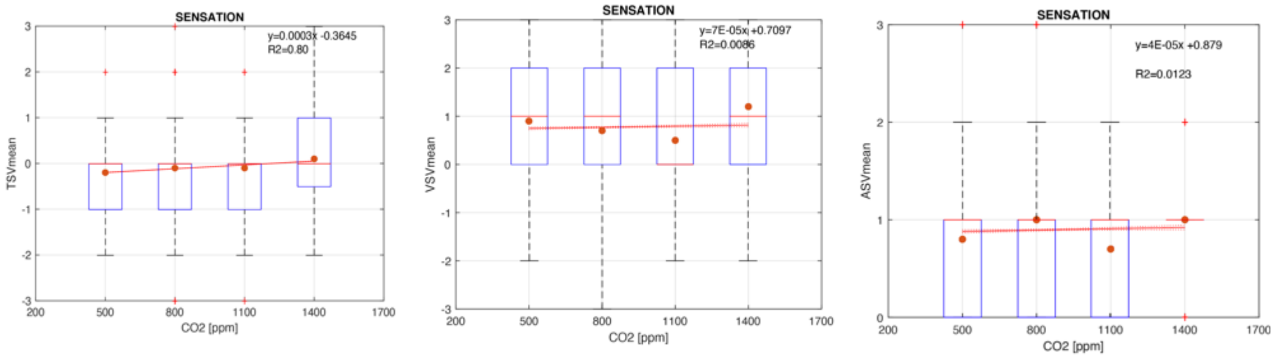
b.

0 = quiet; 1 = slightly noisy; 2= noisy; 3= very noisy

c.

Figure 14. Correlation between IAQSV$_{mean}$ (a), VSV$_{mean}$ (b) and ASV$_{mean}$ (c) votes with the indoor air temperature.

Indoor Air Quality



(-3) = cold; (-2) = cool; (-1) = slightly cool; 0 = nor cold/warm; 1 = slightly warm; 2 = warm; 3 = hot

a.

(-3) = very dark; (-2) = dark; (-1) = slightly dark; 0 = nor dark/bright; 1 = slightly bright; 2 = bright; 3 = very bright

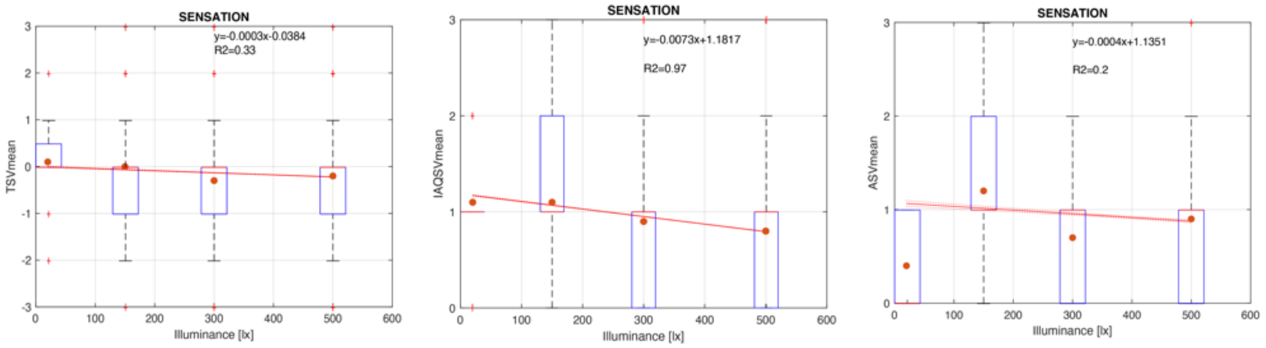
b.

0 = quiet; 1 = slightly noisy; 2= noisy; 3= very noisy

c.

Figure 15. Correlation between TSV$_{mean}$ (a), VSV$_{mean}$ (b) and ASV$_{mean}$ (c) votes with the CO_2 level.

Visual Environment



(-3) = cold; (-2) = cool; (-1) = slightly cool; 0 = nor cold/warm; 1 = slightly warm; 2 = warm; 3 = hot

a.

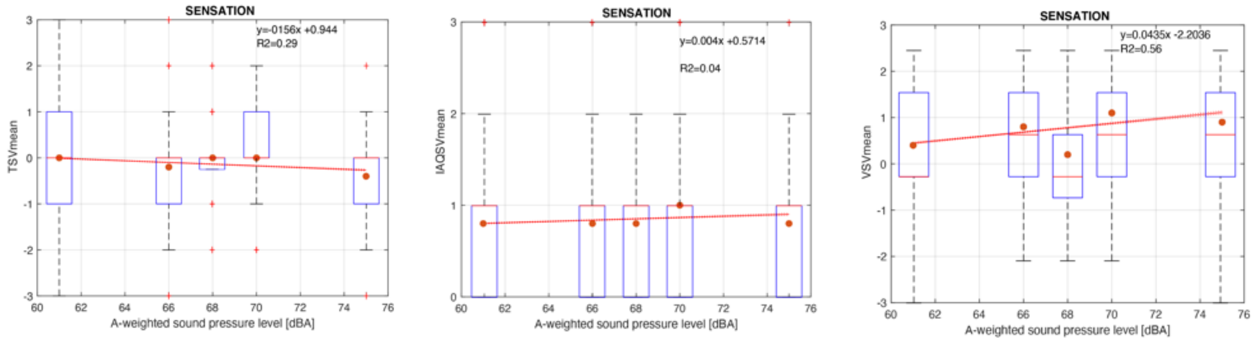
0 = fresh; 1 = slightly stuffy; 2= stuffy; 3= very stuffy

b.

0 = quiet; 1 = slightly noisy; 2= noisy; 3= very noisy

c.

Figure 16. Correlation between TSV$_{mean}$ (a), IAQSV$_{mean}$ (b) and ASV$_{mean}$ (c) votes with the illuminance level.



Acoustic Environment

(-3) = cold; (-2) = cool; (-1) = slightly cool; 0 = nor cold/warm; 1 = slightly warm; 2 = warm; 3 = hot

a.

0 = fresh; 1 = slightly stuffy; 2= stuffy; 3= very stuffy

b.

(-3) = very dark; (-2) = dark; (-1) = slightly dark; 0 = nor dark/bright; 1 = slightly bright; 2 = bright; 3 = very bright

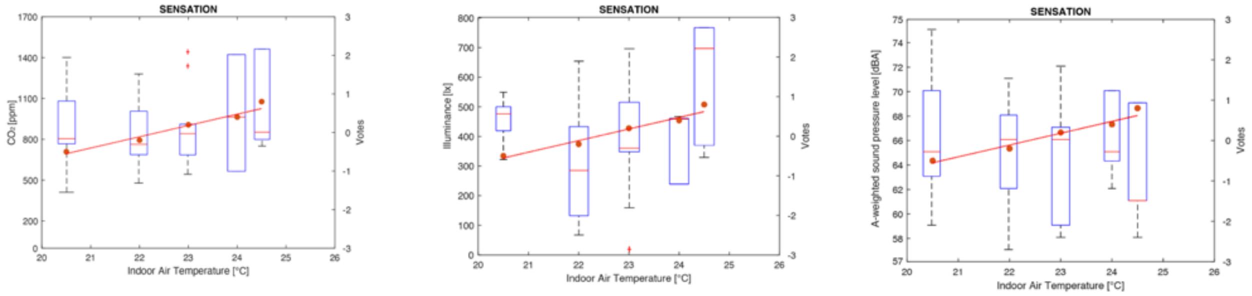
c.

Figure 17. Correlation between TSV_{mean} (a), $IAQSV_{mean}$ (b) and VSV_{mean} (c) votes with the A-weighted sound pressure level.

Multi-domain analysis: objective approach

The main findings of the objective multi-domain analysis are divided according to the four different comfort domains and reported in Figures 18-21 and tables 23-26.

Thermal Environment. The sensation votes expressed for the thermal environment are reported in Figures 18a, b and c. The TSV_{mean} given for each temperature bin (red dots) are plotted together with the distribution of the other physical parameters, i.e. CO_2 level (figure 18a), illuminance level (figure 18b) and A-weighted sound pressure level (figure 18c), by means of boxplots. Those graphs allow to inspect if these physical parameters may have an effect on students' thermal sensation. In the boxplots in each box, the red mark is the median, the box limits denote 25th and 75th percentiles, and the whiskers are the minimum and maximum values of the measured physical parameter.



Thermal Environment

(-3) = cold; (-2) = cool; (-1) = slightly cool; 0 = nor cold/warm; 1 = slightly warm; 2 = warm; 3 = hot

a. b. c.

Figure 18. Distribution of CO_2 level (a), illuminance level (b) and A-weighted sound pressure level (c) with TSV_{mean}.

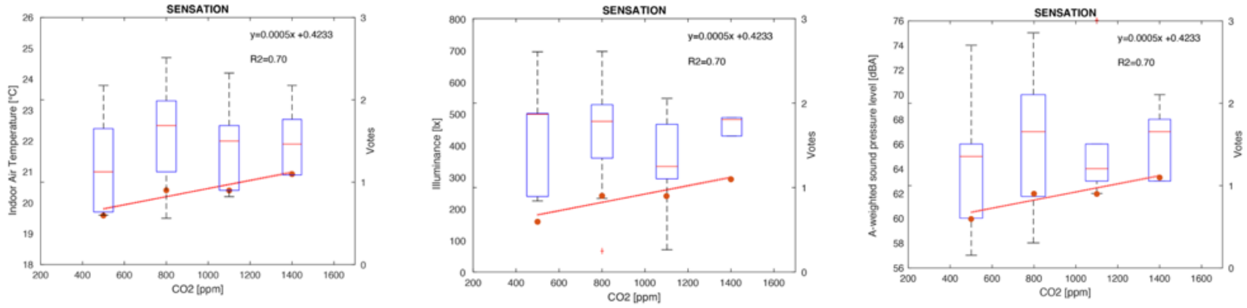
In Figure 18a the boxplots highlight a different distribution of the CO_2 in correspondence of each temperature bins. In details, even if the medians undergo a weak variation, looking at the minimum values (lower whiskers) it can be noticed that they increase as the temperature raises, and so the TSV_{mean} does. Moreover, the upper quartile of the boxplots referring to the last two temperature bins (24 and 24.5 °C) reach the highest value of CO_2 (about 1400 ppm), while the 75th percentiles regarding the other temperature bins lie between approximately 950 and 1100 ppm. This suggests that there is a positive correlation between the CO_2 level and the thermal sensation votes, so this parameter has an effect on the thermal subjective responses given by the groups.

