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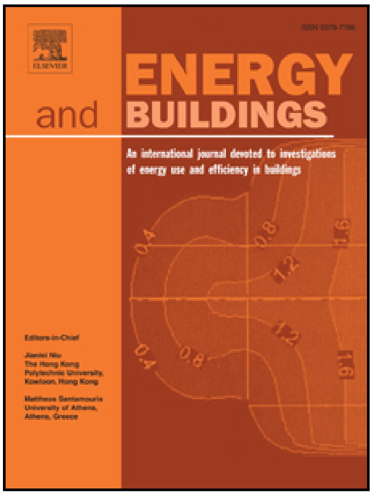

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Highlights

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- Objective IEQ indexes from wall-sensor data match web surveys.
- Contextual factors are essential for interpreting objective and subjective data.
- Perceived IEQ is driven by thermal comfort in winter and indoor air quality in spring.
- Predictive IEQ models should consider sensor position and vertical/horizontal layout.

Long-term monitoring of indoor environmental quality, student comfort and contextual factors in four university classrooms

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Abstract

Indoor environmental quality (IEQ) in university classrooms affects student comfort and learning outcomes. Long-term monitoring of IEQ, student comfort, and contextual factors was performed in four identical recently built classrooms at Politecnico di Torino with different orientation, in spring 2023 and winter 2024. The thermal, acoustic, visual and indoor air quality (IAQ) parameters were monitored using wall-mounted multi-sensors, verified against reference instruments. Concurrently, students completed online questionnaires on comfort, while contextual conditions (door opening, solar shading, use of the voice reinforcement system, etc.) were recorded. The aim was to find the best predictive models of subjective outcomes from objectively monitored data with a long-term objective and subjective assessment system. This setup is expected to support rapid adjustments to maintain optimal conditions, improve occupant comfort, and reduce manual workload for facility managers. The results show that contextual factors are essential to interpret objective and subjective data. The questionnaires showed that in winter, the overall perceived IEQ was mainly influenced by thermal comfort, while in spring it was primarily influenced by indoor air quality, which were the least rated factors in each season. The objective indices for thermal and acoustic quality showed the best agreement with subjective comfort. The acoustic model, which is based on the minimum level of speech required to achieve an optimal signal-to-noise ratio, requires a lower threshold under conditions of good room acoustics. The IAQ and visual models should account for the position of the sensors and their layout, whether vertical or horizontal.

Keywords:
Indoor environmental quality, Student comfort, University classrooms, Indoor air quality, Thermal comfort, Acoustic comfort, Visual comfort

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1. Introduction

1.1. Motivation of the study

Indoor environmental quality (IEQ), which includes thermal, visual, acoustic, and indoor air quality conditions, has been widely investigated in educational buildings through objective measurements and subjective surveys [1–8], with consistent evidence of its impact on student comfort, health, well-being [9] and performance [4, 5, 10, 11]. Among the most robust findings, monitored parameters such as air temperature (T), illuminance (E), sound pressure level (SPL), carbon dioxide (CO_2), show a strong correspondence with perceived satisfaction [8, 12–14]. Reference thresholds of these parameters for educational buildings have been proven to be reliable [8, 13] and supported by well-established standards [15, 16]. In addition, thermal comfort and acoustic comfort emerge as the main drivers of overall environmental quality [1, 7, 8, 10, 11, 17, 18]. Contextual factors, such as occupancy patterns, orientation, lighting use, HVAC control, door opening, solar shading, voice reinforcement system, significantly influence subjective comfort, yet only a limited number of studies have explicitly accounted for them in educational settings [13]. Another common limitation in the literature is that most existing research relies on correlations between averaged objective and subjective data within predefined time windows, without assessing compliance over time. This approach is not suitable for long-term continuous monitoring, which should be based on the time history of the acquired data. Today, the adoption of building information modeling (BIM) and artificial intelligence (AI) for real-time IEQ monitoring and automated control in facility management requires monitoring methods and analyses that can predict IEQ trends over time and allow rapid interventions to maintain optimal conditions [19–21].

The primary objective of this study is to validate a systematic methodology for assessing the combined influence of IEQ parameters, contextual factors, and student perceptions in university classrooms, using a system designed to long-term monitor environmental changes and support immediate adjustments. The framework may use either a single sensor or multiple sensors, typically wall-mounted to ensure circulation remains unobstructed, which are coupled with a web module to gather subjective feedback.

This study also aims to find the best predictive models of subjective outcomes from objective data. The need is for scenario-based IEQ models that reflect combined IEQ stressors and diverse occupant needs, using building and occupant-related indicators. This would move IEQ guidelines beyond comfort-driven, dose-based metrics [22].

1.2. State of the art on IEQ and comfort monitoring in classrooms and contribution of the present study

To review the state of the art on IEQ and comfort monitoring in classrooms, a scoping review was conducted, and 12 recently published studies were examined [1–4, 7, 8, 12–14, 17, 19, 23]. The methodology and the main outcomes of these studies are summarized in Tables A.5 and A.6.

The purpose of the literature search was to examine the methodologies used across the studies and synthesize their main findings, with the goal of moving beyond the current state of the art and offering new insights. The methodology highlighted heterogeneity and the reported results showed limited reproducibility.

Only 55% of the studies [2, 3, 8, 13, 14, 17, 23] provided two opposite seasons monitoring. On average, 8 classrooms were monitored but of different size and shape, and orientation is not declared to be intentionally chosen. In 61% of the studies [1–3, 7, 12, 14], the classrooms were air-conditioned, while 39% relied on natural ventilation [4, 12–14, 23]; however, none of the studies considered both operating modes.

In the 60% of the reviewed studies that implemented long-term monitoring, data were typically collected during classroom occupancy (around 7 hours per day on average), though not for all parameters [1, 12–14, 17, 19]; the remaining 40% relied on short measurement campaigns [2, 4, 8, 23].

Only two studies used a single multi-sensor device, whereas most relied on separate sensors to monitor the different parameters. The sensors, positioned at various locations within the classrooms, do not enable long-term IEQ monitoring over the entire academic year. They were positioned at the back of the room in 17% of the studies [3, 4], in the middle of the room in 33% [4, 7, 13, 23], in more than one position in 42% [2, 4, 12, 13], and wall-mounted in 8% [19]. Only 17% of the studies made comparisons among different sensors locations [12, 13], and none of the studies reported validating the measured quantities against laboratory-grade reference instruments. Instead, the majority relied on the manufacturers' stated accuracy specifications, often for devices that were not laboratory grade rated.

In 83% of the studies, the questionnaire administered to the students was adapted from the literature or standards, but none reported piloting the administration process [1–4, 7, 13, 14, 17, 19, 23]. Just 9% adopted simultaneous questionnaire administration throughout the IEQ monitoring period [19], whereas the remaining 91% relied on spot surveys [1, 2, 4, 7, 8, 12–14, 17, 23].

Apart from Weng et al. [14], previous studies in classrooms did not report IEQ indexes based on the compliance in time of a measured quantity with a given threshold, which would have allowed a direct comparison between IEQ domains [24, 25]. Likewise, none of the studies derived comfort indexes, which would have enabled a direct comparison of perceived comfort across domains and against objective indexes. However, the results obtained in the reviewed studies show that the positive correlation between objective and subjective data was assessed in 77% of the cases [1, 2, 4, 7, 8, 12, 13, 17, 19, 23]. In particular, the strongest relationship has been found between objective quantities or indexes and subjective outcomes for the thermal domain in 35% of the cases [1, 12, 13, 17, 19, 23], followed by indoor air quality [1, 4, 13, 19] and the visual domain [1, 12, 13, 17], both at 24%, and acoustic domain at 17% [1, 12, 13].

Contextual factors (e.g., orientation of the classrooms' orientation, solar shading and curtain status, use of artificial lighting and voice reinforcement system, door operation, and number of students) were analyzed in relation to objective IEQ measurements in 50% of the studies [3, 12–14, 17, 23] and subjective responses in 33% [12, 13, 17, 19].

However, to the authors' knowledge, only Morandi et al. [13] have recently and systematically examined contextual influences on IEQ in educational facilities, while other studies either preselected different orientations a priori or interpreted their findings based on a limited set of contextual factors, which is a crucial aspect, as it is closely related to the strategies that facility management should implement to address unfavourable outcomes.

In this context, the aim is to address the methodological shortcomings identified in previous studies and thereby obtain more generalizable results by using classrooms with comparable size and conditions; conducting long-term monitoring across two contrasting seasons; including rooms with opposite orientations; assessing both natural and mechanical operating modes; employing multi-sensor devices that measure all key IEQ parameters and are validated against reference instruments; installing wall-mounted equipment to avoid obstructing occupant circulation; administering concurrent subjective questionnaires; applying IEQ indexes based on temporal compliance and comparable comfort indexes; and simultaneously monitoring relevant contextual factors. On the basis of these premises, the following research questions arise:

1. Do contextual factors influence IEQ quantities, indexes, and student comfort?
2. Are there consistent relationships between overall perceived IEQ and comfort in the four domains? How do they compare to patterns reported in the literature?
3. Is there an agreement between the predictive IEQ indexes and the comfort indexes in the four domains?

2. Methodology

2.1. Case study

The evaluation of IEQ, from both an objective and subjective point of view, was conducted in three identical university classrooms, identified as 1P, 3P, and 4P classrooms, at the Politecnico di Torino (Italy) campus, with a capacity of 220 students each. The size of the classrooms is approximately 19.5 m in length, 11 m in width, and 4.5 m in height, resulting in a volume of approximately 965 m^3. The classrooms are located on the bare floor of a standalone single-storey building, constructed in 2017. They are positioned at the corners of a rectangular layout and connected by a distribution corridor. Classroom 2P, which is within the same building, was also included in the study, but only for the subjective survey, since there was no monitoring of the IEQ parameters. Figure 1 shows the top view of the building with classrooms identified as 1P, 2P, 3P, and 4P and the front view to the south-east of the building.

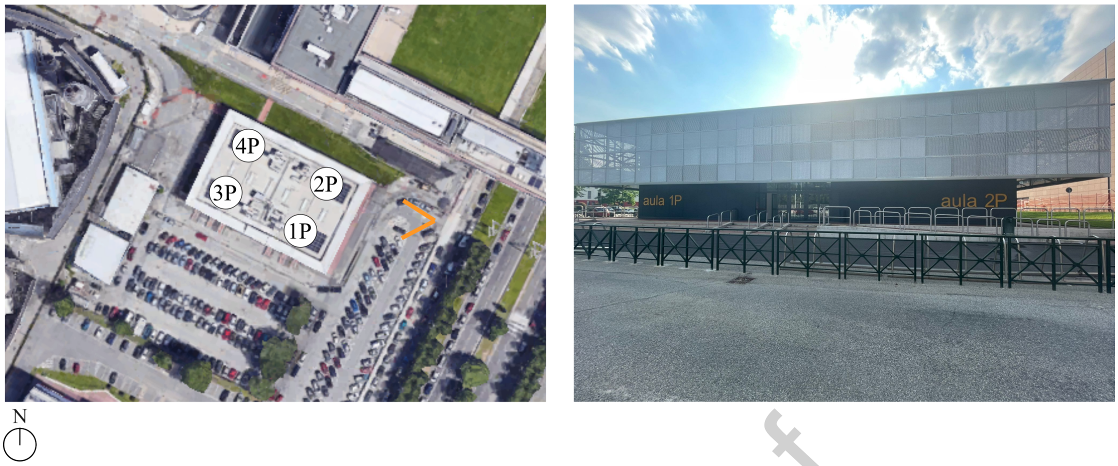


Figure 1: Classrooms 1P, 2P, 3P, 4P in the university campus of Politecnico di Torino (Italy) (left) and south-east front view of the building (right).

The classrooms feature a fully glazed wall along the length of the room, which provides a view of external areas designated for parking (classrooms 1P and 3P, south-west oriented) and pedestrian passage (classrooms 2P and 4P, north-east oriented) in front of a tall building, respectively. In classrooms, there are sound absorbing panels installed on the ceiling and parts of the rear and side walls, along with an autonomous air conditioning and ventilation system equipped with remotely manageable all-air systems. Each classroom is equipped with 24 LED luminaires of 29 W, with a luminous flux of 3600 lumen, a correlated color temperature of 4000 K and a color rendering index higher than 80. Windows and glazed doors are provided with sound absorbing sunscreen roller blinds.

