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"Indoor Environmental Quality & Occupants Comfort Perception In Offices: PROMET&O Questionnaire debug, Mobile application design and A Short-term In-field study in various offices"

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Abstract

According to the most recent data, the majority of individuals spend most of their time indoors. Our well-being and productivity are significantly influenced by the indoor climate we experience. Indoor pollutants not only impact our physical health but also play a role in affecting our psychological well-being. Factors such as light, temperature, humidity, and noise contribute to this complex interplay, influencing both our physical and mental states. This underscores the significance of ensuring satisfactory Indoor Environmental Quality (IEQ) across its various domains. Standards and certifications developed over the years propose a vast number of possible parameters and indexes to be monitored to assess thermal, acoustic, visual and Indoor Air Quality (IAQ) conditions.

Adopting a multidisciplinary approach, the PROMET&O (PROactive Monitoring for indoor EnvironmenTal quality & cOmfort) project engages experts in architecture, building physics, electronic engineering, and computer science engineering to collaboratively develop an innovative and accurate multi-sensor for in-field monitoring of IEQ in offices.

This thesis, titled "Indoor Environmental Quality & Occupants Comfort Perception In Offices: PROMET&O Questionnaire debug, Mobile application design and A Short-term In-field study in various offices" focuses on monitoring IEQ in different environments. The study involves three main stages: (i) debugging and revising the PROMET&O web questionnaire and dashboard design to refine the tool developed for gathering subjective feedback, (ii) designing and prototyping the mobile application to enhance user interaction and subjective data collection, (iii) conducting a short-term in-field measurement in two different laboratories located inside Politecnico di Torino, in two open-space offices inside a company, and inside a room of a university residence building. The in-field study, which includes deploying a multisensor device and collecting objective data, aims to provide insights for future development of the project and multi-sensors improvements.

INDEX

1. Introduction of Experimental Thesis

Indoor Environmental Quality (IEQ) significantly influences the comfort, health, and productivity of office occupants. This experimental thesis, titled "Indoor Environmental Quality & Occupants Comfort Perception in Offices: PROMET&O Questionnaire Debug, Mobile Application Design, and A Short-term In-field Study in various Offices" aims to bridge the gap between perceived and actual environmental conditions. The thesis is part of the PROMET&O (PROactive Monitoring for indoor EnvironmenTal quality & cOmfort) research project. The project employs an innovative multi sensor device that monitors physical quantities related to indoor environmental quality and a questionnaire to collect subjective feedback on comfort perception from building occupants. This device will be deployed in two laboratories in Politecnico di Torino, two open-space offices in a company and in a room inside a university residence building. By focusing on debugging the PROMET&O questionnaire, this study seeks to refine tools used for assessing occupants' comfort levels, ensuring they accurately reflect the real-time experiences of individuals in office environments.

A critical component of this thesis involves the development of the mobile application version of the questionnaire and dashboard already designed for real-time data collection and visualization. The UI/UX design process is paramount to ensure that the mobile application is intuitive and user-friendly. By prototyping new wireframes, the research ensures that the app not only meets the functional requirements but also provides an engaging and efficient user experience. This mobile app serves as a crucial instrument for capturing detailed feedback on IEQ from building users, thereby contributing to more precise and actionable insights.

This research involves three main stages: (i) debugging and revising the PROMET&O web questionnaire and dashboard design to refine the tool developed for gathering subjective feedback, (ii) designing and prototyping the mobile application to enhance user interaction and subjective data collection, (iii) conducting a short-term in-field measurement in two different laboratories located inside Politecnico di Torino, in two open-space offices inside a company, and inside a room in a university residence building. The in-field study includes deploying multi sensor devices for collecting objective data. The study's outcomes will help provide insights for future development of the project and multi-sensors improvements.

2. Description of indoor environmental quality (IEQ)

Energy consumption of buildings significantly depends on indoor environment requirements, building design and operation, and energy systems. Indoor Environmental Quality encompasses four domains: thermal comfort, acoustic comfort, visual comfort, and indoor air quality. IEQ directly impacts the health and productivity of occupants, making its evaluation crucial in understanding occupant behavior in building spaces and systems, such as the use and control of windows, shadings, HVAC systems, and lighting. Recent studies highlight the significant costs associated with poor indoor environmental quality for society, employers, and building owners. Proper assessment of building energy performance must therefore integrate IEQ aspects. International standards and guidelines provide criteria for thermal comfort, indoor air quality, acoustic comfort, and visual comfort. This thesis presents experimental measurement criteria for IEQ in offices, methodologies for conducting in-field measurements, analyzing short-term monitoring data, and subjective surveys.

2.1 IEQ Domains

As previously mentioned, IEQ is a multifaceted concept that includes various interconnected domains, each of which plays a critical role in ensuring a healthy and comfortable indoor environment. Objective metrics for evaluating Indoor Environmental Quality are typically classified into four key areas: thermal comfort, lighting quality, indoor air quality, and acoustic quality. The relationship between these domains is interdependent. When addressing occupant satisfaction with IEQ in a building or office, it's essential to account for the collective impact of all these factors working together to attain the desired IEQ standards. If any single aspect does not meet the specified criteria, it may lead to occupant dissatisfaction with the environment. IEQ encompasses national and international standards and indices that define benchmark values, aiding designers to achieve optimal conditions in indoor environments (Parkinson et al., 2019).

2.1.1 Thermal comfort

Thermal comfort is a crucial aspect of IEQ, significantly impacting the well-being, health, and productivity of building occupants. It refers to occupants' satisfaction with the thermal environment inside a building, influenced by factors such as air temperature, humidity, air speed, and radiant heat exchange. Achieving optimal thermal comfort involves maintaining conditions within a range that neither feels too hot nor too cold, thereby enhancing comfort and performance. ASHRAE emphasizes the use of indices like Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) to assess thermal comfort, which quantify perceived thermal sensation and the likelihood of dissatisfaction with conditions.

Recent research underscores the importance of personalized thermal comfort models that account for individual differences in sensitivity and preference. Adaptive strategies acknowledge occupants' ability to adjust their thermal environment through clothing choices, workspace layout, and personalized controls.

The indoor thermal environment not only affects energy consumption but also shapes the overall human experience within buildings. Achieving a comfortable thermal environment for all occupants is complex due to individual preferences and variations over time and space. Thermal comfort directly impacts human satisfaction, health, and productivity in the built environment. Primary factors influencing comfort include air temperature, humidity, air movement, radiant temperature, clothing insulation, and metabolic rate. Secondary factors such as age, sex, health condition, personal thermal adaptation, and thermal history further modulate comfort preferences and responses (Parkinson et al., 2019).

Research indicates that an uncomfortable thermal environment can lead to negative outcomes such as reduced cognitive function, increased stress, and decreased productivity. Conversely, optimizing thermal conditions can enhance satisfaction, support better health outcomes, and improve productivity in workplaces and homes. Effective strategies involve not only controlling environmental factors but also empowering occupants with adjustable systems and personalized controls tailored to their needs (Well Certified, n.d.).

Indexes and parameters of thermal comfort domains are:

- **Predicted Mean Vote (PMV):** PMV predicts the average thermal sensation vote of occupants based on various environmental factors, including air temperature (t_a), mean radiant temperature (t_{mr}), air speed (v_2), relative humidity, and clothing insulation (Clo).
- **Predicted Percentage Dissatisfied (PPD):** PPD estimates the percentage of occupants dissatisfied with the thermal environment based on the PMV score.
- **Operative Temperature (T_{op}):** T_{op} represents the average temperature of an imaginary uniform surface where heat exchange between the body and the environment is balanced, considering air temperature (t_a), mean radiant temperature (t_{mr}), air speed (v_2), and relative humidity.
- **Standard Effective Temperature (SET):** SET estimates the uniform temperature required to produce the same heat loss from the human body as the actual non-uniform environment, factoring in **air temperature (t_a)**, **mean radiant temperature (t_{mr})**, **relative humidity**, and **clothing insulation (Clo)**.
- **Clothing Insulation (Clo):** Clo measures the thermal insulation provided by clothing, which affects how much heat is transferred between the body and the surrounding environment.
- **Thermal Sensation Vote (TSV):** TSV is a subjective measure of how people perceive the thermal environment, ranging from hot to cold. It complements PMV and PPD by offering qualitative data.
- **Air Temperature (t_a [°C]):** The temperature of the surrounding air measured outside the boundary layer of heated air adhering to the person.
- **Mean Radiant Temperature (t_{mr} [°C]):** The uniform temperature of a theoretical black cavity in which the occupants would exchange the same amount of thermal radiation as they do in the real, non-uniform environment.
- **Air Speed (v_2 [m/s]):** For a seated person, the average air speed around them (measured outside the boundary layer of heated air). For a moving person, this is the relative air speed with respect to the body.
- **Relative Humidity [%]:** The percentage of moisture in the air, affecting the body's ability to cool itself through evaporation.

These indexes and parameters are essential for assessing and designing indoor environments that optimize thermal comfort. They consider physiological responses and psychological factors influenced by environmental variables such as air temperature and relative humidity.

2.1.1.1 Thermal Standard frameworks

Thermal comfort standards provide a structured framework for evaluating and designing indoor environments to ensure occupant comfort. Here are some key components of the thermal comfort standard framework:

- **ASHRAE Standard 55:** This standard provides guidelines for thermal environmental conditions acceptable for human occupancy. It includes methods for determining thermal comfort parameters such as air temperature, humidity, air speed, and radiant temperature. ASHRAE Standard 55 outlines the use of thermal comfort indices like Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) to assess and design for thermal comfort.
- **ISO 7730:2005:** Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. This ISO standard provides methods for assessing thermal comfort based on PMV and PPD indices, offering international guidelines for designers and engineers.
- **EN 16798-1:2019 :** Indoor environmental input parameters crucial for the design and assessment of energy performance in buildings. This European standard provides comprehensive guidelines for various aspects of indoor environmental quality, including thermal comfort, indoor air quality, lighting, and acoustics. It specifies criteria to ensure that indoor environments meet the necessary standards to support both energy efficiency and occupant comfort. The standard aims to harmonize the evaluation of these parameters to achieve optimal building performance and enhance the overall quality of indoor environments.
- **Well Building Standard:** Includes thermal comfort criteria as part of its holistic approach to promoting health and well-being in buildings. It emphasizes achieving optimal thermal conditions that support occupant comfort and productivity.

These standards and guidelines provide a comprehensive framework for assessing, designing, and maintaining indoor thermal environments that promote occupant comfort, health, and productivity. They incorporate scientific research and empirical data to establish criteria for acceptable thermal conditions based on human physiological and psychological responses to the environment.

2.1.2 Visual comfort

Visual comfort is a fundamental aspect of Indoor Environmental Quality crucial for occupant well-being and productivity in indoor spaces. It encompasses the satisfaction of occupants with the visual environment, including lighting quality, glare, illuminance levels, and color rendering. Recent research underscores the profound impact of visual comfort on occupant satisfaction and performance. Studies highlight that well-designed lighting systems not only support visual tasks effectively but also contribute to reduced eye strain, enhanced mood, and overall improved cognitive function.

The indoor visual environment significantly shapes the overall human experience within buildings. Adequate lighting conditions can create welcoming and functional spaces, while poor lighting can lead to discomfort and reduced visual acuity, affecting productivity and well-being . Achieving optimal visual comfort involves balancing illuminance levels to meet task requirements without causing glare or visual fatigue. Proper lighting design considers both quantitative metrics, such as illuminance levels measured in lux, and qualitative factors like color rendering index (CRI), which assesses the fidelity of colors under the light source compared to natural light .

Indexes and Parameters of Visual Comfort Domains:

Natural Lighting:

- **Daylight Factor (DF)**: DF measures the ratio of indoor illuminance to outdoor illuminance at a reference point near a window, indicating the effectiveness of natural light penetration into indoor spaces. It helps assess how well daylight is utilized within a building.
- **Illuminance (Natural)**: Refers to the amount of natural light reaching a surface, measured in lux. It is crucial for evaluating the adequacy of daylight levels in indoor environments.

Artificial Lighting:

- **Unified Glare Rating (UGR)**: UGR evaluates discomfort glare from luminaires, considering factors such as the observer's position, luminaire luminance, and room surface reflectance. It is used to design lighting systems that minimize glare and enhance visual comfort.
- **Color Rendering Index (CRI)**: CRI measures how accurately a light source renders colors compared to a reference light source. A higher CRI improves visual comfort by enhancing the appearance of objects and colors under artificial lighting.
- **Lighting Uniformity:** This parameter assesses the evenness of illuminance distribution across a space. High lighting uniformity ensures consistent lighting conditions, reducing visual discomfort and providing optimal working environments.
- **Glare Control:** Strategies for glare control include selecting appropriate luminaires, optimizing their placement, and using shading devices to manage both natural and artificial lighting. Effective glare control improves visual comfort by minimizing excessive brightness and reflections.
- **Illuminance (Artificial)**: Refers to the amount of light produced by artificial sources reaching a surface, measured in lux. It is essential for ensuring sufficient and effective lighting conditions in various indoor settings.

Visual comfort parameters are crucial for evaluating and designing lighting systems that support occupants' visual needs and enhance their experience within indoor environments (ASHRAE, 17037:2018; IES LM-83-12:2012). These standards provide guidelines for architects, designers, and engineers to create lighting solutions that optimize visual comfort while promoting energy efficiency and occupant well-being.

2.1.2.1 Visual Standard frameworks

Visual comfort standards provide essential guidelines and criteria for evaluating and designing indoor lighting environments to ensure optimal occupant satisfaction and productivity. Here are key components of the visual comfort standard frameworks:

- **ISO 16813:2006:** This ISO standard specifies methods for evaluating the indoor environmental parameters of a building, including lighting quality for visual comfort. It outlines criteria for illuminance levels, glare assessment, and color rendering to ensure satisfactory visual conditions for occupants.
- **EN 17037:2018 :** Focuses on daylight in buildings, setting forth criteria for the amount and quality of daylight necessary to support a healthy and productive indoor environment. This

European standard outlines recommendations for designing buildings to maximize daylight use while considering aspects such as daylight availability, glare control, and energy efficiency.

- **EN 12464-1:2021:** This European standard provides specifications for workplace lighting, focusing on achieving adequate illumination levels to support visual tasks and ensure safety in indoor environments. It defines requirements for different types of work areas, including offices, industrial spaces, and educational facilities, with an emphasis on factors such as illumination levels, uniformity, and glare control. The standard aims to enhance visual comfort and productivity through effective lighting design.
- **IES LM-83-12:2012 :** Published by the Illuminating Engineering Society (IES) that provides guidelines for the measurement and reporting of the photometric performance of LED lighting products. This standard is essential for ensuring that LED fixtures meet specified performance criteria, including luminous output, efficiency, and color characteristics.
- **Well Building Standard:** Incorporates criteria for lighting design as part of its holistic approach to promoting occupant health and well-being in buildings. It emphasizes lighting quality parameters such as illuminance levels, glare control, and circadian lighting to support visual comfort and productivity.

These standards and guidelines offer a structured approach for architects, lighting designers, and engineers to assess, design, and maintain indoor lighting systems that optimize visual comfort. They integrate scientific research and empirical data to establish criteria for lighting quality based on human physiological and psychological responses to light, ensuring spaces that are both visually comfortable and energy-efficient.

2.1.3 Acoustic comfort

Acoustic comfort is a vital component of Indoor Environmental Quality (IEQ), significantly affecting occupants' health, well-being, and productivity in indoor environments. It refers to the satisfaction of occupants with the auditory environment in a building, which includes factors such as sound levels, sound quality, and noise control. Acoustic comfort ensures that indoor spaces provide an auditory environment that supports communication, concentration, and overall comfort without causing distraction or stress.

Recent research highlights the profound impact of acoustic comfort on occupant satisfaction and performance. Studies show that poor acoustic conditions can lead to increased stress, reduced cognitive function, and decreased productivity, particularly in open-plan offices and educational settings. Conversely, environments with good acoustic design promote better concentration, enhanced learning outcomes, and overall higher satisfaction among occupants (Jahncke et al., 2011).

The overall human experience within buildings is greatly influenced by the acoustic environment. Proper acoustic design is essential for creating functional and pleasant spaces, whether for work, study, or leisure. Achieving optimal acoustic comfort involves addressing both airborne and impact noise, ensuring adequate sound insulation, and controlling reverberation times to enhance speech intelligibility and reduce noise disturbances.

Indexes and Parameters of Acoustic Comfort Domains:

- **Sound Pressure Level (SPL):** SPL measures the intensity of sound in a given environment, usually expressed in decibels (dB). Maintaining appropriate SPL levels is crucial to avoid excessive noise that can lead to discomfort and hearing damage.
- **Reverberation Time (RT):** RT is the time it takes for sound to decay by 60 decibels in a closed space. Shorter RTs are generally preferred in spaces where speech clarity is essential, such as classrooms and offices, while longer RTs may be suitable for musical performance spaces.
- **Noise Reduction Coefficient (NRC):** NRC quantifies the ability of materials to absorb sound, reducing echo and reverberation. High NRC values indicate better sound absorption properties, contributing to improved acoustic comfort.
- **Speech Transmission Index (STI):** STI evaluates speech intelligibility in a given space, factoring in background noise, reverberation, and other acoustic properties. Higher STI values indicate clearer speech transmission, important in educational and professional settings.
- **Weighted Sound Reduction Index (Rw):** Rw measures the effectiveness of building elements, such as walls and floors, in reducing airborne sound transmission. Higher Rw values indicate better sound insulation, essential for privacy and noise control between adjacent spaces.
- **Impact Sound Pressure Level (ISPL):** ISPL measures the sound levels generated by impacts on a surface, such as footsteps on a floor. Lower ISPL values are desirable to minimize noise transmission between floors and improve acoustic comfort in multi-story buildings.

2.1.3.1 Acoustic Standard frameworks

- **ASHRAE Standard 189.1:** This standard includes guidelines for sustainable building design, addressing acoustic comfort by recommending design criteria for noise control and sound insulation in various building types.
- **ISO 3382-3:2022:** This standard specifies methods for measuring and assessing acoustic parameters in open plan office environments. The standard provides guidelines for evaluating key acoustic features, such as reverberation time and sound absorption, to ensure optimal acoustic conditions in open office spaces.
- **ISO 22955:2021:** Provides guidelines for measuring and assessing the acoustic performance of spaces with regard to the impact of noise on occupants. This standard focuses on evaluating parameters such as sound absorption, sound insulation, and noise levels in indoor environments to ensure effective acoustic quality.
- **ISO 3382-1:2009**: This standard specifies methods for measuring room acoustic parameters, focusing on performance spaces. It provides guidelines for evaluating the acoustical properties of rooms, such as reverberation time and sound distribution, to ensure optimal acoustic conditions for various activities and uses.
- **NF S31-080:** Specifies the criteria and methods for assessing the acoustic performance of building environments, particularly focusing on the impact of noise on occupant comfort. This French standard provides guidelines for measuring sound levels, sound insulation, and reverberation time, aiming to ensure that indoor spaces meet desired acoustic quality standards. It supports the design and evaluation of building acoustics to enhance overall occupant satisfaction and reduce the negative effects of noise in various types of indoor environments.
- **WELL Building Standard:** This standard incorporates acoustic comfort as part of its comprehensive approach to promoting health and well-being in buildings. It includes criteria

for noise levels, sound masking, and acoustic design strategies to enhance occupant satisfaction.

These standards and guidelines offer a structured framework for evaluating, designing, and maintaining indoor environments that promote acoustic comfort. By integrating scientific research and empirical data, they establish criteria for acceptable acoustic conditions based on human physiological and psychological responses to sound, ensuring spaces that are both acoustically comfortable and conducive to productivity.

2.1.4 IAQ (Indoor Air Quality)

Indoor Air Quality is a critical component of Indoor Environmental Quality, significantly influencing the health, comfort, and productivity of building occupants. IAQ refers to the condition of the air within a building as it relates to the health and well-being of the occupants. Factors such as the presence of pollutants, ventilation effectiveness, and the concentration of indoor contaminants like carbon dioxide (CO_2), volatile organic compounds (VOCs), and particulate matter (PM) all contribute to IAQ. Ensuring good IAQ is essential for preventing respiratory issues, allergies, and other health problems that can arise from prolonged exposure to poor air quality.

Recent research underscores the importance of maintaining high IAQ for occupant health and productivity. Studies have shown that poor IAQ can lead to various health issues, including headaches, fatigue, and respiratory problems, which can reduce productivity and increase absenteeism. Conversely, improving IAQ has been associated with better cognitive performance, higher productivity, and overall well-being. These findings highlight the need for effective IAQ management strategies in both residential and commercial buildings (Parkinson et al., 2019).

The indoor environment significantly shapes the overall human experience within buildings. Achieving optimal IAQ involves controlling indoor pollutant sources, ensuring adequate ventilation, and maintaining acceptable temperature and humidity levels. Proper IAQ management requires a holistic approach that includes regular monitoring, use of air purifiers, and the incorporation of materials and products that emit low levels of pollutants.

Indexes and Parameters of IAQ Domains:

- **Carbon Dioxide (CO_2) Levels**: CO_2 concentration is a common indicator of ventilation effectiveness. High CO_2 levels can indicate insufficient ventilation, leading to occupant discomfort and reduced cognitive performance. ASHRAE recommends maintaining indoor CO_2 levels below 1000 parts per million (ppm) to ensure adequate air quality.
- **Volatile Organic Compounds (VOCs)**: VOCs are emitted by various building materials, furnishings, and cleaning products. High levels of volatile organic compounds (VOCs) can lead to symptoms such as headaches and dizziness, and may also contribute to chronic health issues over time.
- The WELL Building Standard recommends keeping total VOC levels below 500 micrograms per cubic meter (μg/m³).
- **Particulate Matter (PM)**: $PM_{2.5}$ (Particulate Matter less than 2.5 microns in diameter): The WHO recommends an annual average of 5 μg/m³, with a 24-hour average limit of 15 μg/m³.
- PM_{10} (Particulate Matter less than 10 microns in diameter): The WHO guideline for annual PM_{10} concentration is 15 μg/m³, with a 24-hour average of 45 μg/m³.

- **Formaldehyde**: Formaldehyde is a common indoor air pollutant emitted from building materials and household products. It can cause respiratory symptoms and is classified as a carcinogen. ISO specifies methods for measuring formaldehyde levels, recommending concentrations below 100 µg/m³ to minimize health risks.
- **Relative Humidity**: Maintaining indoor humidity levels between 30% and 60% helps control mold growth and dust mites, improving overall air quality and comfort. ASHRAE Standard 62.1 outlines the importance of controlling humidity to prevent health issues and maintain good IAQ.
- **Air Exchange Rate**: The air exchange rate, or ventilation rate, measures how often indoor air is replaced with outdoor air. Proper ventilation helps dilute indoor pollutants and maintain acceptable IAQ. ASHRAE Standard 62.1 recommends a minimum ventilation rate of 0.35 air changes per hour for residential buildings and higher rates for commercial spaces to ensure sufficient air exchange.

These indexes and parameters are integral to assessing and managing IAQ, ensuring that indoor environments are healthy and conducive to occupant well-being. They provide a comprehensive framework for architects, engineers, and facility managers to design and maintain buildings that promote high IAQ and, consequently, better health outcomes and productivity for occupants.

2.1.4.1 IAQ Standard frameworks

- **ASHRAE Standard 62.1:** This standard provides guidelines for ventilation and indoor air quality in commercial and institutional buildings. It includes criteria for minimum ventilation rates, contaminant control, and building envelope design to ensure acceptable indoor air quality. ASHRAE Standard 62.1 emphasizes maintaining adequate air exchange rates and controlling indoor pollutant levels.
- **EN 16798-1:2019 :** The European standard provides essential guidelines for designing and assessing energy performance in buildings by addressing key indoor environmental parameters. It covers thermal comfort, indoor air quality, lighting, and acoustics, setting criteria to ensure indoor spaces are energy-efficient and comfortable for occupants. The goal is to standardize the evaluation of these factors to improve building performance and indoor environmental quality.
- **EN 13779:2007 :** This standard provides guidelines for designing and maintaining ventilation systems in non-residential buildings to achieve high IAQ. It includes criteria for ventilation rates, air filtration, and the control of indoor pollutants to ensure a healthy indoor environment.
- **WELL Building Standard:** The WELL Building Standard incorporates IAQ criteria as part of its holistic approach to promoting occupant health and well-being. It outlines requirements for monitoring and managing indoor air pollutants, enhancing ventilation, and maintaining optimal humidity levels to ensure high IAQ. WELL emphasizes continuous monitoring and the use of low-emitting materials.

References Chapter 2

1. European Committee for Standardization. (2019). ***EN 16798-1:2019*** *Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics - Module M1-6*. CEN. Retrieved from https://standards.iteh.ai/catalog/standards/cen/b4f68755-2204-4796-854a-56643dfcfe89/en-16798-1-2019
2. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (2016). ***ASHRAE Standard 55****: Thermal Environmental Conditions for Human Occupancy*. ASHRAE. Retrieved from https://www.ashrae.org/advertising/handbook-advertising/systems
3. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (2017). **ASHRAE Standard 62.1:** Ventilation for Acceptable Indoor Air Quality. ASHRAE. Retrieved from https://www.ashrae.org/technical-resources/bookstore/standard-62-1
4. International Organization for Standardization (ISO). ***ISO 7730:2005*** *-Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria*. ISO Store. Retrieved from https://www.iso.org/standard/39155.html
5. Illuminating Engineering Society (IES). (2012). ***IES LM-83:2012****: Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)*. IES. Retrieved from https://www.intertekinform.com/en-us/standards/ies-lm-83-2012-573278_saig_ies_ies_1312279/
6. European Committee for Standardization. (2018). ***EN 17037:2018*** *Daylight in buildings*. CEN. Retrieved from https://standards.iteh.ai/catalog/standards/cen/836e5b91-1eb0-4643-a2ba-7ca5a5988e64/en-17037-2018
7. European Committee for Standardization. (2007). ***EN 13779:2007*** *Ventilation for non-residential buildings - Performance requirements for ventilation and room-conditioning systems*. CEN. Retrieved from https://standards.iteh.ai/catalog/standards/cen/7d77e217-29cf-4f02-ae0b-b14c4e07ab40/en-13779-2007
8. European Committee for Standardization. (2021). ***EN 12464-1:2021*** *Light and lighting - Lighting of work places - Part 1: Indoor work places*. CEN. Retrieved from https://standards.iteh.ai/catalog/standards/cen/53fc4ff7-e7df-4ebd-a730-0d5f0ea888e0/en-12464-1-2021
9. **World Health Organization** (WHO). (2018). *WHO global air quality guidelines: Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide*. WHO. Retrieved from https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health
10. International Organization for Standardization (ISO). ***ISO 3382-3:2022*** *- Acoustics Measurement of room acoustic parameters. (Part 3: Open plan offices)* Retrieved from https://www.iso.org/standard/77437.html
11. International Organization for Standardization (ISO). (2021). ***ISO 22955:2021*** *Acoustics - Acoustic quality of open office spaces*. ISO Store. Retrieved from https://www.iso.org/standard/74237.html
12. Association Française de Normalisation (AFNOR). (2006). ***NF S31-080****: Acoustics - Acoustic Performance of Buildings - Criteria for Acoustic Comfort*. AFNOR. Retrieved from

https://www.boutique.afnor.org/norme/nf-s31-080/acoustique-performance-acoustique-des-batiments-criteres-de-confort-acoustique/article/781196/fa189120

13. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 2021). ***ASHRAE standard 189.1****: Standard for the design of high-performance green buildings*. Retrieved from https://www.ashrae.org/technical-resources/bookstore/standard-189-1
14. International Organization for Standardization (ISO). ***ISO 3382-1:2009****- Acoustics Measurement of room acoustic parameters*. Retrieved from https://www.iso.org/standard/40979.html
15. International Organization for Standardization (ISO). ***ISO 16813:2006*** *- Building environment design — Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting, and acoustics*. Retrieved from https://www.iso.org/standard/41300.html
16. Jahncke, H., Hygge, S., Halin, N., Green, A. M., & Dimberg, K. (2011). Open-plan office noise: Cognitive performance and restoration. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S0272494411000429?via%3d Ihub
17. WELL Certified. (n.d.). *WELL Building Standard*. Retrieved from https://v2.wellcertified.com/v/en/overview
18. Parkinson, J., Loftness, V., & Aziz, A. (2019). Continuous IEQ monitoring system: Context and development. *Building and Environment, 149*, 15-25. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S0360132318307467

3. Relation between IEQ indexes and Occupants comfort & well being

Indoor Environmental Quality indexes play a pivotal role in shaping the comfort and well-being of building occupants. In the modern era where people spend the majority of their time indoors, the quality of the indoor environment significantly influences their physical health, mental well-being, and overall productivity. Indoor Environmental Quality encompasses various factors including air quality, thermal comfort, lighting, and acoustics, which collectively contribute to the creation of healthy and comfortable indoor spaces. In office environments, where individuals spend a significant portion of their time, maintaining high IEQ standards is crucial for ensuring not only physical health but also psychological well-being and productivity (Godish & Spengler, 2003). In this chapter I will delve into the relationship between IEQ indexes and the comfort and well-being of office workers, highlighting how different environmental factors influence their daily experiences and performance.