Figure 18b reports the distribution of illuminance level in relation to the different temperature bins. Also in this case, the boxplots show different distribution of the parameter in relation to the increase of the temperature. Notably, if we consider the illuminance distribution related to the bins 22, 23 and 24.5 °C it can be seen that there is a gradual shift upwards highlighting a positive relation between the illuminance level and the thermal sensation votes. In other words, also the illuminance level probably had an effect on the thermal subjective responses given by the groups.

Figure 18c reports the distribution of the A-weighted sound pressure level (L_{Aeq}) in relation to the different temperature bins. The boxplots show different distribution of the A-weighted sound pressure level in relation to the different temperature bins. Despite this, except in the case of the higher temperature bin (24.5 °C), the medians undergo a week variation and it is not possible to highlight a strong relation between the L_{Aeq} and the temperature increase, so this parameter seems to do not have an impact on TSV_{mean}.

Indoor Air Quality. The results regarding the indoor air quality are reported in Figures 19a, b and c. The $IAQSV_{mean}$ related to each CO_2 bins (red dots) are plotted with the distribution of the other physical parameters, i.e. indoor air temperature, illuminance level and A-weighted sound pressure level, by means of boxplots. Those graphs allow to inspect if these physical parameters may have an affect students' sensation about the indoor air quality. In the boxplots in each box, the red mark is the median, the box limits denote 25th and 75th percentiles, and the whiskers are the minimum and maximum values of the measured physical parameter.

Indoor Air Quality



0 = fresh; 1 = slightly stuffy; 2= stuffy; 3= very stuffy

a. b. c.

Figure 19. Distribution of indoor air temperature (a), illuminance level (b) and A-weighted sound pressure level (c) with $IAQSV_{mean}$.

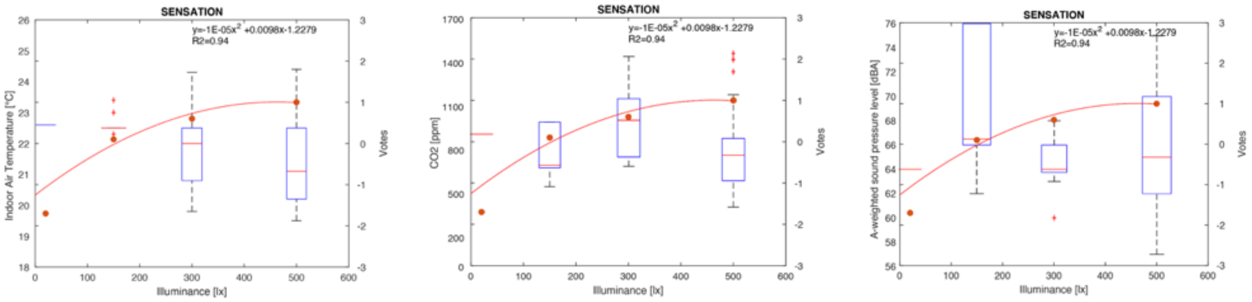
Figure 19a reports the distribution of the indoor air temperature in relation to the different CO_2 bins. The boxplots highlight a different distribution of the temperature in correspondence of each CO_2 bins. In details, looking at the medians, it can be seen an increment from the first bin (500 ppm) and the second bin (800 ppm) and a decrease between 1100 and 1400 ppm. Focusing on the boxplots referring to the 500, 800 and 1100 ppm it can be noticed that the $IAQSV_{mean}$ seems to vary in the same way of the median values of temperature, namely an increase from the first and second bin and weak decrease from the second and third bin. This relation between temperature and $IAQSV_{mean}$ could mean that this physical parameter probably had an influence on IAQ sensation votes.

Figure 19b reports the distribution of the illuminance level in relation to the different CO_2 bins. The boxplots highlight a different distribution of the illuminance in correspondence of each CO_2 bins. Nevertheless, it is not possible to highlight any evident relationship between the illuminance level and the $IAQSV_{mean}$.

Figure 19c reports the distribution of the A-weighted sound pressure level in relation to the different CO_2 bins. The boxplots highlight a different distribution of the A-weighted sound pressure level in correspondence of each CO_2 bins. Looking at the medians, it can be seen an increment from the first and the second bin, respectively 500 and 800 ppm, a decrease in correspondence of 1100 ppm and finally an increase at 1400 ppm. As in the case of the temperature, it can be noticed that the $IAQSV_{mean}$ seems to vary in the same way of the median values of the A-weighted sound pressure level, namely an increase from the first and second bin and weak decrease from the second and third bin. This relation between L_{Aeq} and $IAQSV_{mean}$ could mean that this physical parameter probably had an influence on IAQ sensation votes.

Visual Environment. The results regarding the visual environment are reported in Figures 20a, b and c. The VSV_{mean} related to each illuminance bins (red dots) are plotted with the distribution of the other physical parameters, i.e. indoor air temperature, CO_2 level and A-weighted sound pressure level, by means of boxplots. Those graphs allow to inspect if these physical parameters may have an affect students' visual sensation. In the boxplots in each box, the red mark is the median, the box limits denote 25th and 75th percentiles, and the whiskers are the minimum and maximum values of the measured physical parameter. In view of the results obtained within the single-domain analysis, also in this case linear regression was avoided.

Visual Environment



(-3) = very dark; (-2) = dark; (-1) = slightly dark; 0 = nor dark/bright; 1 = slightly bright; 2 = bright; 3 = very bright

a. b. c.

Figure 20. Distribution of indoor air temperature (a), CO_2 level (b) and A-weighted sound pressure level (c) with VSV_{mean}.

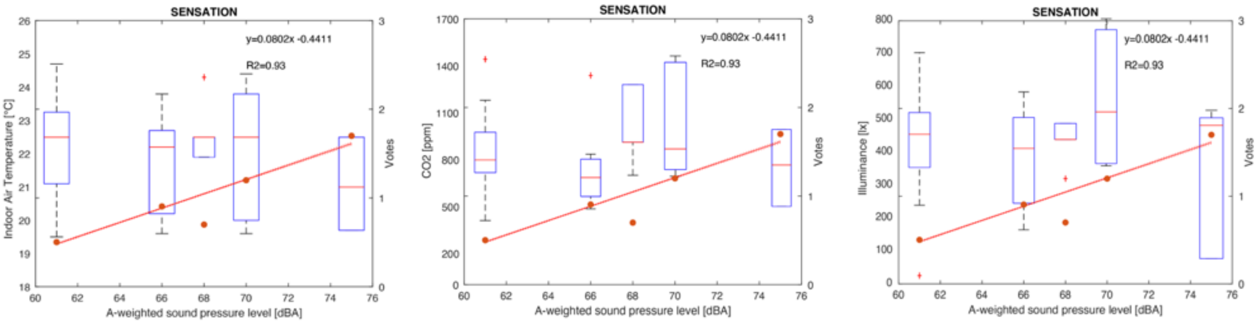
Figure 20a reports the distribution of the indoor air temperature in relation to the different illuminance bins. Looking at the boxplots, it could be seen that in correspondence of the first two illuminance bins, i.e. 20 and 150 lx, the temperature is constant at about 22.5 °C, then lie between 19.5 and 24.4 in correspondence of 300 and 500 lx, showing a decrease of 1 °C in the median between these two illuminance bins. From this analysis no evident relationship between the indoor temperature and the VSV_{mean} can be inferred.

Figure 20b reports the distribution of the CO_2 level in relation to the different illuminance bins. The boxplots highlight a different distribution of the CO_2 level in correspondence of each illuminance bins. In details, looking at the medians, it can be seen an increment from the second bin (150 lx) and the third bin (300 lx) and a decrease between 300 and 500 lx. The VSV_{mean} seems to undergo a similar variation, namely an increase from the second and third bin and weak decrease from the third and fourth bin. This relation between CO_2 and VSV_{mean} could mean that this physical parameter probably had an influence on visual sensation votes.

Figure 20c reports the distribution of the A-weighted sound pressure level in relation to the different illuminance bins. The boxplots highlight a different distribution of the A-weighted sound pressure level in correspondence of each illuminance bins. Nevertheless, it is not possible to highlight any evident relationship between the L_{Aeq} and the VSV_{mean}.

Acoustic Environment. The results regarding the acoustic environment are reported in Figures 21a, b and c. The ASVmean related to each temperature bins (red dots) are plotted with the distribution of the other physical parameters, i.e. indoor air temperature, CO_2 level and the illuminance level, by means of boxplots. Those graphs allow to inspect if these physical parameters may have an affect students' acoustic sensation. In the boxplots in each box, the red mark is the median, the box limits denote 25th and 75th percentiles, and the whiskers are the minimum and maximum values of the measured physical parameter.

Acoustic Environment



0 = quiet; 1 = slightly noisy; 2= noisy; 3= very noisy

a. b. c.

Figure 21. Distribution of indoor air temperature (a), CO_2 level (b) and illuminance level (c) with ASV_{mean}.

Figure 21a reports the distribution of the indoor air temperature in relation to the different A-weighted sound pressure level bins. The boxplots highlight a different distribution of the indoor temperature in correspondence of each L_{Aeq} bins. Looking at the amplitude of 25th and 75th percentiles, it can be seen that it undergoes a shrinking in correspondence of the third bin, i.e. 68 dBA, compared to the previous and following bins, that can partially explain the drop of ASV_{mean} at 68 dBA. Nevertheless, it is not possible to highlight any strong relationship between the variation of the temperature and the ASV_{mean}.

Figure 21b reports the distribution of the CO_2 level in relation to the different A-weighted sound pressure level bins. The boxplots highlight a different distribution of the indoor temperature in correspondence of each L_{Aeq} bins. Nevertheless, as in the case of the indoor temperature, it is not possible to highlight any evident relationship between the variation of the CO_2 and the ASV_{mean}.

Figure 20c reports the distribution of the illuminance level in relation to the different A-weighted sound pressure level bins. The boxplots highlight a different distribution of the illuminance level in correspondence of each L_{Aeq} bins. Nevertheless, as for the CO_2, it is not possible to highlight any evident relationship between the variation of the CO_2 and the ASV_{mean}.

Conclusion and further development of this work. Regarding the single-domain analysis, namely the main parameter related to that domain vs the subjective responses expressed over a comfort domain, the correlation analysis highlighted that there is a correlation between sensation and preference expressed for a comfort domain and between measured physical parameters and students' sensations but the type of dependency between the subjective response and the main environmental parameter associated to the subjective sensation is different from one comfort domain to another. Moreover, according to the analysis, the neutral conditions, namely the environmental conditions under which the sensation vote is equal to 0, occur when the indoor temperature is about 22,5 °C in case of the thermal environment, correspond to CO_2 much lower than 500 ppm for the indoor air quality, occur when the illuminance is 300 lx, according to the sensation vote, and in case of the acoustic environment seems to correspond to a L_{Aeq} lower than 61 dB(A).