2.2. Classroom lighting and acoustic characterization

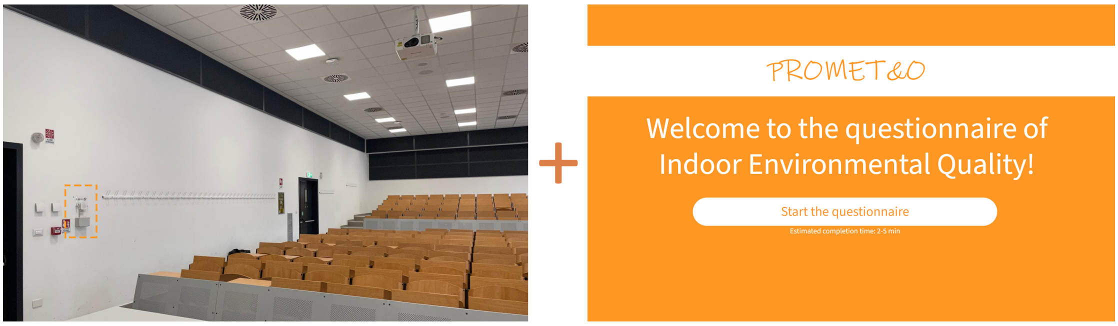
With electric lighting alone, the average horizontal illuminance in all considered classrooms never exceeds the 500 lx required by EN 12464-1:2021 [16]. Nevertheless, it complies with the earlier edition of the standard (EN 12464-1:2011 [26]), which set a maintained average horizontal illuminance of 300 lx for classrooms.

The classrooms were acoustically characterized to meet the passive acoustic requirements of the buildings according to the Italian Ministerial Decree of 23 June 2022 (General Series no. 183 of 06-08-2022) [27], which refers to the standard UNI 11532-2 [28]. The reverberation time averaged between 250 Hz and 2000 Hz is 0.89 s, which is consistent with the requirement. Classrooms were also evaluated for speech clarity and speech intelligibility using the mid-room measured early-to-late arriving sound energy ratio, Clarity $C_{50,0.5-1kHz}$ [29] and Speech Transmission Index (STI), respectively [30]. Measurements were carried out at three reference positions (front row of desks, 3 m from the typical position of a lecturer; central row, 9 m; rear row, 17 m), in unoccupied condition. Clarity $C_{50,0.5-1kHz}$ is 3.7 dB (st. dev. 1.7 dB), and this value exceeds the minimum admissible threshold of 2 dB according to UNI 11532-2 [28]. STI for both "normal" and "high" vocal effort [31] is ≥ 0.62, without the voice reinforcement system, meeting the recommended threshold for schools [30].

2.3. PROMET&O System

The PROMET&O system was developed for the evaluation of the relationships between IEQ, comfort, personal and behavioural factors, in classrooms and offices [32]. It allows long-term IEQ monitoring through a multi-sensor device and acquisition of occupant feedback through an ad-hoc developed questionnaire. A specific PROMET&O multi-sensor was developed in the framework of the project [33, 34], but other commercial devices can also be used for IEQ monitoring and included in the system for data analysis and visualization. The device can be installed flush with the walls or placed on the teacher's desk and measures thermal, acoustic, lighting, and air quality parameters. The data is then sent preprocessed to the cloud platform, where it is stored. This data can be accessed by users through a user-friendly dashboard, developed ad-hoc, where an objective index for each domain is displayed along with the comfort index. The former is calculated from the monitored parameters through the compliance in time principle; the latter is calculated from the responses given by the user to the questionnaire provided with a link to the PROMET&O website. In such a way, objective data regarding actual IEQ can be matched with subjective data provided by users to encourage proactive behaviour. For this specific study, students were not allowed access to the dashboard in which objective data are shown.

Figure 2 shows the multi-sensor flush to the wall in classroom 4P (left) and the home screen of the PROMET&O questionnaire website (right).



Welcome to the questionnaire of Indoor Environmental Quality!

MULTISENSOR
Monitoring of IEQ parameters

QUESTIONNAIRE
Subjective feedback collection

Figure 2: Multi-sensor flush to the wall in classroom 4P (left) and homescreen of the PROMET&O questionnaire webpage (right).

2.4. Monitoring scheduling

Objective and subjective evaluations were conducted in two different academic semesters to capture information from both the spring and winter periods. The selected days, from 30 May 2023 to 9 June 2023, and from 8 January 2024 to 19 January 2024, were chosen, including only lecture days from Monday to Friday and excluding the 2 June, which is holiday in Italy. Moreover, during the objective and subjective monitoring process, contextual information, including outdoor temperature (T_{out}), the status of solar shadings and curtains, the use of artificial lighting and voice reinforcement, the opening and closing status of doors (three leading to the outside and two to the corridor), and the number of students present in the classrooms were collected.

The students were asked to complete the questionnaire during the last 15 minutes of the 1.5 hour (90 minutes) lecture slots, a time slot intentionally allocated by the professors so that the responses would reflect their comfort across the four IEQ domains at the time of the lecture itself. The monitoring hours were from 8:30 am to 7:00 pm, and in total 532 responses were collected in both periods. The survey was approved by the ethical committee of the Politecnico di Torino (protocol n. 55577/2025).

2.5. IEQ monitoring

The commercial multi-sensor device Aircare (Aircare, Rome, Italy) [35] connected to the PROMET&O system was used to monitor the indoor environmental quality in the three classrooms. The parameters used for the analysis included air temperature (T), relative humidity (RH), A-weighted sound pressure level (SPL), vertical illuminance (E_v), carbon dioxide (CO_2) and particulate matter ($PM_{2.5}$ and PM_{10}). The measured data are collected every 5 minutes for each quantity and sent to the cloud via Wi-Fi connection. The multi-sensor was tested in the TEBE L^{2}AB within the Department of Energy of Politecnico di Torino, against more accurate laboratory-grade sensors for each physical variable. Details are available in Table B.7. Good accuracy was shown for air temperature and carbon dioxide, with maximum MAEs (mean absolute errors) of 1.7 °C and 273 ppm. RH is accurate in winter but degrades in summer (maximum MAE 8.2%); illuminance is systematically underestimated (MAE equal to 230 lx), PM readings are lower than the reference in a range of 2.9 μg/m^3 to 6.8 μg/m^3 for PM2.5 and PM10, respectively, and the A-weighted mean SPL differs by 0.7 dB on average.

When these accuracies are compared with the Just Noticeable Difference (JND) of the measured quantities, it appears that for most of them the differences to the real value are perceptible. Observer acceptance of the difference in illuminance is up to 19% when matching the illuminance of one space with another [36]. This result is an admissible difference of 100 lx between the reference and multi-sensor measurements for values of about 500 lx, which is less than the MAE of 230 lx. Regarding temperature, a JND (with 95% accuracy) of 0.92 °C (±0.05 °C), in a temperature range of 23 to 25 °C, was found in [37]. This value is lower than the obtained MAE of 1.7 °C. In terms of SPL, the difference is within the JND of 1 dB [29]. CO_2 is not a perceptible quantity. However, the values obtained by applying the manufacturer uncertainty to the measured reference data is 77 ppm, which is lower than the MAE.

2.5.1. In-field set up

Figure 3 shows the specific installation points of the wall-mounted multi-sensors in classroom 1P, 3P, and 4P. Each sensor was numbered by the Politecnico di Torino staff and these codes were maintained to facilitate the interpretation and use of the study results by the staff itself. One multi-sensor for each classroom, positioned flush to the internal wall close to the entrance beside the teacher's desk, was connected to the electrical grid and ran continuously during the spring and winter periods. These sensors, identified with a blue circled rectangle (i.e., sensors number 1, 3, and 6), were placed about 1.5 m from the floor (illustrated in Figure 2), which is strategic to capture data that truly reflect the environmental conditions experienced by the occupant seated [19]. The other three multi-sensors in classrooms 1P and 4P were either connected with a power bank or supplied with batteries and ran only in the spring period. These are identified with a blue non-circled rectangle (i.e., sensors number 2, 4, 21, 22, 23 and 24), and were placed about 2.3 m from the floor. Shortly after the monitoring process began, the sensor in classroom 2P malfunctioned, resulting in the absence of data from this classroom during the period of interest. During the spring 2023 and winter 2024 monitoring period, all other sensors remained fully operational. Only data from the three multi-sensors connected to the electrical grid were used for comparison with subjective data. The multi-sensors not connected to the electrical grid in classrooms 1P and 4P were used to analyze the influence of sensor position within the same classroom on IEQ data during the spring period. The ad-hoc developed dashboard allowed one to display mean and statistical values across various time ranges.

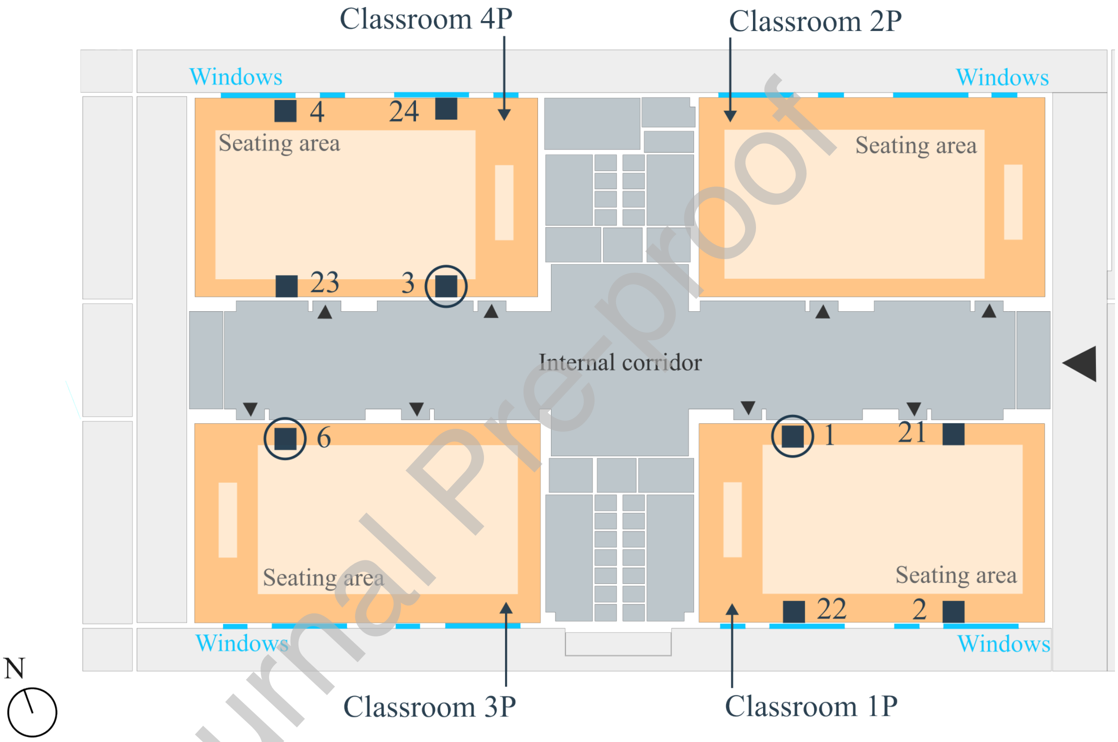


Figure 3: Multi-sensors in the university classrooms 1P, 3P and 4P. The circled sensors were connected to the electrical grid, whereas the non-circled sensors were not connected.

2.6. IEQ indexes

As described in the standard EN 16798-2 [38], an IEQ index can be calculated as the percentage of time in which an indoor environment parameter is within a defined category of expectation (I - high level of expectation, II - medium level of expectation, III - moderate level of expectation, IV - low level of expectation). For typical buildings, Category II limits are generally recommended as the design standard.

In this study, the quality index for each domain is defined as the percentage of time during which the corresponding monitored parameter complies with the identified threshold, calculated for each 1.5 hour lecture slot (a total of 18 data points are acquired, given the acquisition every 5 minutes).

Each parameter can also be obtained from the application of a specific predictive model, as in the case of the adaptive thermal comfort model in spring [39, 40]. This objective index is intended to be compared with a comfort index derived over the same time period. Table 1 presents the monitored parameters and the reference thresholds used to calculate the index for each domain. The overall IEQ index is derived as the mean value of the four domain quality indexes. In the following paragraphs, a detailed description of each quality index is provided.