Health and safety are foundational elements of a conducive office environment. Proper ergonomics, air quality, thermal comfort, and adequate lighting are essential in preventing physical illness and promoting overall health. Poor IEQ can lead to a range of issues collectively known as Sick Building Syndrome (SBS), where occupants experience symptoms like headaches, dizziness, and respiratory problems without a specific identifiable cause (Seppänen, Fisk, & Lei, 2006). Moreover, Building-Related Illnesses (BRI), which include conditions directly attributable to environmental factors like mold or chemical exposures, underscore the critical need for diligent management of indoor environments (Mendell & Heath, 2005). Addressing these health and safety concerns is not only a matter of compliance but also a key factor in enhancing employee satisfaction and productivity. (Nielsen & Taris, 2019)

Understanding the factors that influence comfort perception among office workers is vital for creating optimal working conditions. Demographic factors such as gender and age can significantly affect how individuals perceive their work environment. For instance, studies have shown that women and older workers might have different comfort thresholds compared to their male and younger counterparts (Frontczak & Wargocki, 2011; Veitch et al., 2007). Additionally, the materials used in office construction and furnishings can impact thermal comfort, air quality, and overall aesthetic appeal, further influencing occupants' comfort levels (Bluyssen, 2009). These elements must be carefully considered in the design and management of office spaces to ensure a universally comfortable environment.

The link between comfort and productivity is well-documented, with numerous studies indicating that comfortable workers are more likely to be productive and engaged. When employees are comfortable, they are less likely to be distracted by environmental discomforts and more likely to focus on their tasks, leading to better performance outcomes. Conversely, optimizing IEQ can have significant positive effects on occupants' comfort and well-being. Well-ventilated spaces with low levels of indoor pollutants promote better respiratory health and cognitive function (Seppänen, Fisk, & Lei, 2006). Maintaining thermal comfort through effective HVAC systems and building insulation enhances occupants' satisfaction and concentration levels. Adequate lighting design that balances natural and artificial light sources can improve visual comfort, mood, and productivity (Veitch et al., 2007). Furthermore, minimizing noise pollution through sound-absorbing materials and strategic building layouts creates quieter and more conducive environments for work, rest, and social interaction (Lam et al., 2014).

In conclusion, the relationship between IEQ indexes and occupants' comfort and well-being is complex and multifaceted. By understanding and addressing the various factors that contribute to IEQ, organizations can create healthier, more comfortable, and more productive work environments. This chapter provides a comprehensive overview of the current research and practical considerations for improving IEQ in office settings, underscoring the importance of a holistic approach to indoor environmental management. (Lam et al., 2014)

3.1 Health and safety

Health and safety considerations of office workers are fundamental aspects that directly impact their comfort, well-being, and productivity. Ensuring that office environments are safe and healthy requires a comprehensive understanding of the various factors that contribute to Indoor Environmental Quality . These factors include air quality, thermal comfort, lighting, and noise levels. Poor IEQ can lead to a range of adverse health effects, including Sick Building Syndrome (SBS) and Building-Related Illnesses (BRI), which can significantly reduce the quality of life for office workers and (Mendell & Heath, 2005). In this subchapter I delve into the critical components of health and safety in office environments, highlighting the importance of maintaining high IEQ standards, Sick Building Syndrome (SBS) and Building-Related Illnesses (BRI) and comparison between them.

Air quality is a crucial element of IEQ that affects respiratory health and overall well-being. Poor ventilation and the presence of indoor pollutants such as volatile organic compounds (VOCs), mold, and particulate matter can lead to various health issues, including headaches, dizziness, and respiratory problems (Seppänen, Fisk, & Lei, 2006). Effective ventilation systems and the use of low-emitting materials are essential strategies for improving indoor air quality and protecting the health of office occupants. By ensuring that indoor environments are free from harmful pollutants, organizations can prevent the onset of SBS and promote a healthier, more productive workforce.

Thermal comfort is another key factor in ensuring the health and safety of office workers. Inadequate temperature control can lead to discomfort, decreased concentration, and increased stress levels. Research has shown that maintaining thermal comfort through effective HVAC systems and proper building insulation enhances occupants' satisfaction and cognitive function. Additionally, controlling humidity levels is essential for preventing mold growth and maintaining a healthy indoor environment. By prioritizing thermal comfort, organizations can create office spaces that support the well-being and efficiency of their employees.

Lighting and noise levels also play significant roles in the health and safety of office environments. Adequate lighting, which balances natural and artificial light sources, is crucial for visual comfort, mood, and productivity (Veitch et al., 2007). Poor lighting can cause eye strain, fatigue, and negatively impact mental health. Similarly, minimizing noise pollution through the use of sound-absorbing materials and strategic building layouts can create quieter, more conducive environments for work and relaxation. Addressing these factors not only enhances comfort but also reduces the risk of health issues related to poor lighting and excessive noise (Lam et al., 2014).

Beyond physical health considerations, addressing psychosocial factors is also crucial for promoting a safe and supportive office environment. Creating a positive workplace culture that prioritizes respect, inclusivity, and open communication fosters psychological safety among employees (Health and Safety Executive [HSE], 1995). Implementing policies and procedures to prevent workplace harassment, discrimination, and bullying helps create a supportive and respectful atmosphere where employees feel valued and empowered (Nielsen & Taris, 2019). Furthermore, providing resources for mental health support, such as employee assistance programs and counseling services, demonstrates a commitment to employees' overall well-being (Steen & Hansen, 2023). By addressing both physical and psychosocial health and safety factors, offices can create environments that not only protect employees from harm but also promote their overall health, happiness, and productivity.

3.1.1 Sick building syndrome (SBS)

Sick Building Syndrome refers to a situation in which occupants of a building experience acute health and comfort effects that seem to be linked to time spent in the building, but no specific illness or cause can be identified (Mendell & Heath, 2005). This syndrome often results from poor indoor air quality, inadequate ventilation, and other environmental factors within the built environment. SBS can lead to a variety of symptoms, including headaches, eye, nose, or throat irritation, dry cough, dry or itchy skin, dizziness and nausea, difficulty in concentrating, fatigue, and sensitivity to odors (Seppänen, Fisk, & Lei, 2006).

Key Factors Contributing to SBS:

- **Poor Ventilation:** Inadequate fresh air exchange can result in the accumulation of indoor pollutants. Effective ventilation systems are crucial in preventing SBS by ensuring proper air circulation and pollutant dilution .
- **Chemical Contaminants:** Emissions from building materials, office equipment, cleaning agents, and personal care products can release volatile organic compounds (VOCs) and other harmful chemicals into the indoor environment, contributing to SBS (Seppänen, Fisk, & Lei, 2006).
- **Biological Contaminants:** Mold, bacteria, and other microbial contaminants can proliferate in areas with poor humidity control, leading to SBS-related symptoms such as respiratory issues and allergic reactions (Mendell & Heath, 2005).
- **Physical Factors:** Inadequate lighting, excessive noise, and poor ergonomic design of workspaces can exacerbate the symptoms associated with SBS, affecting overall comfort and productivity (Veitch et al., 2007).

Understanding “Symptoms Associated with Environmental Factors” (SAEF):

Research indicates a strong correlation between environmental factors and the prevalence of symptoms associated with SBS. The concept of “Symptoms Associated with Environmental Factors” (SAEF) highlights how various indoor environmental parameters can influence occupants' health and comfort (Steen & Hansen, 2023).

- **Air Quality:** Poor air quality, characterized by high levels of CO_2, VOCs, and other pollutants, is directly linked to symptoms such as headaches, dizziness, and respiratory issues.
- **Thermal Conditions:** Temperature fluctuations and inadequate humidity control can cause discomfort and exacerbate symptoms like dry skin and eye irritation.
- **Lighting Conditions:** Insufficient or poor-quality lighting can lead to eye strain, headaches, and reduced concentration, contributing to the overall perception of discomfort.

The Health and Safety Executive's guide on dealing with SBS provides comprehensive strategies to mitigate this syndrome in office environments (HSE, 1995).

- **Regular Maintenance and Cleaning:** Ensuring that HVAC systems are regularly maintained and cleaned can prevent the buildup of pollutants and microbial contaminants.
- **Monitoring Air Quality:** Implementing air quality monitoring systems can help in detecting and addressing issues related to indoor pollutants.
- **Improving Ventilation:** Enhancing ventilation by increasing the intake of outdoor air and improving air distribution within the building can reduce the concentration of indoor pollutants.
- **Choosing Low-Emission Materials:** Selecting building materials and office furnishings with low VOC emissions can minimize chemical contaminants in the indoor environment.
- **Addressing Occupant Feedback:** Regularly surveying occupants about their comfort and health can help in identifying and addressing SBS-related issues promptly.

In conclusion, SBS is a complex issue influenced by various environmental factors within office buildings. By understanding the key contributors to SBS and implementing practical measures to improve IEQ, organizations can create healthier and more comfortable working environments, thereby enhancing the well-being and productivity of their employees.

3.1.2 Building related illnesses (BRI)

Building-Related Illnesses (BRI) refer to specific illnesses that can be directly attributed to exposure to indoor environmental contaminants or conditions within buildings. Unlike Sick Building Syndrome (SBS), which is characterized by nonspecific symptoms, BRI involves identifiable health conditions linked to exposure to specific indoor pollutants or biological agents (HSE, 1995).

Common Building-Related Illnesses:

- **Asthma:** Exacerbated or triggered by allergens such as mold spores, dust mites, or pet dander present in indoor environments (Mendell & Heath, 2005).
- **Allergic Rhinitis:** Symptoms include sneezing, runny or stuffy nose, and itchy or watery eyes, often caused by exposure to indoor allergens like pollen or dust.
- **Occupational Dermatitis:** Skin conditions resulting from exposure to irritants or allergens in building materials, cleaning agents, or other workplace substances (Wargocki & Sundell, 2016).
- **Respiratory Infections:** Spread through poor ventilation systems or close contact with infected individuals in crowded office settings (Seppänen, Fisk, & Lei, 2006).

Contributing Factors to BRI:

- **Biological Contaminants:** Mold, bacteria, viruses, and fungi thriving in damp or poorly ventilated areas can lead to respiratory issues and infections (Veitch et al., 2007).
- **Chemical Contaminants:** VOCs from building materials, cleaning products, and furnishings can cause respiratory irritation and exacerbate conditions like asthma (Mendell & Heath, 2005).
- **Poor Ventilation:** Inadequate fresh air intake and circulation can lead to the accumulation of indoor pollutants, increasing the risk of respiratory illnesses (Lam et al., 2014).
- **Indoor Humidity Levels:** Excessive moisture can promote mold growth and microbial proliferation, contributing to allergic reactions and respiratory problems (Wargocki & Sundell, 2016).

Preventive Measures and Mitigation Strategies:

- **Routine Maintenance:** Regular inspection and maintenance of HVAC systems, including cleaning and filter replacement, to ensure adequate ventilation and air quality (HSE, 1995).
- **Moisture Control:** Monitoring and controlling indoor humidity levels to prevent mold growth and mitigate biological contaminants (Seppänen, Fisk, & Lei, 2006).
- **Use of Low-Emission Materials:** Selecting building materials and furnishings with low VOC emissions to minimize chemical exposure.
- **Employee Education:** Providing training on recognizing symptoms of BRI and promoting practices for maintaining a healthy indoor environment (Veitch et al., 2007).

By addressing the specific health risks associated with BRI and implementing proactive measures to improve indoor environmental quality, organizations can safeguard the health and well-being of their employees while promoting a productive work environment.

3.1.3 Comparison between sick building syndrome SBS and BRI

Sick Building Syndrome (SBS) and Building-Related Illnesses (BRI) are both health issues associated with indoor environments but differ in their nature and manifestation. SBS typically involves nonspecific symptoms that affect multiple occupants of a building and are often linked to time spent indoors rather than specific exposure to pollutants. Common symptoms of SBS include headaches, fatigue, eye irritation, and respiratory discomfort, which may arise from poor ventilation, inadequate lighting, or high levels of indoor pollutants such as volatile organic compounds (VOCs). In contrast, BRI refers to specific illnesses with identifiable causes within the building environment, such as asthma exacerbations due to mold exposure or allergic reactions triggered by indoor allergens.

The distinction between SBS and BRI lies in their causative factors and diagnostic criteria. While SBS is characterized by a broad range of symptoms that improve upon leaving the building, BRI involves diagnosable health conditions directly attributable to specific indoor environmental contaminants or conditions. Understanding these distinctions is crucial for implementing effective mitigation strategies and improving indoor environmental quality to promote the health and well-being of building occupants.

3.2 Factors that Influence the Comfort Perception of Office Workers

The comfort perception of office workers is influenced by a complex interplay of environmental, ergonomic, and psychosocial factors, tailored to accommodate the diverse needs and preferences of employees. Understanding these factors is essential for creating environments that promote productivity, satisfaction, and overall well-being among office workers. The comfort perception of office workers can be categorized into contextual and personal dimensions, each impacting the overall well-being and productivity of employees. (Bounajma et al., 2021 & Zhao et al., 2020)

Contextual Factors:

- **Environmental Factors:** Indoor environmental quality (IEQ) components such as air quality, thermal comfort, lighting, and acoustics significantly impact how employees perceive their workspace that we already discussed (Lam et al., 2014).
- **Ergonomic Design:** The ergonomic design of workspaces plays a critical role in reducing physical discomfort and preventing musculoskeletal disorders. Factors such as adjustable

furniture, ergonomic keyboard and mouse placements, contribute to enhancing employee satisfaction and productivity which we are not going to discuss in this thesis.
- **Psychosocial Factors:** Workplace culture, social interactions, and organizational policies are vital determinants of comfort perception. A supportive and inclusive workplace environment fosters positive psychological outcomes, reduces stress levels, and enhances job satisfaction.

Personal Factors:

- **Gender and Age Factors:** Research indicates that gender and age can influence how individuals perceive comfort in the workplace. For instance, studies suggest that female employees may have different preferences for lighting and temperature compared to male counterparts (Clements-Croome, 2022). Similarly, age-related differences in comfort perception may arise due to varying physiological needs and preferences for workspace design elements that we will discuss in this chapter.
- **Relation between Materials and Comfort Factors:** The choice of materials used in office construction and furnishing significantly impacts comfort perception. Factors such as the selection of ergonomic chairs, sound-absorbing materials for acoustical comfort, and non-toxic finishes contribute to a healthier and more comfortable workspace environment that we will discuss in this chapter.

By considering these multifaceted factors comprehensively, organizations can design and manage office environments that not only comply with health and safety regulations but also enhance employee comfort, satisfaction, and overall performance.

3.2.1 Gender and Age factor in office workers satisfaction

Understanding the nuanced preferences and needs of office workers based on gender and age is crucial for designing workplaces that foster satisfaction, productivity, and well-being. Recent research has identified significant differences in how gender and age influence comfort perception and satisfaction within office environments.

Gender Differences:

- **Environmental Preferences:** Studies indicate that gender can influence environmental preferences in the workplace. For example, women often prefer warmer temperatures and more natural lighting, which are associated with higher satisfaction levels and improved productivity (Clements-Croome, 2022). Men, on the other hand, may show a preference for cooler temperatures and brighter artificial lighting conducive to task-oriented work (Andrade et al., 2019).
- **Social and Emotional Factors:** Gender diversity initiatives are essential in shaping workplace culture and satisfaction. Ensuring equitable access to resources, opportunities for career advancement, and addressing biases contribute to overall job satisfaction among all genders (Zou, 2015). Additionally, fostering an inclusive environment where all employees feel respected and valued enhances job satisfaction and reduces turnover rates (Andrade et al., 2019).

Age-Related Preferences:

- **Workspace Design Preferences:** Age plays a significant role in determining workspace preferences. Younger employees often prioritize flexibility in work arrangements, open collaborative spaces, and access to technology that supports mobility and connectivity. Older workers may prefer quieter environments with minimal distractions, ergonomic furniture that supports physical health, and designated areas for focused work (Designing Green Spaces, 2022 & Rothe et al., 2012).
- **Career Stage and Development:** Different career stages may influence satisfaction levels among office workers. Early-career professionals may prioritize learning opportunities and career growth, while mid-career and senior employees may value work-life balance and recognition for their contributions (Zou, 2015). Tailoring professional development programs and mentoring initiatives to address these needs can enhance job satisfaction and retention rates across age groups (Andrade et al., 2019 & & Rothe et al., 2012).

Implications for Workplace Design:

- **Flexible Design Solutions:** Designing flexible workplaces that accommodate diverse preferences can contribute to higher satisfaction and productivity. This includes adjustable furniture, customizable lighting and temperature controls, and varied workspace configurations to support different work styles (Designing Green Spaces, 2022).
- **Inclusive Policies and Practices:** Implementing inclusive policies that promote diversity, equity, and inclusion (DEI) can create a supportive environment where employees of all genders and ages thrive. This involves addressing unconscious biases, providing equitable access to resources, and fostering a culture of respect and collaboration (Andrade et al., 2019).

By integrating these insights into workplace planning and management, organizations can create environments that not only meet regulatory standards but also enhance employee satisfaction, well-being, and overall organizational performance.

3.2.1 Relation between materials and comfort

The choice of materials in office environments significantly influences occupants' comfort, well-being, and overall satisfaction. From ergonomic furniture to sustainable building materials, each element plays a crucial role in creating a supportive and pleasant workspace.

- **Ergonomic Furniture:** Ergonomically designed chairs and desks contribute to physical comfort by supporting posture and reducing the risk of musculoskeletal disorders (MSDs). Adjustable features such as height, lumbar support, and armrests cater to individual preferences and body types (Creating Healthy and Sustainable Buildings, 2019). Research suggests that ergonomic interventions improve productivity and reduce absenteeism due to work-related injuries (Andrade et al., 2019).
- **Acoustical Comfort:** Sound-absorbing materials and strategic placement of acoustic panels are essential for controlling noise levels within office spaces. Excessive noise can lead to stress, reduced concentration, and decreased job satisfaction among employees (Designing Green Spaces, 2022). Designing for acoustical comfort involves selecting materials that minimize sound transmission between work areas and implementing sound masking technologies where needed (Andrade et al., 2019).
- **Sustainable Building Materials:** The use of sustainable materials not only supports environmental stewardship but also enhances indoor air quality and occupant comfort.

Materials such as low-VOC paints, natural finishes, and recycled content contribute to healthier indoor environments (Creating Healthy and Sustainable Buildings, 2019). Green building certifications like LEED emphasize the importance of using environmentally friendly materials that promote occupant health and well-being (Andrade et al., 2019).

- **Technological Integration:** Advances in materials science have led to innovations that improve comfort through technological integration. For example, smart materials capable of regulating temperature and humidity levels can create adaptive environments that respond to occupants' needs in real-time (Zou, 2015). Integrating technology into building materials enhances energy efficiency and user control, further optimizing comfort and satisfaction in office settings (Creating Healthy and Sustainable Buildings, 2019).

By considering these factors and integrating research-backed insights into material selection and design, organizations can create office environments that prioritize occupant comfort, health, and productivity.

3.3 Relation between comfort and productivity

The correlation between comfort and productivity in office settings is a dynamic area of research that examines how various physical, environmental, and psychological factors influence employees' performance and well-being. Creating a conducive work environment that prioritizes comfort can lead to enhanced cognitive function, reduced stress levels, and increased job satisfaction, ultimately boosting productivity.

Physical Comfort Factors:

- **Ergonomics:** Ergonomic furniture and workstation design that support natural posture and movement reduce the risk of musculoskeletal disorders (MSDs) and physical discomfort (Andrade et al., 2019). Also adjustable chairs, desks, and monitor stands accommodate individual preferences and body types, promoting comfort and productivity (Creating Healthy and Sustainable Buildings, 2019).
- **Temperature and Lighting:** Maintaining optimal thermal conditions and appropriate lighting levels is crucial for employee comfort and well-being. Also natural light exposure has been linked to improved mood, energy levels, and productivity, while adjustable artificial lighting supports visual comfort and task performance (Ayoko & Ashkanasy, 2019; Parhizkar et al., 2023).

Environmental Comfort Factors:

- **Air Quality:** Good indoor air quality (IAQ) contributes to respiratory health and cognitive function. Proper ventilation systems and the use of low-VOC (volatile organic compound) materials reduce pollutants and enhance overall air quality (Creating Healthy and Sustainable Buildings, 2019). Also clean air fosters a healthier and more comfortable work environment, supporting productivity and reducing absenteeism due to illness (Andrade et al., 2019).
- **Acoustics:** Managing noise levels through acoustic treatments and sound-absorbing materials improves concentration and reduces distractions. Also optimal acoustical conditions in the workplace promote focus, collaboration, and effective communication, thereby enhancing productivity (Clements-Croome, 2019).

Psychological Comfort Factors:

- **Biophilic Design:** Integrating biophilic elements such as plants, natural materials, and green spaces enhances psychological well-being. Also exposure to nature indoors has shown to reduce stress, increase creativity, and improve overall satisfaction, contributing to higher productivity levels (Ayoko & Ashkanasy, 2019; Parhizkar et al., 2023).
- **Workplace Culture:** A positive and supportive workplace culture that values employee well-being and provides opportunities for social interaction and professional growth fosters engagement and productivity. Encouraging autonomy, recognizing achievements, and promoting work-life balance are essential aspects of a conducive work environment (Andrade et al., 2019 & Bounajma et al., 2021).

Non-Physical IEQ Parameters:

- **Privacy, Furnishing, Office Cleanliness, View from Windows, Available Space, and Personal Control:** Although these factors received less attention in most studies, they are crucial for occupant satisfaction and comfort. Providing privacy, clean and well-furnished offices, pleasant views, adequate space, and a sense of personal control can significantly impact employees' psychological well-being and productivity (Andrade et al., 2019).

References Chapter 3

1. Godish, T., & Spengler, D. (2003). Indoor environmental quality. CRC Press.
2. Bluyssen, P. M. (2009). *The indoor environment handbook: How to make buildings healthy and comfortable*. Earthscan.
3. Seppänen, O., Fisk, W. J., & Lei, Q. H. (2006). Ventilation and performance in office work. Indoor Air, 16(1), 28-36. https://doi.org/10.1111/j.1600-0668.2005.00394.x
4. Mendell, M. J., & Heath, G. A. (2005). Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature. Indoor Air, 15(1), 27-52. https://doi.org/10.1111/j.1600-0668.2004.00320.x
5. Frontczak, M., & Wargocki, P. (2011). Literature survey on how different factors influence human comfort in indoor environments. *Building and Environment, 46*(4), 922-937. https://doi.org/10.1016/j.buildenv.2010.10.021
6. Veitch, J. A., Charles, K. E., Farley, K. M. J., & Newsham, G. R. (2007). A model of satisfaction with open-plan office conditions: COPE field findings. *Journal of Environmental Psychology, 27*(3), 177-189. https://doi.org/10.1016/j.jenvp.2007.04.002
7. Health and Safety Executive. (1995). *How to deal with sick building syndrome: HSG132*. Retrieved from HSE website
8. Steen, E., & Hansen, E. (2023). Understanding "Symptoms Associated with Environmental Factors" (SAEF) in buildings. *Building Research & Information*. Retrieved from University of Tromsø's repository
9. Nielsen, K., & Taris, T. W. (2019). Educated and happy: A four-year study on the connections between education, job fit, and life satisfaction. *Applied Psychology, 68*(1), 3-22. https://doi.org/10.1111/apps.12158
10. Wargocki, P., & Sundell, J. (2016). Subjective perceptions, symptoms and the physiological effects of poor indoor air quality. *Indoor Air, 26*(1), 84-94. https://onlinelibrary.wiley.com/doi/full/10.1034/j.1600-0668.2002.01101.x
11. Clements-Croome, D. (Ed.). (2022). *Creating a productive workplace*. Taylor & Francis. Retrieved from https://www.researchgate.net/publication/279190533_Creating_the_Productive_Workplace
12. Creating Healthy and Sustainable Buildings: An Assessment of Health Risk Factors. (2019). Retrieved from https://www.researchgate.net/publication/333443658_Creating_Healthy_and_Sustainable_Buildings_An_Assessment_of_Health_Risk_Factors
13. Bounajma, S., Salim, L., Marzouk, H., & Lezzar, F. (2021). Time spent in the office and workers' productivity, comfort and health: A perception study. *Building and Environment, 198*, 107872. https://doi.org/10.1016/j.buildenv.2021.107747
14. Zhao, J., Lasternas, B., Lam, K. P., Yun, R., & Loftness, V. (2020). Occupant action patterns regarding spatial and human factors in office environments. Energy and Buildings, 225, 109889. https://doi.org/10.1016/j.enbuild.2020.109889
15. Zou, M. (2015). Gender, work orientations and job satisfaction. *Work, Employment and Society, 29*(1), 3-22. https://doi.org/10.1177/0950017014559267
16. Andrade, M. S., Westover, J. H., & Peterson, J. (2019). Job satisfaction and gender. Journal of Business Diversity, 19(3). https://www.researchgate.net/publication/339338612_Job_Satisfaction_and_Gender

17. Rothe, P., Lindholm, A.-L., Hyvönen, A., & Nenonen, S. (2012). Work environment preferences – does age make a difference? *Journal of Facilities Management, 10*(1), 55-67. https://doi.org/10.1108/02632771211194284
18. Designing Green Spaces for Health Using Plants to Reduce the Spread of Airborne Viruses. (2022). Retrieved from https://doi-org.ezproxy.biblio.polito.it/10.4324/9781003136880
19. Parhizkar, M., Wang, J., & Jaeger, S. R. (Eds.). (2023). Objective indoor air quality parameters and their association to respiratory health and well-being among office workers. In Organizational behavior and the physical environment. Routledge. https://doi.org/10.1016/j.buildenv.2023.110984
20. Lam, K. C., Chan, W. K., & Fung, W. Y. (2014). Indoor environment quality effects on occupant satisfaction and energy consumption: Empirical evidence from subtropical offices. *Energy and Buildings, 82*, 114-122. https://doi.org/10.1016/j.enbuild.2023.113784
21. Ayoko, O. B., & Ashkanasy, N. M. (Eds.). (2019). *Organizational Behaviour and the Physical Environment*. London: Routledge. https://doi-org.ezproxy.biblio.polito.it/10.4324/9781315167237

4. Building Certification Schemes

Building certification schemes have become crucial in the quest for sustainable and healthy built environments. Administered by organizations such as the U.S. Green Building Council (USGBC) and the International WELL Building Institute (IWBI), these schemes establish frameworks and standards for evaluating the environmental, social, and health performance of buildings and their occupants. By adhering to these standards, buildings can attain certification, showcasing their dedication to sustainability, occupant well-being, and environmental responsibility. This chapter delves into these certification schemes, examining their influence on the built environment and their role in guiding future design and construction practices (U.S. Green Building Council, n.d.; International WELL Building Institute, 2018).

