INDOOR ENVIRONMENTAL QUALITY AND OCCUPANTS' COMFORT MONITORING IN TWO OPEN-PLAN OFFICES

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Abstract

Office users' health, comfort and work productivity are influenced by the Indoor Environmental Quality (IEQ) of the environment in which they work. This study presents a three-months monitoring of the acoustic, thermal, visual and air quality conditions of two open-plan company offices, located on the ground and first floor of the building, through a commercial multi-sensor and the PROMET&O (PROactive Monitoring for indoor EnvironmenTal quality & cOmfort) system. It consists of a low-cost calibrated multi-sensor device that monitors the main parameters of IEQ domains, and a questionnaire used to collect feedback on occupants' comfort. A designed user-friendly interface informs building managers and users about the objective and subjective data monitored. Ten PROMET&O multi-sensors, ten commercial sensors and ten tablets were positioned over the occupants' desks. Results show that a good agreement between the objective conditions and the subjective perception is more evident in the thermal and acoustic domains. Carbon dioxide concentrations fall within the recommended values, but a low air quality perception in the ground floor office is evident. Horizontal illuminance values rarely are higher than 500 lx, with occupants more satisfied in the first floor office than in the ground floor one.

Keywords: *indoor environmental quality, occupants' comfort, office, questionnaire, multi-sensor*

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1. Introduction

People spend the majority of their time indoors, where they are exposed to various factors that define the overall environmental quality. The field of Indoor Environmental Quality (IEQ) focuses on these aspects, particularly on thermal, visual, acoustic and Indoor Air Quality (IAQ) conditions, as they play a crucial role in influencing occupants' health, comfort, and work performance [1], [2]. To assess IEQ and occupants' comfort in a building in relation to the four domains, either objective or subjective measurements are used [3]. Objective measurements consist in the monitoring of physical parameters corresponding to each IEQ domain (e.g., air temperature, relative humidity, illuminance, sound pressure level, carbon dioxide and air pollutants). The compliance in time of objective measurements against predefined thresholds can be used to classify a space or a building within each domain and overall IEQ [4]. On the other side, the assessment through subjective evaluations can be done with structured questionnaires, through which occupants' perceptions of IEQ parameters and their overall satisfaction are recorded [5], [6]. In the end, objective measurements can be integrated with occupant's feedback through empirical models to find correlations between the subjective data and the objective monitored parameters.

Thanks to the widespread adoption of Internet of Things (IoT) technology, the assessment of environmental conditions has evolved from the use of expensive data loggers for in-field measurements to the use of low-cost monitoring devices [7], [8]. Low-cost sensors are increasingly used aggregated into single-case units for a more comprehensive and less intrusive evaluation of IEQ. Many prototypes of multi-sensors have already been presented in the literature, e.g., the low-cost battery-powered device by Tiele et al. [9]; the Sentient Ambient Monitoring of Buildings in Australia (SAMBA) by Parkinson et al. [3]; the Intelligent Built Environment Monitor (IBEM) by Geng et al. [10]. However, while existing studies have provided valuable insights into multi-sensor device development, the cloud platform component remains less extensively documented in the literature.

Within this framework, a system was developed to monitor IEQ parameters through a multi-sensor, compute an IEQ index, gather occupants' feedback through a questionnaire, and show all information via an interactive dashboard. The key features and innovations of this system, named PROMET&O (PROactive Monitoring for indoor EnvironmenTal quality & cOmfort) [11], [12], include the integrated capability to continuously monitor all four IEQ domains and evaluate their combined effects, to merge subjective and objective data enabling the comparison between perceived and calculated comfort indexes. Furthermore, to ensure enhanced data reliability, a metrological confirmation process of the multi-sensor was done, based on a three-step calibration procedure designed to support ongoing adjustments. In this work, the results of the in-field application of the PROMET&O system in two open-plan company offices are shown.

2. Methods

2.1. Case study

The evaluation of indoor environmental conditions, both from objective and subjective point of view, was conducted in two open-plan offices of a company located in Turin, Italy. The offices are on the first floor ("FF") and ground floor ("GF") of an independent building recently renovated, equipped with mechanical ventilation system and occupancy sensors for presence detection and automatic lighting control. They include 26 and 15 workstations, respectively, with the GF office also featuring an additional partially separated area with 10 workstations. In the FF office, occupancy remained below 50% for most of the monitored days, with activities primarily related to computer-based work. In contrast, the GF office exhibited occupancy levels above 50%, where users were mainly engaged in call center activities. The experimental campaign was performed from March to May 2025 in the FF office, and in June 2025 in the GF office.