Furthermore, in order to explore the combine effects of different comfort domains, the multi-domain approach analysis was carried out. This analysis included two different approaches. The *subjective approach* investigated if the main physical parameter related to a domain (the same parameter used in the data binning phase in order to form the groups) have an impact also on the sensation votes expressed for the other comfort areas by the same homogeneous group of students; in this analysis the mean value of the physical parameters referring to a specific environment was correlated to the mean sensation votes express for the other domains. The *objective approach* explored if the sensation vote expressed for a comfort area by the same homogeneous group of students is influenced also by the physical parameters related to the other domains. In this analysis the mean sensation vote expressed for a specific domain is correlated to the distribution of physical parameters related to the other domains.

Regarding the subjective approach analysis, namely the main parameter related to a domain vs the subjective responses expressed for the other comfort domain, the analysis highlighted some cross relations between different comfort domains. In details, the regression analysis between temperature and IAQ sensation votes showed that cooler air temperature is perceived as fresher ($IAQSV_{mean}$ = 0.8), while warmer air is perceived stuffier ($IAQSV_{mean}$ = 1.3) and the neutral conditions, namely the environmental conditions under which the IAQ sensation vote is equal to 0 = fresh air, occur when the indoor temperature is lower than about 20.5 °C, while the regression analysis between illuminance and IAQ sensation votes highlighted that a darker room is perceived as slightly stuffy ($IAQSV_{mean}$ = 1,1), while a brighter environment is perceived as fresher ($IAQSV_{mean}$ = 0,8).

Also the objective approach analysis, that explore if the sensation vote expressed for a comfort area by the same homogeneous group of students is influenced also by the physical parameters related to the other domains, highlighted some cross relations between different comfort domains. In more detail, the TSV_{mean} seems to be positively influenced by the increase of CO_2 level varying from about -0.5 (slightly cool / neutral) when the CO_2 level is between 800 and 1000 ppm, to about 1 (i.e. slightly warm) when the CO_2 level ranges from 800 to 1400 ppm. A similar trend could be seen also in case of the illuminance level: when the illuminance ranges from 100 and 500 lx the TSV_{mean} shifts towards 1. Regarding the analysis conducted for the IAQ, it can be noticed that the $IAQSV_{mean}$ seems to vary in the same way of the median values of temperature, namely an increase from the first and second bin and weak decrease from the second and third bin. A similar relation occurs if comparing the variation of the sound level distribution and the $IAQSV_{mean}$. Therelation between temperature and $IAQSV_{mean}$ and between L_{Aeq} and $IAQSV_{mean}$ could mean that these physical parameters probably had an influence on IAQ sensation votes. Moreover, the analysis conducted for the visual environment highlighted a possible relationship between VSV_{mean} and the distribution of CO_2 level: the boxplots of CO_2 level showed an increment in the median from the second bin (150 lx) and the third bin (300 lx) and a decrease between 300 and 500 lx and the VSV_{mean} seems to undergo a similar variation.

A possible development of this work will be the application of the three above mentioned methods to other case studies in order to enlarge the collected database and to test the method under different environmental conditions. Moreover, the dataset will be further analyzed and parametrized according to other factors, e.g.: the position of the subjects inside the room, their clothing level or the age of the subjects in other to highlight possible differences between adult comfort ranges reported in the international standards and those referring to students of different educational stages. Furthermore, also the students' global comfort and correlation between indoor conditions and occupants' performance and behaviour will be considered in future works. Finally, an open issue of the research is to understand if the objective evaluation can be considered an indirect evaluation of occupants' comfort and if one type of evaluation can substitute the other, in other words if questionnaires can replace the physical measurements and vice versa.

5.3 Multi-level multi-step optimization-based calibration

Partial-building model simulation and calibration in Period 1. The first selected period for the calibration process, from 5th to 19th August, is characterize by the absence of occupants while the system is off. In the partial-building model calibration, several buildings' thermophysical properties, the windows thermal and solar transmittance and the shading coefficient have been calibrated. In addition, in order to consider the air coupling between the control rooms, the convective airflows between the stories and to assess the airtightness of the building, three parameters related to the Air Flow Network (AFN) have been calibrated, namely the crack area of the window, the crack area of the door and the wind velocity exponent profile. For all these quantities, tentative values were set and a variability ranges defined. These and the calibrated value after the partial-building calibration are listed in Table 29. As concerns the parameters related to the AFN the variation ranges were defined according to the TRNFLOW manual.

Whole-building model simulation, calibration in Period 1. Calibrated parameters from the partial-building model were then used in the model of the entire school building. In detail, calibrated values of the thermal properties of the envelope (i) and parameters related to the AFN (ii) obtained from the two-zone calibration were extended to all the similar thermal zones in order to construct the whole-building multi-zone initial model. The multi-zone model requires a certain number of additional parameter to be calibrated, namely the single-glazed windows thermal and solar transmittance, additional parameters related to the AFN (i.e. the crack value of the single-glazed window and the pressure drops of the stairwells), the thickness of the ground floor hollow slab and the shading coefficients of the boundary rooms. The variability ranges and the calibrated value of the whole-building calibration are listed in Table 30. For all these quantities, tentative values were set in order to build the whole-building initial model (Table 30) and were calibrated further. For the parameters related to the AFN the variation ranges were defined according to the TRNFLOW manual. The calibration was validated by simulating the building model in the period 20th August–1st September (unoccupied building, passive mode).

Whole-building model simulation and calibration in Period 2. The parameters of the whole-building model calibrated in Period 1 (unoccupied building/system off) was used for constructing the whole-building model in Period 2 (occupied building/system off), from 3rd to 17th of May. This period has been selected in order to calibrate building parameters related to the user behaviour, such as window opening and shading operation during the occupation period. In order to consider students' interaction with the windows, (i.e. windows opening), the Logistic regression model presented in the methodology have been used. The variability ranges and the calibrated value of the 2nd whole-building calibration are listed in Table 3. In order to take into account building occupancy, people are considered at school from Monday to Friday from 8 a.m. to 1 p.m. and Saturday from 8 a.m. to 12 a.m. The number of people in the two control rooms (R1 and R2) was derived from the register books; while in the other classroom was calculated by multiplying the surface area of the classrooms with the concentration rate obtained from the two control rooms (0.38 people per square meter). The library was considered occupied by one person during the occupancy period and in the canteen the occupancy was considered during lunch time and the number students were calculated using the concentration rate 0.6 people per square meter as suggested by the Italian standard UNI 10339.

Table 29: Building parameters calibrated in the partial-building model in the Period 1 (from 5th to 19th August).

Parameters	Initial value	Range value	Calibrated value
External Wall Brick			
• Conductivity λ [kJ/h m K]	2.5	[2-7]	6.75
• Density ρ [kg/m^3]	1500	[1000-2000]	1450
• External Solar Absorptance	0.3	[0.24-0.36]	0.32
Internal Wall Brick			
• Conductivity λ [kJ/h m K]	2.5	[2-7]	6
• Density ρ [kg/m^3]	1500	[1000-2000]	1350
Internal Hollow Slab			
• Conductivity λ [kJ/h m K]	2.5	[1.53-2.84]	2.3

• Density ρ [kg/m^3]	1417	[1070-1417]	1350
Roof Hollow Slab			
• Conductivity λ [kJ/h m K]	2.5	[2-7]	3.2
• Density ρ [kg/m^3]	1500	[1000-2000]	1850
• External Solar Absorptance	0.3	0.4-0.6	0.56
Window 1			
• Frame Transmittance [kJ/(h m^2 K)]	18	[14.4-21.6]	21.6
• Window *	11	[4-14]	13
- glazing U-value [kJ/(h m^2 K)]	6.6	[5.7-11.2]	6.0
- glazing g-value [%]	67.1	[65.9-67.3]	67.2
Shading coefficients			
• Room R1	0	[0-1]	0.75
• Room R2	0	[0-1]	0.35
Air Flow Network			
• Window 1 crack area [kg/s at 1Pascal]	0.000006	[0.000001-0.0012]	0.000564
• Door crack area [kg/s at 1Pascal]	0.0013	[0.0013-0.0024]	0.00184
• Wind velocity exp. profile	0.3	[0.15-0.4]	0.2
Air node thermal capacitance R1	6000	[477-9540]	6201
Air node thermal capacitance R2	6000	[477-9540]	4054

** Windows were evaluated as discrete parameters.*

Whole-building initial model and calibration model in Period 1. Tables 32 and 33 report the standardized statistical indices RMSE, CV(RMSE) and R2 of the partial-building calibrated model, the initial whole-building model, the whole-building calibrated model and the whole-building validated model in Period 1. Comparing the results of the whole-building initial model and those of the partial-building calibrated model, it can be noticed that the air temperature of the two reference rooms is less accurately predicted by the whole-building model. The statistical indices of the two reference rooms (R1 and R2) are worse in the initial whole-building model: RMSD=+86%, CV(RMSD) = +86 %, R2 = +2% for R1 and RMSD =+53 %, CV(RMSD) = +53 %, with the same R2 = 0.99 for R2. But, focusing on the results of the whole-building calibration it can be seen that the calibration significantly enhanced the whole-building model and the statistical indices are very similar to those of the partial-building calibration: RMSD=0.11°C, CV(RMSD) = 0.4 %, R2 = 0.99 for R1 and RMSD =0.18°C, CV(RMSD) = 0.6%, R2 = 0.99 for R2. Looking at the average values of the statistical indices calculated in all 9 monitored zones, the whole-building calibration leads to good improvements of the initial model (RMSDavrg = -80 %, CV(RMSD) avrg = -67 % with the same R2avrg=+1%). During the first validation period, the statistical indices of the control rooms are consistent with the calibrated model with a slightly worse value of the CV(RMSD) of R2. Figure 23 shows that simulated temperatures are within the range of ±0.35 °C from the measured values for almost all the time both in the calibration and in the validation period.

Table 30. Building parameters calibrated in the whole-building model in the Period 1 (from 5th to 19th August).