4.1 LEED Certification Standards

LEED, which stands for 'Leadership in Energy and Environmental Design,' is the most widely recognized sustainability credential for architects, developers, building owners, and designers. LEED originated from the establishment of the US Green Building Council (USGBC) in 1993 by David Gottfried, Mike Italiano, and Rick Fedrizzi. This certification is Known for its strong framework and adaptable rating system. LEED advocates for healthy, efficient, and economically viable building methods applicable to diverse building types and phases (U.S. Green Building Council, n.d.).

According to the LEED website, LEED certification is available for all building project types and all building phases. Each of these categories contains the LEED rating system, scorecard and reference guide that can be followed for obtaining the certification.

- “The Building Design and Construction (BD+C) category”
- “The Interior Design and Construction (ID+C) category”
- “The Building Operations and Maintenance (O+M) category”
- “The Neighbourhood Development (ND) category”
- “The Homes category”
- “The Cities and Communities category”

The LEED rating system, as of LEED v4, is based on a point system where buildings can earn up to 110 points. These points determine the level of certification a building can achieve, setting a benchmark for sustainable development. Once a project's certification rating is verified by a Green Building Council Inspector, a certificate is awarded by a LEED-accredited professional.

The LEED rating system contains four distinct levels of certification:

- LEED Certified: 40-49 points
- Silver Certification: 50-59 points
- Gold Certification: 60-79 points
- Platinum Certification: 80+ points

Fig. 1. LEED rating system (Adapted from "WELL Building Standard v2" by International WELL Building Institute, 2018. Retrieved from https://www.wellcertified.com/)

According to the LEED website, LEED-certified buildings play a crucial role in combating climate change, achieving ESG (Environmental, Social, and Governance) goals, fostering resilience, and promoting equity within communities. LEED considers all essential elements to optimize building performance to enhance building quality by prioritizing:

- Minimize impact on climate change
- Preserve water resources
- Foster sustainable material cycles
- Improve human health
- Safeguard biodiversity and ecosystems
- Elevate community well-being

LEED certification applicants must consider these vital requirements for achieving their sustainable building objectives.

Certification Process to obtain LEED certification:

- **Registration**: The project should be registered with the Green Business Certification Inc. (GBCI).
- **Application**: The project team prepares and submits the necessary documentation to demonstrate compliance with LEED criteria.
- **Review**: GBCI reviews the documentation and either approves the project or requests additional information.
- **Certification**: Once the project meets the requirements, it is awarded one of the four certification levels.

LEED-certified buildings are encouraged to recertify **every five years** to ensure that they continue to meet LEED standards and incorporate any updates or improvements in green building practices.

According to the LEED website, **LEED v5** represents the latest version of the LEED certification system, symbolizing a significant shift towards a low-carbon future in the built environment. This version emphasizes crucial priorities including equity, health, ecosystems, and resilience. LEED Certification Standards are designed to encourage and accelerate global adoption of sustainable building and development practices through a comprehensive and flexible framework.

4.2 WELL Building Certification Standards

The WELL Building Standard was pioneered by Delos Living LLC, a wellness real estate and technology firm founded by Paul Scialla in 2012. Delos collaborated with leading experts in medicine, science, and building design to develop the WELL Standard, which establishes guidelines for creating healthy indoor environments that promote human health and well-being. The WELL Building Standard was developed by the International WELL Building Institute (IWBI) in 2013, with the first version of the standard, known as WELL v1.0, launched in late 2014. Since then, the standard has undergone several revisions and updates to reflect advancements in scientific research and best practices in the field of building design and health (International WELL Building Institute, n.d.; WELL Building Standard v2.1, n.d.).

The WELL Standard covers a wide range of building design, construction, and operational elements, focusing particularly on factors that impact occupant health and well-being.

In May 2018, a new version of the WELL Building Standard (WELL v2) was released with the goal of creating environments that are more thoughtful and purposeful, ultimately promoting human health and well-being. The WELL Building Standard (WELL v2) consists of 110 features. These features, known as concepts, are organized into 10 concepts, each designed to address specific aspects of building design and operations that impact occupant health and well-being. These concepts and their respective points are (International WELL Building Institute, 2018):

Fig. 2. WELL concepts (Adapted from "WELL Building Standard v2" by International WELL Building Institute, 2018. Retrieved from https://www.wellcertified.com/)

- **Air** (Up to 29 points) focuses on indoor air quality, ensuring spaces are free from pollutants and allergens.
- **Water** (Up to 8 points) emphasizes access to clean and safe drinking water while promoting hydration.
- **Nourishment** (Up to 17 points) encourages healthy eating habits and access to nutritious food options.
- **Light** (Up to 14 points) aims to optimize natural and artificial lighting to support circadian rhythms and visual comfort.
- **Movement** (Up to 20 points) encourages physical activity and ergonomic design for active lifestyles.
- **Thermal Comfort** (Up to 10 points) ensures spaces maintain optimal temperature and humidity levels for occupant comfort.
- **Sound** (Up to 11 points) focuses on minimizing noise pollution and creating acoustically comfortable environments.
- **Materials** (Up to 14 points) prioritize the use of non-toxic, sustainable materials to minimize exposure to harmful chemicals.
- **Mind** (Up to 17 points) promotes mental well-being through stress reduction, relaxation, and mindfulness practices.
- **Community** (Up to 15 points) fosters social connections, equity, and access to amenities that support a sense of belonging within the built environment.

WELL Building Standard features are categorized into two main types:

- **Preconditions**: Fundamental requirements essential for certification, focusing on critical aspects of building design, construction, and operation that ensure occupant health and well-being.
- **Optimizations**: Additional enhancements beyond the basic requirements, allowing projects to further optimize indoor environments for maximum health benefits.

The WELL Certification process is a voluntary certification scheme that operates on a point-based system. Project teams can aim for a maximum of 12 points per concept and a total of 100 points across the ten concepts. Additionally, 10 extra points are available within the Innovation concept for innovative credits. WELL Certification requires a performance verification process, where third-party assessors evaluate the building's performance based on the WELL features. This involves on-site testing and documentation review to ensure compliance with WELL standards (International WELL Building Institute, n.d.; WELL Building Standard v2.1, n.d.).

Projects must fulfill all preconditions as well as attain a specific number of points to qualify for different certification levels. WELL certification levels are as follows:

Bronze	Silver	Gold	Platinum
+40<points<50	+50<points<60	+60<points<80	+80<points<110
0<points per concept<12	1<points per concept<12	2<points per concept<12	3<points per concept<12

For projects pursuing the WELL Core Certification pathway (core and shell buildings), a minimum of one point per concept must be earned, and all preconditions must be achieved. The levels of certification for WELL Core are outlined as follows:

Bronze	Silver	Gold	Platinum
+40<points<50	+50<points<60	+60<points<80	+80<points<110
1<points per concept<12	1<points per concept<12	1<points per concept<12	1<points per concept<12

WELL Certification is not a one-time achievement; buildings must undergo recertification every three years to ensure ongoing compliance with WELL features and to incorporate any updates to the standard.

Pilot Program: To expand the applicability of WELL beyond commercial and institutional office buildings, IWBI has developed pilot versions of the standard for various sectors. These include retail, multifamily residential, education, restaurant, and commercial kitchen projects. These pilots help test and refine the standard to suit different building types and uses.

The WELL Building Standard aims to create environments that enhance the health and well-being of occupants, making buildings not just better for the environment but also for the people who use them.

4.3 Comparison between LEED and WELL

Over the last decade, the Leadership in Energy and Environmental Design (LEED) green building program and WELL Building Standard (WELL) have gained national recognition for leading the way in modern, responsible buildings and design. LEED is a certification through the U.S. Green Building Council (USGBC) and WELL is managed by the International WELL Building Institute (IWBI). While both aim to enhance the built environment, they focus on different aspects of building performance and occupant well-being.

LEED Focus and Objectives:

- Developed by the U.S. Green Building Council (USGBC).
- Emphasizes environmental sustainability, energy efficiency, and resource conservation.
- Focuses on reducing the environmental impact of buildings and promoting sustainable construction practices.

WELL Focus and Objectives:
- Developed by the International WELL Building Institute (IWBI).
- Prioritizes human health and well-being.
- Concentrates on creating spaces that improve physical and mental health through design, operations, and behavior.

LEED Certification Categories and Point System:
- **Categories**: Location and Transportation (LT), Sustainable Sites (SS), Water Efficiency (WE), Energy and Atmosphere (EA), Materials and Resources (MR), Indoor Environmental Quality (IEQ), Innovation (IN), and Regional Priority (RP).
- **Points**: Maximum of 110 points.
- **Certification Levels**: Certified (40-49 points), Silver (50-59 points), Gold (60-79 points), and Platinum (80+ points).

WELL Certification Categories and Point System:
- **Concepts**: Air, Water , Nourishment , Light , Movement , Thermal Comfort , Sound , Materials , Mind , and Community
- **Points**: Maximum of 110 points.
- **Certification Levels**: Silver (meeting all Preconditions), Gold (meeting all Preconditions and a minimum number of Optimizations), and Platinum (meeting all Preconditions and a higher number of Optimizations).

Key components and Criteria:

LEED	Energy Efficiency, Water Conservation, Sustainable Sites
WELL	Air Quality, Water Quality, Nourishment, Light, Movement, Mental Health

LEED Certification process:
- **Registration**: Project registration with the Green Business Certification Inc. (GBCI).
- **Documentation**: Submission of documentation demonstrating compliance with LEED criteria.
- **Review**: GBCI reviews the documentation and either approves or requests additional information.
- **Certification**: Awarded upon meeting the requirements, with recertification recommended every five years.

WELL Certification process:
- **Registration**: Project registration with IWBI.
- **Documentation and Performance Verification**: Submission of documentation and on-site performance verification by third-party assessors.
- **Certification**: Awarded based on compliance with WELL features, with recertification required every three years.

Another point to mention is that, in LEED, the emphasis is primarily on documentation, whereas in WELL, alongside documentation submission, WELL Performance Testing Agents carry out on-site performance tests and send various samples to labs for analysis. According to the USGBC, LEED certification can be achieved in around 25 days. In contrast, the timeline for WELL certification spans months rather than weeks.

Impacts and Benefits:

LEED	Environmental	Economic	Social
WELL	Health	Economic	Social

Integration and synergy: Many projects seek dual certification in both LEED and WELL to maximize both environmental sustainability and human health benefits. Integrating both standards can lead to comprehensive strategies that address both the ecological footprint of buildings and the health and wellness of occupants.

4.4 Green Building Council in Italy

The Green Building Council Italia (GBC Italia) is a prominent organization dedicated to promoting sustainable building practices throughout Italy. Established as part of the global Green Building Council network, GBC Italia aims to transform the Italian construction industry by advocating for environmentally responsible and resource-efficient building standards. The council's mission encompasses raising awareness about the benefits of green building, fostering innovation in sustainable construction technologies, and influencing policy to support eco-friendly building practices. Through its efforts, GBC Italia plays a crucial role in addressing climate change and enhancing the quality of life in urban environments across the country (Green Building Council Italia, n.d.).

Key Initiatives and Activities:

- **Certification Programs**: GBC Italia offers certification programs similar to LEED and BREEAM, tailored to the Italian context. These certifications evaluate buildings based on energy efficiency, water conservation, materials selection, indoor air quality, and overall environmental impact.
- **Education and Training**: GBC Italia provides educational programs and training courses to professionals in the building and construction industry. These programs aim to increase awareness of sustainable building practices and certifications.
- **Research and Development**: The organization conducts research initiatives to innovate and improve sustainable building practices. This includes exploring new technologies, materials, and strategies to enhance building performance while reducing environmental impact.
- **Policy Advocacy**: GBC Italia actively engages with policymakers to advocate for green building policies and regulations that support sustainability goals. The organization provides expertise and recommendations to influence national and local policies related to the built environment.
- **Networking and Collaboration**: GBC Italia facilitates networking opportunities and collaboration among industry professionals, government agencies, academia, and NGOs. This

collaborative approach fosters knowledge sharing and promotes best practices in sustainable building design, construction, and operation.

- **Green Building Events**: The organization organizes conferences, seminars, and workshops on green building topics to promote dialogue, exchange ideas, and showcase innovative projects and practices in sustainable construction.

References Chapter 4

1. U.S. Green Building Council. (n.d.). LEED certification. Retrieved from https://www.usgbc.org/leed
2. International WELL Building Institute. (2018). *WELL Building Standard v2*. Retrieved from https://www.wellcertified.com
3. Green Building Council Italia. (n.d.). *About us*. Retrieved from https://www.gbcitalia.org
4. International WELL Building Institute. (n.d.). Retrieved from https://www.wellcertified.com
5. WELL Building Standard v2.1. (n.d.). Retrieved from https://standard.wellcertified.com/v21/well
6. Greenly. (n.d.). LEED certification: Meaning and requirements. Retrieved July 3, 2024, from https://greenly.earth/en-us/blog/company-guide/leed-certification-meaning-and-requirements#anchor-2
7. Kibert, C. J. (2016). *Sustainable Construction: Green Building Design and Delivery* (4th ed.). John Wiley & Sons.
8. Yudelson, J. (2009). *Green Building A to Z: Understanding the Language of Green Building*. New Society Publishers.

PROMET&O SYSTEM

5. PROMET&O System

5.1 PROMET&O multi-sensor

PROMET&O, that accounts for "PROactive Monitoring for indoor EnvironmenTal quality & cOmfort", comprises a multi-sensor device, designed to gather objective data by continuously monitoring indoor environmental quality and its aspects, including thermal, acoustic, lighting, and indoor air quality parameters. Additionally, it includes an online questionnaire aimed at assessing occupants' comfort perception, personal characteristics, and behavioral factors. The collected data is then visualized through a dashboard. The system will be deployed in Politecnico di Torino and other company offices.

5.1.1 Multi-sensor devices in the market

Multi-sensor devices for Indoor Environmental Quality are becoming more common, integrating multiple sensors to monitor various factors such as air quality (temperature, humidity, VOCs, CO_2, PM), as well as thermal comfort, lighting, and acoustics. These devices provide real-time data and insights, allowing users to manage and optimize both air quality and overall indoor conditions effectively. They range from home-use models to advanced commercial systems, offering versatility and convenience for enhancing indoor comfort and health.

5.1.1.1 SAMBA device

SAMBA represents a wireless Indoor Environmental Quality sensor network devised by the IEQ Lab at The University of Sydney, offering an indicative monitoring solution for comprehensive IEQ assessment in commercial office buildings. SAMBA, derived from the acronym Sentient Ambient Monitoring of Buildings in Australia, combines an affordable suite of sensors with modest data-processing capabilities to independently gauge crucial IEQ metrics. Positioned permanently within the occupied zone, it facilitates spatial sampling across the building's floor plate and longitudinal measurements over time, enabling a comprehensive characterization of environmental conditions experienced by office occupants. The SAMBA device comprises two elements: the main unit, measuring 190mm (height) x 90mm (diameter), and the satellite unit, with dimensions of 95mm (height) x 95mm (width) x 95mm (depth).

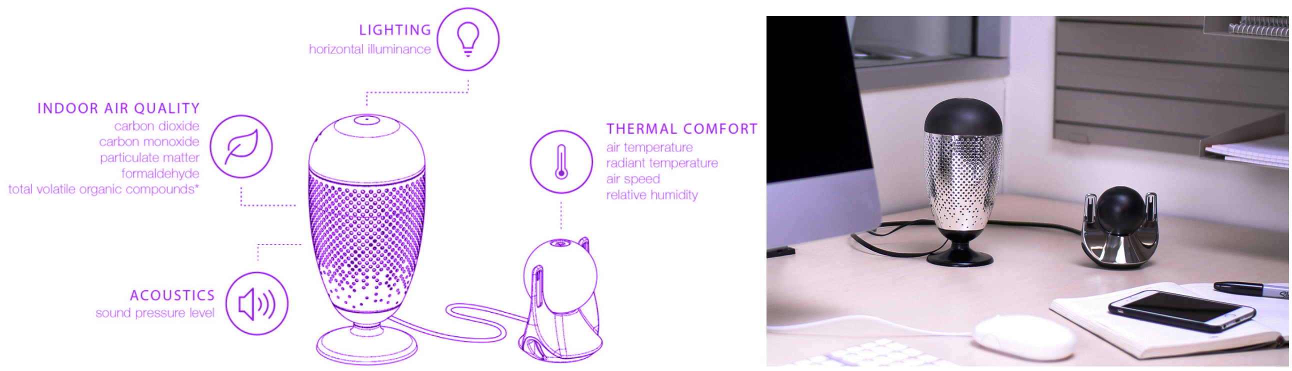


Fig. 1. Diagrammatic representation of SAMBA device and it's sensors positioning (Adopted from https://good-design.org/projects/samba-indoor-environmental-quality-ieq-monitoring-platform/)

The data obtained are wirelessly transmitted to a centralized web service called IEQ analytics. Here, a dashboard displays a real-time visualization of all measured Indoor Environmental Quality parameters and calculated indices in a comprehensible and actionable format for building owners, facility managers, tenants, and occupants. In pursuit of this objective, weekly reports summarizing the overall building performance are sent to users every Monday morning.

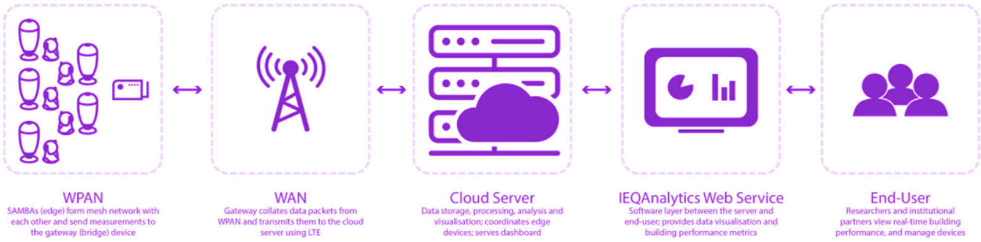


Fig. 2. A diagrammatic representation of the network of IEQAnalytics platform (Adopted from (Parkinson et al., 2019a))

The goal was to position SAMBA on desks within the occupied zones of high-quality commercial offices. SAMBA's sensor performance requirements were designed for the application of 'good enough' big data, allowing substantial reductions in both hardware costs and end-use operational expenses. SAMBA operates efficiently without needing access to the host organization's data, utilizing a wireless personal area network (WPAN). The on-site SAMBA installation was designed to be a simple plug-and-play procedure with no prior knowledge of the system required.

Dashboard design of SAMBA:

There are three rating levels based on the total number of time spent within compliance ranges. Good (green), fair (yellow) and poor (red) (Parkinson et al., 2019a).

- Good is more than 80%
- Fair is between 60% and 80%
- Poor is less than 60%

In the overall IEQ rating, Thermal Comfort and Indoor Air Quality each carry a weight of 0.35, while Lighting and Acoustics contribute 0.15 each, aligning with the NABERS IE rating tool's approach. This distribution acknowledges the broader scope of parameters encompassed within Thermal Comfort and Indoor Air Quality measurements, hence their proportionately higher weighting (Parkinson et al., 2019a).

Fig. 3. SAMBA Dashboard setting (Adopted from https://good-design.org/projects/samba-indoor-environmental-quality-ieq-monitoring-platform/)

The SAMBA multi-sensor device, as outlined by NABERS, integrates several key sensors to monitor indoor environmental conditions. It includes temperature, humidity, and carbon dioxide sensors to assess thermal comfort and air quality. Additionally, it features particulate matter sensors to measure dust and other airborne particles, volatile organic compounds sensors to detect indoor pollutants, and a light sensor to evaluate lighting levels. This comprehensive array of sensors provides a thorough assessment of indoor air quality and environmental comfort, aiding in effective management and optimization of the indoor environment.

5.1.1.2 AIRCARE device

Aircare® is an innovative IoT device designed to monitor air quality and indoor well-being, with a primary goal of enhancing the indoor air quality within buildings. It prioritizes the health and comfort of occupants by focusing on both air quality and comfort levels. With its smooth and white surface and compact dimensions of 10x10x7cm, it boasts a minimalist design and seamlessly integrates into any indoor environment. Leveraging the local Wi-Fi network, Aircare detects air quality parameters and transmits them to a cloud-based dashboard. Whether for a household, professional setting, or company, users can access a dedicated control panel via a provided link to monitor their indoor air quality. With its array of sensors (up to 15), Aircare enables continuous monitoring of pollutants and other metrics, issuing alerts if preset thresholds are exceeded. Additionally, Aircare features an integrated battery with a long lifespan, offering convenient and hassle-free operation.

Aircare devices can measure up to 12 parameters in Air quality, Environmental comfort and Electrosmog.

- Air Quality Parameters:

Volatile Organic compounds	Particulate Matters ($PM_{2.5}$)	Air quality index
Particulate Matters (PM_{10})	Particulate Matters (PM_1)	CO_2

- Environmental comfort Parameters:

Noise pollution	Temperature	Humidity

Ambient Brightness	Atmospheric pressure	-

- Electrosmog:

Wifi (Networks detected)

In 2022 Aircare was officially certified according to the European norm UNI CEI EN ISO/IEC 17025:2018 covering the measurements of PM2.5, CO2, TVOC.

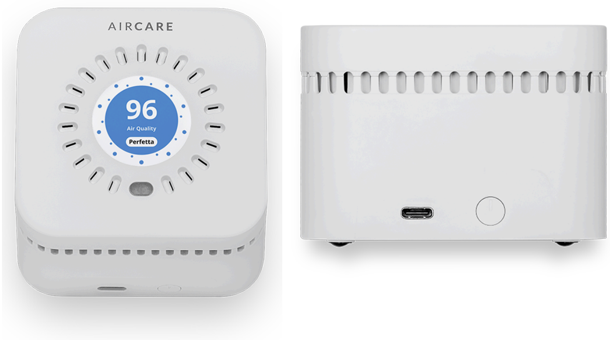


Fig. 4. Representation of AIRCARE device (Adopted from https://www.aircare.it/aircare-servizio-misura/)

Features of the Aircare device:

- The **case is equipped** with a customizable **LCD** display that provides a unique and tailored view. With an interactive **area touch** feature and an embedded **NFC tag**, the case offers a user-friendly and dynamic experience.
- The device supports versatile **charging options**, including **USB-C** and **Power over Ethernet (POE)**, ensuring flexibility in power sources. Additionally, it features a **rechargeable battery** with a 6-month lifespan for convenient and long-lasting operation.
- The device offers diverse **connectivity** options, including **Wi-Fi** and **Power over Ethernet (POE)** for efficient data transmission. Additionally, it supports optional connectivity through **Narrowband IoT** and **LoRa**, providing flexibility to suit specific communication requirements.
- The **integration** of the system supports secure communication through protocols such as **HTTPS** and **MQTTs**, ensuring robust data exchange. Additionally, it facilitates seamless interaction with external systems through a **REST API**, enhancing interoperability and expanding integration possibilities.
- **Safety** is reinforced through the implementation of **AWS Certificate**, ensuring a secure and encrypted environment for data transmission and storage.

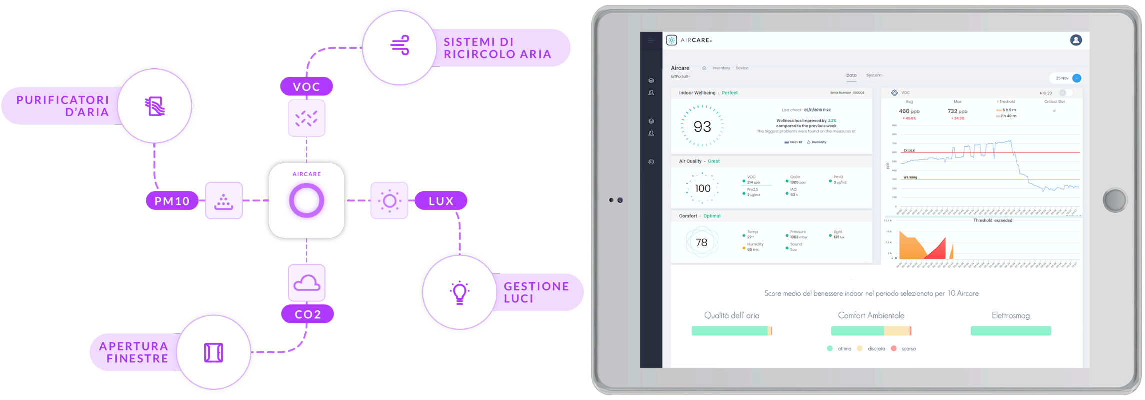


Fig. 5. Representation of AIRCARE parameters and dashboard (Adopted from https://www.aircare.it/en/aircare-mini-2/ and https://www.aircare.it/en/occpancy-counting/)

Installation and configuration: Aircare provides a seamless and user-friendly installation and configuration process Experience. Users can effortlessly set up their devices just by downloading the configuration app and activating their Aircare device in a matter of minutes, prioritizing ease and efficiency for an optimal user experience.

Dashboard design of AIRCARE: Aircare provides the opportunity to Control all your IoT devices on one dashboard to have a comprehensive vision of the condition of the indoor environment. By tracking how and when the parameters change, AIRCARE devices will suggest actions to make the work environment healthier and more productive.

5.1.1.3 Other devices

The market offers a diverse range of Indoor Environmental Quality multi-sensors, each designed with specific features and functions. These devices prioritize user-friendliness and simplicity, providing real-time monitoring of key indoor environmental parameters to empower users with actionable insights for a healthier and more comfortable indoor environment. By addressing various aspects of IEQ, including air quality, thermal comfort, lighting, and acoustics, these multi-sensors cater to different user needs and preferences. Connected to dashboards or mobile apps, these devices enable users to track their data in real-time, allowing for prompt identification of issues or changes in environmental conditions and enabling timely actions to optimize indoor quality. Here are a few examples of IEQ multi-sensors available on the market.