2.2. The PROMET&O system

The PROMET&O system was developed for the evaluation of the relationships between IEQ, comfort, personal and behavioural factors of the occupants, in offices and classrooms [13]. It allows long-term IEQ monitoring through a multi-sensor device, and the acquisition of occupants' feedback through an ad-hoc developed and validated questionnaire [14]. The PROMET&O multi-sensor was developed in the framework of the project and embeds low-cost sensors (which measure thermal, acoustic, lighting, and air quality parameters) in an ad-hoc designed 3D printed external case [11], [12]. The calibration of the bare sensors was done before applying it in this experimental campaign, while a second step of calibration was done after it, additionally optimizing the sensors placement. However, other commercial devices can also be employed for IEQ monitoring and integrated into the system for data analysis and visualization. The monitored data are preprocessed, sent to a cloud platform for storage and then accessible through a user-friendly, ad-hoc designed dashboard, where both domain specific objective and subjective indexes are displayed. The objective acoustic, lighting and IAQ indexes are calculated as the percentage of time the parameters are within a defined threshold, which is taken from the main standards (Table 1), while the thermal comfort is calculated according to the adaptive model. The subjective indexes related to each domain are 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 perceptions.

Table 1: Monitored parameters (P) through the PROMET&O multi-sensor and their thresholds for office environments.

P	Threshold	Reference
T_a	Winter: (20–24) °C Summer: (23–26) °C	EN 16798-1:2019 [15]
RH	(25–60) %	EN 16798-1:2019 [15]
E	$\geq$ 500 lx	EN 12464-1:2021 [16]
SPL	$\leq$ 45 dBA	NF S 31-080 [17]
ΔCO_2	$\leq$ 800 ppm	EN 16798-1:2019 [15]
CO	24 h mean $\leq$ 7 mg/m^3	EN 16798-1:2019 (WHO Guidelines) [15]
NO_2	Annual mean $\leq$ 20 μg/m^3	EN 16798-1:2019 (WHO Guidelines) [15]
$PM_{2.5}$	24 h mean $\leq$ 25 μg/m^3	EN 16798-1:2019 (WHO Guidelines) [15]
PM_{10}	24 h mean $\leq$ 50 μg/m^3	EN 16798-1:2019 (WHO Guidelines) [15]
CH_2O	30 min. mean $\leq$ 100 μg/m^3	EN 16798-1:2019 (WHO Guidelines) [15]
TVOC	$\leq$ 500 μg/m^3	WELL Building Standard [18]

2.3. IEQ monitoring

Ten PROMET&O multi-sensors and ten commercial multi-sensors were placed side by side, as shown in Fig. 1 over 10 workstations selected based on the specific occupancy and to cover the whole office area. They monitored air temperature (T_a), relative humidity (RH), A-weighted sound pressure level (SPL-A), horizontal illuminance (E), carbon dioxide (CO_2), and particulate matter ($PM_{2.5}$ and PM_{10}).

On 24 April the PROMET&O devices were removed while the commercial multi-sensors continued recording data, thus only in the FF office a comparison between the two types of devices is possible. In fact, the aim was to perform a first period of monitoring in real environments to then be able to conclude the PROMET&O multi-sensor validation.

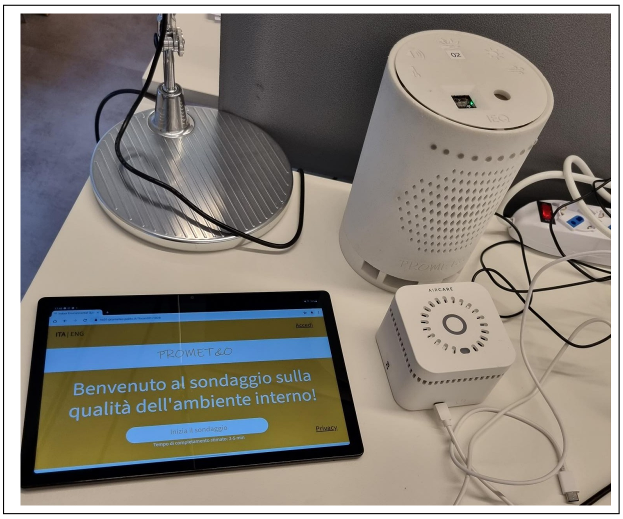

Figure 1: Measurement set up: the PROMET&O multi-sensor, the commercial multi-sensor and the tablet are placed on a workstation in the office.