Parameters	**Initial value**	**Range value**	**Calibrated value**
Basement floor Hollow slab			
• *Slab thickness [m]*	0.5	[0.4-0.5]	0.4
Window 2			
• Frame Transmittance [kJ /(m^2 K)]	7	[5.6-8.4]	7.2
• Window *	1	[1-3]	2
- glazing U-value [kJ/(h m^2 K)]	20.5	[20.2-20.5]	20.2
- glazing g-value [%]	85.5	[82.7-85.5]	82.7
Air Flow Network			
• Window 2 crack area	0.000006	[0.000001-0.0012]	0.001

- Discharge coeff. stairs 1	1	[0-1]	0.8
- Discharge coeff. stairs 2	1	[0-1]	0.2
Shading coefficients			
- Room B1	0.45	[0.25-0.75]	0.58
- Room B2	0	[0-1]	0.9
- Room B3	0	[0-1]	0.7
- Room B5	0	[0-1]	0.8
- Room B6	0.25	[0.25-0.75]	0.48
Air node thermal capacitance B1	2000	[420-8406]	1681
Air node thermal capacitance corr. T4	4000	[890-17804]	11129
Air node thermal capacitance B4	2000	[477-9540]	4531
Air node thermal capacitance B7	2000	[477-9540]	4054
Air node thermal capacitance room T6	2000	[890-17806]	6677

** Windows were evaluated as discrete parameters.*

Table 31. Building Parameters calibrated in the whole-building model during the Period 2 (from 3rd to 17th May).

Parameters	**Lower limit**	**Upper limit**	**Calibrated value**
Logistic regression			
- Probability threshold (opening)	0.8	[0.6-0.95]	0.68
- Probability threshold (closing)	0.8	[0.6-0.95]	0.6
- Regression param. β_0	-19	[-21/-18]	-20.75
- Regression param. β_1	0.922	[0.85-0.99]	0.86
Air Flow Network			
- Wind velocity coeff.	1	[0.2-1]	0.25
- Discharge coeff. window 2	0.6	[0.01-1]	0.01
- Discharge coeff. door	0.8	[0.01-1]	0.23
Shading coefficients			
- Basement	0.5	[0-1]	0.21
- Basement (east)	0.5	[0-1]	0.65
- Basement (west)	0.5	[0-1]	0.61
- Ground floor (east)	0.5	[0-1]	0.57
- Ground floor (west)	0.5	[0-1]	0.68
- First floor (east)	0.5	[0-1]	0.51
- First floor (west)	0.5	[0-1]	0.5
- Room R1	0.5	[0-1]	0.87
- Room R2	0.5	[0-1]	0.87
- Room B2	0.5	[0-1]	0.6
- Room B1	0.5	[0-1]	0.42
- Room B5	0.5	[0-1]	0.59

Table 32. Comparison of the Statistical indices of Reference Room1 (R1) and 2 (R2) in Period 1 (from 5th to 19th August).

Model type	**RMSD [°C]**		**CV(RMSD) [%]**		**R^2**	
	R1	**R2**	**R1**	**R2**	**R1**	**R2**
Partial-building calibration	0.09	0.18	0.32	0.6	1	0.99
Whole-building initial model	0.66	0.38	2.33	1.28	0.98	0.99
Whole-building 1st Calibration	0.11	0.18	0.4	0.6	1	0.99
Whole-building 1st Validation	0.3	0.18	1.21	0.72	0.99	0.99

Table 33. Overview of the Statistical indices of the whole-building model during Period 1 (from 5th to 19th August).

Whole-building model										
Thermal zone		**RMSD [°C]**			**CV(RMSD) [%]**			**R^2**		
		Initial Model	1st Calibration	1st Validation	Initial Model	1st Calibration	1st Validation	Initial Model	1st Calibration	1st Validation
Basement	**B1**	0.85	0.25	0.65	3.31	0.99	2.81	0.94	0.96	0.88
Ground floor	**R1**	0.66	0.11	0.3	2.33	0.4	1.21	0.98	1	0.99
	B2	1.22	0.19	0.36	4.39	0.66	1.49	0.97	1	0.99
	B3	0.92	0.18	0.43	3.21	0.62	1.73	0.97	1	0.98
	B4	0.81	0.34	0.32	2.88	1.2	1.32	0.99	0.99	0.98
1st floor	**R2**	1.28	0.18	0.18	1.28	0.6	0.72	0.99	0.99	0.99
	B5	3.06	0.3	0.39	3.06	1.05	1.58	0.98	0.99	0.96
	B6	1.27	0.31	0.22	1.27	1.03	0.88	0.98	0.98	0.99
	B7	0.94	0.28	0.36	0.94	0.95	1.45	0.99	0.99	0.96
Average of the 9 zones		1.22	0.24	0.36	2.52	0.83	1.47	0.98	0.99	0.97

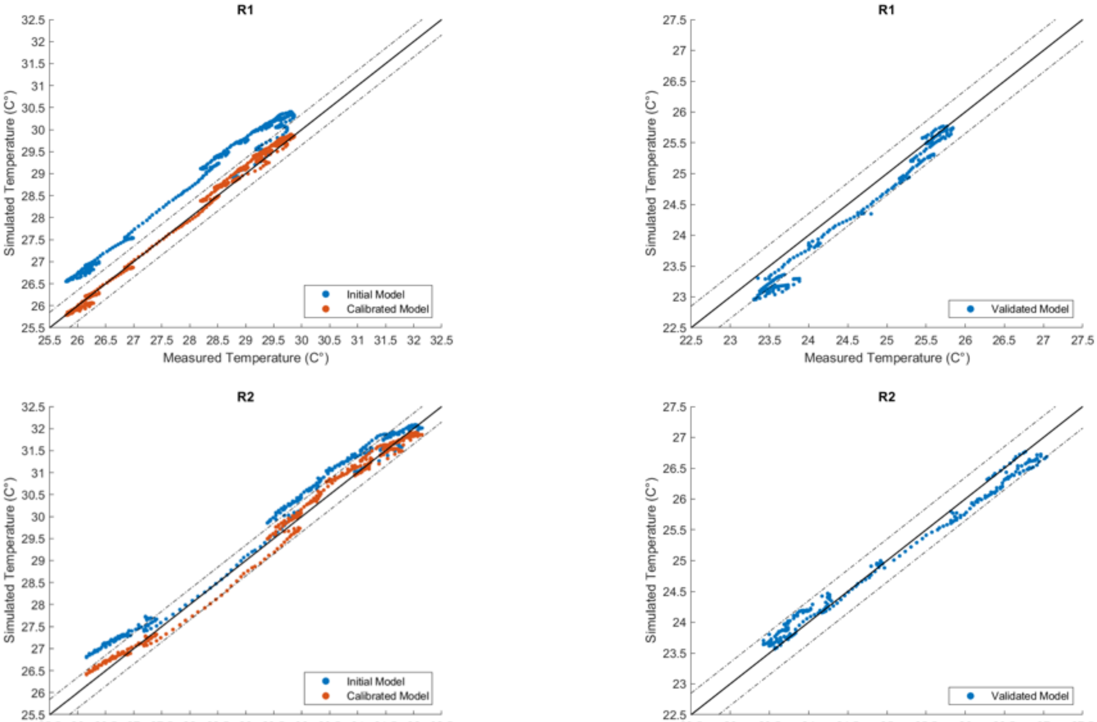


Figure 23. Comparison of the initial model, calibrated model and validated model in Period 1 (unoccupied-passive mode): measured vs simulated temperature of room R1 (top) and R2 (bottom) at the same time-step.

Whole-building initial model and calibration model in Period 2. Table 6 reports the standardized statistical indices RMSE, CV(RMSE) and R^2 of the initial whole-building model, the whole-building calibrated model and the whole-building validated model in Period 2. Comparing the statistical indices of R1 and R2 obtained with the whole-building initial model and those obtained with the whole-building calibrated model, it can be noticed that the calibration leads to a fair improvement of the initial model, with RMSD= -59%, CV(RMSD) = -59 %, R^2 = +58% for R1 and RMSD = -39 %, CV(RMSD) = -38%, R^2 = +39% for R2). Globally, looking at the average values of the statistical indices calculated in all 9 monitored zones, the whole-building calibration leads to fair improvements of the initial model (RMSD$_{avrg}$ = -27%, CV(RMSD)$_{avrg}$ = -27% and R^2_{avrg}= +39%). During the validation period (from 18th to 31st May), the statistical indices of the control rooms are worse than those of the calibrated model in terms of RMSD and CV(RMSD) with a slight improvement in terms of R^2.

Table 6. Overview of the Statistical indices of the whole-building model during Period 2 (from 3rd to 17th May).

Whole-building model										
Thermal zone		**RMSD [°C]**			**CV(RMSD) [%]**			**R^2**		
		Initial Model	2nd Calibration	2nd Validation	Initial Model	2nd Calibration	2nd Validation	Initial Model	2nd Calibration	2nd Validation
Basement	**B1**	1.03	0.95	1.53	5.45	5.07	8.73	0.55	0.44	0.28
Ground floor	**R1**	0.69	0.28	0.53	3.34	1.37	2.88	0.33	0.78	0.82
	B2	0.6	0.37	0.53	3.04	1.87	3.07	0.41	0.56	0.89
	B3	0.7	0.33	0.4	3.38	1.59	2.15	0.25	0.68	0.83
	B4	0.58	0.56	0.83	2.91	2.77	4.68	0.69	0.76	0.93
1st floor	**R2**	0.59	0.36	0.5	2.8	1.72	2.71	0.45	0.74	0.85
	B5	0.49	0.39	0.53	2.44	1.94	3.09	0.55	0.70	0.93
	B6	0.42	0.29	0.51	2.04	1.38	2.82	0.53	0.78	0.84
	B7	0.66	0.67	0.92	3.2	3.29	5.14	0.57	0.60	0.83
Average of the 9 zones		**0.64**	**0.47**	**0.7**	**3.18**	**2.33**	**3.92**	**0.48**	**0.67**	**0.80**