1. **Awair Multi sensor**: Awair offers various indoor environmental quality monitors, including the Awair Element and Awair Omni. Awair Element measures 5 environmental factors including temperature, humidity, CO_2, TVOCs (volatile organic compounds), and $PM_{2.5}$ (particulate matter). This multi-sensor can be used for home scale. On the other hand, Awair Omni measures 7 environmental factors including temperature, humidity, CO_2, TVOCs (volatile organic compounds), $PM_{2.5}$ (particulate matter), noise, and light. This multi-sensor can be used for various scales, ranging from individual offices and educational facilities to multiple buildings, tenants, and business locations.

2. **Foobot Multi sensor**: Foobot is another IEQ monitor that tracks various indoor pollutants such as VOCs, $PM_{2.5}$, CO_2, temperature, and humidity. It provides real-time insights and alerts to help improve indoor air quality. They offer various devices for residential (Foobot Home)

and commercial use (Foobot SAT). Foobot can be connected to home automation smart devices (HVAC), directly from the Foobot app.

3. **uHoo Multi sensor**: uHoo is a comprehensive indoor air quality monitor that offers two devices for Home and Business use. uHoo measures 9 air quality factors for home devices including temperature, humidity, CO_2, CO, VOCs, NO_2, $PM_{2.5}$, air pressure, and ozone that affect health and well-being, with real-time insights, virus index, and smart home integration. For Business devices, besides other parameters, it also tracks PM_1, PM_4, PM_{10}, formaldehyde, light, and sound. It provides insights into indoor air quality and health recommendations.

5.1.2 PROMET&O software & hardware

The PROMET&O system includes an advanced multi-sensor device that monitors various aspects of indoor environmental quality, such as thermal, acoustic, visual, and air quality factors. This device features 10 affordable sensors that measure parameters including air temperature, relative humidity, sound pressure level, illuminance, particulate matter, carbon dioxide, carbon monoxide, nitrogen dioxide, volatile organic compounds, and formaldehyde. Its compact design allows for easy integration into diverse indoor environments. Data is transmitted via Wi-Fi to a server, where it is processed and displayed on a dashboard. This dashboard provides real-time, graphical representations of the measured parameters and their variations over time, facilitating visualization and analysis.

The PROMET&O system not only measures objective indoor environmental factors but also includes a questionnaire to assess occupant comfort. This questionnaire collects feedback on thermal, acoustic, visual, and air quality conditions, integrating subjective impressions with the objective data. Wi-Fi connectivity enables seamless data transfer between the multi-sensor device and the server, allowing for continuous monitoring and analysis. This combined approach helps stakeholders effectively monitor and enhance indoor environmental quality, addressing both physical parameters and occupant comfort.

The initial phase of designing the PROMET&O multi-sensor, the team focused on selecting sensors based on key factors such as cost, dimensions, accuracy, and measurement range. They used standards and WELL protocol for accuracy and range, considering the physical size of the sensors. Additional criteria included market availability, interface type, and response time for handling sudden changes in measurements. This thorough evaluation aimed to ensure the multi-sensor device's functionality, reliability, and efficiency.

Table. 1. Parameters in Multi-Sensor device (Adopted from Astolfi, Fissore et al., 2024)

Parameter		Sensor measurement range	Threshold for offices	Reference
Air Temperature (T_a)	°C	-40-125 °C	Winter: (20-24) °C	ISO 7730:2005
			Summer: (23-26) °C	
Relative Humidity (RH)	%	0-100%	(25-60) %	EN 16798-1:2019
Illuminance *(E_v)*	lx	0.0072-120000 lx	Writing, typing, reading, data processing ≥ 500 lx	EN 12464-1:2021

Carbon monoxide *(CO)*	mg/m3	0-1145.609 mg/m3	15 min. mean ≤ 100 mg/m3	EN 16798-1:2019
			1 h mean ≤ 35 mg/m3	
			8h mean ≤ 10 mg/m3	
			24 h mean ≤ 7 mg/m3	
Carbon dioxide *(CO_2)*	ppm	0-40000 ppm	≤ 800 ppm	EN 16798-1:2019
Nitrogen dioxide *(NO_2)*	µg/m 3	0-9409 µg/m 3	1 h mean ≤ 200 µg/m3	EN 16798-1:2019
			Annual mean ≤ 20 µg/m3	
Particulate matter *($PM_{2.5}$)*	µg/m 3	0-1000 µg/m 3	24 h mean ≤ 25 µg/m3	EN 16798-1:2019
			Annual mean ≤ 10 µg/m3	
Particulate matter *(PM_{10})*	µg/m 3	0-1000 µg/m 3	24 h mean ≤ 50 µg/m3	EN 16798-1:2019
			Annual mean ≤ 20 µg/m3	
Formaldehyde *(CH_2O)*	µg/m 3	0-3229 µg/m 3	30 min. mean ≤ 100 µg/m3	EN 16798-1:2019
Sound Pressure Level *(SPL)*	dB(A)	0-1228 µg/m 3	≤ 45 dB(A)	NF S 31-080

For the PROMET&O multi-sensor project, various components were carefully selected for precise environmental monitoring. Devices were mounted to capture temperature, sound, and light, with strategic placement to optimize accuracy. Air quality is monitored by measuring key pollutants such as carbon monoxide, nitrogen dioxide, carbon dioxide, particulate matter, volatile organic compounds, and formaldehyde. All components are wire-connected, positioned to ensure proper airflow, and designed to operate without interference. Following this selection, the multi-sensor case was crafted to include essential features such as a charger port for wired connection and LED lights for visual feedback. The case is compact, functional, designed for 3D printing with a modular structure—comprising interlocking pieces (top, body, and base) secured with screws for easy assembly and maintenance while maintaining a nice appearance.

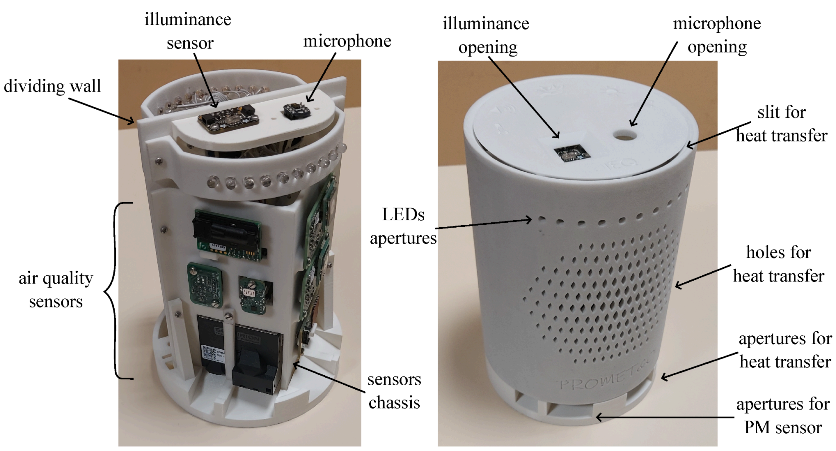


Fig. 6. Internal and External Structure of Multi-Sensor Device (Adopted from Fissore et al., 2024)

5.1.3 PROMET&O indexes and KPIs

The PROMET&O system employs several Key Performance Indicators (KPIs) to comprehensively assess indoor environmental quality and occupant comfort, including **Thermal Comfort**, which uses the adaptive comfort model to evaluate how well indoor temperatures align with occupants' preferences, ensuring a thermally comfortable environment. **Visual Comfort** measures lighting conditions to support visual tasks and reduce eye strain, enhancing productivity and well-being. **Acoustic Comfort** evaluates sound pressure levels to maintain a quiet, conducive environment, minimizing noise pollution's impact on health and focus. The **Indoor Air Quality Index** combines parameters like particulate matter, carbon dioxide, carbon monoxide, nitrogen dioxide, formaldehyde, and volatile organic compounds to provide a clear picture of the space's air quality. Together, these KPIs ensure a holistic view of environmental and comfort factors.

Fig. 7. Representation of Key Performance Indicators

Index within the PROMET&O system provides a comprehensive measure of indoor environment quality on a scale from 0 to 100%. This index is derived by equally weighting four domains each contributing 25% to the overall calculation.

Key Performance Indicators are then calculated at report times based on statistical analysis of the data acquired during sampling intervals. These report times occur at various intervals including real-time (RT), 3 hours, 24 hours, 3 days, 1 week, and 1 month. This structured approach to data collection and analysis ensures that trends and variations in indoor environmental quality are captured effectively over different time scales.

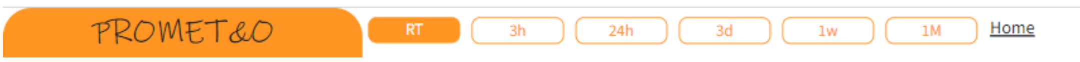


Fig. 8. Representation of Dashboard showcasing the timing intervals

Fig. 9. Representation of Dashboard showcasing the parameters

Visualization of the IEQ Index and its component parameters is provided at these designated visualization times, offering stakeholders insights into how the indoor environment performs relative to comfort and health standards. This multi-tiered approach allows for proactive management of indoor environments, enabling timely interventions and adjustments to optimize occupant comfort and well-being.

5.2 PROMET&O questionnaire structure

Questionnaires are widely used to gather valuable insights, preferences, and feedback from the target audience. They are versatile tools that solicit input on various aspects of a project, including user needs, preferences, expectations, and satisfaction levels. By facilitating the systematic collection of both quantitative and qualitative data, questionnaires enable comprehensive analysis and interpretation of findings. Advances in technology have further enhanced the state of the art of questionnaires, leading to the development of online survey platforms.

To ensure users can comprehensively access all the monitored and calculated data from the PROMET&O multi-sensor, it was essential to design the multi-sensor with an integrated IT dashboard. By offering a centralized platform for data visualization, the dashboard will enable users to easily interpret the information and understand the environmental conditions. Additionally, it will include advanced features such as real-time data visualization.

5.2.1 ISO 28802:2012 - Ergonomics of the physical environment

In the state of art of PROMET&O questionnaire (Fissore et al., 2023), the detailed questions on the four domains are based on ISO 28802:2012. Ergonomics of the physical environment — Assessment of environments by means of an environmental survey involving physical measurements of the environment and subjective responses of people. The presented International Standard outlines techniques for assessing comfort through both objective measures of the environment and subjective feedback from individuals. It offers methodologies for evaluating thermal, acoustic, visual, and lighting conditions, as well as air quality factors. Each environmental aspect is accompanied by procedures for quantifying the physical environment and capturing subjective reactions to it.

Physical environment measurements are performed utilizing appropriate instrumentation, including devices like thermometers, sound level meters, or illuminance meters. When necessary, guidance regarding the specifications of these instruments is referenced from relevant International Standards. Subjective methodologies measure individuals' responses to their environment through subjective scales. The assessment's third aspect involves observation, with guidance offered on what to include in an observation assessment form for each environmental element.

The design of an environmental survey will vary depending on its specific objectives. Two key principles governing such design are the physical environmental conditions and the subjective responses of individuals exposed to the environment.

Measurement of the Physical environment: Instruments must be chosen based on relevant specifications and standards, taking into account factors such as range, accuracy, sensitivity, and durability. Calibration procedures are essential to ensure that the instruments accurately measure according to specifications. The goal of these measurements is to quantitatively assess the physical environment experienced by individuals.

Measurement of Subjective responses: Subjective methods measure individuals' responses to an environment using subjective scales, which are rooted in relevant psychological constructs. Understanding the properties of these scales is crucial for accurate result interpretation. Sensation scales, such as those measuring hot or cold sensations, along with preference, comfort, annoyance, smell, and stickiness scales, are commonly employed in comfort assessment. Subjective methods offer simplicity in administration and a direct connection to the psychological phenomenon, making them advantageous for comfort assessment. When utilizing subjective measures, it's crucial to inquire about subjects' current feelings and experiences within the specific space being assessed. (ISO Standard No. 28802:2012)

ISO 10551:2019 standard. Ergonomics of the physical environment — Subjective judgment scales for assessing physical environments, provides guidance on the construction of subjective scales for assessing thermal comfort in office environments. It identifies five types of scales:

1. **Perceptual Scales**: These scales measure how individuals perceive their current thermal environment based on sensory experiences, such as feeling "hot" or "cold."
2. **Affective Scales**: Affective scales assess individuals' emotional responses to their thermal environment, focusing on feelings of comfort or discomfort.
3. **Preference Scales**: Preference scales measure individuals' preferences regarding their thermal environment, indicating whether they would prefer it to be warmer, cooler, or remain unchanged.
4. **Acceptance Scales**: Acceptance scales evaluate individuals' overall acceptance or rejection of their current thermal environment, indicating whether it is deemed acceptable or unacceptable.
5. **Tolerance Scales**: Tolerance scales assess individuals' tolerance levels for their current thermal environment, indicating whether it is tolerable or intolerable based on their comfort thresholds.

By incorporating these different types of scales, this standard facilitates a comprehensive assessment of thermal comfort, allowing for a Detailed understanding of individuals' experiences and preferences in office settings. Constructing subjective scales for assessing the impact of the environmental conditions. Some common scales utilized in evaluating environmental conditions according to (ISO Standard No. 10551:2019).

Satisfaction scale: “Please rate on the satisfaction scale.”

- Satisfied
- Not Satisfied

Preference scale: “Please rate on the following scale how YOU would like to be NOW.”

- Much warmer/Much lighter
- Warmer/lighter
- Slightly warmer/Slightly lighter
- No change

- Slightly cooler/Slightly darker
- Cooler/darker
- Much cooler/Much darker

It's crucial to recognize that:

- Presentation and administration of scales impact results
- Single-sheet questionnaires enhance completion rates
- Clear question wording ensures accurate responses
- Frequency of completion should align with design goals
- Cultural aspects influence scale translation
- Participant training aids accurate understanding
- Avoid leading questions to prevent bias

Based on these insights, the guidelines for the PROMET&O questionnaire were defined as follows:

- **Simplicity and Speed**: The questionnaire is designed to be simple and fast to complete, minimizing user effort and time commitment.
- **Intuitive Dashboard**: An intuitive dashboard is provided to make it easy for users to enter their questionnaire responses.
- **Feedback Implementation**: Feedback from the questionnaire is actively incorporated and reflected back to the user, showing them the impact of their input.
- **Data Visualization**: Users are able to see their responses in real-time, presented in clear and interactive tables and graphs.

5.2.2 IEQ questionnaire and personal information structure

In PROMET&O questionnaire, we are employing an online platform survey to systematically gather data from office workers regarding their satisfaction with their Indoor Environmental Quality. Through this survey, we seek to gain a deeper understanding of individuals' perceptions and experiences related to Indoor Environmental Quality, including thermal comfort, air quality, lighting and acoustic comfort. This approach allows us to gather quantitative and qualitative data from a large sample size, enabling comprehensive analysis and interpretation of findings, which will inform our efforts to enhance environmental conditions and promote occupant well-being in educational and workplace settings.

According to **ISO 28802:2012** and **ISO 10551:2019,** PROMET&O questionnaire is available in both English and Italian language to accommodate the diverse linguistic backgrounds of our respondents. The estimated completion time is 2-5 minutes. Questionnaire structured into two parts for ease of navigation and efficient data collection. The first part comprises questions focused on Indoor Environmental Quality (IEQ) satisfaction, covering various aspects such as thermal comfort, indoor air quality, lighting and acoustic. These questions are designed to gauge respondents' perceptions and experiences regarding their indoor environment. The second part consists of optional personal and behavioral questions, which respondents can choose to skip if desired. However, providing responses to these personal questions will enable us to gather additional demographic information, thereby facilitating more accurate data analysis and interpretation. By offering a streamlined questionnaire format and bilingual options, we aim to encourage broad participation and gather comprehensive insights into IEQ satisfaction among our target audience.

The list of questions included in IEQ satisfaction part of the questionnaire are:

- Are you **satisfied with** Thermal, Acoustic, Visual and Air quality conditions in your environment?
- Your evaluation is **Negative**, can you tell us which environmental quality aspects are you dissatisfied with? (In case of a negative answer, more detailed questions for the dissatisfying domains are displayed.)
- Your evaluation is **Positive**, can you tell us which environmental aspects you consider particularly satisfying?

The list of questions included in personal and behavioral information part of the questionnaire are:

- Would you provide information about yourself? (Including gender, age, country of birth, educational qualification, intended use of building, role, number of people in the environment, visual impairments, hearing impairments and …)
- Would you provide information about your behavior? (Including Do you have control on…? And Do you think it’s important to have control on…?)

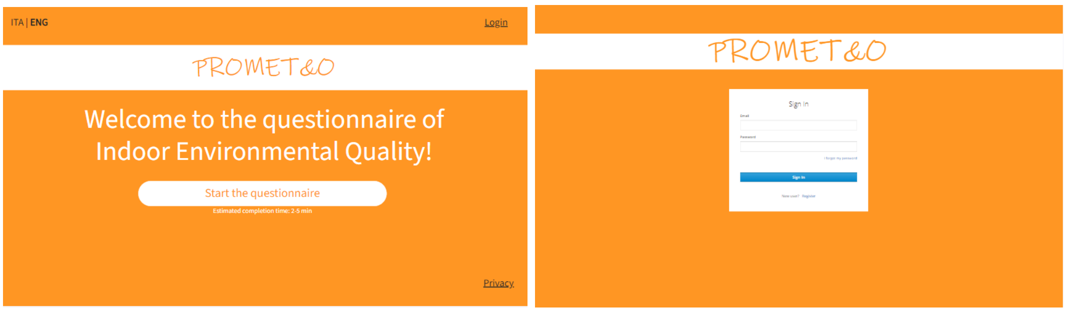


Fig. 10. Interface of questionnaire Home page & Log-in page

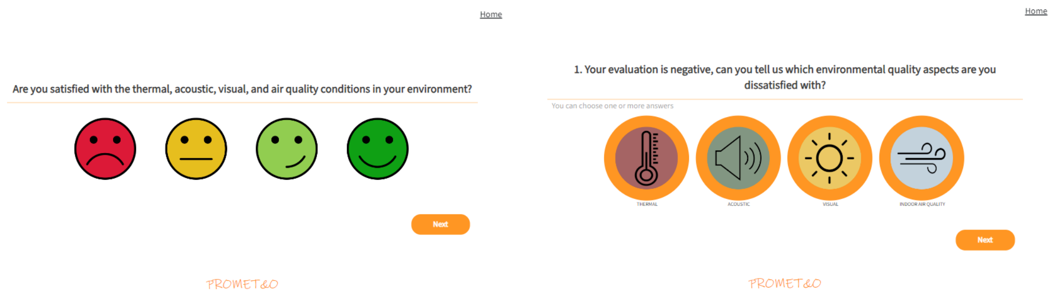


Fig. 11. Interface of PROMET&O questionnaire IEQ part

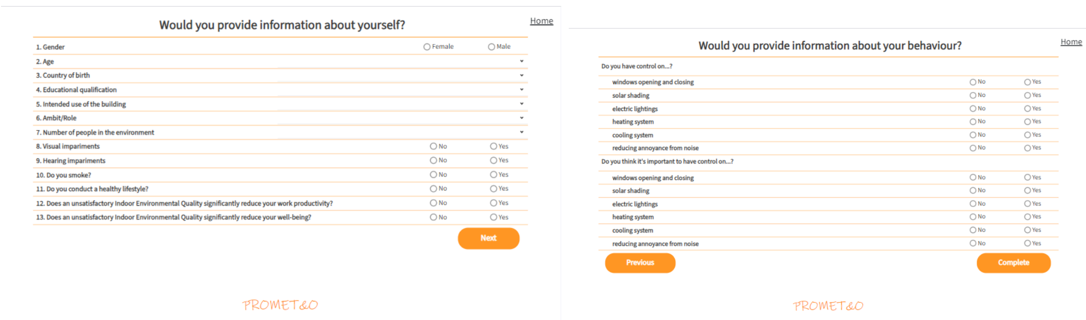


Fig. 12. Interface of personal and behavioral information part

5.3 PROMET&O Dashboard Structure

The dashboard provides a centralized platform where users can access and visualize the data collected by the devices. This enables users to track indoor environmental quality metrics throughout the day.

The objective and subjective report within the dashboard of PROMET&O integrates quantitative data from sensor measurements with qualitative insights gathered through user feedback. This combined approach offers a comprehensive view of indoor environmental quality, enabling users to monitor and evaluate both factual metrics and occupants' subjective comfort perceptions effectively.

Fig. 13. Representation of Dashboard including all indexes

The dashboard of PROMET&O offers comprehensive functionality, providing users with access to various indexes and parameters for real-time monitoring and analysis. Users can view indoor environmental quality metrics such as air temperature, humidity, sound levels, lighting conditions, and air quality indices across multiple time intervals: real-time, 3 hours, 24 hours, 3 days, 1 week, and 1 month. Each parameter is presented graphically, allowing for detailed visualization and comparison. The dashboard includes a unique feature that enables users to compare graphs in two different modes: either selecting one timing with four different parameters or choosing one parameter and comparing it across four different time intervals. This flexibility enhances usability, enabling users to gain deeper insights into trends and variations in indoor environmental conditions over time.

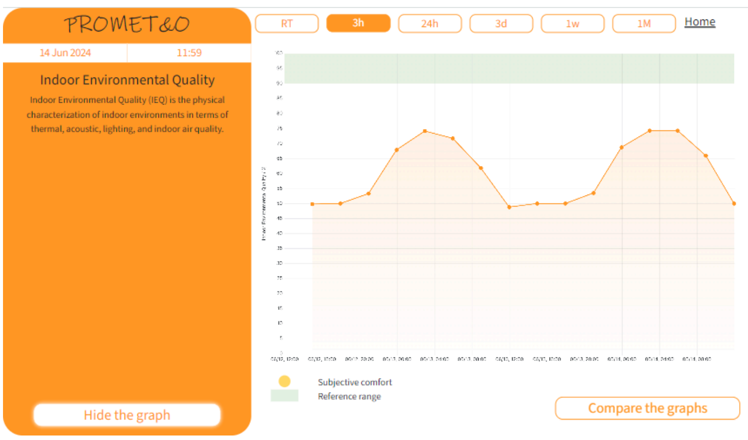


Fig. 14. Representation of Dashboard in one parameter one timing showing the graph mode

Fig. 15. Representation of Dashboard in four parameter one timing comparison mode

5.4 PROMET&O questionnaire & dashboard debugging

This chapter will focus on questionnaire and dashboard debugging. Documenting the iterative nature of the project and its ongoing refinement. I undertook the task of debugging and enhancing the dashboard designed to collect both objective and subjective data through various sensors. Upon receiving directives from my professor, I analyzed each component of the dashboard, including the Home page, IEQ questionnaire section, personal and behavioral questionnaire section, and the comprehensive dashboard encompassing all timing and parameter aspects relevant to the objective and subjective data collection. I conducted a debugging process, identifying any technical, user interface and user experience design issues or discrepancies encountered. Subsequently, I shared my detailed findings, enabling informed decisions regarding further improvements. Moving forward, I am poised to implement the recommended enhancements, documenting them in the subsequent chapter of my thesis to reflect the iterative nature of the project and its ongoing refinement.