Table 1: Parameters monitored through the multi-sensor and thresholds for domain quality indexes.

Parameter	**Threshold**	**Reference**	**Domain**
Temperature	Winter: (21-23) °C	EN 16798-1:2019	Thermal
	Spring: adaptive thresholds (cat. I)		
Relative humidity	(25-60) %		
Vertical illuminance	≥ 120	-	Lighting
A-Weighted SPL	≥ 55 dB	-	Acoustic
Carbon dioxide (ΔCO_2)	≤ 550 ppm	EN 16798-1:2019	IAQ
Particulate matter ($PM_{2.5}$)	Annual mean $\leq 10\ \mu g/m^3$	EN 16798-1:2019 (WHO Guidelines)	
Particulate matter (PM_{10})	Annual mean $\leq 20\ \mu g/m^3$		

2.6.1. Thermal comfort and indoor air quality

Thermal condition in spring was assessed with the EN 16798-1 adaptive comfort model using Category I limits [15], based on monitored indoor temperature and outdoor temperatures retrieved online for Turin [41]. In winter, Category I heating-season thresholds from EN 16798-1 were applied, consistent with those used for mechanically ventilated buildings. The adaptive comfort model can also be reliably applied in air-conditioned buildings when occupants retain some control over the indoor environment, such as in this case study, where students were allowed to keep the glazed doors open in spring despite air-conditioning [12, 17, 42–44].

The thresholds for CO_2, PM2.5 and PM10 were also defined according to the EN 16798-1 standard [15]. The Category I for CO_2 has been assumed and a default outdoor CO_2 concentration was considered equal to 400 ppm according to standard

EN 16798-2 [38]. The IAQ index was obtained as a mean value of the percentages of compliance in time of each parameter with the respective threshold.

2.6.2. Visual quality

EN 12464-1:2021 [16] sets a required maintained horizontal illuminance E_h on the task area for classrooms; accordingly, a linear regression model was developed to estimate the mean desk-level horizontal illuminance from the vertical illuminance E_v measured by the wall-mounted multi-sensor near the teacher's desk. Measurements were carried out at the same time of both E_h and E_v in classroom 3P, south-west oriented, and 4P, north-east oriented. The PRC luxmeter (PRC Krochmann, Germany) was used to measure horizontal illuminance on student desks in 20 uniformly distributed measurement points. Different lighting conditions were identified, and measurements were carried out on two different days at the end of February 2024.

Taking into account a value for E_h equal to 300 lx, according to standard EN 12464-1:2011 [26], that was in force when the lighting system was designed and installed, the corresponding value for E_v was calculated with the defined models, which are $E_v = 0.5 \cdot E_h - 36.9$ [lx] in classroom 3P and $E_v = 1.2 \cdot E_h - 232.5$ [lx] in 4P. The obtained values are 117 lx and 121 lx in the 3P and 4P classrooms, respectively; therefore, given the minor difference between the two values, a unique threshold has been defined for both classrooms equal to 120 lx as the minimum E_v monitored through the multi-sensor. Since the position, the characteristics of the classrooms, and the relative arrangement of the multi-sensor and the horizontal plane are the same, the model was also extended to the other two classrooms (1P and 2P). The developed model compensates for differences in measurement location (vertical instead of horizontal), as well as for sensor measurement error. One should note that the identified model is site-specific and should not be interpreted as an absolute relationship. The relationship between E_v and E_h should be determined based on the specific characteristics of the environment, the lighting system and the sensors positions (vertical and horizontal).

2.6.3. Acoustic quality

For acoustic quality, in the same way as it was done for visual quality, a predictive model was developed to assign a threshold to a vertical (wall-mounted) measure, based on measures at ear-level (1.2 m) in the sitting area. In classroom 3P, taken as reference, the level of unoccupied background noise measured in the center of the room with an NTi Class A microphone (NTi, Liechtenstein) was 36 dB(A). Speech-shaped signal SPLs were then recorded using a NTi TalkBox source at the teacher's desk equipped with an omnidirectional Mipro cheek microphone (Taiwan), and the NTi microphone at four source–receiver distances along the central longitudinal axis, plus one position flush to the wall near the multi-sensor microphone. The wall-flush configuration yielded SPL values 4 dB higher than those measured at the four positions in the room, on average. For the assessment of acoustic quality, a minimum signal-to-noise ratio of 15 dB was adopted to ensure satisfactory speech intelligibility in classrooms (ISO 9921 [31]); accordingly, any SPL measured by the wall-mounted multi-sensor $\geq$ 55 dB(A) was classified as conforming.

2.7. Comfort indexes derived from student feedback

Student feedback along with their personal information and preferences was collected voluntarily through an online questionnaire developed according to the ISO 28802 standard [45]. The questionnaire, shown in Appendix C, has been validated through a pilot test [46]. The data acquisition process includes four levels:

1. The first page includes a question on overall satisfaction with all IEQ domains using a 4-point scale represented by colored smiley faces, ranging from positive (dark green and light green) to negative (yellow and red) perceptions.
2. In the case of a positive overall evaluation, the subject selects which domains is particularly satisfied with. The light green smiley chosen at level 1 assigns a comfort index (or comfort percentage) of 75% to each selected domain, while the dark green smiley assigns 100%. Unselected domains do not receive a score.
3. In the case of a negative overall evaluation at level 1, the subject selects which domains are particularly dissatisfied with and specifies the reasons using domain-specific 4-point scales, ranging from “very annoying” to “not annoying” for acoustic comfort, from “very uncomfortable” to “not uncomfortable” for visual comfort, and from “very smelly” to “not smelly” for air quality. Thermal comfort is evaluated using a 7-point scale from +3 (hot) to −3 (cold), with 0 in the middle (neutral) [38] and on a 4-point scale from “very draughty” to “not draughty” for air velocity. The scores on the 4-point scales are converted into comfort percentages of 25%, 50%, 75% and 100%. For the 7-point scale, the 25%, 50%, 75% are assigned to the + /- 3, +/- 2, +/-1 scores, respectively, while the 100% are assigned to 0. The thermal comfort score is calculated as the average between the 7-point scale and the air velocity 4-point scale, both expressed as a percentage.
4. Additional questions are asked for each comfort aspect to better understand the causes of discomfort (e.g., to indicate specific noise sources such as people chatting, building systems, or road traffic, or specific glare sources such as windows, lamps, reflective surfaces, as well as other possible causes listed in Appendix C).

For example, if on the first page the subject selects the dark green smiley face and then on the second page the subject indicates higher satisfaction with the thermal and acoustic conditions, as a result, the comfort indexes for thermal and acoustic domains both attain 100%, while the indexes for visual and air quality remain unscored. If, on the opposite, the subject selects a yellow smiley face on the first page and selects the visual domain in the second page as the domain for which she/he is particularly dissatisfied with, a 4-point scale ranging from "very uncomfortable" to "not uncomfortable" appears on the third page. If the subject scores 2 on the scale, she/he gathers a comfort index equal to 50% for visual domain, while 100% is scored for the other domains.

The comfort index for each domain, calculated in percentage as detailed above, is also referred to 1.5 hour lecture slot by averaging the comfort indexes of the different subjects. This comfort index is compared with the objective index derived over the same time slot. The overall comfort index is derived as the mean value of the four domains.

During the spring period, 94 questionnaires were completed in classroom 4P. No responses were collected in classrooms 1P and 2P and in classroom 3P only 10 questionnaires were completed. During the winter period, data was collected with 107, 91, 189, 41 questionnaires completed in classrooms 1P, 2P, 3P, and 4P, respectively. Data from classrooms 1P, 2P, and 3P were excluded due to the insufficient number of responses in the spring period; thus, a total of 532 questionnaires were collected, a number higher than the average of questionnaires collected in similar reference studies shown in Table S1 [1–4, 7, 8, 12–14, 17, 19, 23], which is equal to 371. The 4P classroom questionnaires were used to compare responses from the spring and winter periods. Questionnaires from classrooms 1P, 2P, 3P, and 4P were used for comparisons during the winter period.

2.8. Statistical analysis

To perform statistical analyses, the dark green, light green, yellow, and red smiley faces representing overall IEQ satisfaction were assigned values 1, 2, 3, and 4, respectively. When overall IEQ dissatisfaction was indicated by a red or yellow smiley, selected unsatisfactory domains were assigned a score of 1, while unselected domains received a score of 2. In contrast, when overall satisfaction was indicated by a dark or light green smiley, selected satisfactory domains were assigned a score of 4, and unselected domains received a score of 3. Note that the numbering is reversed between scales: 1 indicates high overall satisfaction but low satisfaction for individual domains.

Pearson's coefficient was calculated to find correlations between students overall satisfaction and satisfaction related to individual domains. The Mann–Whitney U test [47] was used to compare overall, thermal, acoustic, visual, and IAQ satisfaction in the 4P classroom between the spring and winter periods. The test allows to rank the observations from two independent groups and assesses whether one group systematically produces higher (or lower) ranks than the other considering a significance level of 0.05.

The Linear Mixed Model (LMM) [48] was applied to examine whether contextual factors (number of students, use of solar shading, door and window openings, lighting, and voice reinforcement usage) and personal and behavioral information from the questionnaire influenced overall, thermal, acoustic, visual, and IAQ satisfaction. In LMM, overall, thermal, acoustic, visual and IAQ satisfaction were the dependent variables, the classrooms were treated as a random effect, and contextual, personal and behavioural variables were included as fixed effects.

3. Results

3.1. Contextual conditions

Table 2 shows the percentages of lessons slots in which a certain contextual condition occurred during the two monitoring periods in the four classrooms.

The average occupancy of the students was between 9% and 19%. The solar shadings were open for more than 50% of the time, apart from classroom 3P in spring, for which they were open 12% of the time; the lights were all turned on for more than 85% of the time, apart from classroom 4P in winter, where only 8 lamps were turned on for more than 98% of the time; and professors used the voice reinforcement system during lectures from 16% to 41% of the time in spring and from 70% to 81% in winter. At least two doors facing the outside were open for approximately 57% of the time in spring, while the doors facing the corridor were all closed for more than 96% of the time.

3.2. Indoor environmental quality monitoring

Table 3 reports the mean values (8:30 am to 7:00 pm) and standard deviations of the parameters monitored in the classrooms 1P, 3P, and 4P in spring and winter. Non compliant values are highlighted in italic bold.

Regarding thermal comfort and IAQ, all parameters remained within the optimal ranges in both seasons, except for the winter air temperature in classroom 4P, which fell below the 21 °C threshold specified by EN 16798-1, Category I [15].

Only in spring the mean A-weighted sound pressure levels were below the 55 dB threshold in all three classrooms, confirming the less frequent use of the voice reinforcement system compared to winter, as reported in Table 2.

Table 2: Percentages of lessons slots in which a certain contextual condition occurred during the winter (W) and spring (S) monitoring periods in the four classrooms.

Contextual conditions		**Percentages of contextual conditions**							
		1PS	2PS	3PS	4PS	1PW	2PW	3PW	4PW
Student occupancy		13.6	9.1	13.7	7.7	19.1	15.9	17.3	17.3
Solar shadings	Closed	0	0	0	12.5	10	0	10	40
	Half-Open	12.5	0	87.5	12.5	40	10	40	0
	Open	87.5	100	12.5	75	50	90	50	60
Lamps (from the back of the classroom)	Off	16.1	0	0	14.3	2.9	5.7	2.9	0
	4 On	0	0	5.4	0	0	0	0	1.4
	8 On	0	0	0	0	0	0	0	98.6
	12 On	0	0	0	0	0	0	0	0
	16 On	0	0	0	0	0	0	1.4	0
	20 On	3.6	0	0	0	0	0	2.9	0
	24 On	80.4	100	94.6	85.7	97.1	94.3	92.9	0
Voice reinforcement	No	83.9	73.2	58.9	83.6	25.7	30	18.6	37.1
	Yes	16.1	26.8	41.1	16.4	74.3	70	81.4	62.9
Glazed doors facing outside	Closed	0	0	0	0	95.7	100	100	95.7
	1 Open	33.9	37.5	30.4	36.4	4.3	0	0	4.3
	2 Open	60.7	53.6	64.3	50.9	0	0	0	0
	3 Open	5.4	8.9	5.4	12.7	0	0	0	0
Doors facing the corridor	Closed	100	100	100	96.4	100	100	100	100
	1 Open	0	0	0	3.6	0	0	0	0
	2 Open	0	0	0	0	0	0	0	0

During winter, the vertical illuminance measured by the wall-mounted sensor in classrooms 1P and 4P was slightly below the 120 lx threshold. As shown in Table 2, 1P exhibited a lamp switch pattern comparable to the other classrooms, whereas in 4P it was consistent with the lower number of lamps switched on during this period.