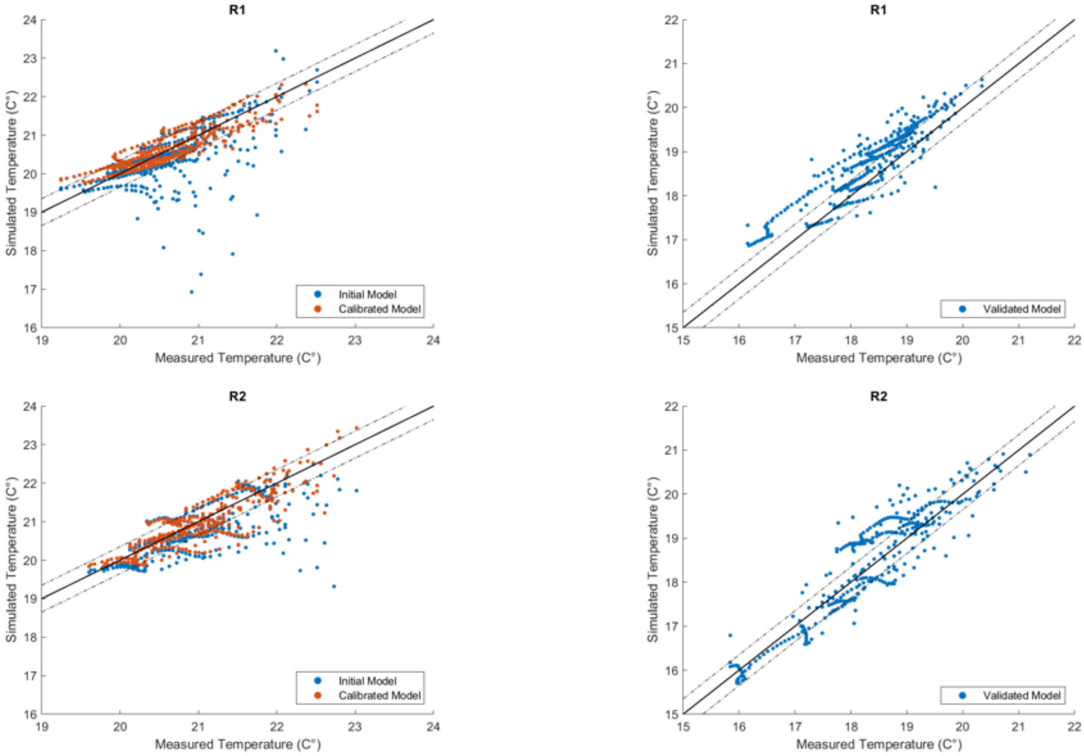


Figure 24 – Comparison of the initial model, calibrated model and validated model in Period 2 (occupied-passive mode): measured vs simulated temperature of room R1(top) and R2 (bottom) at the same time-step.

Conclusion and further development of this work. The calibration phase is split into two main levels: (i) the calibration of a small part of the building (i.e. partial-building calibration) and (ii) the subsequent calibration of the whole-building model (i.e. whole-building calibration). The main advantages of this method are that it enables (i) to extend the calibrated building parameters in the calibration of a partial-building model to the entire building in order to build the whole-building initial model in the same period and (ii) to use the measurements inside a small portion of a building during short periods (i.e.: short-term measurements in 9 rooms) to calibrate the whole building, avoiding any additional monitoring costs. This method was tested and validated in a real school building. The application of this approach to the case study highlights that the partial-building model calibrated in Period 1 (non-occupied building, passive mode) is a reliable approximations of the whole-building model in the same period. However, the subsequent calibration of the additional building parameters of the whole-building model can further enhance the prediction of the temperature trend in the whole-building model in the same period, as shown by the statistical indices. Results from the Period 2 (occupied building, passive mode) show that the presence of people inside a building augments the complexity of a calibration because of the lack of knowledge about occupant behavior, namely the opening and closing of windows and doors especially in the corridors, in the canteen and in the library. This leads to a reduction in convective air exchanges and air change rates within the building, affecting the temperature of the classrooms, resulting in an overestimation of the internal temperatures compared to the measured ones.

A further development of this work will be to use the calibrated models in Period 1 in order to calibrate the building operation during the heating period, considering two more periods respectively an unoccupied one with active heating and an occupied one with active heating. Moreover, the validation of the model towards air humidity and energy consumption will be a further step of the work.

6. Conclusions and further developments

The present doctoral research investigates the main approaches for the assessment of indoor environmental quality (IEQ) and students' comfort inside educational buildings, namely the objective evaluation through the monitoring of the main indoor physical parameters related to the four comfort domains (i.e. IAQ, thermal, visual and acoustic environment) and the subjective evaluation by means of questionnaires.

The literature review carried out both on international standards and scientific works in the last decades has highlighted that the main issues to be solved in the assessment of students' comfort by means of objective and subjective evaluation are from one hand the urge of a questionnaire that uses questions and evaluation scales consistent for the all four environmental aspects (thermal, visual, acoustical and air quality) and allows the correlation with the physical measurements, from the other the need of a rigorous method for the data aggregation and analysis in order to deepen the knowledge about which are the neutral conditions for people's comfort and about the combined effects of one comfort domain to another. Considering the literature review the research gaps can be summarize as follow:

- Long-term monitoring could be costly and time consuming;
- Choosing the representative periods and spaces of the building to monitor could be tricky;
- Standards do not suggest a standardized procedure for collecting the appropriate dataset for evaluating people's comfort ranges;
- Standards do not suggest possible strategies to guarantee the adequate well-being of the building occupants;
- Including environment with different functions, the monitoring of a school building could be challenging;
- International standards focused on subjective evaluation refer to adults, in office buildings or in laboratories;
- Most of the standards consider only thermal environment and those that inspect also other comfort domains do not provide a consistent structure of the questions nor a unique wording of questions and evaluation scales;
- The lack of consistency in the evaluation of the four comfort domains, i.e. IAQ, thermal, visual and acoustic environment, precludes to assess the contribution of each to the students' global comfort and to understand the interactions between the domains;
- In order to be reliable and accurate, building energy models need to be calibrated and validate.

Starting from those research gaps, the work carried out during the three years of my doctoral study and presented in this thesis focused on the design and validation of a questionnaire aiming to solve the discrepancy and inconsistency of inspected psychological continua, questions wording and related evaluation scales currently present in the standards and scientific works, together with the definition of a rigorous method for processing the dataset collected with the in-field monitoring and exploring the correlation between physical measurements and subjective responses gathered with the standard questionnaire.

The applicability of the correlation method is strictly dependent on the consistency of the subjective responses collected by questionnaires. For this reason, the first part of the proposed methodology (Chapter 3. Methodology) is focused on the design of the questionnaire evaluated and validated upon part of the large dataset collected during the last two years, consisting of 694 questionnaires gathered in classrooms located in Bolzano and Rome.

Validation of the questionnaire. The KPIs used for the validation are three, namely questionnaire *effectiveness* aiming at demonstrating its capability of discriminating different subjective responses in different environmental conditions, questionnaire *efficiency* for checking if questions are as many as necessary to understand which environmental and contextual factors affect comfort and to understand how occupants express comfort, and questionnaire *resolution* in order to highlight if the questionnaire is able to capture the different levels of judgement on each question. The questionnaire effectiveness was evaluated by analyzing the mean sensation, preference, and comfort votes expressed in each panel, and by relating these votes to a physical parameter that was deemed to be representative of the environmental conditions of each domain. The questionnaire efficiency was tested by performing a multilinear regression analysis in which individual sensation votes are predictors and comfort votes are the response variables, by checking the significance level of the variables. The questionnaire resolution was investigated by means of a qualitative analysis of the distribution of the votes expressed in the sensation and preference scales, in the four domains. As concerns the effectiveness, mean sensation/preference/comfort votes were found in good agreement with the environmental parameters. Nevertheless, in some domains, such as for visual comfort and IAQ this correlation is weaker than in others. Further work is needed to evaluate if this mismatch is due to the formulation of the questions, or due to a difficulty of the occupants to discriminate or evaluate different environmental conditions, as it seems the case with CO_2 concentration and IAQ. As for the questionnaire efficiency, a regression analysis showed that not all the sensation questions used in this research are significantly correlated to the comfort votes. It will be necessary to assess whether, these variables gain significance using alternative analysis techniques or additional inputs, otherwise sensation questions will need to be reformulated or discharged accordingly. Concerning the questionnaire resolution, the analysis of the distribution of preference votes based on sensation votes is regarded as a preliminary step towards the investigation of the resolution of the scales and their mutual relations. In particular, the analysis has demonstrated that the 7-point scale for thermal and visual sensation and the 4-point scale for IAQ and acoustic sensation are suitable to discriminate conditions related to different preference distributions. A clear correspondence was found between thermal and IAQ sensation and preference scales, while in the acoustic and visual domains, the distribution of neutral preference votes encompassed sensation votes related to noisier and darker conditions respectively. This aspect will be further investigated by collecting more subjective responses in environments with more "extreme" comfort conditions.

Application of the correlation method between objective and subjective data. Once the questionnaire was validated, the correlation analysis between objective data and subjective responses was applied to all the dataset collected during the last two years, namely 21 experimental campaigns for a total of 52 panels and 952 questionnaires.

The experimental campaigns included both long-term monitoring (more than 1 year of measurements) and right-now measurements during regular classes. For the correlation analysis dataset from the second type of monitoring has been used.

In order to correlate the objective data collected through the in-field measurements with the subjective votes gathered with questionnaires inspecting students' comfort in different environmental conditions, it is necessary to analyze sufficiently representative data. On the one hand, the raw measurements need to be pre-processed in order to identify different indoor conditions in terms of indoor air quality, thermal, visual and acoustic environment. On the other hand, it is necessary to group the panels (i.e. groups of students exposed at the same conditions) based on the environmental conditions in order to treat a representative number of responses. For this reason, the tested and validated method included the aggregation of different panels according to specific physical parameters ranges or bins, representing the different indoor conditions to which subjects have been exposed, i.e., indoor air temperature, CO_2 content, horizontal illuminance level and equivalent sound pressure level, need to be calculated. Regarding the IAQ, thermal and acoustic environment the time averaged value of the physical parameters measured during the questionnaire administration inside each classroom was considered, while for the visual environment, the illuminance level has been calculated as the spatial mean value of the horizontal illuminance level measured at all the desks inside the classroom. For grouping subjects three main steps were followed. First, the environmental conditions, to which the panels (i.e. groups of students exposed to the same conditions) were exposed, have been binned considering specific ranges of the measured physical parameters (Data binning). In this way, subjects of panels exposed to similar indoor conditions in terms of indoor air temperature, CO_2 content, illuminance level and sound pressure level were aggregated into preliminary groups. The preliminary groups were then checked by analyzing the distribution of sensation votes of each group by means of statistical tests: panels with the same distribution of sensation votes within a specific bin were aggregated (Preliminary Data aggregation), while the panel with any or the fewest matches with other panels were not considered in the analysis. Secondly, the same statistical tests were used for verifying the groups (Definition of the groups) using the following approach: (a) if the distributions of sensation votes of two groups referring to subsequent bins are the same, it is possible to aggregate forming a broader; (b) conversely if they had different distributions they were considered as separate groups. Finally, the correlation between measured parameters and the subjective responses of the final groups has been inspected (Analysis of the groups). To analyze the correlation between measured environmental conditions and the subjective response within the same comfort domain, the mean value of the physical parameters referring to a specific environment domain was plotted on a graph against the mean sensation, preference and comfort votes referring to the same domain (regression models).