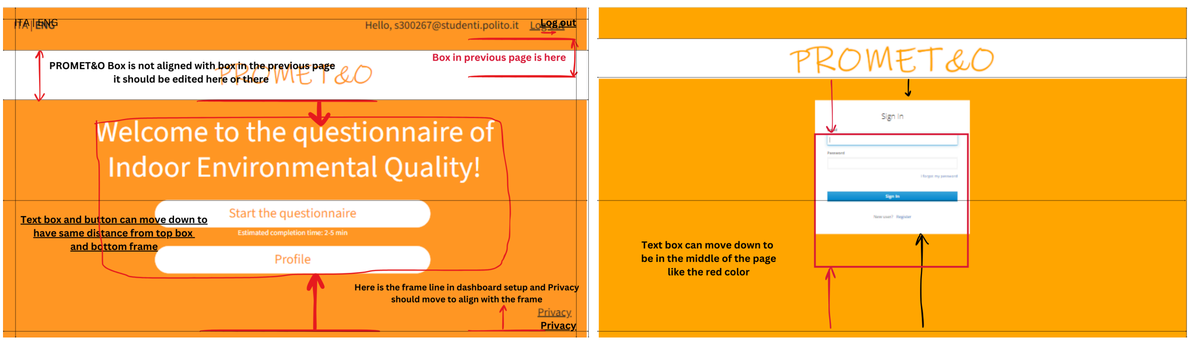
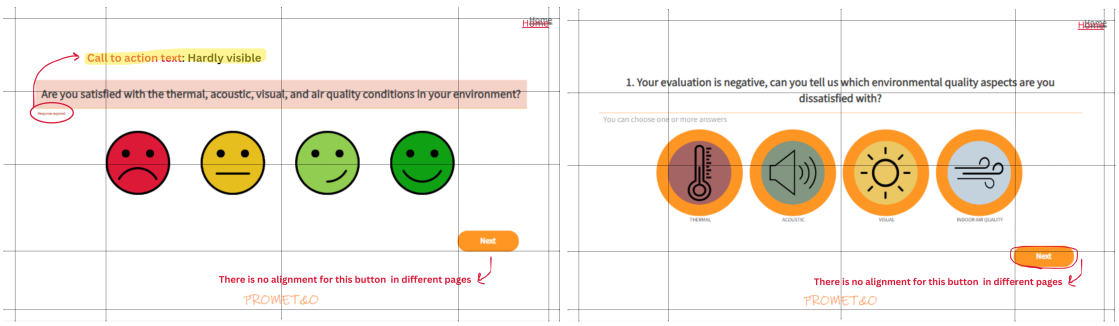


Fig. 16. Interface of Questionnaire Home page & Log-in page



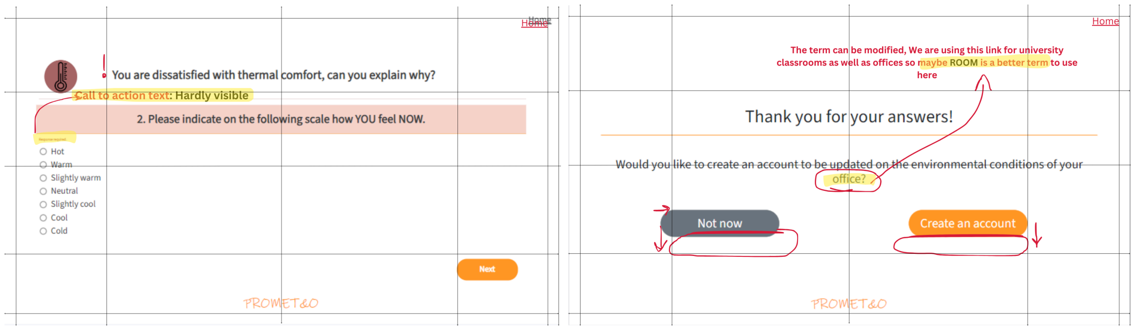


Fig. 17. Interface of IEQ Question part of the questionnaire

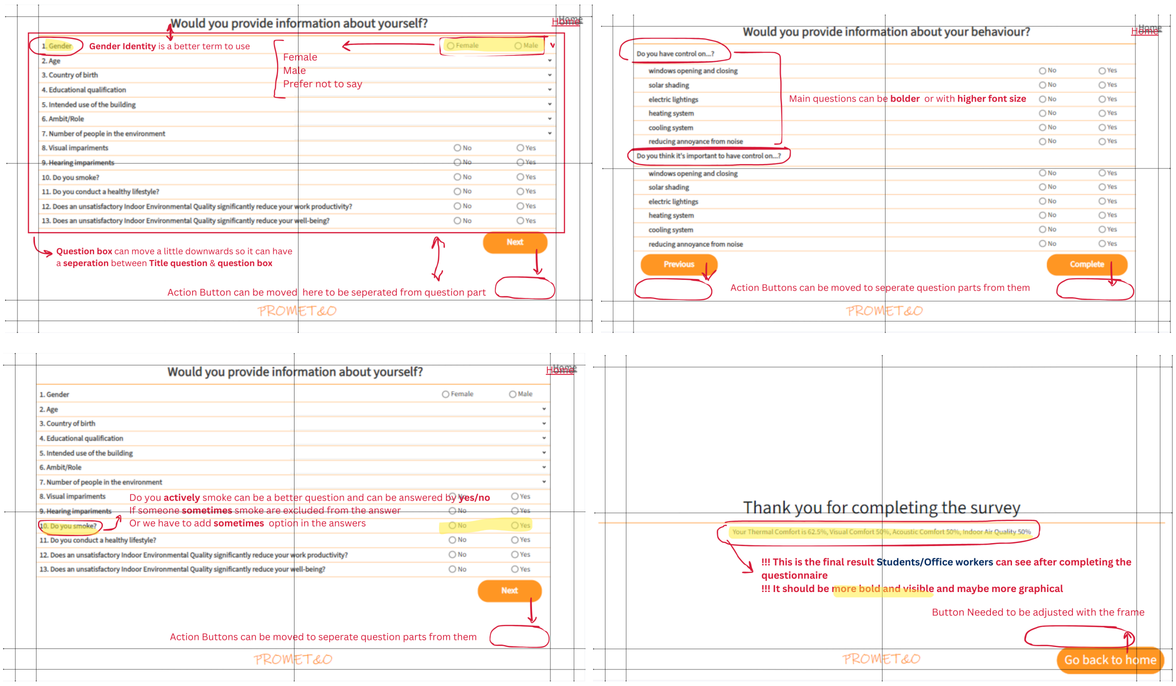


Fig. 18. Interface of Personal information part of the questionnaire

Fig. 19. Interface of Dashboard with all IEQ Parameters

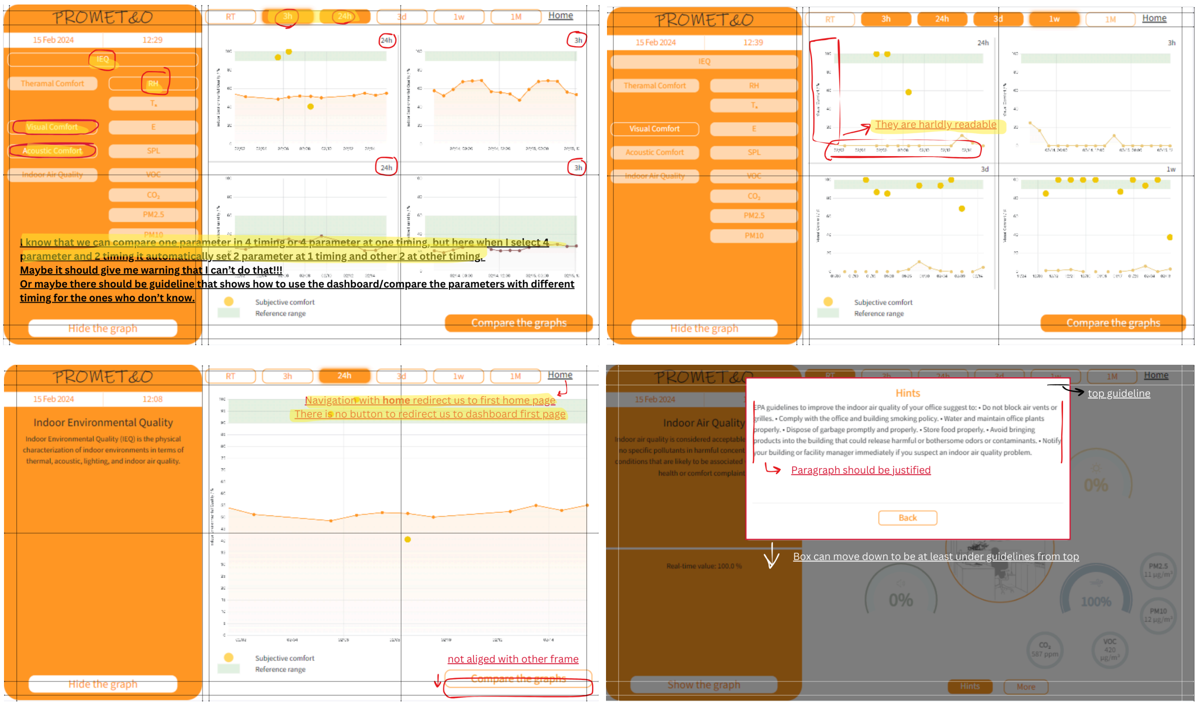


Fig. 20. Interface of Single graph & Compare Graphs for Parameters

5.4.1 Questionnaire & dashboard revise design with FIGMA/HTML/CSS

After identifying the issues during the debugging of the questionnaire, I initiated the redesign process by creating new wireframes in Figma. Figma's intuitive interface allowed me to effectively address the problems and enhance the user interface with improved design elements. To streamline the development process, I utilized a Figma plugin to convert the redesigned wireframes into HTML/CSS code. However, the automatically generated HTML/CSS did not meet our precise requirements and design specifications.

As a result, I began manually editing the HTML/CSS code in Visual Studio Code, making necessary adjustments to align with our desired outcome. This task required a meticulous approach, involving a back-and-forth process between Figma and Visual Studio Code. I continuously refined both the design in Figma and the HTML/CSS code in Visual Studio Code, ensuring that each iteration brought us closer to the final desired design. This iterative approach was crucial in addressing unforeseen issues and making incremental improvements.

As a result a refined and polished interface that aligned our initial vision and the project's objectives was developed..

Here is the final design outcome, which showcases the redesigned interface. This design incorporates all the feedback and adjustments made throughout the iterative process to ensure a user-friendly and visually appealing experience. The final Figma layout effectively addresses all the initial issues identified during the debugging phase, resulting in a polished and well-optimized interface.

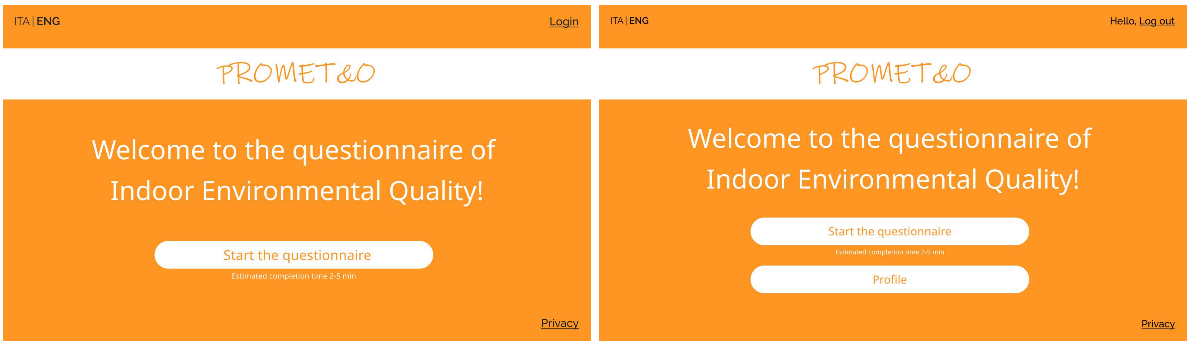


Fig. 21. Interface of Home page with revise changes

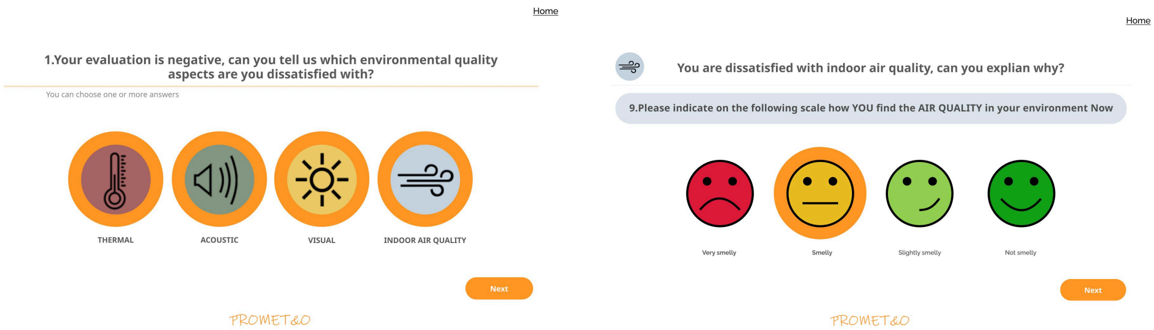


Fig. 22. Interface of IEQ pages with revise changes

Figma: As previously mentioned, I used Figma to revise the design of debugged pages. Figma is a powerful web-based design tool ideal for interface design & prototyping. It offers high-fidelity design and wireframe creation, vector-based tools for precision and scalability, and built-in prototyping features for interactive user experience simulations. Figma also supports plugins and integrations, enhancing functionality and streamlining workflows.

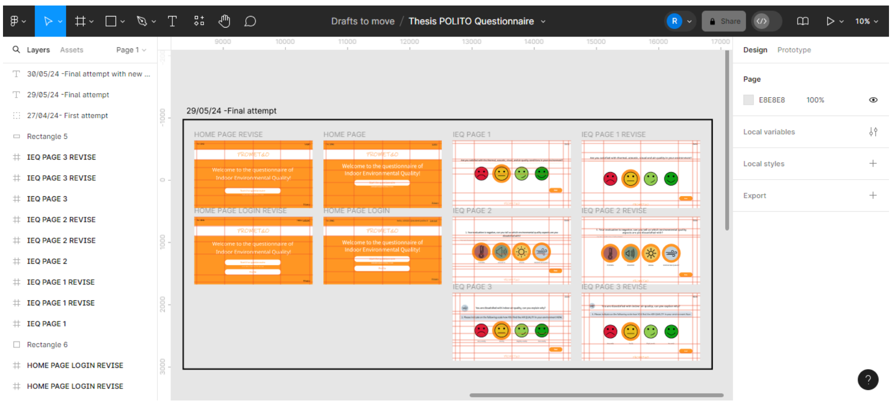


Fig. 23. Interface of FIGMA Design canvas (Adopted from my figma personal page)

Visual Studio Code: As previously mentioned, I used Visual Studio Code, commonly known as VS Code, an open-source code editor developed by Microsoft. I specifically used it to edit HTML and CSS codes obtained from the Figma plugin to ensure the design on the web page appears as desired. While the Figma plugin is helpful for extracting CSS properties of HTML elements, it does not provide accurate layout information, as it uses absolute positioning. In contrast, web pages typically rely on grid or flex layouts for responsive design, requiring further adjustments during development.

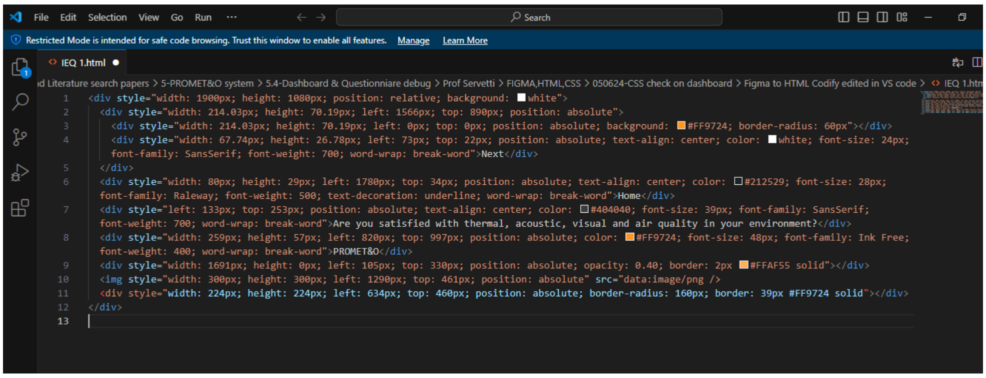


Fig. 24. Interface of Visual studio code canvas (Adopted from my VS code personal page)

HTML (HyperText Markup Language): HTML, or HyperText Markup Language, serves as the fundamental markup language for creating and organizing content on the internet. It acts as the cornerstone of web pages, laying out the essential framework upon which additional technologies such as CSS and JavaScript operate. HTML plays a critical role in ensuring web content is well-structured and accessible, benefiting both users and search engines alike.

CSS (Cascading Style Sheets)

CSS, known as Cascading Style Sheets, functions as a stylesheet language crucial for managing the presentation and visual design of HTML documents. It empowers developers to apply diverse styles to HTML elements, including colors, fonts, spacing, and layout, thereby enriching the overall appearance and user experience of web pages. By segregating content (HTML) from design (CSS), developers can uphold a cohesive look across numerous web pages and streamline the process of implementing design updates. CSS plays a pivotal role in crafting visually captivating and intuitive web interfaces.

Fig. 25. HTML and CSS code (Adopted from https://it.wikipedia.org/wiki/HTML & https://en.wikipedia.org/wiki/CSS)

References Chapter 5

1. International Organization for Standardization (ISO). **ISO 28802:2012** - Ergonomics of human-system interaction -- environmental design for non-keyboard input devices. Retrieved from https://www.iso.org/standard/44964.html
2. International Organization for Standardization (ISO). **ISO 10551:2019** - Ergonomics of human-system interaction — Test methods for evaluating subjective responses. Retrieved from https://www.iso.org/standard/67186.html
3. International Organization for Standardization. **UNI CEI EN ISO/IEC 17025:2018** - General requirements for the competence of testing and calibration laboratories. Retrieved from https://www.uni.com/wp-content/uploads/Indagine-internazionale-sullapplicazione-della-norma-UNI-CEI-EN-ISO-IEC-17025_2018.pdf
4. Fissore, V., Arcamone, G. et al. (2024). Multi-sensor device for traceable monitoring of indoor environmental quality. Sensors, 24(9), 2893. Retrieved from https://doi.org/10.3390/s24092893
5. Astolfi, A., Carullo, A. et al. (2023). *Development and metrological characterization of a multi-sensor device for indoor environmental quality (IEQ) monitoring*. https://doi.org/10.1109/MetroLivEnv56897.2023.10164058
6. Aircare - New Energy Organism. (n.d.). Aircare 2. Retrieved June 21, 2024, from http://www.newenergyorganism.com/en/aircare-2/
7. Aircare. (n.d.). Aircare 2.0. Retrieved June 21, 2024, from https://www.aircare.it/en/aircare-2-0/
8. Figma. (n.d.). *Figma: The collaborative interface design tool*. Retrieved June 21, 2024, from https://www.figma.com/
9. Wikipedia. (n.d.). HTML. Retrieved June 21, 2024, from https://it.wikipedia.org/wiki/HTML
10. Wikipedia. (n.d.). CSS. Retrieved June 21, 2024, from https://en.wikipedia.org/wiki/CSS

MOBILE APPLICATION DESIGN

6. PROMET&O mobile app UI/UX design and hi-fi prototype

To ensure users have convenient access via their mobile devices, we decided to redesign the web page to be fully responsive to various screen sizes. This redesign is crucial for users to seamlessly receive all information about Indoor Environmental Quality, personal information, and data calculated by the PROMET&O multi-sensor. Making the online questionnaire responsive and user-friendly across all devices is fundamental to our approach. A responsive design guarantees that users can easily interact with and complete the questionnaire on smartphones, providing a consistent and efficient user experience regardless of the device used. This enhancement not only improves accessibility but also ensures that data collection is accurate and comprehensive, capturing user feedback effectively.

In this chapter, I delve into the user interface (UI) and user experience (UX) design of the mobile app, adapted from the webpage design to ensure responsiveness and ease of access for USERS answering the questionnaire. The objective is to adapt the design to fit mobile phone screens seamlessly, facilitating straightforward navigation and interaction. This chapter is organized into three sub-chapters: the IEQ Question Part, the Personal Information Part, and the Dashboard Part. Each section details the process of translating the web page design into a mobile-friendly format, starting with taking screenshots from the webpage. These screenshots serve as a reference point for adapting the layout and ensuring consistency. The design process then moves to hand-drawn sketches, which conceptualize the initial layout and functionality for mobile screens. Finally, these sketches are refined and transformed into high-fidelity prototypes created in Figma, resulting in a polished, interactive design that is ready for development and testing.

The application's access routes are designed to differ based on whether the device is registered or not. For registered devices, users will have streamlined access to personalized features, such as saved progress and personalized settings, ensuring a seamless and efficient experience. On the other hand, unregistered devices will follow a different route, requiring users to go through initial setup steps or log in to access the full functionality of the app. This distinction ensures that the app can provide a secure and tailored user experience, enhancing convenience for returning users while maintaining robust security and user onboarding for new or unregistered devices.

In applying UI/UX design principles to the mobile application, **Gestalt principles** play a crucial role in enhancing both usability and visual coherence.

- **Proximity** related elements such as form fields in the Personal Information section are grouped together, facilitating intuitive data entry.
- **Similarity** through color, shape, and size ensures that interactive elements like buttons maintain a unified appearance across screens, promoting familiarity and ease of use.
- **Continuity** guides users seamlessly through navigation flows, such as swiping between questionnaire sections, ensuring a cohesive user experience.
- **Closure** principles are employed to suggest interactivity, enticing users to engage with partially revealed icons or elements on the dashboard.
- **Symmetry** and order throughout the app's layout enhances visual harmony and usability, contributing to a stable and organized interface.
- **Figure-Ground** Ensure important elements like call-to-action buttons stand out against the background to catch the user's attention.

By integrating these UI/UX and Gestalt principles, the mobile application optimizes user engagement, prioritizes clarity, and ensures efficient navigation of complex information and tasks.

6.1 Questionnaire IEQ part UI/UX design and hi-fi prototype

The Indoor Environmental Quality question part is a crucial component of the mobile app, designed to gather valuable insights from office workers about their working environment. This section aims to ensure that USERS can easily and effectively respond to questions regarding various aspects of their indoor surroundings, such as air quality, lighting, acoustic and visual comfort. The design prioritizes clarity and user-friendliness, adapting the original web page layout into a mobile-friendly format that facilitates quick and intuitive interaction. By focusing on a responsive and accessible design.

Because mobile screens are generally smaller, creating effective information architecture for a mobile app involves several key challenges. Firstly, it is crucial to focus on the essential content and strategically eliminate or rearrange less important information to avoid clutter and ensure clarity. This prioritization ensures that users can quickly access the most relevant features and information without being overwhelmed. Secondly, the size and spacing of touchscreen targets must be carefully considered to enhance usability; touch targets should be large enough and spaced adequately to prevent accidental taps and ensure a smooth user experience. Lastly, ensuring that the text is large enough to be easily readable on smaller screens is vital for accessibility and user comfort. Good information architecture lays the foundation for a design layout that promotes intuitive navigation, helping users effortlessly move through the content. By keeping these principles in mind, I designed a mobile app that is both user-friendly and efficient, providing an optimal experience on any device.

6.1.1 Screenshots from webpage

The process of taking screenshots from the webpage begins by thoroughly reviewing the existing design to capture all relevant elements and functionalities. Screenshots are taken systematically, covering each section and interactive component of the webpage to ensure a comprehensive reference. This includes capturing different states of interactive elements, such as dropdown menus, modals, and hover effects. These screenshots serve as a crucial reference point, providing a visual guide for maintaining consistency in layout, color schemes, typography, and overall design aesthetics during the transition to a mobile-friendly format. By meticulously documenting the original design through screenshots, I ensure that the essential features and visual integrity of the webpage are preserved and accurately translated into the mobile app design.

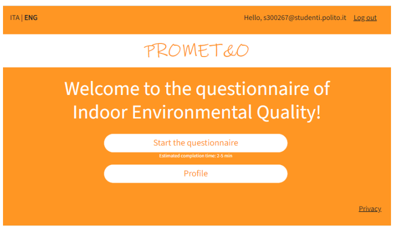


Fig. 1. Screenshots taken from the webpage ns02 for Home and log-in related pages

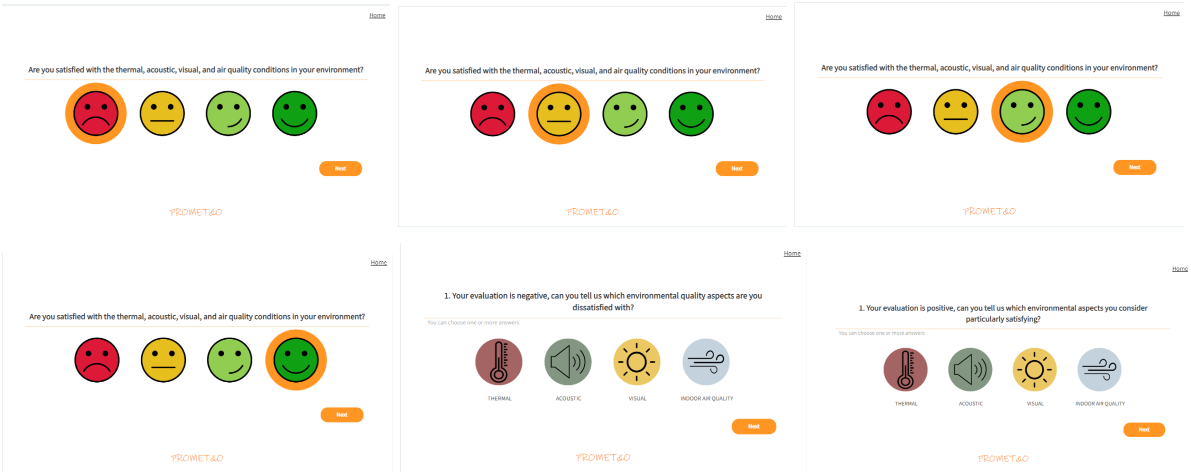


Fig. 2. Screenshots taken from the webpage ns02 for IEQ part

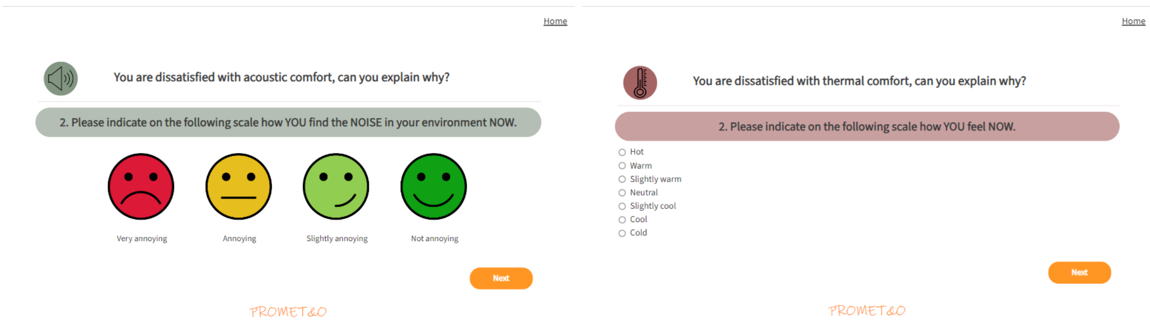


Fig. 3. Screenshots taken from the webpage ns02 for Negative response

6.1.2 Hand-drawn sketches

To conceptualize the layout from the main web page design, hand-drawn sketches were created as an initial step. These sketches serve as a visual brainstorming tool, capturing the essential elements and structure of the interface while allowing for quick iterations. By translating the webpage's core components into mobile-friendly formats, the sketches focus on optimizing usability and ensuring that key functionalities are easily accessible on smaller screens. This process helps in visualizing the overall flow and identifying potential design challenges early, laying a solid foundation for the subsequent creation of high-fidelity prototypes.

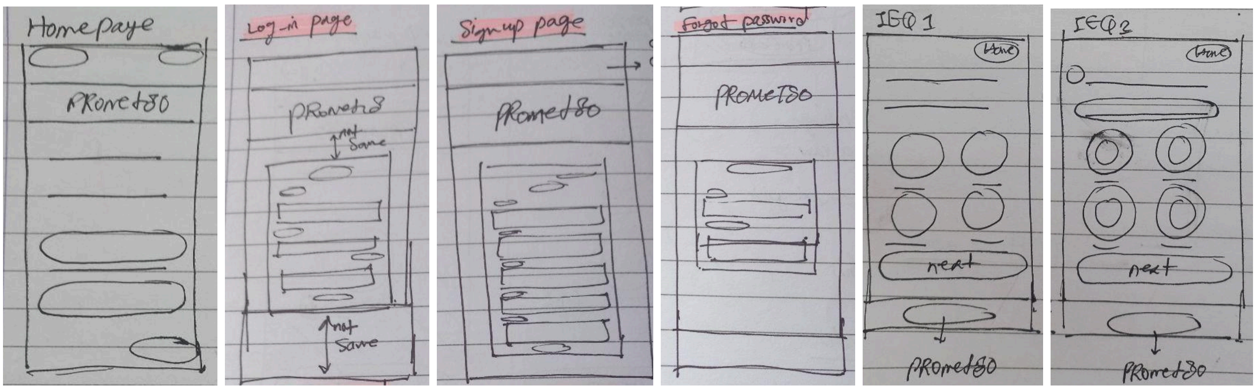


Fig. 4. Hand-drawn sketches for the Home pages and Log-in related pages and IEQ related pages

6.1.3 High-fidelity design in Figma

High-fidelity designs were created in Figma to bring the hand-drawn sketches to life with precision and detail. Using Figma, I translated the conceptual designs into interactive, visually polished prototypes that closely resemble the final product. This step involved selecting appropriate color schemes, typography, and imagery consistent with the original webpage, while ensuring the interface is responsive and intuitive for mobile use. Interactive elements such as buttons, navigation menus, and input fields were meticulously designed and linked to simulate real user interactions. The high-fidelity prototypes not only serve as a detailed visual guide for developers but also allow for usability testing and feedback to refine the design further before implementation.