2.4. Occupants' feedback collection

The PROMET&O questionnaire was used to collect office occupants' comfort feedback. The data collection process includes four levels: i) a first question on overall satisfaction with all IEQ domains (using a 4-point scale represented by colored smiley faces), ii) the selection of the domains particularly satisfying or dissatisfying, iii) additional questions on the dissatisfying domains, based on the standard ISO 28802:2012 [19], iv) personal and behavioural questions. The questionnaire was administered to the building occupants via tablets. To ensure spatial consistency, 10 tablets were positioned at the same workstations where the multi-sensors were installed. In such a way, a direct comparison between the monitored conditions and how these were perceived by the occupant was possible.

3. Results

For the analysis of the IEQ objective monitoring data from 8:30 to 17:30 of working days were used. Concerning the questionnaires, a total of 49 and 75 answers were collected in the FF and GF offices, respectively. In the FF office, 44.9% of the occupants were satisfied with the overall IEQ conditions, 18.4% were slightly satisfied, 26.5% were slightly dissatisfied and 10.2% were dissatisfied. In the GF office, occupants were satisfied, slightly satisfied, slightly dissatisfied and dissatisfied respectively at 5.3%, 16%, 9.3% and 69.3%.
Fig. 2 represents the air temperature, horizontal illuminance, carbon dioxide and A-weighted sound pressure level monitored by three PROMET&O multi-sensors (P1, P2, P3) and three commercial multi-sensors (CS1, CS2, CS3) in the FF office, and by three commercial multi-sensors (CS1, CS4, CS5) in the GF office. These multi-sensors were selected as they were equally spaced and representative of the three main areas of each office, namely the front, central, and rear zones. In each graph, in green is shown the optimal range according to the main international standards, as detailed in Table 1.

In Fig. 3, the results of the subjective evaluations for the four IEQ domains are presented in relation to the corresponding values measured by the commercial multi-sensors. In the FF office, the subjective responses are paired with sensors CS1, CS2, and CS3, whereas in the GF office they are associated with sensors CS1, CS4, and CS5. The x-axes represent the occupants' satisfaction levels, where the values 1, 2, 3, and 4 correspond to "satisfied", "slightly satisfied", "slightly dissatisfied", and "dissatisfied", respectively. Also in this figure, in green is shown the optimal range of monitored parameters according to the main international standards.

The temperature values in the FF office fell within the optimal range of 20-26 °C [15], and occupants declared to be satisfied with the thermal conditions in the majority of the cases. Only in two cases the thermal domain was considered dissatisfying, even though the monitored temperature was around 22 °C, as shown in Fig. 3. In the GF office, on the other hand, the mean air temperature values recorded by the three multi-sensors exceeded 26 °C, leading to a predominance of occupant dissatisfaction with the thermal conditions. In a few cases, occupants reported being slightly satisfied or slightly dissatisfied with temperature values in the range of 26–28 °C. Horizontal illuminance values were predominantly lower than the minimum threshold of 500 lx [16] in both offices. Nevertheless, occupants in the FF office reported being satisfied or slightly satisfied. In the GF office, the highest level of dissatisfaction was associated with sensor CS1, which recorded the lowest illuminance values, whereas occupants of the workstations corresponding to sensors CS4 and CS5 were slightly satisfied, with partially higher illuminance values.
Among the commercial multi-sensors, only the CS1 and CS2 recorded carbon dioxide concentrations. The monitored values in both offices were under the maximum threshold of 1200 ppm defined according to standard EN 16798-1:2019 [15]. Occupants declared to be mainly slightly satisfied and dissatisfied in the FF and GF offices, respectively.
A different trend between the two offices was observed in the A-weighted sound pressure levels. In the FF office, values were below 45 dB for all multi-sensors except P1 and P2, whereas in the GF office they exceeded 45 dB for all multi-sensors. This is evident also in the occupants' perceptions, who reported satisfaction with the acoustic domain in the first case and dissatisfaction in the latter.
Fig. 4 compares the IEQ domains associated with each overall satisfaction rating provided by users in the FF and GF offices, considering all ten tablets. Focusing on the acoustic domain, different patterns emerged between the two environments. In the FF office, acoustics was mainly associated with positive evaluations, being selected by 76% of fully satisfied