Regarding the single-domain analysis, namely the main parameter related to that domain vs the subjective responses expressed over the same comfort domain, the correlation analysis highlighted that there is a correlation between sensation and preference expressed for a comfort domain and between measured physical parameters and students' sensations but the type of correlation between the subjective response and the main environmental parameter associated to the subjective sensation is different from one comfort domain to another. Moreover, according to the analysis, the neutral conditions, namely the environmental conditions under which the sensation vote is equal to 0, occur when the indoor temperature is about 22,5 °C in case of the thermal environment, correspond to CO_2 much lower than 500 ppm for the indoor air quality, occur when the illuminance is 300 lx, and in case of the acoustic environment seems to correspond to a sound level lower than 61 dB(A).

Furthermore, in order to explore the combined effects of different comfort domains, the multi-domain approach analysis was carried out. This analysis included two different approaches. The *subjective approach* investigated if the main physical parameter related to a domain (the same parameter used in the data binning phase in order to form the groups) have an impact also on the sensation votes expressed for the other comfort areas by the same panels. The *objective approach* explored if the sensation vote expressed for a comfort area by the same homogeneous group of students is influenced also by the physical parameters related to the other domains.

Regarding the subjective approach analysis, the analysis highlighted some cross relations between different comfort domains. In details, the regression analysis between temperature and IAQ sensation votes showed that cooler air temperature is perceived as fresher ($IAQSV_{mean}$ = 0.8), while warmer air is perceived stuffier ($IAQSV_{mean}$ = 1.3) and the neutral conditions, namely the environmental conditions under which the IAQ sensation vote is equal to 0 = fresh air, occur when the indoor temperature is lower than about 20.5 °C, while the regression analysis between illuminance and IAQ sensation votes highlighted that a darker room is perceived as slightly stuffy ($IAQSV_{mean}$ = 1,1), while a brighter environment is perceived as fresher ($IAQSV_{mean}$ = 0,8).

Also the objective approach analysis, that explore if the sensation vote expressed for a comfort area by the same homogeneous group of students is influenced also by the physical parameters related to the other domains, highlighted some cross relations between different comfort domains. In more detail, the TSV_{mean} seems to be positively influenced by the increase of CO_2 level varying from about -0.5 (slightly cool / neutral) when the CO_2 level is between 800 and 1000 ppm, to about 1 (i.e. slightly warm) when the CO_2 level ranges from 800 to 1400 ppm. A similar trend could be seen also in case of the illuminance level: when the illuminance ranges from 100 and 500 lx the TSV_{mean} shifts towards 1. Regarding the analysis conducted for the IAQ, it can be noticed that the $IAQSV_{mean}$ seems to vary in the same way of the median values of temperature, namely an increase from the first and second bin and weak decrease from the second and third bin. A similar relation occurs if comparing the variation of the sound level distribution and the $IAQSV_{mean}$. The relation between temperature and $IAQSV_{mean}$ and between sound pressure level and $IAQSV_{mean}$ could mean that these physical parameters probably had an influence on IAQ sensation votes. Moreover, the analysis conducted for the visual environment highlighted a possible relationship between VSV_{mean} and the distribution of CO_2 level: the boxplots of CO_2 level showed an increment in the median from the second bin (150 lx) and the third bin (300 lx) and a decrease between 300 and 500 lx and the VSV_{mean} seems to follow a similar trend.

This research is a contribution in the knowledge about the effect of the indoor environmental parameters on the subjective comfort under different strains.

Future developments of this work will be the application of the three above mentioned methods to other case studies in order to enlarge the collected database and to test the method under different environmental conditions. Moreover, the dataset will be further analyzed and parametrized according to other factors, e.g.: the position of the subjects inside the room, their clothing level or the age of the subjects in other to highlight possible differences between adult comfort ranges reported in the international standards and those referring to students of different educational stages.

Furthermore, also the students' global comfort and correlation between indoor conditions and occupants' performance and behaviour will be considered in future works.

Application of the multi-level multi-step building calibration method. A parallel topic investigated in this research concerns the development of a BES calibration methodology. Building Simulation can be used not only to calculate real building energy demand, but also to calculate the indoor environmental conditions and to predict subjective comfort by means of specific comfort indices or relationships. However, the first issue of a building model is its reliability and a model calibration is fundamental to guarantee the effectiveness of the model in representing the real building physical behavior. Long-term monitoring conducted in a school building located near Vicenza (Italy) were used to test and validated a calibration methodology based on a multi-stage multi-level approach. The calibration phase is split into two main levels: (i) the calibration of a small part of the building (i.e. partial-building calibration) and (ii) the subsequent calibration of the whole-building model (i.e. whole-building calibration). As compared with the previous published works, the innovative part of this method is the multi-level approach, i.e. the extension of the simulation and calibration to the whole-building starting from the measurement carried out in a portion of the building. The main advantages of this method are that it enables (i) to extend the calibrated building parameters in the calibration of a partial-building model to the entire building in order to build the whole-building initial model in the same period and (ii) to use the measurements inside a small portion of a building during short periods (i.e.: short-term measurements in 9 rooms) to calibrate the whole building, avoiding any additional monitoring costs. This method was tested and validated in a real school building. The application of this approach to the case study highlights that the partial-building model calibrated in Period 1 (non-occupied building, passive mode) is a reliable approximation of the whole-building model in the same period. However, the subsequent calibration of the additional building parameters of the whole-building model can further enhance the prediction of the temperature trend in the whole-building model in the same period, as shown by the statistical indices. Results from the Period 2 (occupied building, passive mode) show that the presence of people inside a building augments the complexity of a calibration because of the lack of knowledge about occupant behavior, namely the opening and closing of windows and doors especially in the corridors, in the canteen and in the library. This leads to a underestimation of convective air exchanges and air change rates within the building, affecting the temperature of the classrooms, resulting in an overestimation of the internal temperatures compared to the measured ones. A further development of this work will be to use the calibrated models in Period 1 in order to calibrate the building operation during the heating period, considering two more periods respectively an unoccupied one with active heating and an occupied one with active heating. Moreover, the validation of the model towards air humidity and energy consumption will be a further step of the work.

Concluding, the collected dataset and the developed strict methods presented in this work should be considered as part of one complex and replicable approach which can serve as a basic conceptual framework for future studies focusing on the assessment the IEQ of educational buildings and other complex buildings can be used for further investigation on the assessment of IEQ and comfort in educational buildings.

7. Appendixes

7.1 Appendix 1: Tables of the International Standard for the assessment of IEQ by means of questionnaires

Table 1. Review of the international standard EN 15251:2007 (CEN 2007).

	EN 15251:2007
Title	*Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics*
Purpose	This European Standard specifies the indoor environmental parameters which have an impact on the energy performance of buildings.
Focus	Indoor Environment
Target	Adult
Assessed environment	Thermal; Air Quality
Type of evaluation	Right-now
Type of questions/scales	General acceptance of the indoor environment, thermal sensation, perceived air quality shall be used.
Suggested Evaluation periods	winter-spring-summer-fall
Period of the day	middle morning / middle afternoon
Administration frequency / sampling method	Daily; weekly; monthly
Administration method	PC, sheet
Results presentation / interpretations	average values distributions (A weighted average according to the number of people in the different spaces are calculated and used for classification)
Output	Space categories definition (I-IV) **

Questionnaires' focus

Assessed environment	**Thermal sphere**	**Type of question**	**Wording**	**Type of scale**	**Description**	**Metric**	**Labels**
Thermal	N/A	N/A	*How do you rate your thermal sensation?*	Thermal sensation scale	N/A	N/A	COLD, cool, slighly cool, NEUTRAL, slightly warm, warm, HOT
		N/A	*Do you want the room temperature?*	N/A	N/A	N/A	higher, no change, lower
	N/A	N/A	*How do you perceive the temperature?*	N/A	N/A	N/A	clearly acceptable, just acceptable, just unacceptable, clearly acceptable
Air Quality	N/A	N/A	*How do you perceive the air quality?*	N/A	N/A	N/A	clearly acceptable, just acceptable, just unacceptable, clearly acceptable
							no odour, weak odour, moderate odour, strong odour, very strong odour, overpowering odour

N/A = not mentioned

Table 2. Review of the international standard ASHRAE Standard 55-2013.

ASHRAE Standard 55-2013

Title	*Thermal Environmental Conditions for Human Occupancy*
Purpose	To specify the combinations of indoor thermal environmental factors (temperature, thermal radiation, humidity, air speed) and personal factors (activity and clothing) that will produce thermal environmental conditions acceptable to a majority of the occupants within the space.
Focus	Occupants
Target	Healthy adult
Assessed environment	Thermal
Type of evaluation	• **Right-now** (point-in-time): thermal sensation survey; indirect; aim: to correlate thermal comfort with environmental factors, such as those included in PMV model (metabolic rate, clothing, air temp, etc) • **Long-term:** satisfaction survey; direct
Type of questions/scales	• **Right-now:** Sensation / Acceptability / Preference • **Long-term:** Satisfaction
Suggested Evaluation periods	Heating and cooling season
Period of the day	N/A
Administration frequency / sampling method	• **Right-now:** to be implemented under multiple thermal condition and in multiple building operating modes • **Long-term:** every six months (heating and cooling season)
Administration method	N/A
Results presentation / interpretations	**Long-term surveys:** acceptability is determined in two ways: a) By the percentage of occupants who have responded “neutral through “very satisfied” (0, +1, +2, or +3) with their environment; b) By taking a slightly broader view of acceptability, including the percentage who have responded (-1, 0, +1, +2, +3).
Output	Satisfied / Unsatisfied building occupants

Questionnaires’ focus

Assessed environment	**Thermal sphere**	**Type of question**	**Wording**	**Type of scale**	**Description**	**Metric**	**Labels**
Thermal *right-now* (thermal sensation survey; indirect)	N/A	1. Sensation	*What is your general thermal sensation?*	ASHRAE thermal sensation scale	N/A	N/A	Hot, Warm, slightly warm, NEUTRAL, slightly cool, cool, cold
		3. Preference	*Prefer to be: / Prefer:*	ASHRAE thermal preference scale	N/A	N/A	cooler, no change, warmer / less air movement, no change, more air movement
	N/A	2. Acceptability	*Is the environment thermally acceptable? (direct question)*	N/A	N/A	N/A	from very unacceptable to very acceptable

Thermal *long-term* (satisfaction survey; direct)	N/A	Satisfaction	*How satisfied are you with the temperature in your space?*	7-point satisfaction scale	N/A	N/A	from very satisfied to very dissatisfied

N/A = not mentioned

Table 3. Review of the international standard EN ISO 28802:2012.