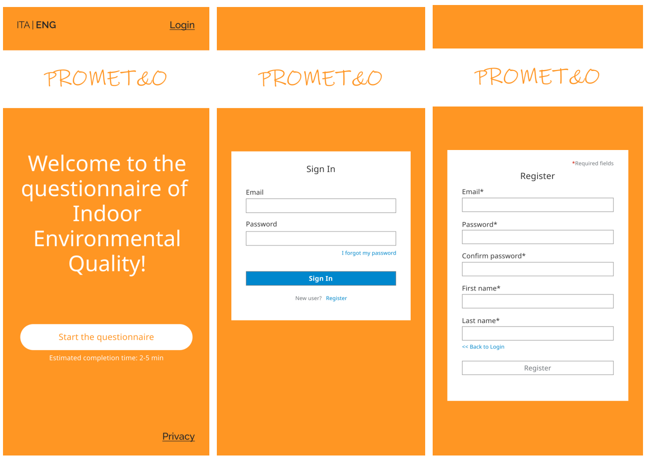


Fig. 5. High-Fidelity wireframes design in Figma for Home and log-in related pages

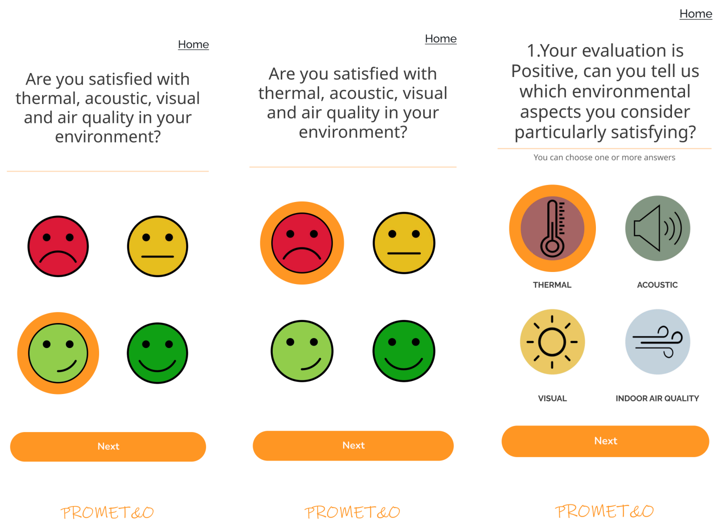


Fig. 6. High-Fidelity wireframes design in Figma for IEQ related pages part1

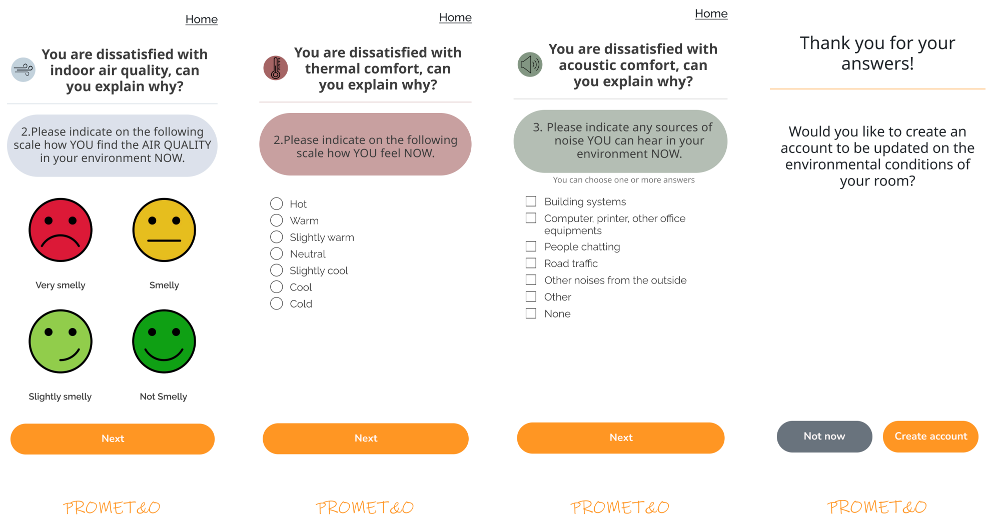


Fig. 7. High-Fidelity wireframes design in Figma for IEQ related pages part2

6.1.4 Final prototype in mobile view

The final prototype in mobile view represents the culmination of the design process, meticulously refined to ensure an optimal user experience for USERS accessing the questionnaire on their phones. This prototype incorporates seamlessly blending functionality with visual appeal. Key elements such as the IEQ questions presented in a user-friendly manner, with intuitive navigation and clear, readable layouts. Interactive components have been thoroughly tested to ensure responsiveness and ease of use on various mobile devices. The final mobile prototype not only mirrors the aesthetic and functional integrity of the original webpage but also enhances accessibility and engagement, providing a polished, ready-to-develop design that aligns with user needs and expectations.

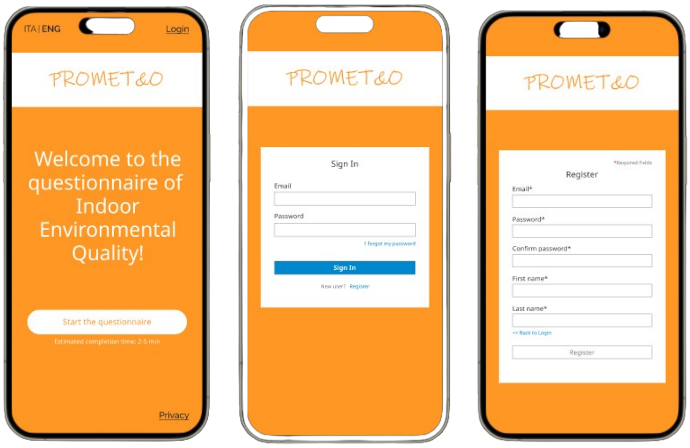


Fig. 8. Final prototype in Mobile view for Home and log-in related pages

Fig. 9. Final prototype in Mobile view for IEQ related pages

The interaction flow in Figma ensures that each step of the user journey is mapped out clearly, providing a seamless and intuitive experience within the mobile application.

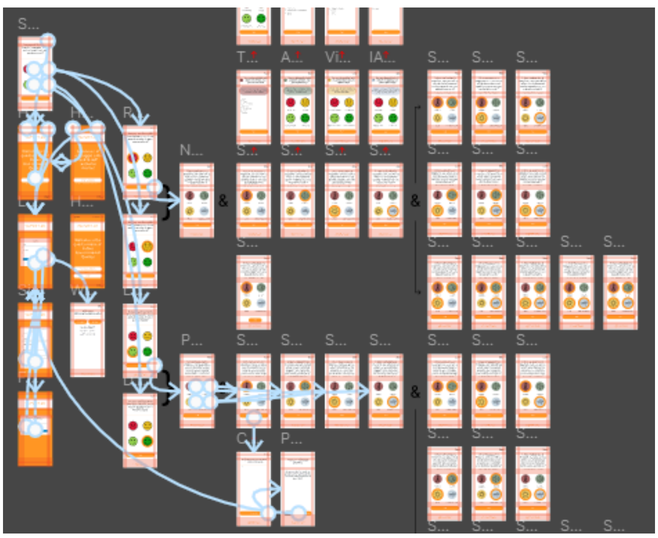


Fig. 10. Interactions flow in Figma Prototype for home page and IEQ part

6.2 Questionnaire personal information part UI/UX design and hi-fi prototype

This part collects personal information from USERS. The design must be straightforward to prevent user frustration and ensure data accuracy. The Personal Information part of the questionnaire User interface/User experience design and prototype is essential for collecting **demographic** and **personal data** from USERS, ensuring that the gathered information is comprehensive and accurate. This section is designed with a focus on simplicity and ease of use, transforming the original web page layout into a mobile-friendly interface that facilitates quick and straightforward data entry. Each form field is clearly labeled and optimized for touch inputs, providing intuitive guidance and real-time validation to enhance the user experience. The high-fidelity prototype ensures that the design is visually cohesive, accessible, and efficient, enabling USERS to complete their personal information with minimal effort and maximum accuracy.

6.2.1 Screenshots from webpage

For the Personal Information part, I began by taking screenshots from the webpage to capture its layout and design elements. This ensured consistency with the original design as I conceptualized the layout through hand-drawn sketches and refined it into a high-fidelity prototype in Figma, optimizing the interface for mobile use.

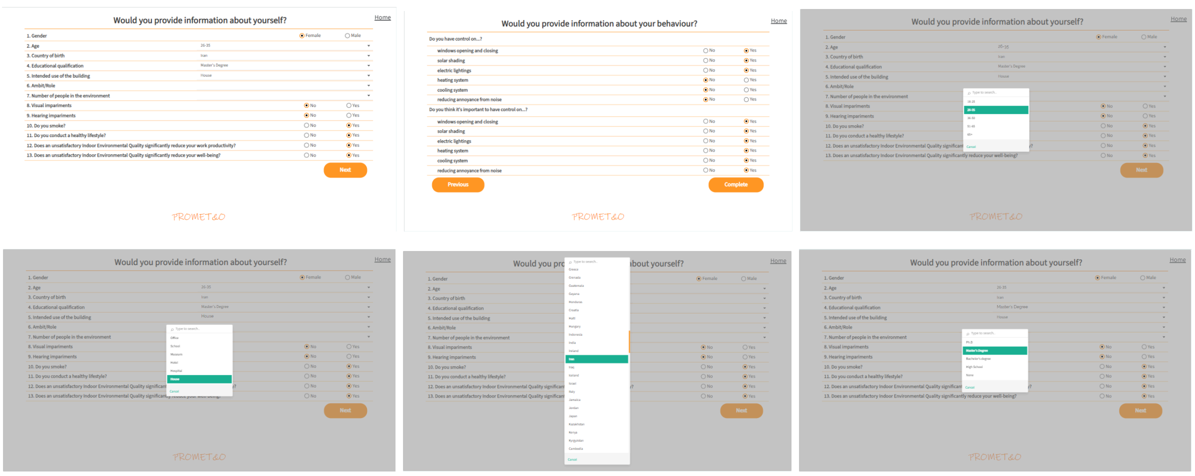


Fig. 11. Screenshots taken from the webpage ns02 for Personal info pages

6.2.2 Hand-drawn sketches

The hand-drawn sketches for the Personal Information part translated the webpage's layout into a mobile-friendly format, organizing form fields logically and intuitively. This step maximized readability and accessibility, with clear labels, sufficient spacing, and visual cues for required fields, forming a solid foundation for the high-fidelity prototypes.

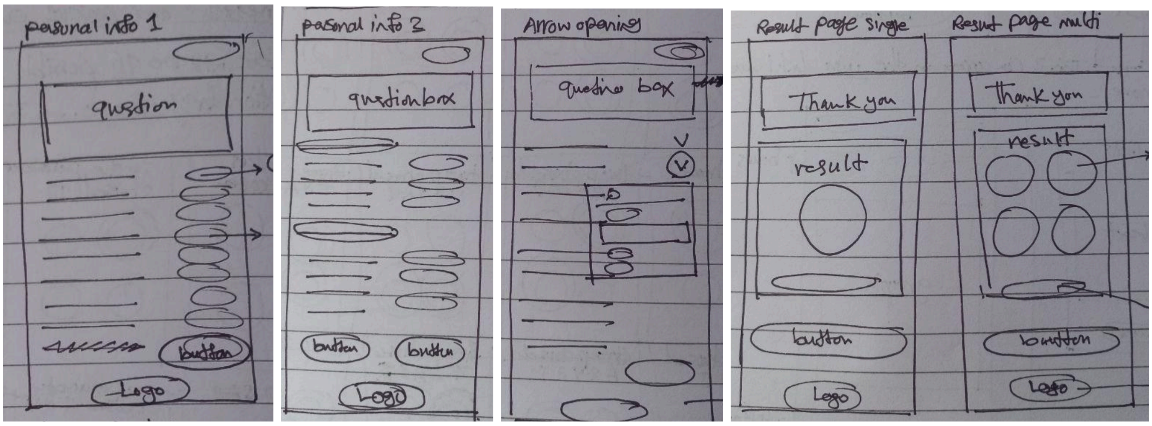


Fig. 12. Hand-drawn sketches for the Personal info pages

6.2.3 High-fidelity design in Figma

In the high-fidelity design phase in Figma for the Personal Information part, hand-drawn sketches were transformed into detailed, interactive prototypes, fine-tuning visual aesthetics and ensuring consistency with modern UI principles. This phase involved adding interactive elements for seamless navigation and data entry, providing a realistic preview for usability testing and ensuring the design was user-friendly and ready for development.

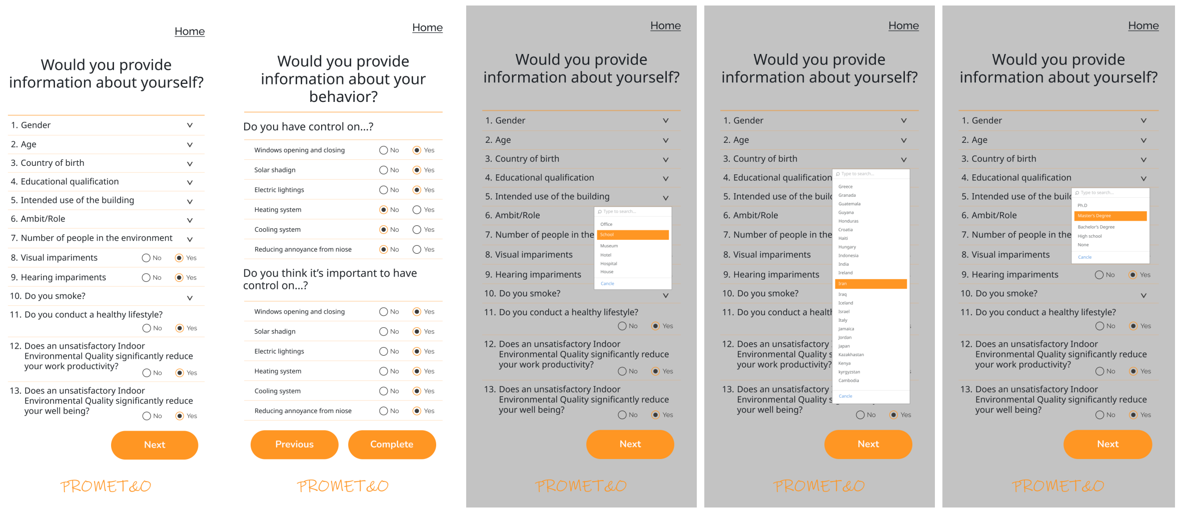


Fig. 13. High-Fidelity wireframes design in Figma for Personal information pages

6.2.4 Final prototype in mobile view

Here is the final result of the high-fidelity design in mobile view. This polished prototype demonstrates the user-friendly, intuitive interface tailored for seamless navigation and data entry on mobile devices.

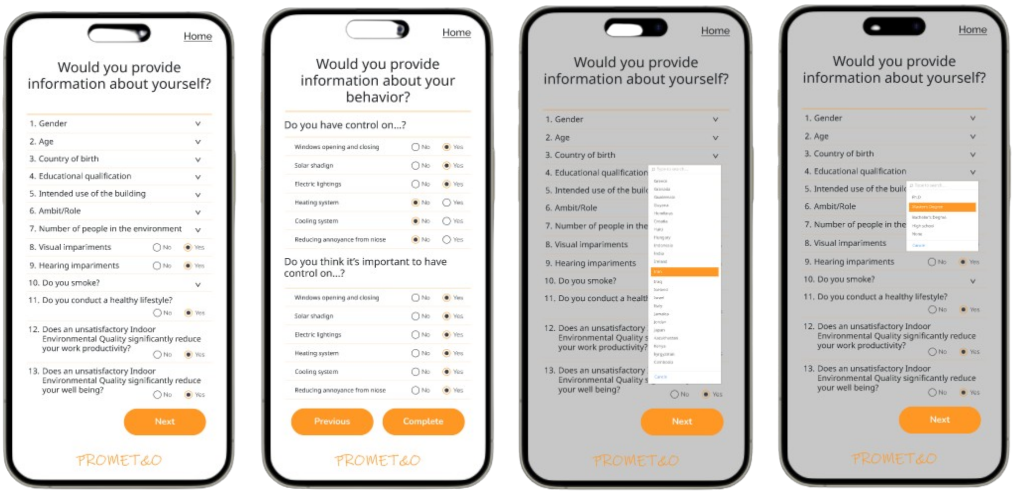


Fig. 14. Final prototype in Mobile view for Personal information pages

Fig. 15. Final prototype in Mobile view for Personal information pages

The interaction flow in Figma ensures that each step of the user journey is mapped out clearly, providing a seamless and intuitive experience within the mobile application.

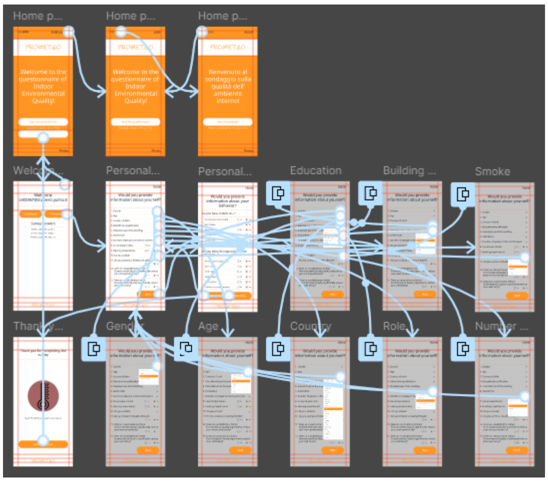


Fig. 16. Interactions flow in Figma Prototype for Personal information part

6.3 Questionnaire dashboard part UI/UX design and hi-fi prototype

The Dashboard part of the questionnaire UI design and prototype serves as the central hub for USERS, providing a comprehensive overview of their questionnaire progress and results. This section is crafted to be visually engaging and highly functional, translating the original web page design into a responsive mobile format that offers seamless navigation and interaction. The dashboard features include summary of responses, and access to detailed feedback, all presented through intuitive visual elements like charts and icons. The high-fidelity prototype ensures a cohesive and user-friendly interface, making it easy for USERS to monitor their progress, revisit previous questions, and understand their results at a glance. This design aims to enhance user engagement and satisfaction by offering a clear, organized, and interactive experience.

6.3.1 Screenshots from webpage

For the Dashboard webpage, I began by taking screenshots from the webpage to capture its layout and design elements. This ensured consistency with the original design as I conceptualized the layout through hand-drawn sketches and refined it into a high-fidelity prototype in Figma, optimizing the interface for mobile use.

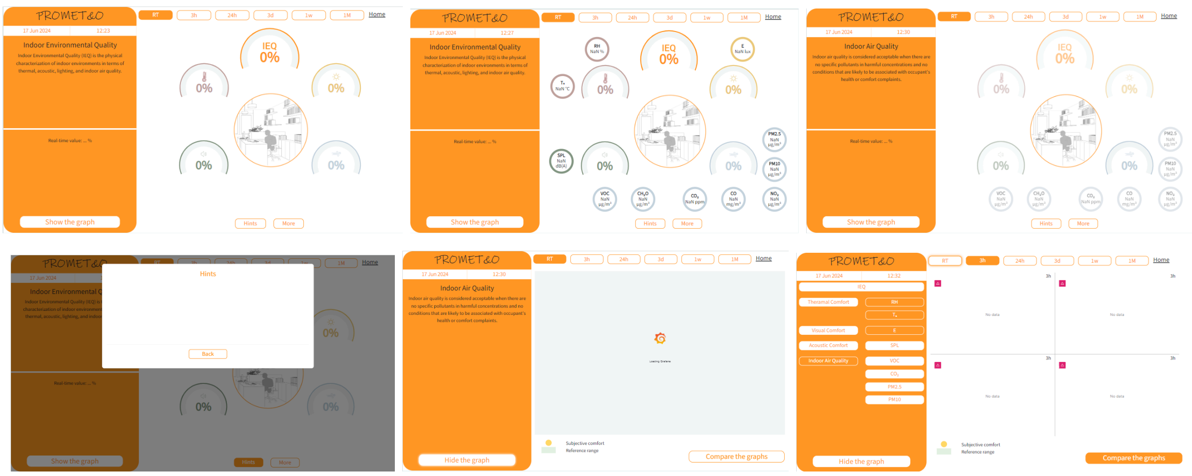


Fig. 17. Screenshots taken from the Dashboard pages

6.3.2 Hand-drawn sketches

The hand-drawn sketches for the Dashboard webpage translated the layout into a mobile-friendly format, which was particularly challenging due to the dense information on one page. This step focused on organizing content logically and intuitively, maximizing readability and accessibility with clear labels and sufficient spacing. By creating these initial sketches, I established a solid foundation for the high-fidelity prototypes.

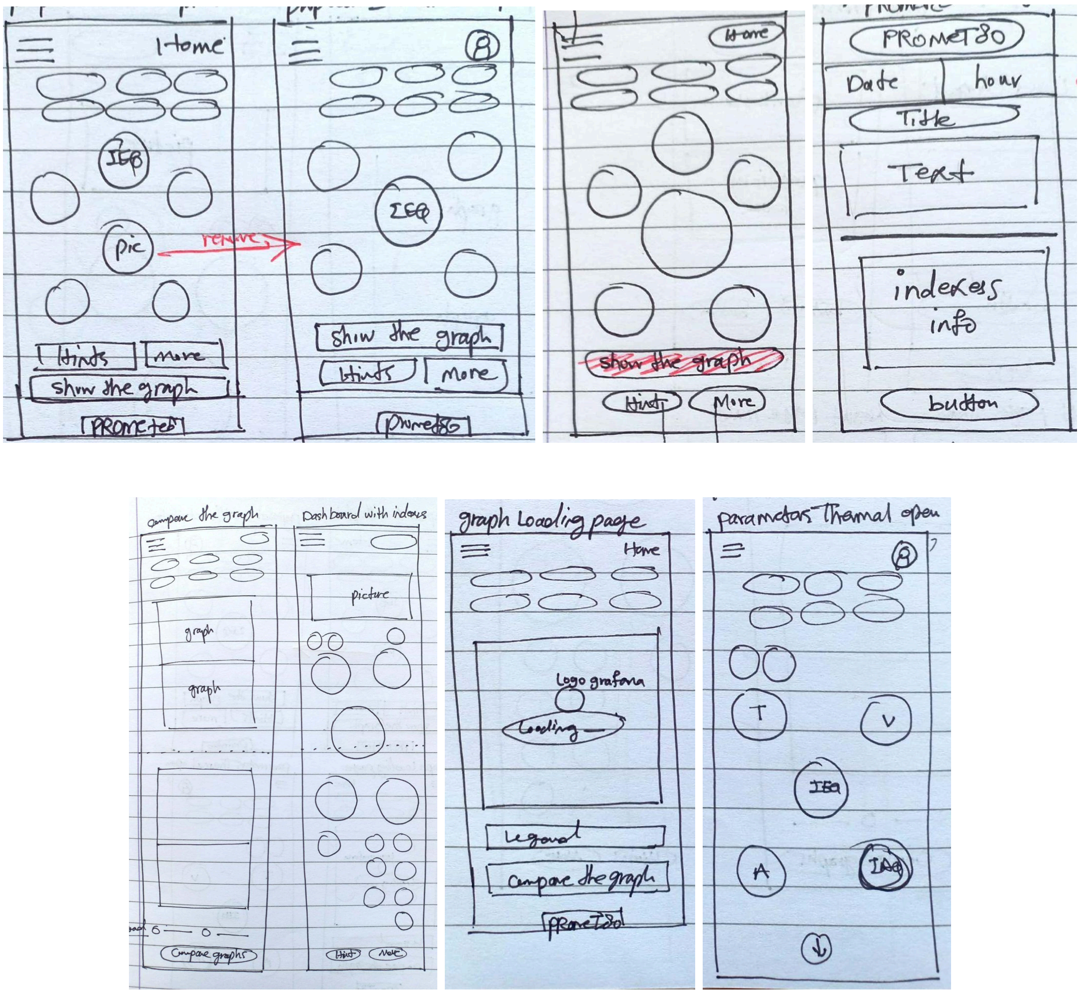


Fig. 18. Hand-drawn sketches for dashboard pages

6.3.3 High-fidelity design in Figma

In the high-fidelity design phase in Figma for the Dashboard, hand-drawn sketches were transformed into detailed, interactive prototypes, fine-tuning visual aesthetics and ensuring consistency with modern UI principles. This phase involved adding interactive elements for seamless navigation and information access, providing a realistic preview for usability testing. This ensured the design was user-friendly, handled the dense information effectively, and was ready for development.

Fig. 19. High-Fidelity wireframes design in Figma for dashboard pages

6.3.4 Final prototype in mobile view

Here is the final result of the high-fidelity design for the Dashboard in mobile view. This polished prototype demonstrates a user-friendly, intuitive interface tailored for seamless navigation and efficient information access on mobile devices.

Fig. 20. Final prototype in Mobile view for Dashboard pages

The interaction flow in Figma ensures that each step of the user journey is mapped out clearly, providing a seamless and intuitive experience within the mobile application.

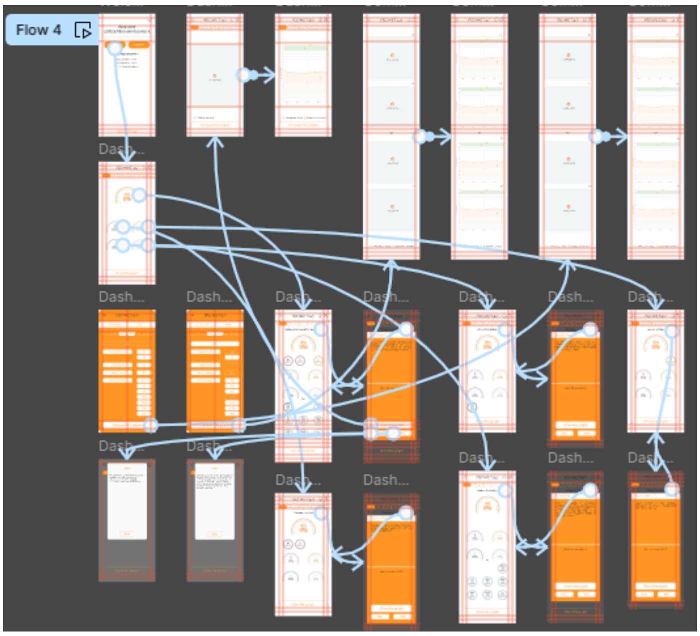


Fig. 21. Interactions flow in Figma Prototype for dashboard pages

References Chapter 6

1. Nielsen, J., & Loranger, H. (2006). *Prioritizing web usability*. New Riders Publishing.
2. Tidwell, J. (2010). *Designing interfaces: Patterns for effective interaction design*. O'Reilly Media.
3. Cooper, A., Reimann, R., & Cronin, D. (2014). *About face: The essentials of interaction design*. John Wiley & Sons.
4. Figma. (n.d.). Retrieved June 28, 2024, from https://www.figma.com
5. Apple Inc. (n.d.). *Human interface guidelines*. Retrieved August 9, 2024, from https://developer.apple.com/design/human-interface-guidelines/

IN-FIELD EXPERIMENT

POLITECNICO DI TORINO

7. In-Field application of PROMET&O system in the Living Lab & Audio Space Lab (ASL) laboratories in Politecnico di Torino

In-field measurement of Indoor Environmental Quality in Politecnico di Torino Living Lab and A.S.L (Audio Space Lab) using PROMET&O multi-sensors involves objective data collection to comprehensively assess the indoor environment's impact on occupants.