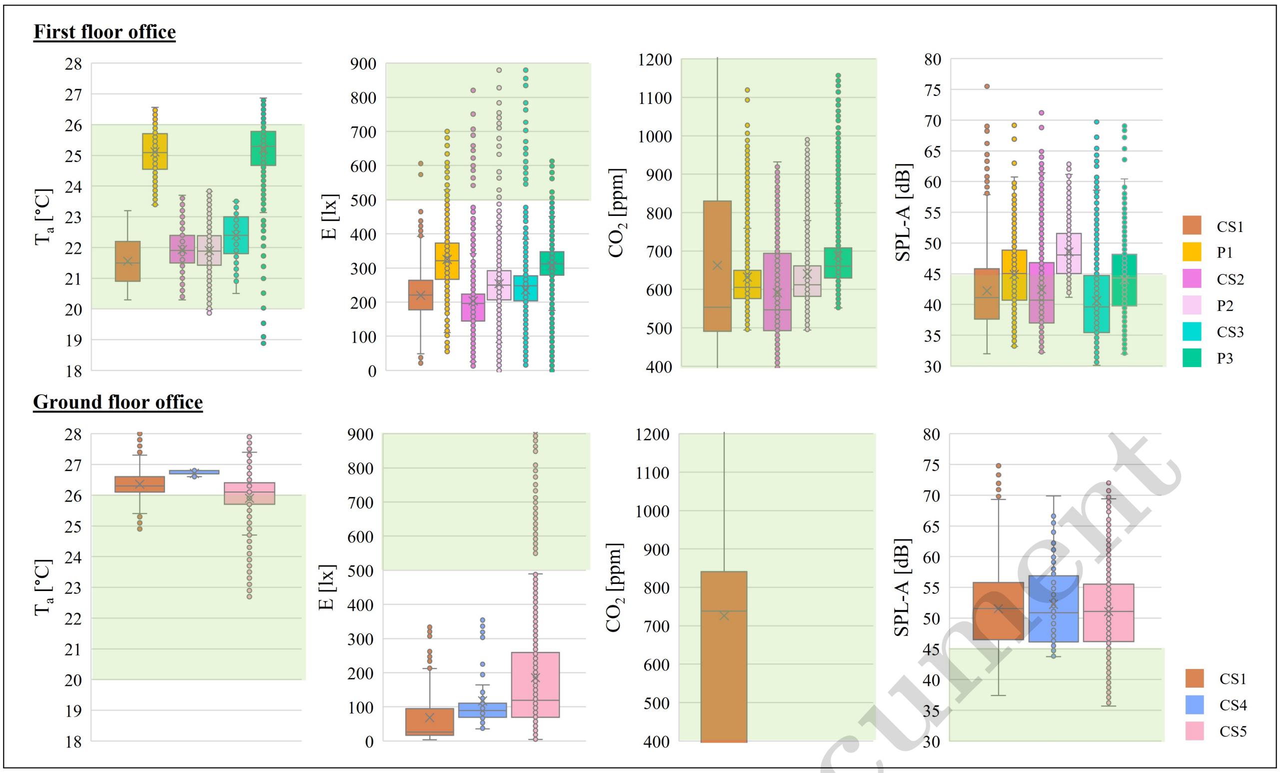

Figure 2: Results of air temperature, horizontal illuminance, carbon dioxide and A-weighted sound pressure level monitored with three PROMET&O multi-sensors (P1, P2, P3) and three commercial multi-sensors in the FF office (CS1, CS2, CS3) (top) and in the GF office (CS1, CS4, CS5) (bottom). In green are shown the optimal ranges according to the main international standards.

respondents and 22% of slightly satisfied respondents, whereas it was indicated by 31% of slightly dissatisfied respondents. Conversely, in the GF office, the acoustic domain was strongly associated with negative evaluations: it was selected by 71% of slightly dissatisfied respondents and 68% of dissatisfied respondents, compared with only 8% of slightly satisfied respondents. Furthermore, conversations among colleagues were identified as the main source of annoyance (46%), followed by road traffic (23%), building systems (9%), other noise from the outside (7%), computer (5%), printer (5%) and other office equipments (5%).

