# Development and In-field Application of a System for Indoor Environmental Quality Monitoring and Occupants' Feedback Collection

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Virginia Isabella Fissore[1], Alberto Barbaro[2[0009-0008-6941-3133]], Pietro Chiavassa[3[0000-0003-3907-5934]], Gustavo Adolfo Ramirez Espinosa[4[0000-0002-8607-593X]], Edoardo Giusto[5[0000-0001-8371-6685]], Giuseppina Emma Puglisi[6[0000-0002-8935-693X]], Erica Raviola[2[0000-0003-2555-3958]], Louena Shtrepi[1[0000-0002-0794-9695]], Antonio Servetti[3[0000-0002-0159-5718]], Bartolomeo Montrucchio[3[0000-0003-0065-8614]], Franco Fiori[2[0000-0002-7159-0322]], Arianna Astolfi[1[0000-0003-2010-6884]]

[1] Department of Energy, Politecnico di Torino, Turin, Italy
[2] Department of Electronics and Telecommunications, Politecnico di Torino, Turin, Italy
[3] Department of Control and Computer Engineering, Politecnico di Torino, Turin, Italy
[4] Department of Electronics, Pontificia Universidad Javeriana, Bogotá, Colombia
[5] Department of Electrical Engineering and Information Technology, Università di Napoli Federico II, Naples, Italy
[6] Campus Management, Logistics and Sustainability Department, Politecnico di Torino, Turin, Italy
virginia.fissore@polito.it

**Abstract.** Indoor Environmental Quality (IEQ) affects occupants' health, well-being and comfort, making its assessment increasingly required. This work presents a system designed to collect subjective and objective data on IEQ, referred to as PROMET&O (PROactive Monitoring for indoor EnvironmenTal quality & cOmfort). It is built on a survey and a low-cost and accurate multi-sensor device. The former was developed to collect feedback on occupants' comfort perception and personal and behavioural information. The latter was developed to monitor the thermal, lighting, acoustic and air quality conditions in indoor environments. The monitored parameters (air temperature, relative humidity, carbon dioxide, carbon monoxide, nitrogen dioxide, particulate matter, volatile organic compounds, formaldehyde, illuminance and sound pressure level) were selected based on international standards. A three-step calibration of the device is applied to ensure the measurements' reliability. The monitored data is transferred and processed on an open-source platform and the thermal comfort, visual comfort, acoustic comfort, indoor air quality and IEQ indexes are calculated and displayed on a user-friendly interface. This interface was designed to inform both building managers and occupants on IEQ trends and to provide them with more information on monitored parameters and hints on actions to improve their comfort. Preliminary tests in laboratory and in-field have shown the validity and scalability of the system's design.

**Keywords:** Indoor Environmental Quality, Overall Comfort, Multi-sensor Device.

# 1 Introduction

Nowadays people spend most of their time indoors and are affected by a multitude of factors that determine the quality of the environment itself. The research field of Indoor Environmental Quality (IEQ) addresses these factors particularly the thermal, lighting, acoustic and Indoor Air Quality (IAQ), that influence occupants' health, well-being and comfort [1]. The review by Ghaffarianhoseini et al. [2] demonstrated that IEQ parameters (e.g., temperature, humidity, ventilation, illuminance, noise level and air quality) can be contributors to building users' Sick Building Syndrome (SBS) symptoms growth (e.g., nose, eyes and skin irritation, headache and tiredness). Guaranteeing healthy environments has become a main concern, and national and international standards, along with building certification schemes, specify requirements to be met for this objective.

To assess users' satisfaction with the environment they are in, the Post-Occupancy Evaluation (POE) method is applied, which consists of administering questionnaires to end-users [3,4]. Nevertheless, there are contextual factors (e.g., office typology and occupancy hours [5]) and personal factors (e.g., age [6] and place of residence [5]) that influence the comfort perception [7] and, for this reason, they have to be considered.

For the monitoring of IEQ parameters, low-cost sensors are increasingly used and their aggregation into a single-case unit allows a more comprehensive evaluation of IEQ in a less intrusive solution. Questions regarding the performance of low-cost sensors are still open, since they don't meet the requirements of regulatory equivalent reference instruments and calibration procedures are lacking [8].