The process of in-field measurement, crucial for assessing Indoor Environmental Quality, incorporates sensor calibration alongside data collection and analysis (Fissore et al., 2024). Initially, each sensor undergoes calibration using reference standards. This calibration ensures accurate measurement of parameters such as formaldehyde, particulate matter, and CO2 levels, crucial for reliable data collection. Throughout the measurement period, sensors continuously log environmental data, capturing fluctuations and trends over several days to weeks. Post-collection, retrieved data is subjected to thorough analysis of the patterns and compliance with IEQ benchmarks such as ASHRAE and the WELL Building Standard. This comprehensive approach not only enhances data accuracy but also informs targeted strategies for optimizing indoor environments to support occupant health and well-being effectively.

Objective data collection involves using PROMET&O multi-sensors to measure various environmental parameters. This often includes sensor deployment, data logging, data retrieval and data analysis.

When conducting in-field measurements of Indoor Environmental Quality in offices, it's essential to consider several factors to ensure accurate analysis and interpretation of the data.

- **Sensor Placement**: Place multi-sensors strategically throughout the office space to capture variations in IEQ across different areas. Consider factors such as proximity to pollution sources, ventilation outlets, and occupant density when positioning multi-sensors.
- **Data Collection**: Continuously monitor IEQ parameters over an extended period to capture variations throughout the day. Ensure that multi-sensors are calibrated regularly to maintain accuracy.
- **Occupant Surveys**: Supplement objective IEQ data with subjective feedback from office workers through online questionnaires. Gather information about occupants' comfort perceptions, and satisfaction with the indoor environment.
- **Data Analysis**: Analyze the collected data using statistical methods to identify trends, correlations, and potential issues with IEQ. Compare objective measurements with subjective responses to gain insights into the relationship between environmental conditions and occupant comfort.
- **Intervention Strategies**: Based on the analysis results, develop intervention strategies to address any identified deficiencies or areas for improvement in IEQ. This may involve adjusting HVAC settings, improving ventilation, implementing air purifiers, or modifying building materials and furnishings.
- **Continuous Monitoring**: Establish a system for continuous monitoring and periodic reassessment of IEQ to track improvements over time and ensure ongoing occupant satisfaction and well-being.

By following these steps, it is possible to effectively measure IEQ in offices and implement targeted strategies to create a healthier and more comfortable indoor environment for office workers.

7.1 Calibration process

In preparation for the in-field measurement study, the calibration of the bare sensors included in the multi-sensors was performed. Particularly, the calibration presented in this work is related to formaldehyde, particulate matter, and CO2 quantities and was conducted in October, November, and December 2023. We adjusted and verified sensor readings against reference standards to guarantee precise data collection. This calibration process was essential to ensure the integrity of the environmental data gathered.

Putty: Putty is a versatile and widely-used open-source terminal emulator that facilitates secure connections to remote systems. In our calibration process for the PROMET&O multi-sensors used in assessing Indoor Environmental Quality, we employed Putty. This tool allowed us to establish reliable connections with the sensors, enabling configuration and adjustment of settings to ensure accurate measurement of parameters like formaldehyde, particulate matter, and CO_2 levels. Putty's intuitive interface and robust functionality streamlined our calibration procedures, facilitating real-time monitoring and adjustments to optimize sensor performance. Its role in our calibration process was instrumental in achieving consistent and reliable data collection.

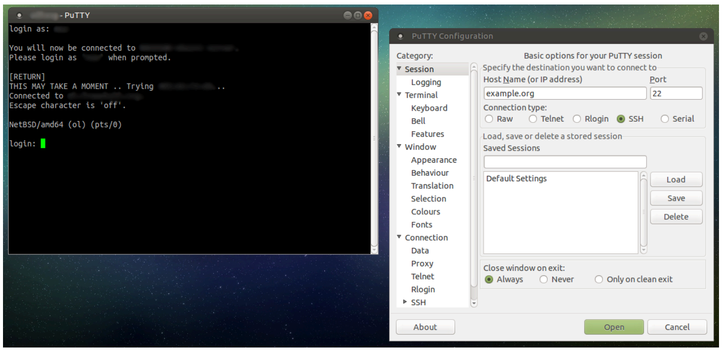


Fig. 1. Interface of PUTTY software (Adopted from https://en.wikipedia.org/wiki/PuTTY)

For configuring Putty to connect with the sensor and load specific settings, we followed a structured approach to ensure accurate data retrieval and calibration.

- **Serial Line:** Set to the name of the USB port connected to the PC for sensor reading.
- **Speed**: Configured at 115200 baud for optimal data transmission.
- **Connection Type**: Selected as Serial to establish a direct communication link.
- **Clean Exit**: Enabled "Only on clean exit" for stability during operations.
- **Port Name**: Entered "Nucleoh-COM" followed by the port number where the USB connection was established.
- **Tab Window**: Utilized a tab window on the left side, configured to Control 10000 for efficient data management.

Formaldehyde calibration: We visited the DIATI department to conduct formaldehyde measurements within an office environment. Using equipment from PPM Technology LTD, we utilized specialized software to connect the formaldehyde measurement device to a PC, configuring it for a comprehensive two-day measurement period. Alongside this setup, the Testo 480, designed for measuring temperature and pressure, was employed with the formaldehyde measurement device and its corresponding calibration cylinder. Initially, efforts were focused on resetting the device and calibrating it within the optimal range, to ensure accurate and reliable data collection throughout the assessment process.

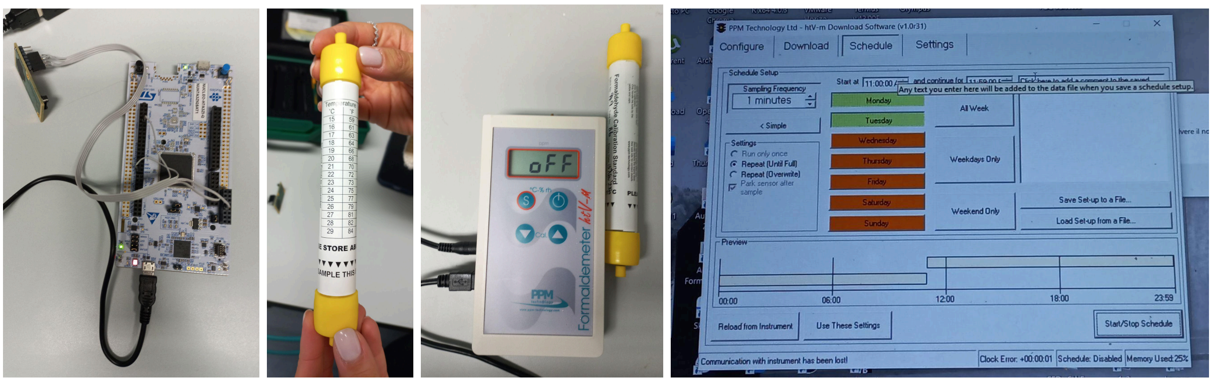


Fig. 2. Formaldehyde calibration in October 2023

Particulate matter calibration: We visited the DIATI department to conduct particulate matter measurements in the office. Equipped with advanced monitoring tools, we aimed to assess the concentration of particulate matter in the air, focusing on key pollutants such as $PM_{2.5}$ and PM_{10}. Together, we set up the necessary equipment and prepared to gather comprehensive data over the specified measurement period.

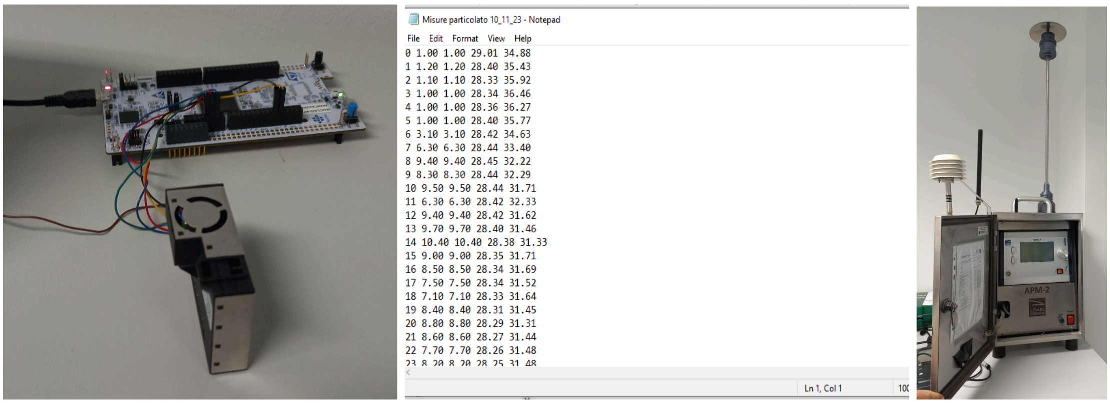


Fig. 3. Particulate matter calibration in November 2023

Carbon dioxide (CO_2) calibration: We headed to the DENERG building to conduct CO_2 measurements. Followed by setting up Putty and the Lumasoft gas app, ensuring they were correctly configured with the USB port and settings needed. Placing the multi-sensor in the CO_2 measurement box alongside a CO_2 measurement device TESTO 400 and a Temperature sensor Testo 480, we connected the box to the Lumasense device using wires. Once set up, we initiated Putty, Lumasoft app, and Testo devices to commence the measurement process. Initially measuring around 773 ppm, our target was to reach 2000 ppm for calibration, achieved by introducing CO_2 from a balloon into the box. This process was repeated twice until reaching 2103 ppm, at which point we ceased additional CO_2 input. The following day we gathered data and shut down the setup.

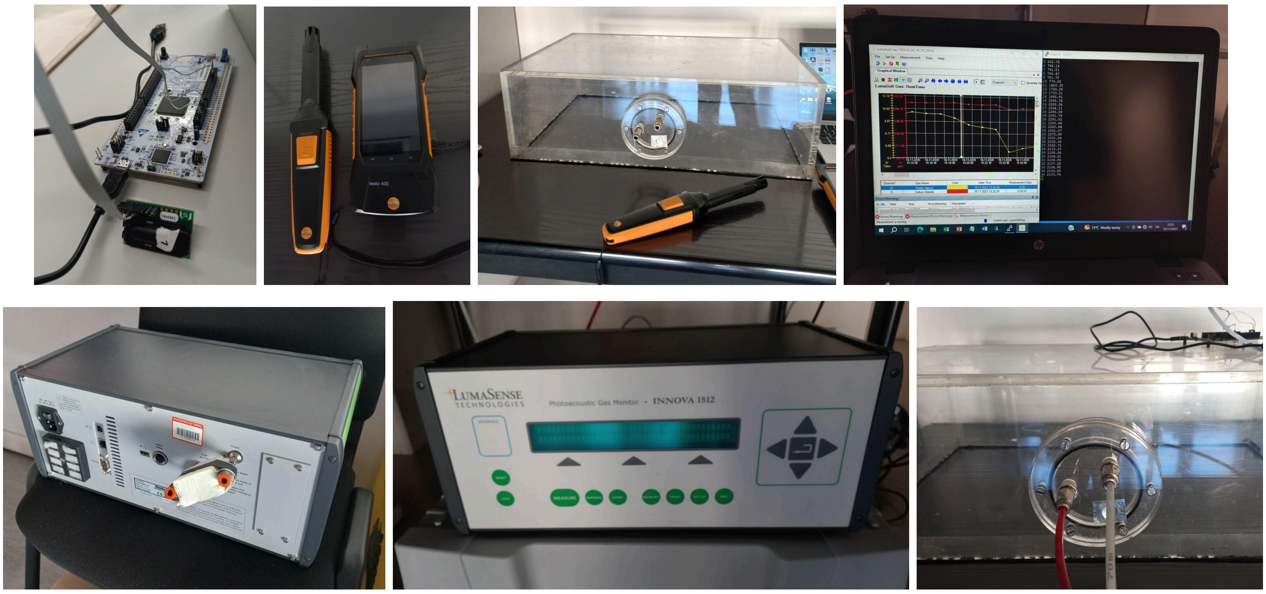


Fig. 4. CO2 calibration in November 2023

7.2 In-field application

In the Living Lab and Audio Space Lab (A.S.L), sensors were systematically deployed to measure various environmental parameters. This initial setup involved careful coordination and the positioning of multiple sensors to ensure comprehensive coverage and accurate data collection. Concurrently, specialized equipment and reference devices were set up for acoustic, illuminance and air quality measurements.This dual-facility approach ensures that a diverse range of environmental conditions and parameters are effectively measured, setting the foundation for detailed analysis and future calibration.

7.2.1 Politecnico di Torino Living Lab

In this chapter, I will delve into a focused study of in-field measurements conducted in the Polito Living Lab over a short period from **July 8th to July 15th, 2024**. This analysis involves a detailed examination of Indoor Environmental Quality parameters using the designed PROMET&O multi-sensors to capture real-time data.

Implementation Process of Multi-Sensor Systems in the Living Lab, Politecnico di Torino: Day 1 Measurement (8th of July from 12:30 - 9th of July at 15:30)

On the first day of sensor deployment at the Living Lab, the following procedural steps were undertaken to set up the multi-sensor systems for measurement.

1. **Initial Coordination and Equipment Collection:** once retrieved the multi-sensor devices, chargers, and Wi-Fi equipment, we moved to the secondary DENERG building to access the Living Lab, which is a compact room with one door, ceiling lighting system, an airflow window and two insulating wall panels.
2. **Setup of Air Quality Measurement Instruments:** we installed the particulate matter measurement device and programmed it for a continuous measurement period.

3. **Sound Pressure Level Measurement:** Following the setup of the particulate matter measurement instrument, we installed the sound level meter measurement instrument, specifically the NTI Audio XL2.
4. **Illuminance Measurement Setup:** At the Living Lab three Gigahertz-Optik illuminance sensors were deployed. Sensors were assigned numerical identifiers (1, 2, and 3), and data access was managed using the OS-X200 software.
5. **Final Arrangements:** The setup included ten PROMET&O multi-sensor units (Sensors 1, 2, 3, 4, 6, 7, 8, 9, 10, 11), three illuminance sensors, one AIRCARE device, one sound level meter, and one particulate matter device. During this process the calibration of the sound pressure level instrument was done.
6. **Data Verification and Finalization:**. Finally, a photographic record of the multi-sensor setup and room was taken before concluding the day's activities. The measurements started at 12:30 on 8th of July.

Fig. 5. Figure of the Living Lab Polito location and photo

Fig. 6. Figure of the Living Lab Polito photo

Fig. 7. Day 1 sensors arrangements on 8th of July at Living Lab Polito

Fig. 8. Living Lab Plan with Sensor Positioning Day 1

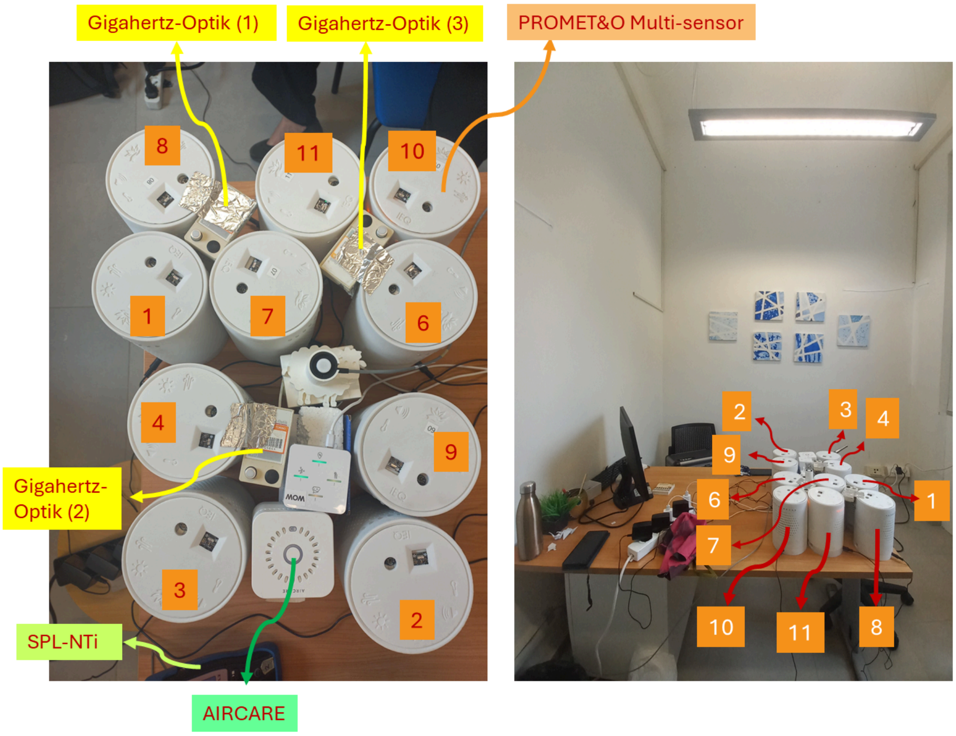


Fig. 9. Day 1 Sensors and reference device positioning on 8th of July at Polito Living Lab

We utilized **Gigahertz-Optik's** high-accuracy illuminance sensors to monitor illuminance levels in the Living Lab, providing detailed data crucial for assessing indoor lighting and its impact on comfort and productivity. The sampling time for this device is 5 minutes.

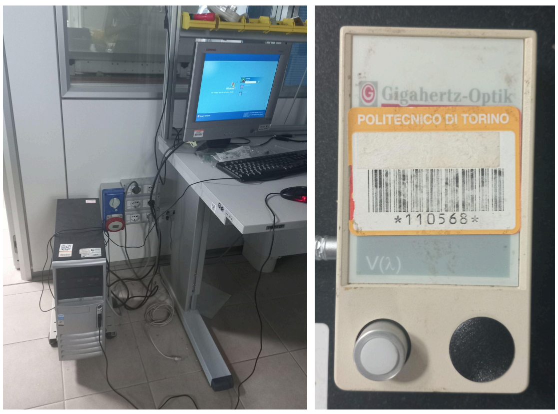


Fig. 10. Gigahertz-Optik for measuring illuminance

The **NTI Audio XL2 SPL instrument**, known for precision and ease of use, captured acoustic data in our study within the Living Lab. We utilized it to check the microphone included in the multi-sensors, ensuring accurate assessment of indoor environmental quality. The sampling time for this device is 1 second.

Fig. 11. The Sound Level Meter for measuring SPL in the living lab

For the measurement of **particulate matter** in the room, we utilized the **LVS/MVS Low and Mid Volume Samplers from Ektimo**. This device is specifically designed for accurately measuring particulate matter 2.5 and 10 concentrations by drawing air through a filter at a controlled flow rate. In addition to particulate matter, the LVS/MVS samplers also have the capability to measure relative humidity, which is crucial for understanding the environmental conditions that can influence particulate matter levels. By capturing both particulate matter and humidity data, this device provides comprehensive insights into the air quality within the room, allowing for a more detailed analysis of the environmental factors at play.

Fig. 12. The Particulate matter measuring in the living lab (Third photo obtained from https://www.j-aguirre-sl.com/en/product/particulate-matter-collection/)

To measure the **formaldehyde levels** in the room, we used the **Formaldemeter htV-M from PPM Technology.** This advanced device is specifically designed to detect and quantify formaldehyde concentrations in the air, providing real-time monitoring and precise measurements. The Formaldemeter htV-M is equipped with sensitive electrochemical sensors that can accurately detect even low levels of formaldehyde, making it an ideal choice for environments where air quality is a concern. By using this device, we were able to continuously monitor the formaldehyde levels in the room, ensuring that we collected accurate and reliable data for our analysis.

Fig. 13. The Formaldehyde measuring in the living lab (Second photo obtained from https://www.techrentals.com.my/PPM-HTV-M-Formaldehyde-Meter)

For measuring the levels of **carbon monoxide** and **carbon dioxide** in the room, we used the **Testo 480** and **Testo 400** devices. These instruments are well-suited for environmental monitoring, providing precise and real-time measurements of gas concentrations in indoor settings. The Testo 480 offers a comprehensive solution for evaluating indoor air quality, with sensors designed to detect a range of parameters, including CO and CO_2 levels. Similarly, the Testo 400 is a versatile device capable of accurate measurements and is equipped with intuitive features for assessing various air quality metrics. By using both the Testo 480 and Testo 400, we were able to obtain data on the CO and CO_2 levels in the room, contributing to a thorough assessment of air quality.

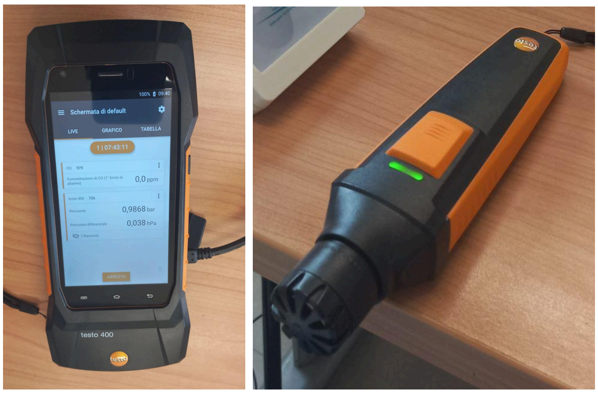


Fig. 14. Testo kit 400 and 480 for measuring CO and CO_2 in the living lab

As other main reference devices in the room, we utilized the **AirCare** and **AirCare Wow** device, along with the **Lux Meter - Delta Ohm LPPHOT01** connected to a wired lab-grade acquisition system. The AireCare and AireCare Wow are IEQ monitoring devices that provide real-time data on various environmental parameters, helping to ensure accurate and comprehensive measurements of environmental conditions. These devices are particularly effective for monitoring particulate matter, temperature, humidity, and other key air quality indicators. Additionally, the Lux Meter - Delta Ohm LPPHOT01 was used to measure the illuminance levels in the room. By employing these reference devices, we were able to achieve a detailed and accurate analysis of the environmental conditions in the room.

Fig. 15. Aircare device, Aircare wow device and Lux-meter device in the living lab

Implementation Process of Multi-Sensor Systems in the Living Lab, Politecnico di Torino: Day 2 Measurement (9th of July from 15:30 - 10th of July at 15:30)

For day 2 the arrangement of the sensors had been adjusted, arranging the multi-sensors in pairs (1 and 2), which requires changing the sensors every day at 15:30. Data was accessed from the grafana dashboard.

The monitoring period officially started at **15:30 on July 9th**. For the main setup, we deployed 2 PROMET&O multi-sensors, alongside 3 illuminance devices, 1 Aircare device, a SPL device, a PPM device, Testo 400 kit and a formaldehyde device. For this day, we set up **PROMET&O multi-sensor 1** and **multi-sensor 2.**

Fig. 16. Day 2 sensors arrangements on 9th of July at Living Lab Polito

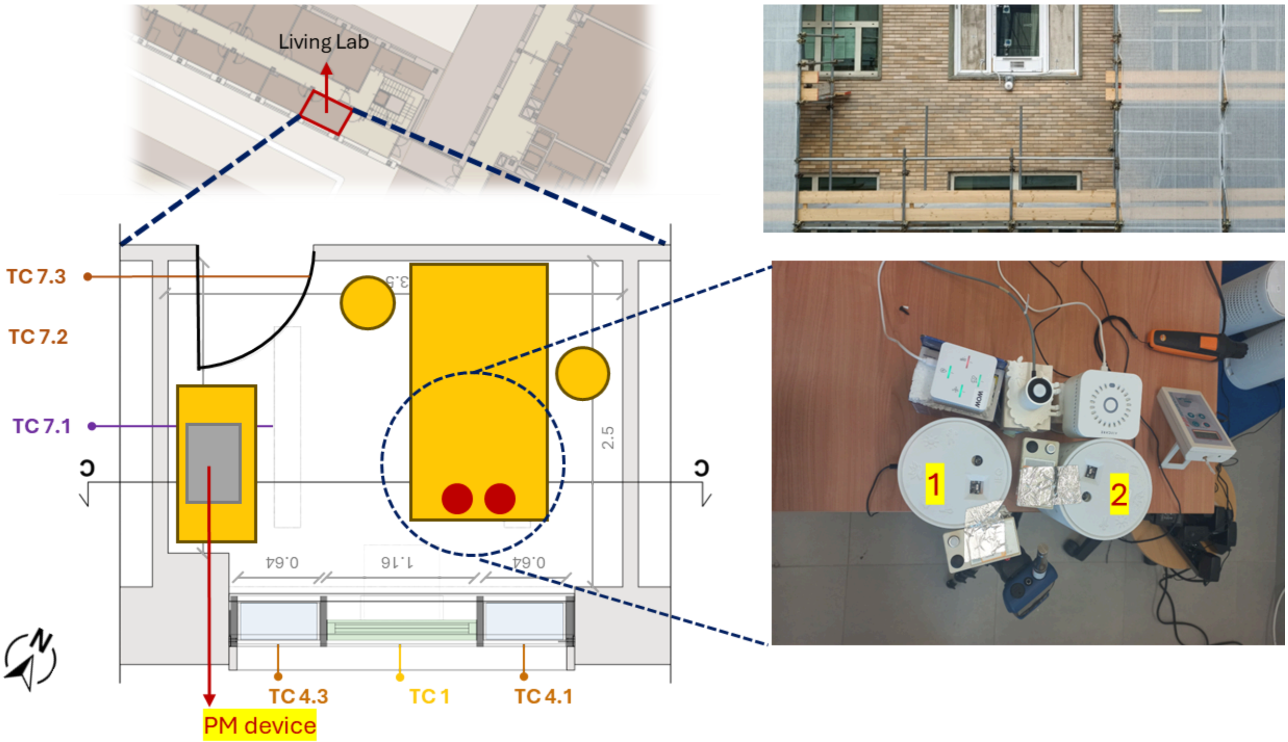


Fig. 17. Living Lab PLan with Sensor Positioning Day 2

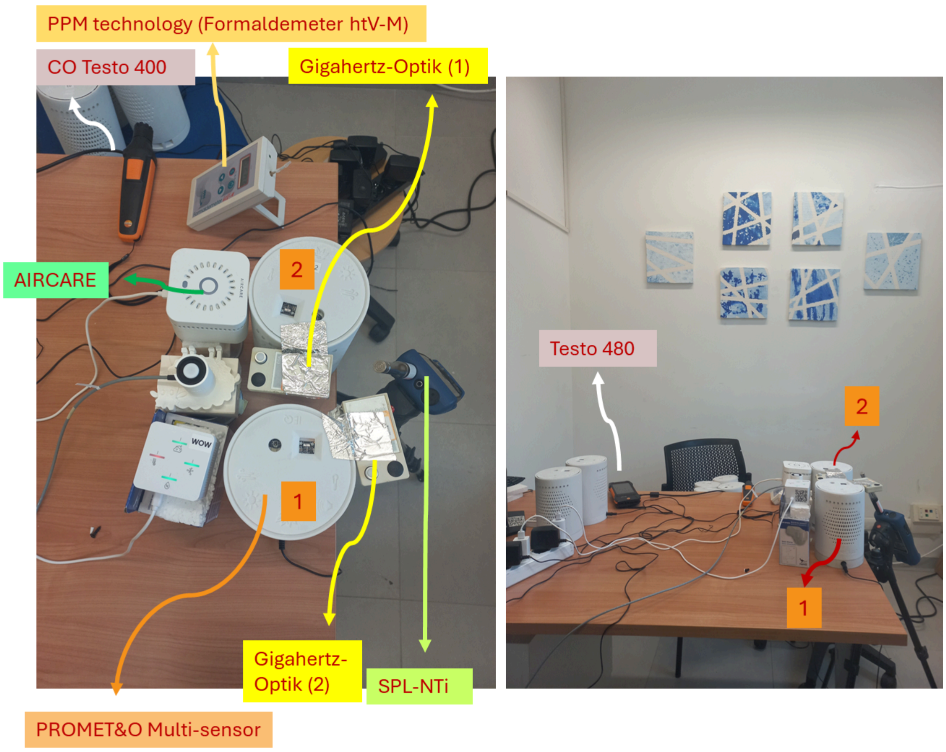


Fig. 18. Day 2 Sensors and reference device positioning on 9th of July at Living Lab Polito

Implementation Process of Multi-Sensor Systems in the Living Lab, Politecnico di Torino: Day 3 Measurement (10th of July from 15:30 - 11th of July at 15:30)

On the third day of sensor deployment at the Living Lab the following procedural steps were undertaken to set up the multi-sensor systems for measurement.