4. Discussion and conclusions

In this study the in-field monitoring of the acoustic, thermal, visual, and air quality conditions of two open-plan offices in a company was carried out along with the collection of subjective feedback on comfort. The monitoring campaign lasted a total of three months, from March to May in an office located on the first floor of the building, and in June in an office located on the ground floor. Ten PROMET&O multi-sensors, ten commercial multi-sensors and ten tablets were placed side by side over ten workstations in order to cover the whole office area. The multi-sensors monitored sound pressure level, air temperature, relative humidity, horizontal illuminance, carbon dioxide, and particulate matter, while the tablets displayed the questionnaire for office occupants' feedback collection. The results indicate a good agreement between objective measurements and subjective perceptions in the thermal and acoustic domains. The office located on the first floor had a lower occupancy and the recorded SPL-A were lower, confirmed by the higher satisfaction of the occupants with the acoustic conditions. In the office located on the ground floor, call center activities were performed and the SPL-A were higher, such as the dissatisfaction of the occupants, with people chatting being the main source of annoyance. Illuminance values were usually lower than the 500 lx threshold [16], probably due to presence-based automatic lighting controls. The carbon dioxide values were lower than the defined threshold of 1200 ppm, but in the GF office, the satisfaction was very low, suggesting that additional air pollutants should also be monitored.

Concerning the performance of the PROMET&O multi-sensors, an overestimation of air temperature values is evident for sensors P1 and P3 compared to the nearby commercial devices. A similar behaviour was observed for the other monitored parameters. This study proved crucial in highlighting the need for an additional calibration step, consisting in the repetition of the calibration procedures previously defined for the bare sensors, after their assembly within the external case, in order to assess the mutual influence