3.2.1. Comparison among multi-sensors position

Data from the four multi-sensors in classroom 1P and 4P in the spring period are reported in Figures 4 and 5 for comparison.

In classroom 1P during spring, air temperature was about 2 °C higher at the corridor-side front wall (multi-sensor 1) and at the outdoor-side back wall (multi-sensor 2). This difference is best attributed to the placement of the sensor near the corridor door and the glazed doors, which were often open for access even during lessons. The plausibility of the readings from multi-sensor 1 was verified by comparing with multi-sensor 6 in classroom 3P, which was installed in an equivalent location and in a classroom with the same orientation.

The sound pressure level and the $PM_{2.5}$ did not show marked differences among the sensors. Multi-sensors 22 and 24 recorded the lowest values of $PM_{2.5}$ in the two classrooms probably due to their proximity to the windows. Figure 5 shows large differences in illuminance between the multi-sensors, driven by daylight availability and lamp switch patterns. In classroom 1P, multi-sensor 21 recorded the lowest illuminance, consistent with the lower share of lesson slots with lamps reported in Table 2.

Table 3: Mean values (m.v.) and standard deviations (s.d.) of the monitored parameters (P) in classrooms 1P, 3P, 4P in the spring and winter periods, whose thresholds are reported in Table 1. Incompliant values are highlighted in italic bold.

P	**Spring period**						**Winter period**					
	1P		**3P**		**4P**		**1P**		**3P**		**4P**	
	m.v.	**s.d.**	**m.v.**	**s.d.**	**m.v.**	**s.d.**	**m.v.**	**s.d.**	**m.v.**	**s.d.**	**m.v.**	**s.d.**
T_{in} [°C]	26.3	0.7	26.8	0.5	25.3	0.8	22.8	0.9	21.6	0.7	***20.4***	1.4
RH [%]	47.9	3.9	47.1	3.8	49.2	4.6	28.4	4.6	30.6	4.6	32.8	5.0
CO_2 [ppm]	699	242	686	162	633	210	557	146	567	125	527	91
PM2.5 [μg/m^3]	9.4	3.7	9.5	2.7	8.1	3.8	9.4	7.0	9.4	3.4	6.2	3.3
PM10 [μg/m^3]	10.4	3.7	10.5	2.7	9.1	3.8	10.4	7.2	8.4	3.4	7.2	3.3
SPL_A [dB]	***51.0***	8.6	***51.9***	8.8	***49.2***	10.1	56.7	5.9	57.2	7.3	58.7	6.4
Ev [lx]	169	94	203	102	152	106	***99***	33	121	68	***95***	47

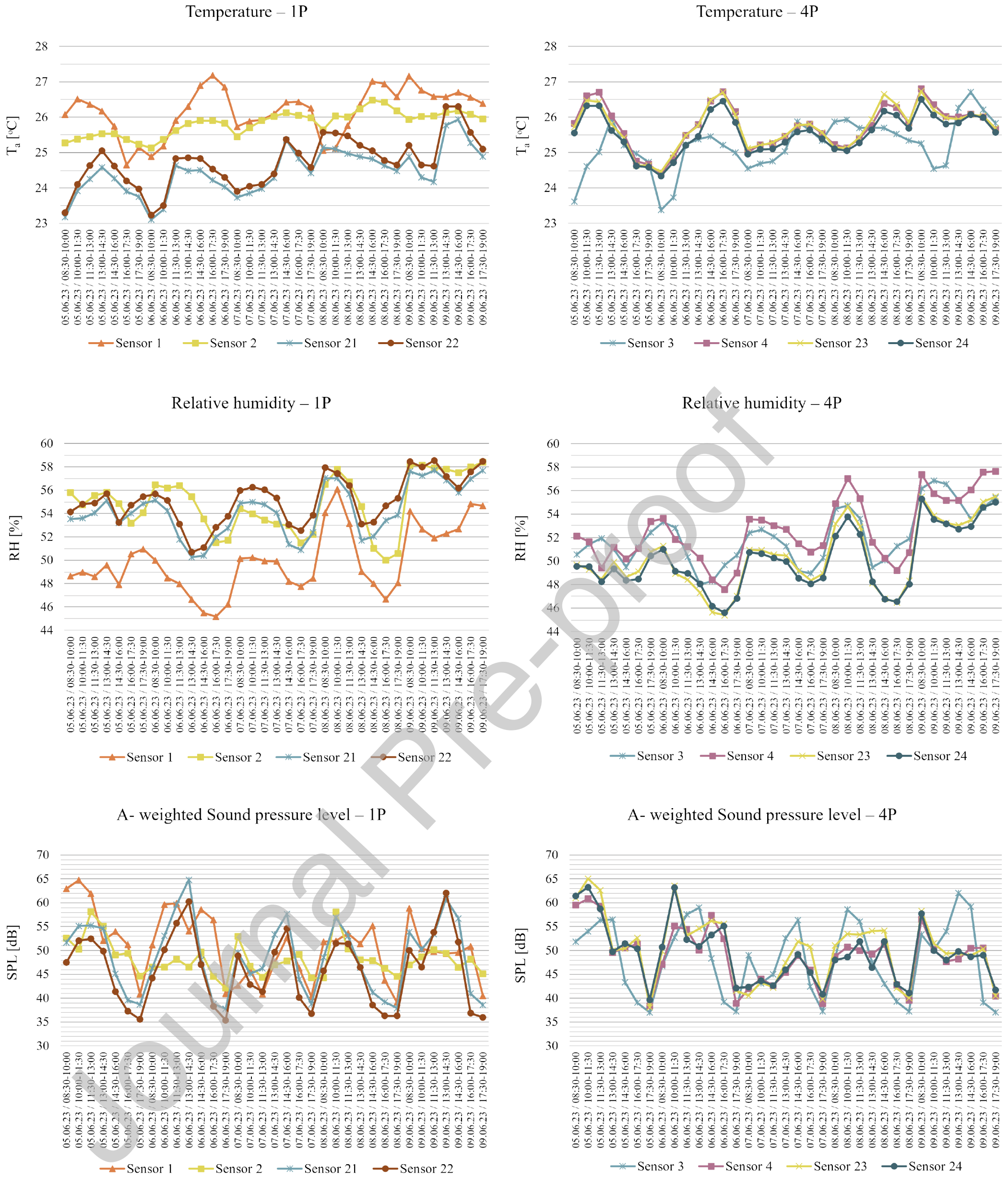


Figure 4: Comparison of temperature, relative humidity and sound pressure level measured by the 4 sensors in 1P and 4P in the spring period, daytime, from 05/06/2023 to 09/06/2023 as mean value for every lecture slot (1.5 hour).

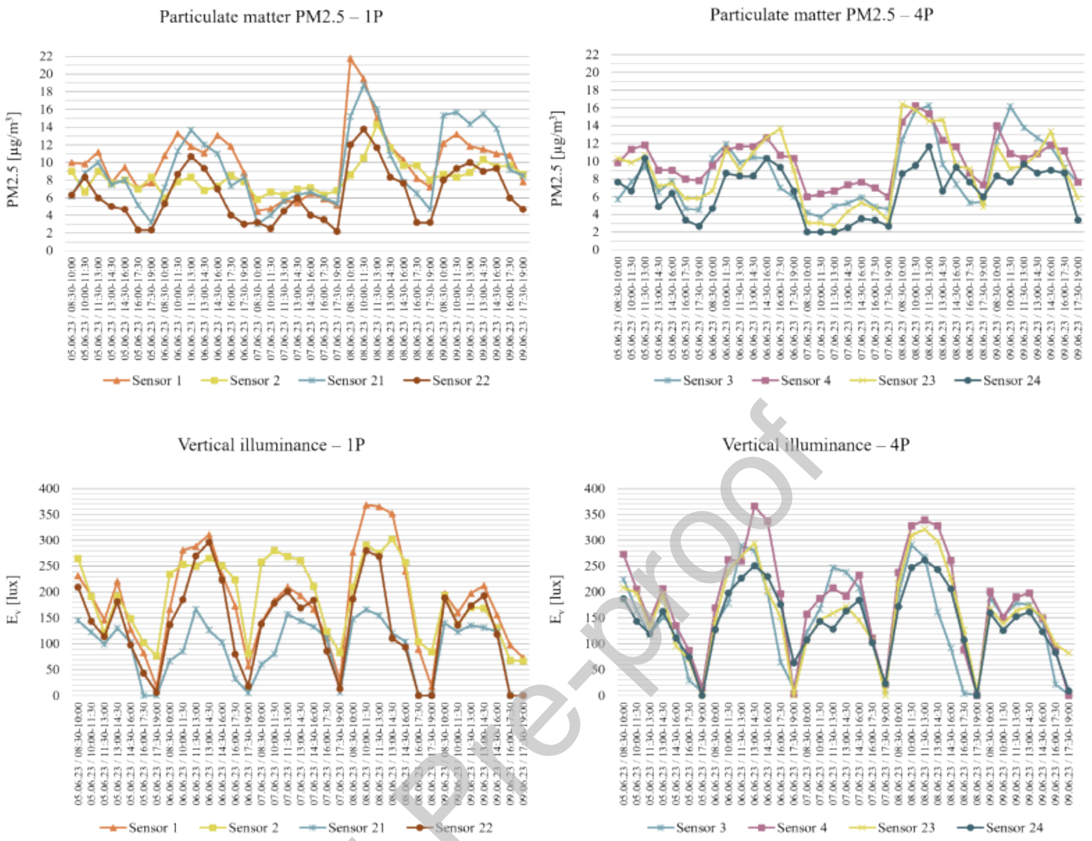


Figure 5: Comparison of particulate matter PM2.5 and illuminance values measured by the 4 sensors in 1P and 4P in the spring period, daytime, from 05/06/2023 to 09/06/2023 as mean value for every lecture slot (1.5 hour).

3.3. Student feedback

Figure 6 shows the percentage of students satisfied, slightly satisfied, slightly dissatisfied, and dissatisfied with the overall environment, based on their responses to the first question of the questionnaire. The lowest satisfaction was observed in classroom 4P during winter, whereas the highest occurred in 3P during winter. This contrast is likely related to their different orientations, namely north-east for 4P and south-west for 3P.

Figure 6: Percentages of students satisfied, slightly satisfied, slightly unsatisfied and unsatisfied with the overall IEQ condition (thermal, acoustic, visual and air quality conditions) in classroom 1P, 2P, 3P and 4P in the winter period and in 4P in the spring period.

The satisfaction of the students with each IEQ domain was analyzed based on the responses to the second question of the questionnaire, which asked them to specify the domains they were satisfied or dissatisfied with. For this comparison, students who selected "satisfied" or "slightly satisfied" were grouped as satisfied, while those who selected "dissatisfied" or "slightly dissatisfied" were grouped as dissatisfied.

As shown in Figure 7, visual comfort achieved the highest satisfaction, with more than 78% of students satisfied in all classrooms, followed by the acoustic domain, which exceeded 62%. The perceived air quality and thermal comfort were both around 50% satisfaction, except in the classroom 4P for thermal comfort in winter, where only 12% of students were satisfied and 88% were dissatisfied.