EN ISO 28802:2012

Title	*Ergonomics of the physical environment - Assessment of environments by means of an environmental survey involving physical measurements of the environment and subjective responses of people (ISO 28802:2012)*
Purpose	This international standard provides an environmental survey method for the assessment of the comfort and well-being of occupants of indoor and outdoor environments. It presents the principles for conducting an environmental survey to assess the comfort and well-being of people in environments. It gives guidance on the design of the surveys and the environmental measurements used to quantify the occupants' responses to their environment.
Focus	Occupants
Target	Adult
Assessed environments and topics	a) Thermal / Acoustical / Visual and lighting / Air quality / Vibration environments b) Occupants' adaptive opportunities to avoid discomfort or dissatisfaction
Type of evaluation	• **Right-now:** preferable • **Long-term**: where possible, to be avoid due to poor reliability
Type of questions/scales and suggested order	**Thermal environment** (ref. EN ISO 10551:2001): 1. Thermal sensation (ref. ISO 7730) 2. Uncomfortable 3. Stickiness 4. Preference 5. Acceptability 6. Satisfaction 7. Draughtiness 8. Dryness • **Acoustical environment:** 1. Annoyance (ref. ISO/TS 15666) 2. Preference 3. Satisfaction 4. Acceptability 5. Sources of noise • **Visual and lighting environment** (Ref. ISO 8995-1) 1. Discomfort 2. Preference 3. Acceptability 4. Satisfaction 5. Sources of glare • **Air quality environment** 1. Smelliness 2. Acceptability 3. Satisfaction 4. Sources of smell

Administration frequency / sampling method	The frequency of completion of the questionnaire should be balanced with the overall aim of design, i.e.: at times of the day when conditions are representative of the environments to which people are exposed.
Administration method	A single paper sheet is preferable to a number of pages.
Results presentation / interpretations	N/A
Output	N/A

Questionnaires' focus

Assessed environment	Type of judgment	Scope	Wording suggestions	Type of subjective judgment scale	Description	Structure	Wording of the degrees
Thermal	**Sensation**	To assess **how a person feels**, not how the environment seems to be	*"Please rate on the following scale how YOU feel NOW"*	**Sensation scale**	Discrete intervals or continuous form (line)	From +3 to -3	Hot (+3), Warm (+2), slightly warm (+1), NEUTRAL (0) , slightly cool (-1), cool (-2), cold (-3)
	Uncomfortable			**Uncomfortable scale**		From 1 to 4 (absence of effect at the base of the scale)	Very uncomfortable (4), Uncomfortable (3), Slightly uncomfortable (2), Not uncomfortable (1)
	Stickiness			**Stickiness scale**			Very sticky (4), Sticky (3), Slightly sticky (2), Not sticky (1)
	Preference	To compare **how the subject is** with **how he or she would like to be**.	*"Please rate on the following scale how YOU would like to be NOW"*	**Preference scale**		bipolar	Much warmer (7), Warmer (6), Slightly warmer (5), **No change (4)*** Slightly cooler (3) Cooler (2), Much cooler (1)
	Satisfaction	"No change" in preference question will indicate a form of acceptability, preference and satisfaction	N/A	**Satisfaction scale**	Direct measure	N/A	Satisfied / Not satisfied
	Acceptability			**Acceptability scale**			Acceptable / Not acceptable
	Dryness	N/A	N/A	**Dryness scale**	Discrete intervals or continuous form (line)	From 1 to 4 (absence of effect at the base of the scale)	Very dry (4), Dry (3), Slightly dry (2), Not dry (1)
	Draughtiness	N/A		**Draughtiness scale**			Very draughty (4), Draughty (3), Slightly draughty (2), Not draughty (1)

Acoustical	**Annoyance**	N/A	N/A	**Annoyance scale**	Discrete intervals or continuous form (line)	From 1 to 4 (absence of effect at the base of the scale)	Very annoying (4), Annoying (3), Slightly annoying (2), Not annoying (1)
	Preference	To compare **how the environment is** with **how he or she would like it to be**.	*“Please rate on the following scale how YOU would like it to be NOW”*	**Preference scale**	Discrete intervals or continuous form (line)	From 1 to 4	Much quieter (4), Quieter (3), Slightly quieter (2), **No change (1)****
	Satisfaction	*“No change” in preference question will indicate a form of acceptability, preference and satisfaction	N/A	**Satisfaction scale**	Direct measure	N/A	Satisfied / Not satisfied
	Acceptability		N/A	**Acceptability scale**			Acceptable / Not acceptable
	Sources of noise	N/A	*“Please indicate any sources of noise YOU can hear in your environment NOW”*	Checklist	/	/	/
Visual and lighting	**Discomfort**	N/A	*“Please rate on the following scale YOUR visual discomfort NOW”*	**Discomfort scale**	Discrete intervals or continuous form (line)	From 1 to 4 (absence of effect at the base of the scale)	Much discomfort (4), Discomfort (3), Slightly discomfort (2), No discomfort (1)
	Preference	To compare **how the environment is** with **how he or she would like it to be**.	*“Please rate on the following scale how YOU would like your visual environment to be NOW”*	**Preference scale**	Discrete intervals or continuous form (line)	bipolar	Much lighter (7), Lighter (6), Slightly lighter (5), **No change (4)*** Slightly darker (3) Darker (2), Much darker (1)
	Satisfaction	*“No change” in preference question will indicate a form of	N/A	**Satisfaction scale**	Direct measure	N/A	Satisfied / Not satisfied
	Acceptability		N/A	**Acceptability scale**			Acceptable / Not acceptable
	Sources of glare	N/A	*“Please indicate if YOU are experiencing any glare NOW”*	Checklist	/	/	/
Air quality	**Smelliness**	N/A	N/A	**Smelliness scale**	Discrete intervals or continuous form (line)	From 1 to 4 (absence of effect at the base of the scale)	Very smelly (4), Smelly (3), Slightly smelly (2), Not smelly (1)
	Satisfaction		N/A	**Satisfaction scale**	Direct measure	N/A	Satisfied / Not satisfied
	Acceptability		N/A	**Acceptability scale**			Acceptable / Not acceptable
	Sources of smells		*“Please indicate any sources of smell in your environment NOW”*	Checklist	/	/	/

N/A = not mentioned

Table 4. Review of the international standard EN ISO 10551:2019.

EN ISO 10551:2019

Title	*Ergonomics of the thermal environment - Assessment of the influence of the thermal environment using subjective judgement scales (ISO 10551:1995)*
Purpose	This standard covers the construction and use of judgement scales (scales of thermal perception, thermal comfort, thermal preference, acceptability expression form and tolerance scale) for use in providing reliable and comparative data on the subjective aspects of thermal comfort or thermal stress.
Focus	• Occupants: a) Personal thermal state (perception, present active assessment, future preference) b) Thermal ambience • Environment
Target	Adult workers
Assessed environments	Thermal / Acoustical / Visual and lighting / Air quality / Vibration environments
Type of evaluation	a) Present or past; b) Instantaneous (right-now) or extended over a period of time (long-term)
Subjective evaluation purpose	To judge **thermal state of the body** for knowing how the workers feel themselves than knowing how they judge the local climate. This standard retains judgment that workers make about their own thermal state as a whole and it distinguishes between perception, present active assessment (comfort/discomfort) and future preference
Suggested evaluation conditions	**Occupants:** • Sedentary working activity (60 $W/m^2 < Met < 70 W/m^2$) • Normal clothing (0,5 – 0,2) < I_{cl} < (1,0-2,0) • After a stay of at least 30 min **Environment:** • Steady climatic conditions; • temperate environments and more intensely hot or cold environments
Type of questions and suggested order	**Personal state*:** 1. Perception (at this precise moment) 2. Affective evaluation (at this precise moment) 3. Preference (at this precise moment) **Ambience*:** Personal Acceptability (extra; personal level/general) Personal Tolerance (extra; personal level/general) ** only for the thermal environment all the above-mentioned questions are presented in the standard.*
Administration frequency / sampling method	Repeated expression of the judgments at regular intervals (e.g. 30 min) using the same scales (Longitudinal sampling).
Administration method	Written/video display unit
Results presentation / interpretations	• Central tendency, median • Scatter, semi-interquartile distance • Association in probability

- Dissatisfaction index vs PPD
- Unacceptability index
- Painfulness index

Questionnaires' focus

Assessed environment	Thermal sphere	Type of judgment	Wording suggestions	Type of subjective judgment scale	Description	Structure	Wording of the degrees
Thermal	**Personal state**	**Perceptual**	*"How are you feeling now?"*	Perceptual scale	**Temperate environment:** Symmetrical 7-degree two-pole scale **Temperature or slightly cold or hot**: Symmetrical 9-degree two-pole scale	Pole A < Degrees (-) < 0 = POINT OF INDIFFERENCE < Degrees (+) < Pole B A= COLD; B=HOT; 0=ABSENCE OF HOT AND COLD	(Very hot) Hot Warm Slightly warm Neutral Slightly cool Coll Cold (Very Cold)
		Affective evaluation	*"Do you find this…?"*	Evaluation scale	4 OR 5-degree one-pole scale	0=POINT OF ORIGIN>3 (4) degrees 0= COMFORT, ABSENCE OF DISCOMFORT> DISPLEASURE, DISSATISFACTION or DISCOMFORT	Comfortable Slightly uncomfortable Uncomfortable Very uncomfortable Extremely uncomfortable
		Thermal Preference	*"Please state how you would prefer to be now"*	Preferential scale	Symmetrical 7 OR 3-degree two-pole scale	Pole A < Degrees (-) < 0 = POINT OF INDECISION < Degrees (+) < Pole B A= COOLER; B=WARMER	(Much cooler) **Cooler** A little cooler **Neither warmer nor cooler (no change)** Slightly warmer **Warmer** (Much warmer)
	Ambience	**Personal Acceptability**	***Explicit terms.*** *How do you judge this environment (local climate) on a personal level?"*	Acceptability statement form	Binary structure or continuous scale	2 degrees yes/no;	ACCEPTABLE/ UNACCEPTABLE
			With initial statement*: Taking into account only your personal preference:*			0 > 4 degrees. Unique pole	clearly acceptable, just unacceptable, clearly unacceptable