Researchers have already developed different prototypes of multi-sensors, 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. [10]; the Intelligent Built Environment Monitor (IBEM) by Geng et al. [11]. Along with the development of a multi-sensor device, researchers focus on the definition of an IEQ index to report the environmental conditions to end-users [12].

Within this context, the development of a system able to monitor IEQ parameters through a designed multi-sensor, calculate an IEQ index, collect occupants' feedback through a questionnaire, and communicate all information in a dashboard is carried out. The highlights and innovation of this system, named PROMET&O (PROactive Monitoring for indoor EnvironmenTal quality & cOmfort), are (i) the continuous monitoring of all the four IEQ domains for the assessment of their combined effects, (ii) the collection of both subjective and objective data, thus allowing for the comparison of calculated subjective and objective comfort indexes; (iii) the reliability of the measured data through the implementation of a metrological confirmation process. Indeed, a three-step calibration was designed to perform continuous adjustments and upgrades ensuring a more accurate data traceability.

The next paragraphs will detail the development of the PROMET&O system and will present preliminary results of a measurement session of one afternoon inside an office located in Politecnico di Torino.

# 2 Development of the PROMET&O system

## 2.1 Multi-sensor device for IEQ monitoring

The main international standards and building certification schemes were analyzed to select the IEQ parameters to be monitored through the multi-sensor for the assessment of indoor environments (see Tab. 1).

**Table 1.** Monitored parameters through the PROMET&O multi-sensor and their thresholds for office environments.

| Parameter | Threshold | Reference |
|---|---|---|
| Temperature | Winter: (20-24) °C | ISO 7730:2005 |
| | Summer: (23-26) °C | |
| Relative humidity | (30-70) % | |
| Illuminance | ≥ 500 lx | EN 12464-1:2021 |
| Sound pressure level | ≤ 45 dB(A) | NF S 31-080 |
| Carbon dioxide ($\Delta CO_2$) | ≤ 800 ppm | EN 16798-1:2019 |
| Carbon monoxide | 15 min. mean ≤ 100 mg/m$^3$ | EN 16798-1:2019 (WHO Guidelines) |
| | 1 h mean ≤ 35 mg/m$^3$ | |
| | 8 h mean ≤ 10 mg/m$^3$ | |
| | 24 h mean ≤ 7 mg/m$^3$ | |
| Nitrogen dioxide | 1 h mean ≤ 200 µg/m$^3$ | |
| | Annual mean ≤ 20 µg/m$^3$ | |
| Particulate matter (PM2.5) | 24 h mean ≤ 25 µg/m$^3$ | |
| | Annual mean ≤ 10 µg/m$^3$ | |
| Particulate matter (PM10) | 24 h mean ≤ 50 µg/m$^3$ | |
| | Annual mean ≤ 20 µg/m$^3$ | |
| Formaldehyde | 30 min. mean ≤ 100 µg/m$^3$ | |
| Total volatile organic compounds | ≤ 500 µg/m$^3$ | WELL Building Standard |

IEQ parameters are detected by the low-cost sensors and data is transferred to the WiFi module to be sent to the cloud platform. The sensor calibration is performed through a three-step procedure which consists of (i) calibration of the bare sensors in the laboratory [13], (ii) calibration of the assembled multi-sensor in the laboratory, to analyze the mutual influences of hardware components, (iii) evaluation in a controlled office against laboratory-grade sensors, to assess the uncertainty over the measurement ranges typical of offices.

Fig. 1 shows the arrangement and case of the multi-sensor components, which is 3D printed with a cylindric shape of 188 mm in height and 130 mm in diameter. It was designed with a set of small holes and four bigger openings on the bottom to reduce the overheating inside the device and provide sensors with direct access to external air. The multi-sensor itself provides end-users with information on IEQ conditions through two clusters of ten LEDs, that turn on in number proportionally to the IEQ index calculated from the monitored parameters. This IEQ index consists in a percentage value describing the quality of the environment and is calculated as mean value of thermal, acoustic, visual and indoor air quality indexes. These are calculated based on the principle of compliance in time of the monitored parameters belonging to the correspondent domain.