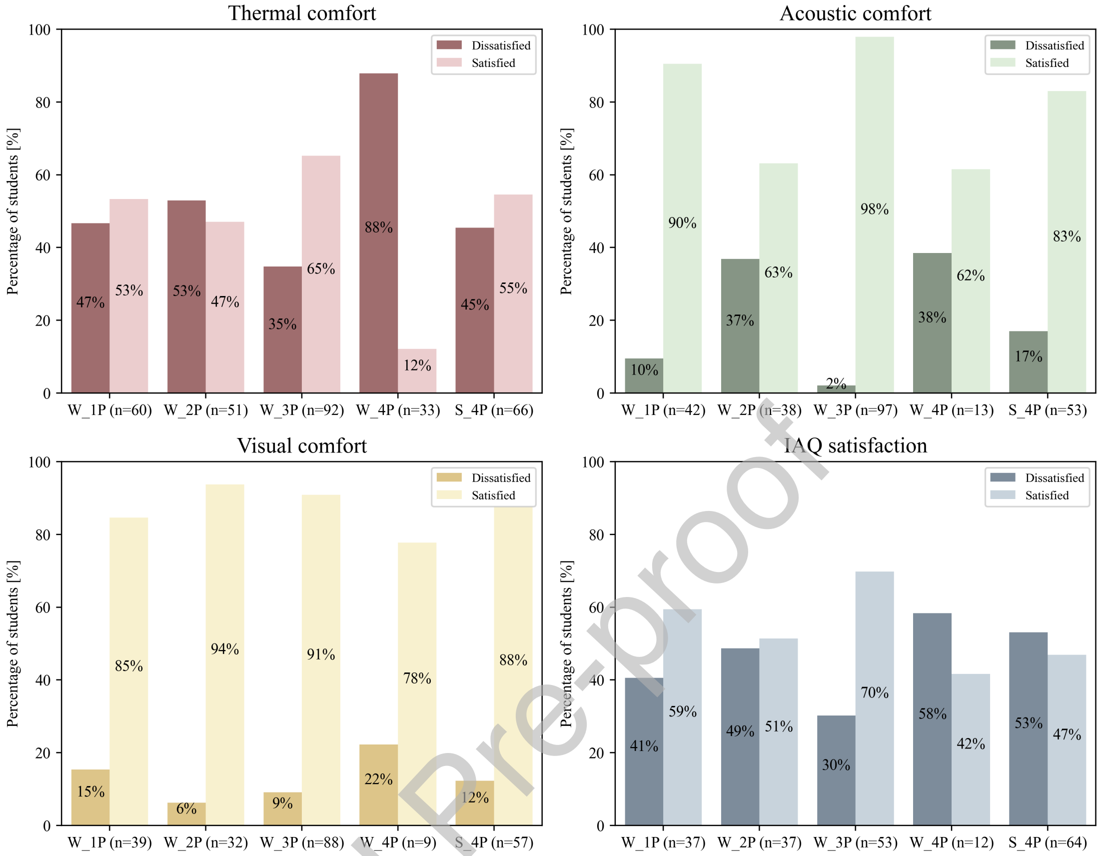


Figure 7: Percentage of students satisfied and dissatisfied with each domain (thermal comfort, acoustic comfort, visual comfort, indoor air quality satisfaction), in classrooms 1P, 2P, 3P, 4P in the spring (S) and winter (W) periods.

Figure 8 provides a more detailed overview of dissatisfaction by domain, showing the distribution of student ratings for thermal (a–b), visual (c–d), acoustic (e), and air quality (f) conditions, on the domain-specific scales reported in paragraph 2.7 (level 3). These detailed assessments were only asked when students first reported dissatisfaction for one or more specific domain.

For thermal sensation, as shown in Figure 8(a), the responses spread across the entire scale in winter, with a peak for “cold” in 4P, but also a peak for “hot” in 1P. “Slightly cool” and “cool” are the most voted conditions in 3P and 2P, respectively. This matches the air temperature patterns measured in classrooms, as shown in Table 3. Indeed, in winter it was below the 21 °C threshold in 4P, while it approached the upper threshold of 23 °C in 1P and was slightly below the central values of the optimal range in 3P. In spring, 4P showed a higher proportion of students reporting "hot" (36.7%), "warm" (36.7%) and "slightly warm" (26.7%) conditions. Although we have applied the adaptive comfort model, this matches quite well the air temperature measured in the classroom, which is slightly below the upper value of the optimal range of 23.5-25.5 °C in the EN 16798-1 standard [15].

Students who were unhappy with the visual environment were fewer than satisfied, as shown in Figure 7. The lowest satisfaction occurred in winter in classrooms 4P and 1P, consistent with the low levels of vertical illuminance recorded in these rooms, which were below the 120 lx threshold. In spring, most dissatisfied students in classroom 4P rated the visual environment as "uncomfortable," despite measured illuminance being above the required threshold. Consistently, Figure 7(d) shows that 42.9% of them would have preferred a "lighter" environment, indicating perceived visual discomfort.

Among the relatively small proportion of students who reported noise discomfort, most described the noise as "annoying" (Figure 8(e)). This pattern appears independently of class size, voice reinforcement use, classroom orientation, or the opening of glazed doors and doors. In winter, students identified conversations and building services as the main noise sources, whereas in spring they mainly pointed to conversations together with road traffic and other outdoor sounds.

Finally, dissatisfied students describe the perceived air quality equally as "not smelly", "slightly smelly" and "smelly", apart from classroom 4P in spring, which is evaluated primarily as "smelly" (69.7%), as shown in Figure 8(f). This is consistent with higher concentrations of carbon dioxide and particulate matter.

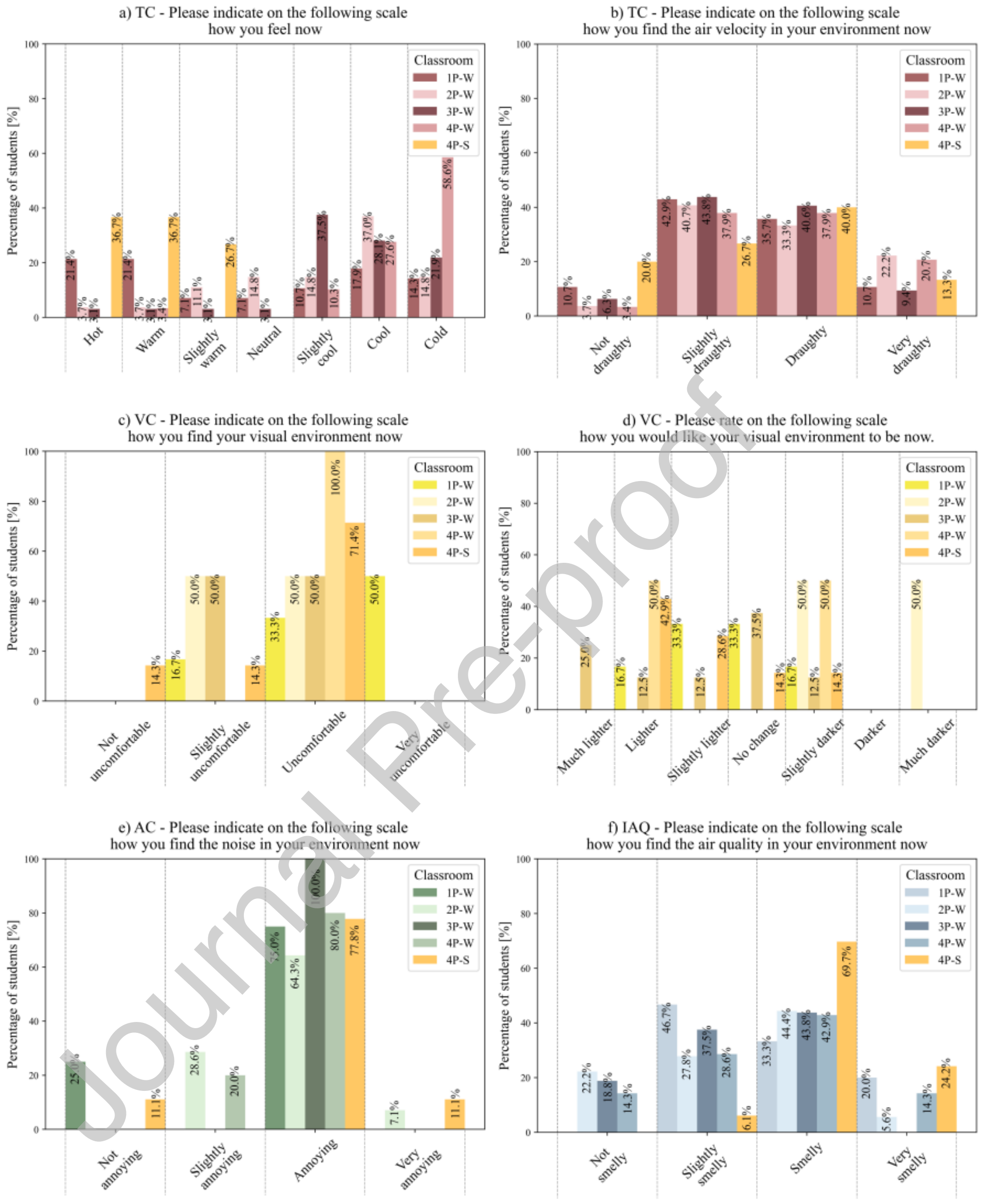


Figure 8: Distribution of student evaluations for the four IEQ domains in the monitored classrooms. For each domain, the histograms report the percentage of responses in the different categories of the questionnaire scales, for classrooms 1P, 2P, 3P and 4P in winter (1P-W, 2P-W, 3P-W, 4P-W) and for classroom 4P also in spring (4P-S). TC = thermal comfort, VC = visual comfort, AC = acoustic comfort, IAQ = indoor air quality.

3.4. Comparison between IEQ indexes and comfort indexes

Figure 9 shows the comparison between the boxplots of the four domain quality indexes and the correspondent comfort indexes referred to 1.5 hour time slots, in the four classrooms in winter and in classroom 4P in spring. Overall, there is reasonable agreement between the two in the thermal and acoustic domains, except for the 4P classroom during the winter and spring period, respectively. The visual objective model always underestimates comfort, while the opposite occurs for the IAQ model. For each classroom and condition (spring or winter), a minimum of 4 (two cases) and a maximum of 13 time slots have been compared, providing good insight for future studies.

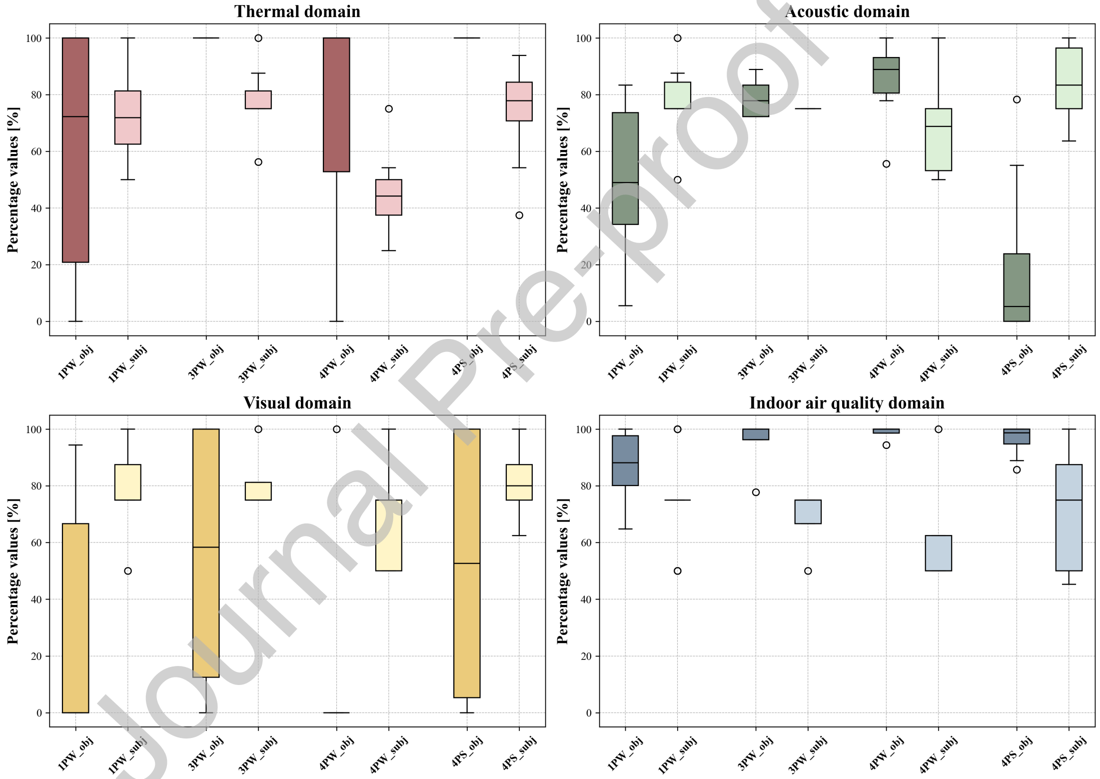


Figure 9: Comparison between the boxplots of the thermal, acoustic, visual, indoor air quality indexes (obj) and comfort indexes (subj), referred to 1.5-hour time slots in the four classrooms in winter (W) and in classroom 4P in spring (S).