			Would you rather accept/reject this environment than reject/accept it?				
		Personal Tolerance	"Is it….?"	Tolerance scale	Unipolar 5-degrees scale	0 > 4 degrees. Unique pole 0=perfectly TOLERABLE; 4= INTOLERABLE	Perfectly bearable Slightly difficult to bear Fairy difficult to bear Very difficult to bear Unbearable
Acoustic	**Personal state**	**Personal Annoyance**	Is it…?	Personal Annoyance scale	unipolar	From 1 to 4 (absence of effect at the base of the scale)	Not annoying Slightly annoying Annoying Very annoying
		Preference	*"Please state how you would prefer to be now"*	Preference scale	unipolar	From 1 to 4	No change Slightly quieter Quieter Much quieter
	Ambience	**Personal Acceptability**	***Explicit terms.*** *How do you judge this environment (local climate) on a personal level?"*	Acceptability statement form	Binary structure or continuous scale	2 degrees yes/no;	ACCEPTABLE/ UNACCEPTABLE
			With initial statement*:* *Taking into account only your personal preference:* *Would you rather accept/reject this environment than reject/accept it?*			0 > 4 degrees. Unique pole	clearly acceptable, just unacceptable, clearly unacceptable
Visual	**Personal state**	**Perceptual**	*The lighting environment now is…?*	Perceptual scale	Symmetrical 7-degree two-pole scale	Pole A < Degrees (-) < 0 = POINT OF INDIFFERENCE < Degrees (+) < Pole B A= DARK; B=LIGHT	Extremely dark … Extremely light
		Evaluative judgment	*"Do you find this…?"*	Evaluation scale	4-degree one-pole scale	0=POINT OF ORIGIN>3 degrees 0= COMFORT, ABSENCE OF DISCOMFORT> DISPLEASURE, DISSATISFACTION or DISCOMFORT	No discomfort Slightly discomfort Discomfort Much Discomfort

		Preference	*"Please state how you would prefer to be now"*	Preferential scale	Symmetrical 7 OR 3-degree two-pole scale	Pole A < Degrees (-) < 0 = POINT OF INDECISION < Degrees (+) < Pole B A= DARKER; B=LIGHTER	(Much darker) **Darker** Slightly darker **No change** Slightly lighterr **Lighter** (Much lighter)
	Ambience	**Personal Acceptability**	***Explicit terms.*** *How do you judge this environment (local climate) on a personal level?"*	Acceptability statement form	Binary structure or continuous scale	2 degrees yes/no;	ACCEPTABLE/ UNACCEPTABLE
			With initial statement: *Taking into account only your personal preference: Would you rather accept/reject this environment than reject/accept it?*			0 > 4 degrees. Unique pole	clearly acceptable, just unacceptable, clearly unacceptable
IAQ	**Personal state**	**Smelliness**	*Do you find the air to be…?*	Smelliness scale	unipolar	From 1 to 4 (absence of effect at the base of the scale)	Not smelly Slightly smelly Smelly Very smelly
	Ambience	**Personal Acceptability**	***Explicit terms.*** *How do you judge this environment (local climate) on a personal level?"*	Acceptability statement form	Binary structure or continuous scale	2 degrees yes/no;	ACCEPTABLE/ UNACCEPTABLE
			With initial statement: *Taking into account only your personal preference: Would you rather accept/reject this environment than reject/accept it?*			0 > 4 degrees. Unique pole	clearly acceptable, just unacceptable, clearly unacceptable
Methods of presentation of the scales			Discontinuous format: separate degrees				
			Continuous format: a straight line or curve (This format allow to locate response anywhere within the intervals between marks)				

N/A = not mentioned

7.2 **Appendix 2**: The four central sections of the designed and validated IEQ questionnaire: sensation, preference, comfort and satisfaction for the IAQ, thermal, visual, acoustic environment.

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THERMAL ENVIRONMENT

Thermal Sensation	**Thermal Preference**	**Thermal Comfort**	**Thermal Satisfaction**
How do you feel now?	How would you prefer to be now?	Considering all the above-mentioned thermal aspects, how do you feel now?	Referring to the last hour, are you satisfied with the thermal environment?
-3 cold	-3 much colder		
-2 cool	-2 colder		
-1 slightly cool	-1 slightly colder		
0 0 neither cool nor warm	0 no change	0 comfortable	0 yes
+ 1 slightly warm	+ 1 slightly warmer	+ 1 slightly uncomfortable	+ 1 no
+ 2 warm	+ 2 warmer	+ 2 uncomfortable	
+ 3 hot	+ 3 much warmer	+ 3 very uncomfortable	

INDOOR AIR QUALITY

IAQ Sensation (air)	**IAQ Preference**	IAQ Comfort	IAQ Satisfaction
How do you perceive the indoor air now?	How would you prefer the indoor air to be now?	Considering all the above-mentioned aspects related to the IAQ, how do you feel now?	Referring to the last hour, are you satisfied with the indoor air quality?
0 fresh	0 no change	0 comfortable	0 yes
+ 1 slightly stuffy	+ 1 slightly fresher	+ 1 slightly uncomfortable	+ 1 no
+ 2 stuffy	+ 2 fresher	+ 2 uncomfortable	
+ 3 very stuffy	+ 3 much fresher	+ 3 very uncomfortable	
IAQ Sensation (odour)			
How do you perceive the odour now?			
0 odourless			
+ 1 slightly odorous			
+ 2 odorous			
+ 3 very odorous			

VISUAL ENVIRONMENT

Visual Sensation (room)	**Visual Preference**	**Visual Comfort**	**Visual Satisfaction**
How do you perceive the room now?	How would you prefer the visual environment to be now?	Considering all the above-mentioned visual aspects, how do you feel now?	Referring to the last hour, are you satisfied with the visual environment?
-3 very dark	-3 much darker		
-2 dark	-2 darker		
-1 slightly dark	-1 slightly darker		
0 neither dark nor bright	0 no change	0 comfortable	0 yes
+ 1 slightly bright	+ 1 slightly brighter	+ 1 slightly uncomfortable	+ 1 no
+ 2 bright	+ 2 brighter	+ 2 uncomfortable	
+ 3 very bright	+ 3 much brighter	+ 3 very uncomfortable	
How do you perceive your desk now?	How can you see your notes on your desk?		
-3 very dark			
-2 dark			
-1 slightly dark			
0 neither dark nor bright	0 clear		
+ 1 slightly bright	1 slightly unclear		
+ 2 bright	2 unclear		
+ 3 very bright	3 very unclear		

How do you perceive the blackboard now?	How can you see your notes on your desk?
-3 very dark	
-2 dark	
-1 slightly dark	
0 neither dark nor bright	0 clear
+ 1 slightly bright	1 slightly unclear
+ 2 bright	2 unclear
+ 3 very bright	3 very unclear

ACOUSTIC ENVIRONMENT

Acoustic Sensation (room)	**Acoustic Preference**	**Acoustic Comfort**	**Acoustic Satisfaction**
How did you perceive the room during the last hour?	How would you prefer the room?	*Considering all the above-mentioned acoustic aspects, how* do you feel now?	Referring to the last hour, are you satisfied with the acoustic environment?
0 quiet	0 no change	0 comfortable	0 yes
+ 1 slightly noisy	+ 1 slightly quieter	+ 1 slightly uncomfortable	+ 1 no
+ 2 noisy	+ 2 quieter	+ 2 uncomfortable	
+ 3 very noisy	+ 3 much quieter	+ 3 very uncomfortable	
Acoustic Sensation (voice)	**Sound and voices during the lecture**		
How did you hear the teacher’s voice?	How did you hear the sounds and voices?		
-3 very soft	-3 very sharp (without rumbles)		
-2 soft	-2 sharp		
-1 slightly soft	-1 slightly sharp		
0 neither soft nor load	0 neither sharp nor rumbling		
+ 1 slightly loud	+ 1 slightly rumbling		
+ 2 loud	+ 2 rumbling		
+ 3 very loud	+ 3 very rumbling		

7.3 **Appendix 3.** Publications

Note: papers are available in two separated files.

List of publications:

Journal paper:

- *L. Pistore, I. Pittana, F. Cappelletti, A. Gasparella, P. Romagnoni, Analysis of subjective responses for the evaluation of the indoor environmental quality of an educational building, Science and Technology for the Built Environment, 2019. DOI: 10.1080/23744731.2019.1649460*

Papers published in indexed International Conference Proceedings:

- *I. Pittana, R. Albertin, A. Prada, F. Cappelletti, A. Gasparella, Exploring the possibility of calibrating a whole-building model from the short-term monitoring of selected reference rooms, Building Simulation 2021 Conference, Bruges, Belgium, 2021 (waiting for DOI/ISBN)*

- *I. Pittana, A. Prada, F. Cappelletti, A. Gasparella, Multi-stage multi-level calibration of a school building energy model, 4th Building Simulation Application Conference – BSA, Bolzano, Italy, 2019 (ISBN: 978-88-6046-176-6)*

Papers published in International Conference Proceedings:

- *I. Pittana, F. Morandi, F. Cappelletti, A. Gasparella, A. Tzempelikos, Understanding the effects of environmental factors on human perception by means of surveys and in field measurements, IAQ 2020: Indoor Environmental Quality Performance Approaches, Athens, Greece, 2022.*

- *F. Morandi, I. Pittana, F. Cappelletti, A. Gasparella, A. Tzempelikos, Assessing The Overall Indoor Environmental Comfort And Satisfaction: Evaluation Of A Questionnaire Proposal By Means Of Statistical Analysis Of Responses, IAQ 2020: Indoor Environmental Quality Performance Approaches, Athens, Greece, 2022.*

- *I. Pittana, F. Cappelletti, P. Romagnoni, Subjective evaluation of indoor environmental quality in educational buildings: the case of University IUAV of Venice (2019), Proceeding of 51st International Conference AiCARR: The human dimension of building energy performance, Venice, Italy,2019.*

- *L. Pistore, I. Pittana, F. Cappelletti, A. Gasparella, P. Romagnoni (2018), Classification of the indoor environment in a high-school building by means subjective responses, Proceeding of International Building Physics Conference, IBPC 2018 Syracuse.*

Nomenclature

BES = Building Energy Simulation
IEQ = Indoor Environmental Quality
IAQ = Indoor Air Quality
TSV = Thermal Sensation Vote
TPV = Thermal Preference Vote
TCV = Thermal Comfort Vote
IAQSV = Indoor Air Quality Sensation Vote
IAQPV = Indoor Air Quality Preference Vote
IAQCV = Indoor Air Quality Comfort Vote
VSV = Visual Sensation Vote
VPV = Visual Preference Vote
VCV = Visual Comfort Vote
ASV = Acoustic Sensation Vote
APV = Acoustic Preference Vote
ACV = Acoustic Comfort Vote

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01 Introduction

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