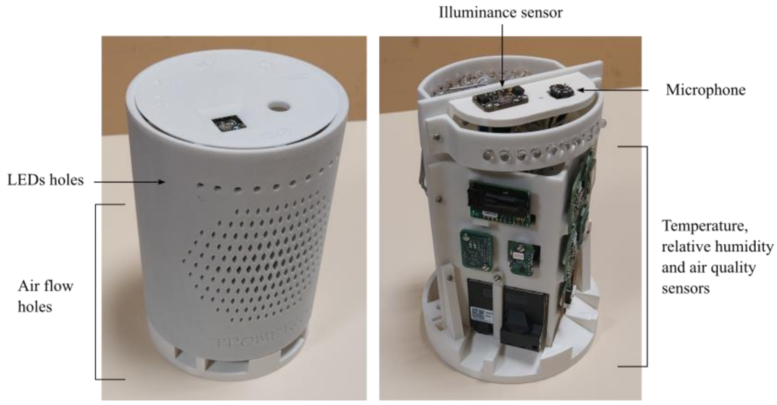


**Fig. 1.** Photograph of the assembled PROMET&O multi-sensor and its internal components.

### 2.2 Cloud platform and user interface

The PROMET&O multi-sensor exploits the Message Queue Telemetry Transport (MQTT) protocol for the data transfer to the cloud server. Data is stored, analytics are performed, and an API is used for external access. A questionnaire to collect occupants' feedback on their overall and single domain-related comfort perception and personal information was developed and validated [14]. The developed dashboard (Fig. 2) shows the temporal trend of the thermal, lighting, acoustic and air quality conditions of the environment, making a graphical comparison with the comfort percentages calculated for each domain from the user's answer to the questionnaire.


**Fig. 2.** Dashboard screenshot representing values of the IAQ index.

Data can be visualized with different time aggregations which are computed considering a configurable space-utilization calendar. Through the dashboard end-users are provided with useful hints and more specific information on IEQ topics and their proactive behavior towards IEQ improvement is fostered.

## 3 Preliminary results

Fig. 3 shows the monitored data of $CO_2$ with the PROMET&O multi-sensor (black line) and with the reference instrument Delta Ohm HD37VBTV.1 (dashed blue line). Measurements were performed during one afternoon in a single office at Politecnico di Torino, occupied by one person who could control windows and door openings and temperature settings. The graph shows that the trend of $CO_2$ concentration monitored by PROMET&O is consistent with the one of the reference instrument. Furthermore, the data collected shows that the $CO_2$ concentration falls within the acceptable ranges for office environments according to EN 16798-1.

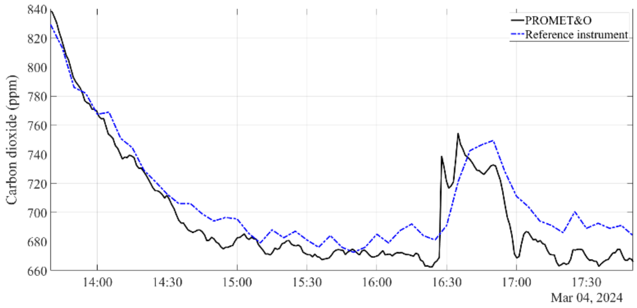


**Fig. 3.** $CO_2$ monitored data with the PROMET&O multi-sensor (black line) and the reference instrument (dashed blue line) in an office environment.

## 4 Conclusions and future work

The correlation between thermal, acoustic, lighting and air quality conditions of indoor environments with occupants' health, well-being, comfort and performance is demonstrated by the literature, thus solutions for IEQ assessment are sought. This work presents the design and development of the PROMET&O system, which comprises a low-cost multi-sensor for IEQ monitoring, a questionnaire for the collection of users' feedback on comfort perception and personal information, and a dashboard for overall data visualization. The main highlights of the PROMET&O system are (i) the real-time correlation and graphical visualization of objective and subjective data, (ii) the user's engagement through the dashboard and the IEQ level visualization thanks to LEDs lighting feedback, (iii) the three-step calibration of the multi-sensor aimed at ensuring a more accurate data traceability. The future work will include (i) the large-scale application of the system, (ii) the correlation between objective and subjective comfort indexes, (iii) the correlation between overall IEQ and the single IEQ domains.

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