3.5. Results of statistical analysis

3.5.1. Correlation between overall and single domain satisfaction

Table 4 shows the mean student satisfaction scores and standard deviation for each IEQ domain. In winter, the highest overall IEQ scores are for classrooms 3P and 1P, which also show the highest thermal scores. The acoustic and visual scores are the highest on average. Note that high values denote low overall satisfaction but high satisfaction in the individual domains. Table 4 also shows the results of Pearson's correlations between overall satisfaction and satisfaction with individual domains, for classrooms 1P, 2P, 3P, 4P in winter and 4P in spring. With a two-tailed significance threshold of $p < 0.01$, every correlation proved statistically reliable. In the winter period, the perception of overall indoor environmental quality was strictly correlated with the perception of thermal comfort, whereas in the spring period it was strictly related to the perception of indoor air quality, which are the lowest rated aspects, respectively.

Table 4: Mean student satisfaction scores and standard deviation for each IEQ domain. High values denote low overall satisfaction but high satisfaction in the different domains. Pearson's correlation between student satisfaction with overall IEQ and with each domain, for classrooms 1P, 2P, 3P, 4P in the winter period and 4P in the spring period. In bold is the highest correlation for each classroom.

Mean satisfaction scores ± st. dev.

Classroom	Overall	Thermal	Acoustic	Visual	IAQ
1P W	2.20 ± 0.81	2.72 ± 1.14	3.01 ± 0.89	2.95 ± 0.90	2.75 ± 0.95
2P W	2.40 ± 0.81	2.52 ± 1.19	2.68 ± 1.03	2.89 ± 0.91	2.60 ± 1.02
3P W	2.05 ± 0.74	2.94 ± 1.02	3.29 ± 0.82	3.17 ± 0.86	2.90 ± 0.81
4P W	2.95 ± 0.92	1.68 ± 1.11	2.37 ± 0.94	2.41 ± 0.84	2.24 ± 0.89
4P S	2.31 ± 0.91	2.63 ± 1.29	2.93 ± 1.11	3.01 ± 1.11	2.54 ± 1.25

Pearson's correlation of overall satisfaction with the single domains

Classroom	Thermal	Acoustic	Visual	IAQ
1P W	**-0.820**	-0.737	-0.727	-0.765
2P W	**-0.844**	-0.768	-0.775	-0.759
3P W	**-0.750**	-0.706	-0.684	-0.722
4P W	**-0.826**	-0.815	-0.753	-0.658
4P S	-0.845	-0.816	-0.808	**-0.853**

3.5.2. *Comparison between overall and single domain satisfaction in spring and winter periods in classroom 4P*

The comparison between the spring and winter periods was made for the 4P classroom. The domain-by-domain comparison confirmed that seasonal conditions influenced student comfort. The Mann–Whitney U test indicated that overall satisfaction increased in spring compared to winter ($p < 0.05$). The satisfaction with the thermal condition also increased in spring ($p < 0.05$), showing that the heating season remains the period of the greatest thermal dissatisfaction in this classroom. Note that for single domains, the assessment scale is inverted compared to overall satisfaction, as described in 2.8. Visual and acoustic satisfaction also increased significantly in spring ($p < 0.05$). However, for perceived indoor air quality, no statistical significance was reached (p equal to 0.21), suggesting either that IAQ conditions varied little between seasons or that students were less sensitive to such variations than to the thermal, lighting, and acoustic domains. To ensure that the sample size was adequate, a post hoc power analysis was performed using the statistical software G*Power 3.1 [49, 50]. Assuming a two-tailed condition, an effect size of 0.5, 94 participants in spring and 41 in winter, and a significance level set at 0.05, the statistical power is 0.70. This confirms that the study had sufficient statistical power, but we acknowledge that future studies with larger and more diverse samples would be valuable to improve generalizability.

3.5.3. *Linear Mixed Model*

The LMM results show that contextual factors affected perception mainly in spring. Specifically, a reduction in the number of doors facing the outdoors that remained open was statistically associated with a higher satisfaction of the students with the overall IEQ, the thermal environment and the IAQ, with coefficients β of 0.981 ($p = 0.000$), -1.02 ($p = 0.002$) and -0.999 ($p = 0.002$), respectively. Furthermore, the decrease in the glass area screened was related to the improvement of overall, thermal, acoustic, and visual satisfaction, with coefficients β equal to 0.670 ($p = 0.0002$), -0.934 ($p = 0.0002$), -0.712 ($p = 0.001$), -0.560 ($p = 0.003$), respectively.

Concerning personal and behavioural questions, students who declared having control on solar shading exhibited a statistically significant association with the improvement of overall, thermal, acoustic, visual and IAQ satisfaction (p-value equal to 0.0002, 0.002, 0.002, 0.001, 0.005, respectively). Students for whom an unsatisfactory IEQ did not significantly reduce their well-being were more satisfied with overall and thermal quality (p-value equal to 0.0008 and 0.012, respectively). Students who declared having no control over the heating system were more dissatisfied with overall, thermal, and IAQ conditions (p-value equal to 0.011, 0.002, 0.019, respectively).

All reported p-values were adjusted for multiple comparisons using the Bonferroni correction [51].

4. Discussion

The main findings of this study are discussed below in relation to the research questions related to (i) the influence of contextual factors on IEQ monitoring and student perception; (ii) the relationship between overall perceived IEQ and comfort across the different domains; and (iii) the agreement between estimated thermal, acoustic, visual, and air quality indexes and comfort indexes. In the following, the consistency of the spring subjective data is limited due to fewer survey responses than in winter, with data available only for classroom 4P.

4.1. Contextual factors and IEQ monitoring

Contextual factors were not consistently analyzed in the literature, either in relation to IEQ measurements or, to a lesser extent, from a subjective perspective. Instead, their monitoring is mandatory to better justify discomfort and address negative outcomes. It was found they both affect objective and subjective data. About the objective results, the lower air temperature in winter in classroom 4P compared to classrooms 1P and 3P can be explained by the orientation, which is north-east for 4P and south-west for 1P and 3P. The infrequent operation of the voice reinforcement system resulted instead in a lower SPL in spring than in winter, and the lower illuminance observed in 4P during winter was likely attributable to the reduced number of luminaires that were switched on.

Contextual conditions likewise influence IEQ monitoring outcomes depending on the placement of the sensors [12, 52]. Placing an air-temperature sensor on a classroom wall can bias readings compared with the room centre, because the measurement is influenced by nearby surface temperatures and radiative effects as well as local airflow. As a result, the temperature at the sensor location may differ from the conditions in the occupied zone, especially in perimeter areas near external walls or windows [53]. The same is true for sound pressure level [54], lighting parameters [55] and for air pollutants [56]. To ensure comparable results between rooms, sensors should be installed on horizontal surfaces, away from occupants, and sufficiently far from doors, windows, and ventilation inlets. However, horizontal placements (e.g., on the teacher's desk [13]) must not obstruct circulation and should allow long-term monitoring. A practical solution is to place the sensors on the interior wall midway between the teacher's desk and the rear wall, preferably on the wall on the side of the corridor, as in the present study. In this case, the conversion between vertically (wall-mounted) and horizontally (close to the desks) measured data is mandatory. Selecting the same wall mount position in each classroom improves comparability between rooms and seasons. Integrate data from multiple sensors and relate them to clustered subjective responses by zone, is also indicated [57].

4.2. Contextual factors and student perception

Regarding subjective outcomes, student satisfaction with IEQ in spring was found to increase when exterior doors are opened less frequently, the glass screened area is reduced, and solar shading can be manually controlled. Students who were aware that they had no control over the heating system were more dissatisfied. Similarly, Nico et al. [58], found that when the microclimate control is increased in university classrooms, the feeling of satisfaction with environmental conditions improved. Classroom orientation can also explain the lowest overall IEQ satisfaction in winter in classroom 4P and the highest recorded in 3P, followed by 1P (Figure 6). In Figure 7 a similar pattern emerges for thermal satisfaction, with 4P showing the poorest scores and 3P the best. On the other hand, the lower visual satisfaction in winter in 4P compared to 3P, 2P and 1P may also be attributable to the smaller number of lights switched on. These results align with previous research showing that contextual factors play a significant role in IEQ. For example, Papadopoulos et al. [12] showed that visual satisfaction mainly depends on daylight availability. They also reported that acoustic comfort is affected by outdoor noise. However, this study did not monitor contextual factors; it only interpreted the results based on contextual conditions assessed at the end of the study. In contrast, Morandi et al. [13] recently conducted a systematic investigation of contextual factors and confirmed that façade orientation strongly affects indoor-condition variability and, consequently, the distribution of sensation votes. In particular, classrooms with a south or south-west orientation showed higher thermal sensation votes than those oriented north or north-west. They also reported that the building's external context affects indoor noise, and that windowless rooms worsen perceived air quality.

Based on these findings, monitoring should include contextual variables in addition to environmental data. Examples include monitoring door and window operation, detecting occupancy, and assessing electric lighting use, leveraging building automation to enhance comfort while reducing energy consumption [59, 60].

4.3. Relationship between overall perceived IEQ and comfort across the different domains

The relationship between perceived IEQ and comfort across different domains may be shaped by multiple factors, including climate, building type, and the extent to which occupants can control the indoor environment [61]. In university classroom settings, several studies have examined these relationships, yielding differing results. In this study, in winter, overall perceive IEQ was strongly associated with thermal comfort, while in spring it was more closely related to indoor air quality. These were also the least satisfactory domains in winter and spring, respectively, although in winter IAQ dissatisfaction was nearly as high as thermal dissatisfaction. Overall, winter showed the highest dissatisfaction in the thermal, visual, and acoustic domains compared with spring, while IAQ was rated lowest in both seasons, with only minor variation.

Kim and De Dear [18], in their study in offices, concluded that some IEQ factors have a predominantly negative impact on occupant overall satisfaction when the building underperformed, and include temperature and noise level. Other IEQ factors have a predominantly linear relationship with overall satisfaction, which means that increments or decrements of equal magnitude in the building performance on these factors led to a broadly similar magnitude of enhancement or diminution in occupant overall satisfaction. These include among others, air quality and visual comfort. In this study, thermal comfort performed poorly in winter and was coherently closely related to overall satisfaction, while IAQ in spring worsened compared to winter. As shown in Table 3, it was the least rated domain and exhibited a strong relationship with overall IEQ, which was similarly rated quite low.

The strong relationship between IEQ and thermal comfort has been found elsewhere in university classrooms. In China, Weng et al. [11], in autumn and winter, found a strong relationship between IEQ and thermal and acoustic comfort, with an higher weight for thermal comfort, while Yang and Mak [8], in spring and autumn, found a strong relationship with thermal comfort. In Oman, Akhzami et al. [7] revealed a significant relationship of indoor environmental quality with thermal and acoustic conditions in summer, while in Ireland, Zuhaib et al. [17] found that thermal comfort caused the greatest discomfort in winter, while IAQ was the main contributor to IEQ in autumn, winter and spring.

Astolfi and Pellerey [10] reported that in acoustically renovated secondary school classrooms in Italy, the overall satisfaction was more closely correlated to thermal satisfaction, while in non-renovated classrooms it was more closely correlated to acoustical satisfaction. According to Lee et al. [1], based on their study at Hong Kong Polytechnic University, while thermal comfort, indoor air quality and visual environment were of comparable importance, aural environment was the major determining factor in overall IEQ vote, even if the survey revealed that students were 90% satisfied with aural environment compared to 84% with thermal environment.

These findings suggest that the thermal domain largely drives overall IEQ judgement, especially when all the other domains perform well, followed by acoustic one. The results of this study are in line with literature thus proving that the methodology experimented in this paper based on web-based questionnaires acquired after lesson, is comparable to studies in more controlled environments.