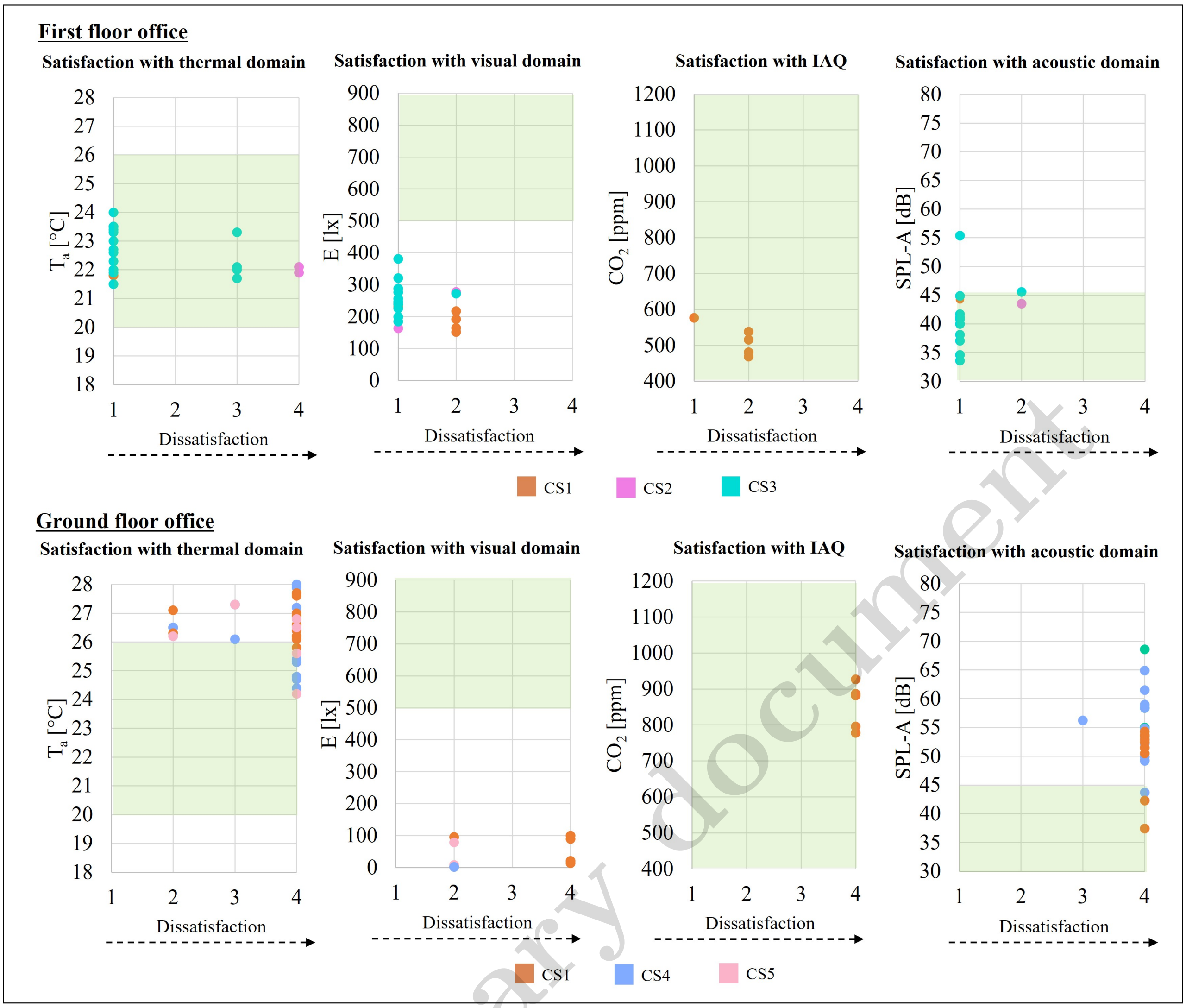

Figure 3: Results of subjective evaluations related to the four domains in relation to the correspondent monitored value by the commercial multi-sensor (CS), in the FF office (top) and GF office (bottom). In green are shown the optimal ranges according to the main international standards.

of the hardware components and of the external case itself. This effect was found to impact especially the air temperature and sound pressure levels measurements. Ad-hoc calibration procedures were therefore implemented, while further improvements are currently under investigation.

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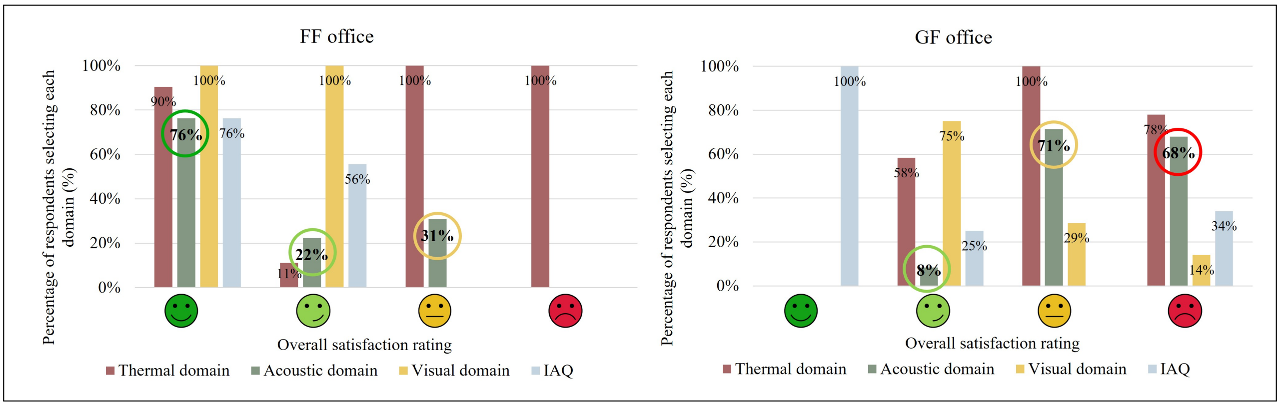

Figure 4: Percentage of respondents selecting each IEQ domain according to their overall satisfaction rating in the first floor (FF) and ground floor (GF) offices. The highlighted values refer to the acoustic domain.

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