4.4. Agreement between the estimated thermal, acoustic, visual, and air-quality indexes and the student comfort indexes

In our findings, the IEQ indexes closely correspond to the comfort indexes reported for the thermal and acoustic domains, with the exception of classroom 4P in winter and spring, respectively, as shown in Figure 9.

4.4.1. Thermal environment

Predictive models for thermal comfort work quite well, but a discrepancy is observed in classroom 4P during winter where, although the indoor temperature satisfied the threshold, the occupants still reported uncomfort. As shown in Figure 7, the assessment of thermal comfort by the students is evenly divided between satisfaction and dissatisfaction, and among those who were dissatisfied, Figure 8 shows as their dissatisfaction in winter was either due to environment that was too warm (1P, south-west oriented) or too cold (4P, north-east oriented). However, from the graph in Figure 9, which includes satisfied and unsatisfied students, it appears that in winter the colder environment (4P) leads to greater discomfort than the warmer one (1P). This aligns with Corgnati et al. [6], who reported that students in classrooms feeling slightly cold preferred a warmer environment, whereas those feeling slightly warm expressed no change preference.

4.4.2. Acoustic environment

The closest match between the acoustic quality index and the comfort index was observed in the acoustic domain. The predictive model is based on the minimum speech level to guarantee an optimal signal-to-noise ratio. It performed well in classrooms with extensive use of voice reinforcement during winter, while in classroom 4P, the limited use of voice reinforcement in spring led to a lower acoustic quality index despite a high comfort rating, which is quite uniform across classrooms as shown in Figure 9. This mismatch can be explained as follows. Given the very good room acoustics, confirmed by a high speech clarity and optimal reverberation time, students are in acoustic comfort even with a signal-to-noise ratio lower than 15 dB, which we have considered to determine the threshold for the assessment of the acoustic quality index for satisfactory speech intelligibility. A threshold of 10 dB may have been sufficient [62–64].

4.4.3. Visual environment

The students rated the visual environment positively, despite the fact that the illuminance exhibits the poorest compliance with the threshold. Even though horizontal illuminance is not considered a fully exhaustive metric [2, 65], previous studies have found relationships between E_h and satisfaction with the visual environment [4, 8, 66] and the 300 lx is a common used threshold [8, 13, 67, 68], thus the mismatch between objective and subjective outcomes could be likely related to the model used to convert one point vertical illuminance into horizontal illuminance at the students' desks level. This is challenging because long-term horizontal-plane illuminance measurements are difficult to perform without interfering with classroom activities.

Direct experimental comparisons between wall-mounted and central illuminance measurements are rarely reported in the literature, as vertical surfaces are not considered representative of the luminous conditions in the occupied zone. Illuminance measured on walls is known to be strongly affected by daylight directionality and surface reflectance, and therefore cannot be assumed to reflect the illuminance experienced at the work plane or in the center of the room [69]. However, the ability of horizontal illuminance to predict visual comfort remains debated, with the most important studies carried out in offices. For example, Davoodi et al. [70] showed that simple task illuminance measures (E_{h-room} and E_{h-task}) in offices correlate well with perceived visual comfort, while Konis et al. [71] found luminance-based indicators to be more effective than glare indexes or vertical/horizontal illuminance. The issue in this framework is how to measure the luminance, which is a hard task with inexpensive wall-mounted sensors. According to Salamone et al. [72], low-cost cameras can be used for luminance mapping only if they undergo a time-consuming but essential calibration process. In the study by Mah et al. [73], low-cost programmable cameras integrated into the workspace (e.g., behind a monitor or on a wall) were proposed as a less intrusive alternative to laboratory-grade cameras, which often interfere with the daily activities of the occupant. These cameras can be installed in classrooms, including flush-mounted on the wall at seated student height.

4.4.4. Indoor air quality

The IAQ index overestimates comfort percentages for indoor air in all classrooms with an almost equal gap of 15%, while a good agreement was found by Brink et al. [4] with an objective model which includes CO_2, PM2.5 and TVOC, and perception. This implies that TVOC should be included in the monitoring campaigns in classrooms, even if TVOC concentration is usually correlated with CO_2 concentration. Maigari et al. [19], Morandi et al. [13] and Yang and Mak [8], found high carbon dioxide concentrations cause occupant discomfort, while, on the opposite, Al-Akhzami et al. [7] found no correlation of this quantity with the IAQ domain, but in hot aride climate.

In this study, IAQ perception appears to be influenced by CO_2 concentration. However, the approximately 15% discrepancy observed between objective (higher) and subjective (lower) indexes, consistently in classrooms, could be associated with sensor positioning. Specifically, wall sensors may have captured air quality conditions that are not fully representative of the occupied zone, potentially leading to lower measured CO_2 concentrations, as suggested by [74]. However, indoor airflow patterns under different ventilation modes largely determine the diffusion and distribution of the contaminant, while the position and characteristics of the source of the pollutant also play a key role [75], [76]. In this case study, the exterior glazed doors were randomly opened in spring and mostly closed in winter, as shown in Table 2, the HVAC system operated under identical conditions in both seasons, with ceiling-mounted supply diffusers and return grilles located above the main desk, but no differences in the students' responses have been observed. The students' exact positions were unknown, but they were assumed to be in the front rows near the professor, corresponding to sensors 1, 6, and 3, mounted flush with the internal wall near the entrance and the teacher's desk, and used for comparison with subjective data. In conclusion, a specific calibration procedure should be carried out in future investigations, ideally at different occupancy levels and with students positioned in various locations throughout the classroom, to derive the difference between the concentration of CO_2 in correspondence with the area of the students (or within the return air duct) compared to the one at the sensor position.

5. Limitations of the study

A key limitation of this study is the limited number of multi-sensors available for IEQ monitoring because those not connected to the electrical grid stopped operating. Furthermore, in spring, not enough students in some classrooms answered the questionnaire. Consequently, objective–subjective comparisons relied only on the single sensor operating in both seasons in three classrooms. This allowed to fully compare 1P, 3P and 4P in winter and only 4P in winter and spring.

The generalisability of the findings is limited. The analysis is restricted to four identical classrooms within a single university building, which, on the one hand, allows for controlled comparisons (i.e., different orientation but same size, shape, building envelope, equipment, and activity), but, on the other hand, limits the extent to which the results can be transferred to other educational buildings and contexts.

The accuracy of commercial sensors is another limitation that should be taken into account. In particular, the illuminance sensor exhibits a mean absolute error (MAE) compared to lab-grade device, which is higher than the JND, and underestimates the real value. However, the conversion model between vertical and horizontal illuminace took this difference into account and resulted in calibrated data. A similarly larger MAE than the JND is observed for air temperature, whereas for carbon dioxide the MAE exceeds the manufacturer-stated uncertainty of the reference instrument.

6. Conclusions

This study investigates long-term IEQ and student comfort in four identical, recently built classrooms at the Politecnico di Torino with different orientations.

The wall-mounted vertical multi-sensor setup, together with the web-based comfort surveys, are expected to be integrated into a BIM and AI framework, enabling rapid adjustments to maintain optimal conditions, improve occupant comfort, and reduce the facility manager's manual workload. Using a structured methodology based on time-based compliance objective indexes and incorporating contextual factors, this study provides additional insight compared to existing literature for developing models that predict subjective outcomes from objective data. The main generalizable findings that address the research questions are grouped as follows.

(i) Contextual factors:

- It is recommended to simultaneously monitor contextual factors, such as solar shading usage, door and lighting operation, and voice reinforcement system use, to correctly interpret the measured IEQ results.
- The IEQ monitoring results are strongly affected by the position of the sensors and their layout, whether vertical or horizontal.
- The highest dissatisfaction with overall IEQ in winter is related to the orientation of the north-east classroom, while the highest satisfaction is in the south-west.
- The possibility of having control of the solar shading and heating system is associated with an improvement in student satisfaction.

(ii) Relationship between overall perceived IEQ and comfort in the different domains:

- The overall perceived IEQ in winter is strictly related to thermal comfort, while in spring it is related to perceived air quality. These were also the least satisfactory domains in winter and spring, respectively.

(iii) IEQ objective indexes and comfort indexes:

- Thermal predictive models work well in winter and spring, with the latter based on an adaptive algorithm. In winter, people experience the most thermal discomfort in colder conditions rather than in warmer ones.
- Predictive models for visual comfort and indoor air quality would benefit from vertical (wall-mounted) to horizontal (desk level) data conversion algorithms.
- The predictive model for acoustic quality, based on the minimum signal-to-noise ratio required for satisfactory speech intelligibility, would better align with subjective evaluations in classrooms with good room acoustics if a lower threshold of 10 dB instead of 15 dB was used.

This study demonstrates that satisfaction prediction models based on wall-mounted sensors are effective for the long-term monitoring of indoor environmental quality (IEQ) in classrooms, although limitations related to data conversion and sensor placement remain, and additional cohort studies are needed.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. State of the art

Table A.5: Summary of the objective IEQ monitoring characteristics in the reviewed studies and in the present study. The following information is provided: season and duration of monitoring (W=winter, SP=spring, S=summer, A=autumn); hours monitored during weekdays (H); number of monitored classrooms (N); building orientation; number and type of sensors; sensors position; whether different sensor positions were compared; whether sensor accuracy was verified against reference devices; whether measurements were carried out simultaneously between classrooms (S.M.); and whether long-term monitoring was performed.

Ref.	**Season/months (m)/days (d)**	**H**	**N**	**Building orientation**	**N. of sensors**	**Sensors position**	**Positions comparison**	**Sensors accuracy verification**	**S.M.**	**long-term monitoring**
[1]	Season n.a./ 3m	3.5	8	n.a.	Many sensors	1 point nearest the sitting respondents	No	No, only provided by the manufacturers	No	Yes
[2]	SP, A	2	4	n.a.	Many sensors	1 to 9 positions	No	No	No	No
[4]	W/5d	5	2	NW	1 multi-sensor for thermal and IAQ, many sensors for other parameters	Middle, front and back of the classroom	No	No, only provided by the manufacturers	No	Yes, but only over 2 h
[7]	S/16 d	8	9	n.a.	Many sensors	Middle of the room, E on a grid	No	No, only provided by the manufacturers	n.a.	n.a.
[8]	A, W, SP, S (12m)	n.a.	8	n.a.	n.a.	n.a.	No	No, only provided by the manufacturers	No	No
[12]	SP/2d	5	2	SW, NE	Many sensors	14 measurement positions	Yes	No, only provided by the manufacturers	No	Yes, but only during crowded hours and in one day
[13]	W, SP, S, A (24m)		22	S, N, NW, SE	Many sensors	Middle of the room, teachers's desk, E over each desk	Yes	No	No	Yes, during lecture hours, excluding illuminance
[14]	A/2m, W/2m	13	10	S, E, W, N	1 multi-sensor	One meter around students, E over the desktop	No	No, only provided by the manufacturers	Yes	Yes, excluding illuminance
[17]	W/27d, S/21d, A/23d, SP/29d	8	4	NE, SW, NW	Many sensors	Many point-in-time measurements	No	n.a.	Only Ta, RH	Yes
[19]	W/5m	8	7	n.a.	Many sensors	Wall-mounted in 1 position	No	No, only provided by the manufacturers	Yes	Yes

Ref.	Season/months (m)/days (d)	H	N	Building orientation	N. of sensors	Sensors position	Positions comparison	Sensors accuracy verification	S.M.	long-term monitoring
[3]	W/2m, SP/3m, S/1m	10	18	S	Many sensors	Close the rear wall	No	No, only provided by the manufacturers	n.a.	n.a.
[23]	W/3d (amph.), S/36d (seminary), S/3d (amph.)	2.5	1	seminary E, amph. N/S	Many sensors	Middle of the room	No	No, only provided by the manufacturers	No	Yes, but only over 2.5 h
This study	SP/W	11		NE, SW	1 multi-sensor	Wall-mounted in one position	Yes	Yes	Yes	Yes

Table A.6: Summary of the subjective data collection and methodological aspects in the reviewed studies and in the present study. The following information is provided: number of collected questionnaires (N.Q.); whether a validated questionnaire was used (V.Q.); whether cognitive performance and well-being investigations were carried out; whether subjective data were collected simultaneously with IEQ objective measurements; whether the questionnaire administration was long-term; whether contextual, personal and behavioural factors were gathered; whether objective and comfort indexes based on compliance in time and questionnaire answers, respectively, were defined; whether the correlation between objective and subjective data was assessed; and whether the influence of contextual factors on IEQ and student perception was assessed.

Ref.	N.Q.	V.Q.	Cognitive perfomance and well-being	Simultaneously with IEQ measurements	long-term admin.	Contextual, personal, behavioural factors	Objective quality indexes	Subjective comfort indexes	Correlation between obj. and subj. data	Influence of contextual factors on IEQ parameters	Influence of contextual factors on subjective answers
[1]	312	Yes	Yes	Yes	No	No	No	No	Yes	Not analyzed	Not analyzed
[2]	928	Only thermo-hygrometric	No	Yes	No	Yes	No	No	Yes	Not analyzed	Not analyzed
[4]	163	Yes	Yes	Yes	No	Yes	No	No	Yes	Not analyzed	Not analyzed
[7]	475	Yes	No	Yes	No	Yes	No	No	Yes	Not analyzed	Not analyzed
[8]	224	No	No	n.a.	No	No	No	No	Yes	Not analyzed	Not analyzed

Ref.	N.Q.	V.Q.	Cognitive perfomance and well-being	Simultaneously with IEQ measurements	long-term admin.	Contextual, personal, behavioural factors	Objective quality indexes	Subjective comfort indexes	Correlation between obj. and subj. data	Influence of contextual factors on IEQ parameters	Influence of contextual factors on subjective answers
[12]	153	No	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes
[13]	825	Yes	No	Yes	No	Yes	No	No	Yes	Yes	Yes
[14]	399	Yes	Yes	Yes	No	Yes	Yes	No	No	Yes	No
[17]	144	Yes	No	Yes	No	Yes	No	No	Yes	Yes	Yes
[19]	163	Yes	No	Yes	Yes	Yes	No	No	Yes	Not analyzed	Yes
[3]	300	Yes	No	Partially	n.a.	Yes	No	No	No	Yes	Not declared
[23]	n.a.	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes	Not declared
This study	532	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Appendix B. Multi-sensor verification against reference devices

The multi-sensor was tested in the TEBE L^{2}AB, a single office located within the Department of Energy of Politecnico di Torino and was used as a living lab for research purposes. This test aimed to compare the multi-sensor measurements against those of more accurate laboratory-grade instruments for each physical variable. To this end, comparison was made over several distinct time periods, as detailed below. The specified accuracies of the devices are ±2.5% for the relative humidity device, ±0.15°C for the temperature thermocouples, 50 ppm +3% of measured value for the carbon dioxide device, ±0.5% at 1 kHz for the level RMS with flatness of ±0.1 dB from 12 Hz to 21.3 kHz, 4% for the horizontal illuminance device, respectively. The accuracy of the particulate matter device was not provided by the manufacturer.

Measurements of temperature, relative humidity, carbon dioxide concentration and illuminance were carried out from 20 July 2024 to 6 August 2024 in the summer period and from 20 December 2024 to 10 February 2025 in the winter period. The sampling time of the multi-sensor and all the reference devices was set at 5 minutes. During the monitoring campaign the laboratory was occupied by one person during working hours.

Measurements of particulate matter were carried out for five days, from 8 July 2024 to 15 July 2024, while the measurements of sound pressure level lasted from 9 July 2024 to 12 July 2024. The sound level meter was set with a sampling time of 1 second while the particulate matter device provided every 2 minutes a value of PM2.5 and a value of PM10 alternatively, thus the sampling time for each of them was 4 minutes. Measurements of particulate matter were compared with the principle of the nearest value in time. The data monitored with the reference sound level meter were averaged on the basis of sound energy every 5 minutes. During these days the laboratory was not occupied, the operators entered the room only to check the data acquisition. All devices continuously monitored during day and night time, except for the sound level meter, which was only active during working hours.

Considering the sound pressure level, it has to be noticed that although the datasheet of the multi-sensor refer to dB SPL, from the comparison in the living lab and in classroom 3P, it emerges that it measures A-weighted SPL. The difference in dB SPL between the multi-sensor and the reference sound level meter is 8.9 dB in the living lab, and 10.5 dB and 10.7 dB in classroom 3P with the active Talkbox. If the difference in dBA is considered, it is 0.7 dB in the living lab, and 1.4 dB and 4.5 dB in classroom 3P. This comparison was done considering the frequency range 50 Hz - 20 kHz. This could be due to the non-flat frequency response of the MEMS microphone below 100 Hz, which better matches the A-weighted SPL behaviour. In the living lab the averaged differences of SPL values are based on measurements across 4 days and 7 hours per day, while in classroom 3P are based on spot measurements over 5 minutes.

Table B.7 shows, for each measured parameter and considering only data monitored during occupancy hours (with the exception of sound pressure level and particulate matter measurements), the mean values (MEAN) of the reference instrument and of the multi-sensor, as well as the Mean Absolute Error (MAE), which is a metric that quantifies the average magnitude of the absolute error between predicted and actual values.

Table B.7: Summary of multi-sensor (M) performance analysis in comparison to the reference devices (R) in the living lab. The mean values (MEAN) and the Mean Absolute Error (MAE) are shown for the summer (S) and winter (W) measurements.

	Index	**T [°C]**		**RH [%]**		**CO$_2$ [ppm]**		**E$_h$ [lx]**		**PM2.5** [μg/m^3]		**PM10** [μg/m^3]		**SPLA** [dB]	
		R	M	R	M	R	M	R	M	R	M	R	M	R	M
S	MEAN	27.0	27.5	52.5	47.2	883	1151	530	300	11.9	9.2	17.0	10.2	42	42.7
	MAE	–	1.7	–	8.2	–	273	–	230	–	2.9	–	6.8	–	4.3
W	MEAN	22.5	22.5	30.2	32.9	–	–	–	–	–	–	–	–	–	–
	MAE	–	0.4	–	2.7	–	–	–	–	–	–	–	–	–	–

Regarding temperature readings, the mean values of the commercial multi-sensor and the reference device are similar, confirmed also by low MAE values. Relative humidity performs better in winter. Concerning carbon dioxide, a tendency toward overestimation is shown, as also reflected in the MAE equal to 273 ppm. Illuminance values, on the other hand, show a tendency in underestimation, with MAE equal to 230 lx. Particulate matter readings are in good agreement concerning PM2.5, while higher discrepancies are evident in PM10. Concerning SPL, good agreement is reported between the mean values, with a difference of 0.7 dB, which is within the Just Noticeable Difference of 1 dB [29], although the MAE is equal to 4.3 dB, due to different integration times of the sensors.

After carrying out the verification of the multi-sensor against reference instruments, it can be concluded that it is a cost-effective device for conducting environmental monitoring for research purposes. Only one multi-sensor was tested because, according to [77], for the same batch of multi-sensors the errors remain within the acceptable limits for this type of application.

Appendix C. Questionnaire on Indoor Environmental Comfort

1. Are you satisfied with the thermal, acoustic, visual, and air quality conditions in your environment?

Figure C.10: Faces representing the defined answers to the first questions.

2. Your evaluation is negative, can you tell us which environmental aspects are you dissatisfied with?
2.5 Your evaluation is positive, can you tell us which environmental aspects you consider particularly satisfying?

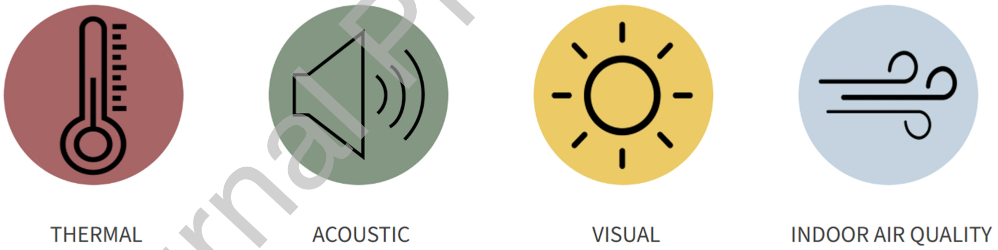

Figure C.11: The representation of the answers to questions 2 and 2.5; multiple option can be selected.

You are dissatisfied with thermal comfort, can you explain why?
3. Please indicate on the following scale how YOU feel NOW.

- +3 Hot
- +2 Warm
- +1 Slightly warm

- 0 Neutral
- -1 Slightly cool
- -2 Cool
- -3 Cold

4. Please indicate on the following scale how YOU find the AIR VELOCITY in your environment NOW.

- Very draughty
- Draughty
- Slightly draughty
- Not draughty

You are dissatisfied with acoustic comfort, can you explain why?

5. Please indicate on the following scale how YOU find the NOISE in your environment NOW.

- Very annoying
- Annoying
- Slightly annoying
- Not annoying

6. Please indicate any sources of noise YOU can hear in your environment NOW.

- Building systems
- Computer, printer, other equipments
- People chatting
- Road traffic
- Other noises from the outside
- Other

- None

You are dissatisfied with visual comfort, can you explain why?

7. Please indicate on the following scale how YOU find your VISUAL environment NOW.

- Very uncomfortable
- Uncomfortable
- Slightly uncomfortable
- Not uncomfortable

8. Please indicate any sources of glare YOU can see in your VISUAL environment NOW.

- Windows
- Lamps
- Glass surfaces
- Computer screens
- Reflective surfaces
- Other
- None

9. Please rate on the following scale how YOU would like your visual environment to be NOW.

- Much lighter
- Lighter
- Slightly lighter
- No change
- Slightly darker

- Darker
- Much darker

You are dissatisfied with indoor air quality, can you explain why?

10. Please indicate on the following scale how YOU find the AIR QUALITY in your environment NOW.

- Very smelly
- Smelly
- Slightly smelly
- Not smelly

11. Please indicate any sources of pollution that contribute to the AIR QUALITY in your environment NOW.

- Tobacco smoke
- Human odours
- Chemical odours
- Other
- None

12. If you want, you can leave other comments.

Would you provide information about yourself?

13. Gender

- Male
- Female
- Non-binary
- Prefer not to say

14. Age

- 18-25

- 26-35
- 36-50
- 51-65
- 65+

15. Country of birth

- Italy
- France
- Germany
- China
- . . .

16. Educational qualification

- Ph.D
- Master's degree
- Bachelor's degree
- High School
- None

17. Intended use of the building

- Office
- School
- Museum
- Hotel
- Hospital
- House

- Other

18. Ambit/Role

- Office
    - Engineering
    - Management
    - Administration
    - Creative, design and architecture
    - Sales and public affairs
    - Teaching and research
    - Services
    - Other
- School
    - Head teacher
    - Teacher
    - Administrative staff
    - Technical staff
    - Auxiliary staff
    - Student
    - Other
- Museum
    - Manager
    - Research, care and management of collections staff
    - Services and relations with public staff
    - Administrative, financial, management and public relations staff
    - Facilities and safety staff
    - Tourist guide
    - Tourist

  - Other
- Hotel
  - Manager
  - Administrative staff
  - Receptionist
  - Chambermaid
  - Waiter
  - Chef
  - Barman
  - Customer
  - Other
- Hospital
  - Medical director
  - Administrative staff
  - Hospital secretary
  - Doctor
  - Nurse
  - Social health operator
  - Patient
  - Other
- House
  - Inhabitant
  - Guest
  - Housekeeper
  - Other

19. Number of people in the environment

- 1
- 2 to 5
- 6 to 10
- 10 +

20. Visual impairments

- Yes
- No

21. Hearing impairments

- Yes
- No

22. Do you smoke?

- Yes
- No

23. Do you conduct a healthy lifestyle?

- Yes
- No

24. Does an unsatisfactory Indoor Environmental Quality significantly reduce your productivity?

- Yes
- No

25. Does an unsatisfactory Indoor Environmental Quality significantly reduce your well-being?

- Yes
- No

Would you provide information about your behaviour in your environment?
26. Do you have control on. . . ?
o windows opening and closing

- Yes
- No

o solar shading

- Yes
- No

o electric lightings

- Yes
- No

o heating system

- Yes
- No

o cooling system

- Yes
- No

o reducing noise annoyance

- Yes
- No

27. Do you think it is important to have control on. . . ?
o windows opening and closing

- Yes
- No

o solar shading

- Yes
- No

o electric lightings

- Yes
- No

o heating system

- Yes
- No

o cooling system

- Yes
- No

o reducing noise annoyance

- Yes
- No

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