1. **Initial Coordination and Equipment Collection:** I rotated the multi-sensors daily at 15:30 with another set of sensors. We would continue with a three-sensor setup for the following days. Furthermore, we integrated an additional device to measure carbon monoxide.
2. **Setup of Equipment:** after ensuring the network was functioning, I recorded the SPL data and took a photo of the readings. Sensor 11 was not functioning, so I reset it by unplugging and plugging it back in.
3. **Final Arrangements:** at around 3 PM all sensors were disconnected except for sensors 1, 2 (required for that day's measurements), and 4 (which was not performing well). After waiting for 10-15 minutes, I reconnected the sensors and reconfigured the setup with sensors 3, 6, and 7, and connected an additional Gigahertz device.
4. **Data Verification and Finalization:** after implementing the new sensor arrangement, we verified the new setting and that all devices were functioning correctly and took a photograph to document the setup for this day.

The monitoring period officially continued at **15:30 on July 10th**. For this new setup, we deployed **multi-sensors 3, 6, and 7,** alongside three illuminance devices, one Aircare device, one sound pressure level device, one particulate matter (PPM) device, the Testo 400 kit, and one formaldehyde device.

Fig. 19. Day 3 sensors arrangements on 10th of July at Living Lab Polito

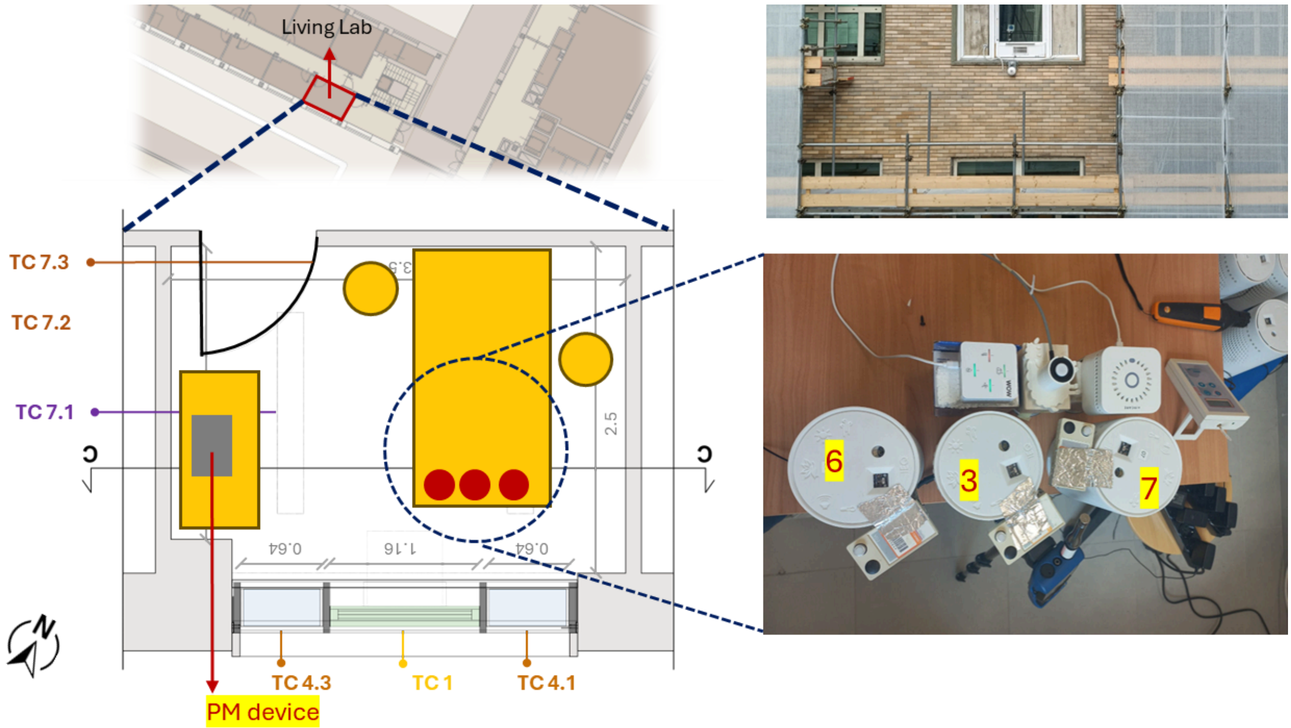


Fig. 20. Living Lab PLan with Sensor Positioning Day 3

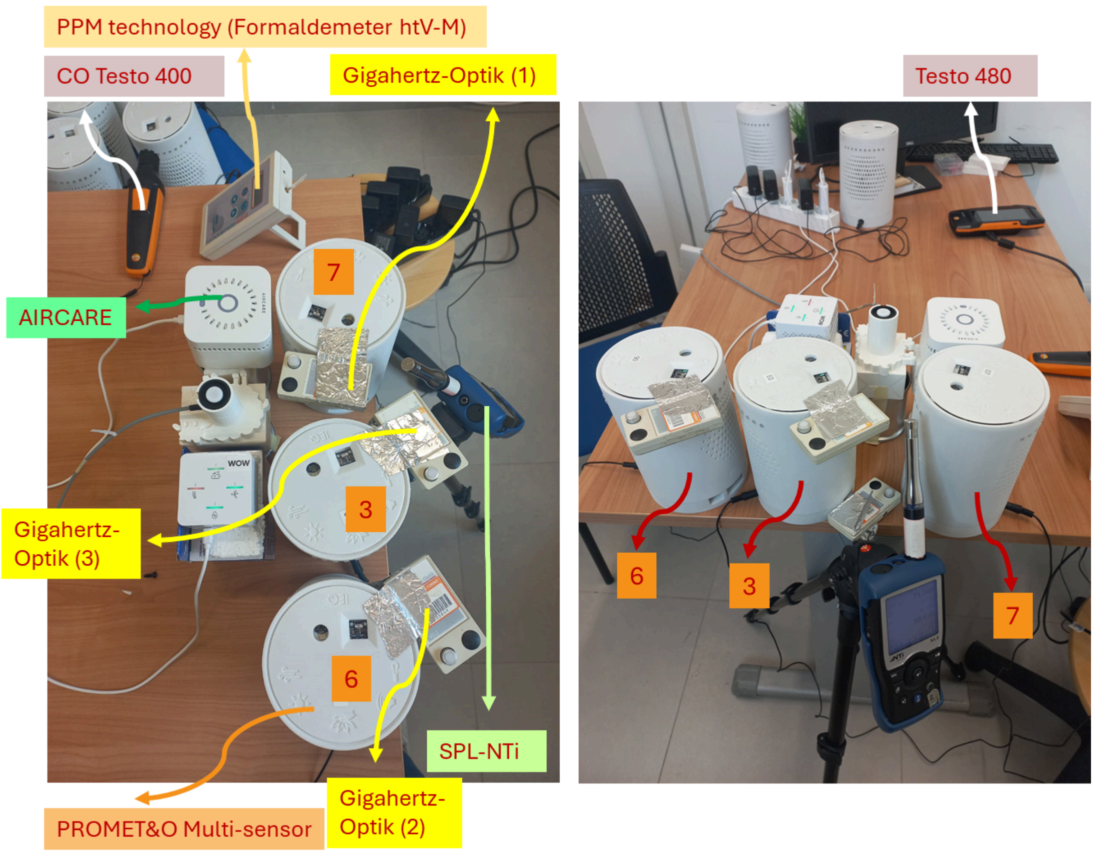


Fig. 21. Day 3 Sensors and reference device positioning on 10th of July at Living Lab Polito

Implementation Process of Multi-Sensor Systems in the Living Lab, Politecnico di Torino: Day 4 Measurement (11th of July from 15:30 - 12th of July at 15:30)

The methodology involved regular checks to verify system functionality and address any issues with sensor performance. During the monitoring period, sensors 6 and 7 encountered data transmission problems, likely due to a Wi-Fi connectivity issue. Despite attempts to resolve the issue, only sensor 6 resumed functioning. Due to the disruption in data collection, the decision was made to retain the same multi-sensors for further measurements rather than swapping them as initially planned.

Implementation Process of Multi-Sensor Systems in the Living Lab, Politecnico di Torino: Day 5 Measurement (12th of July from 15:30 - 15th of July at 09:30)

1. **Initial Coordination and Setup:** today we continued the measurements in the morning with sensors 3, 6, and 7, as we had not collected all the required data from yesterday.
2. **Monitoring and Midday Checks:** for the afternoon round we installed **sensors 8, 9, 10, as well as sensors 4 and 11**. A new SPL device was added next to sensors 4 and 11 to enhance measurement accuracy. The new configuration was activated, and measurements began at 16:44. In this new setup, Gigahertz 1 was connected to PROMET&O 8, Gigahertz 3 to PROMET&O 10, and Gigahertz 2 to PROMET&O 9.
3. **Final Adjustments and Planning:** Given that today was the last working day of the week, and next days will be weekend, this sensor setup will remain unchanged until Monday.

Fig. 22. Day 5 sensors arrangements on 12th of July at Living Lab Polito

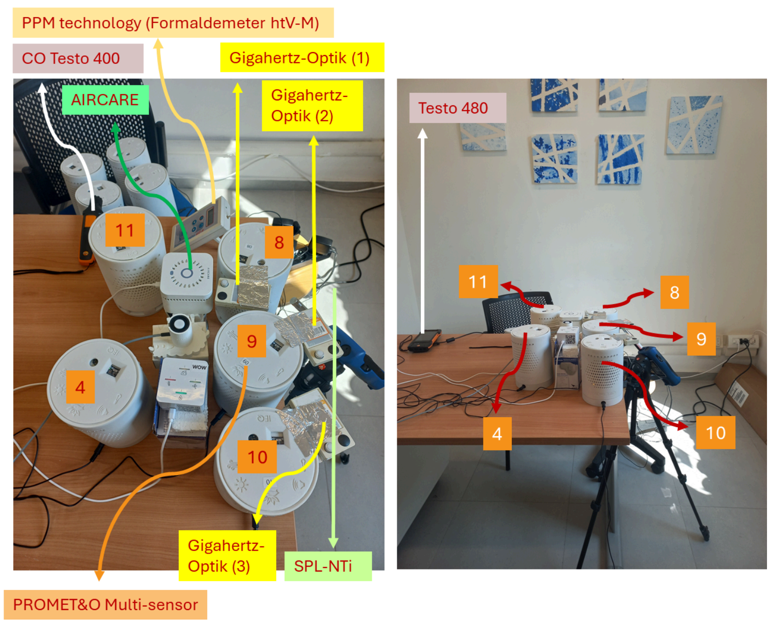


Fig. 23. Day 5 Sensors and reference device positioning on 12th of July at Living Lab Polito

Note: As the monitoring period commenced, a table was prepared each day, documenting the operational status of every sensor and compiling the collected data. This approach ensured that all necessary information was organized and readily available for subsequent analysis. By maintaining this structured record of sensor performance and data acquisition day by day, we ensured the reliability and completeness of the dataset, facilitating analysis and interpretation of the indoor environmental quality parameters measured.

TESTED PROMET&O	8-Jul-24	9-Jul-24	10-Jul-24	11-Jul-24	12-Jul-24
1	x	S1 PM	S1 AM		
2	x	S2 PM	S2 AM		
3	x		S3 PM	x	S3 AM
4	x				S4 PM
6	x		S6 PM	x	S6 AM
7	x		S7 PM	x	S7 AM
8	x				S8 PM
9	x				S9 PM
10	x				S10 PM
11	x				S11 PM

Fig. 24. Figure of PROMET&O devices presented in Living Lab measurements

OTHER DEVICES	8-Jul-24	9-Jul-24	10-Jul-24	11-Jul-24	12-Jul-24
Aircare	x	x	x	x	x
Aircare wow	x	x	x	x	x
Luxmeter - Delta Ohm LPPHOT01	x	x	x	x	x
Gigahertz 1	x	x	x	x	x
Gigahertz 2	x	-	PM part x	x	x
Gigahertz 3	x	x	x	x	x
Termocoppie	x	x	x	x	x
Umidità - E + E Elektronik EE160	x	x	x	x	x
Sound level meter - NTi	x	x	x	x	x
Formaldeide	-	x	x	x	x
Particulate matter	x	x	x	x	x
CO2 - Delta Ohm HD37VBTV.1	x	x	x	x	x
CO - Testo	-	-	x	x	x
Sound level meter - NTi 2	-	-	-	-	x

Fig. 25. Figure of presented device in Living Lab measurements

Note: In the previous figure, the cells highlighted in pink indicate elements that were present during the measurement process. However, since we do not have the corresponding data for these elements, they will not be considered in the subsequent steps of analysis.

Conclusion for Living Lab measurement: On the **15th of July** In the morning, we went to the lab to collect the multi-sensors, but encountered an issue with the Wi-Fi connections, which resulted in data loss. Despite this, we retrieved all the equipment and collected the sound pressure level data from both SPL devices. We then accessed the data from Gigahertz devices 1, 2, and 3. Data was saved from the carbon monoxide device, which consistently recorded zero levels. Additionally, data from all sensors for the past few days were downloaded. Moving forward, we need to place the multi-sensors in the Audio Space Lab for one day, before relocating them in the company for further measurements.

7.2.2 Politecnico di Torino A.S.L.

Implementation Process of Multi-Sensor Systems in the Audio Space Lab (ASL), Politecnico di Torino: Day 1 Measurement (18th of July from 16:30 - 18:00)

Upon arrival, the team and I set up all the equipment.This included connecting the Gigahertz devices to the sensors, preparing chargers for the multi-sensors, and configuring the SPL level device. To maintain the controlled environment, we turned off the lights, closed both doors securely, and exited the room. The recording started at **16:30 on 18th of July**.

This measurement involved placing 10 multi-sensors, 3 Gigahertz devices, a carbon monoxide monitor and the SPL device. Although the measurement period was brief, from **16:30 to 18:00**, it was crucial for evaluating the parameter levels. After concluding the measurements, we returned at 18:00 to collect the reference equipment, leaving the multi-sensors in place for ongoing data collection.

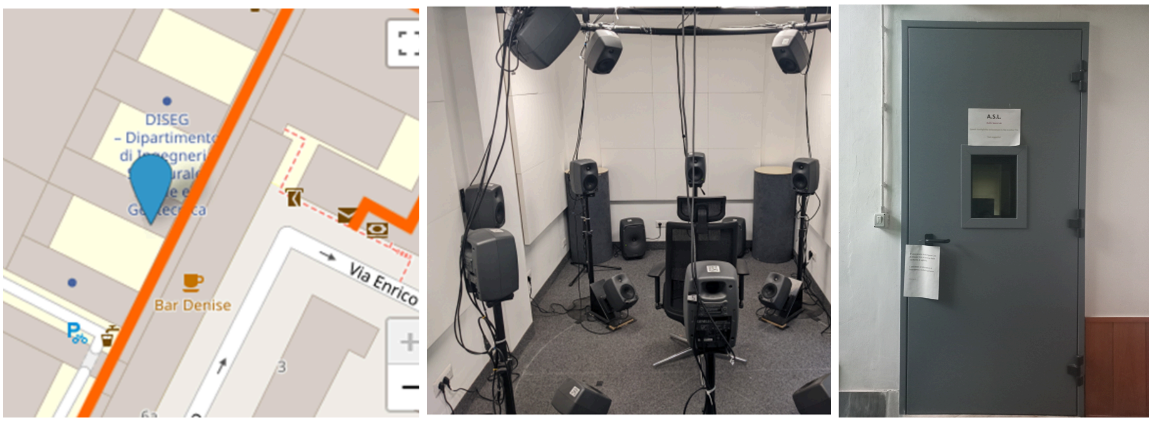


Fig. 26. Figure of the Audio Space Lab (A.S.L) Polito location and photo

Fig. 27. Figure of the Audio Space Lab (A.S.L) environmental conditions and reference devices

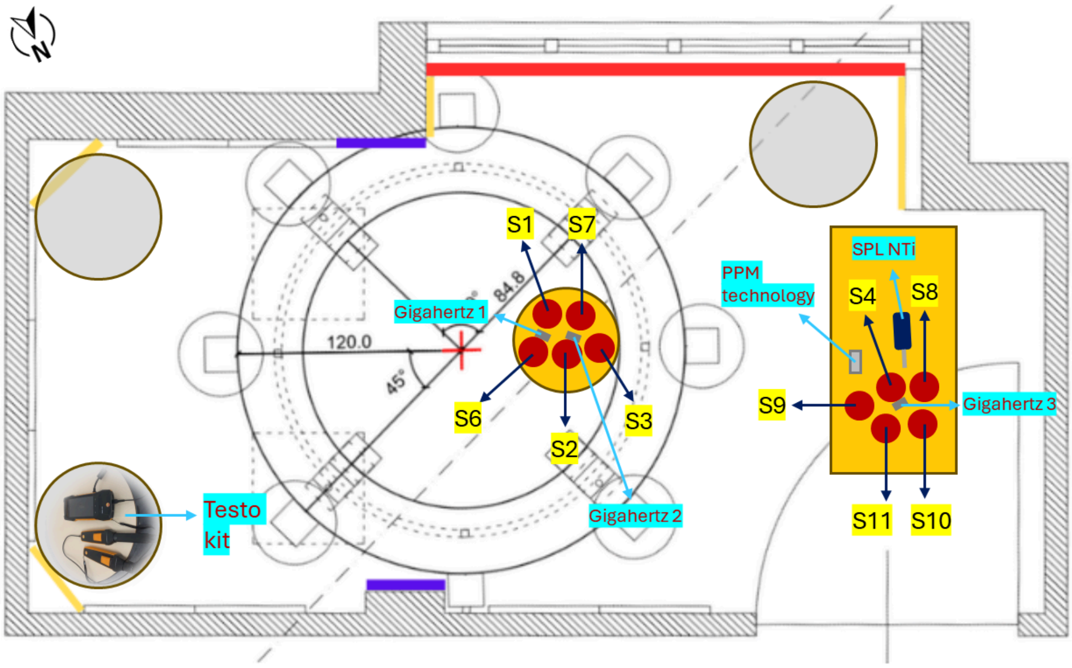


Fig. 28. Figure of the Audio Space Lab plan with sensors positioning (Adopted from https://www.doi.org/10.61782/fa.2023.0698)

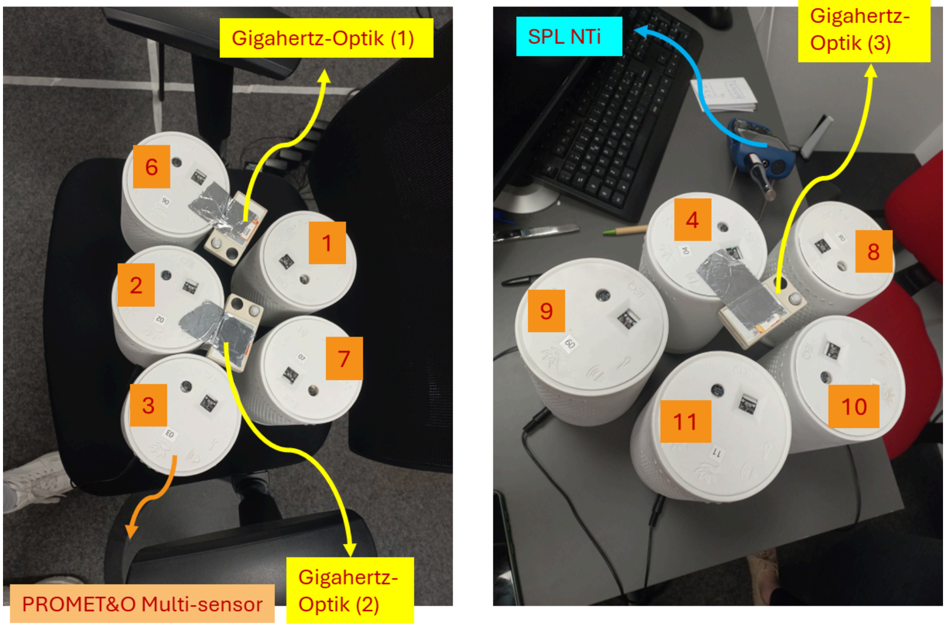


Fig. 29. Sensors arrangements on 18th of July at A.S.L

7.3 Data collection and preparation

In our study, we are utilizing Grafana to generate graphs for selected parameters over specific time slots, enhancing our ability to visualize and analyze indoor environmental quality data. The process involves collecting data directly from the PROMET&O multi-sensors through the Grafana dashboard. We configure queries within Grafana to aggregate and display the information over chosen time periods and dates. These visualizations help us identify hotspots, trends, and potential issues, providing valuable insights for optimizing indoor environments and ensuring occupant comfort and health.

To access the Grafana dashboard for monitoring and downloading data from each sensor, we used specific credentials, including a username and password. By logging in via the provided link we were able to view real-time data and historical trends for all the sensors deployed in the room. The Grafana interface allows us to track various environmental parameters, providing a comprehensive overview of the sensor data. Additionally, this platform enables us to download the collected data for further analysis, ensuring that we can effectively monitor the room's conditions.

By following these steps, we successfully accessed and downloaded the necessary data for further analysis.

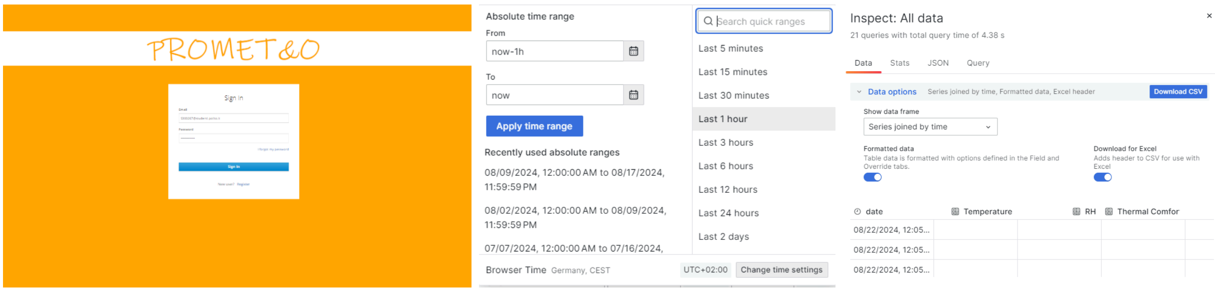


Fig. 30. Step By step performance in grafana dashboard

Here is the complete visualization of the Grafana dashboard, which displays both the data graph and associated metrics.

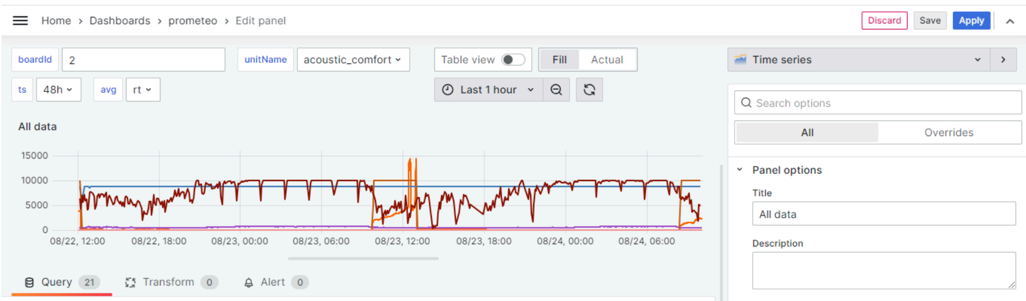


Fig.31. Interface of grafana showing the data after choosing the sensor and time and date

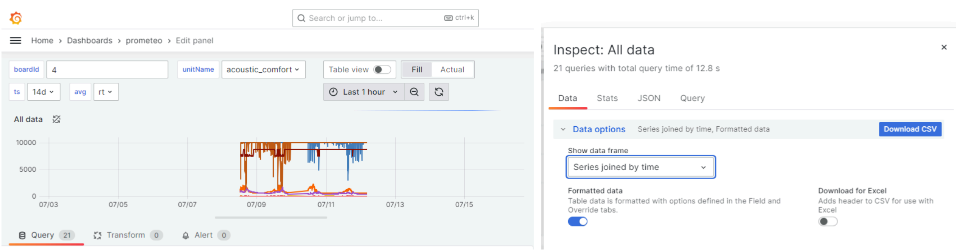
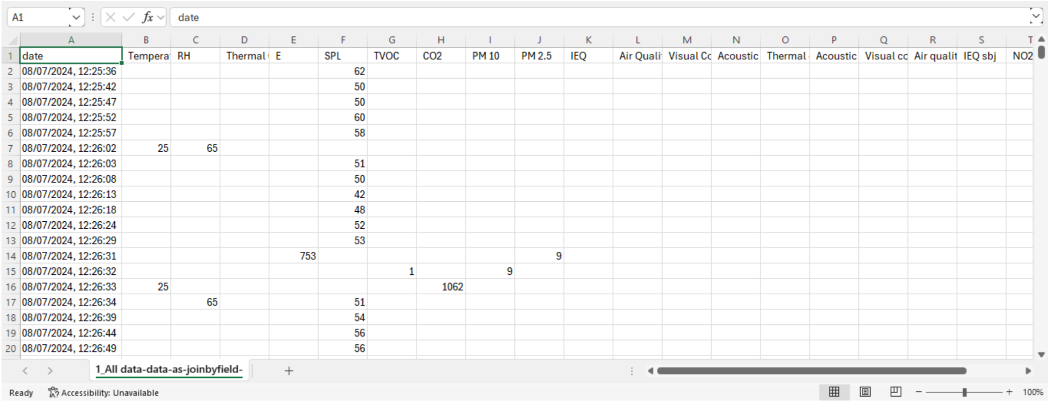


Fig. 32. Interface of grafana showing the data collection

It is possible to see an example of the data collected by the server for Multi-Sensor 1. This visual representation includes various IEQ parameters such as temperature, humidity, CO2 levels, and particulate matter concentrations, captured in real-time over the monitoring period. This file illustrates how these parameters fluctuate throughout the day, providing valuable insights into the environmental conditions within the office space. By examining this data, we can identify patterns and trends that are crucial for understanding and improving indoor environmental quality.

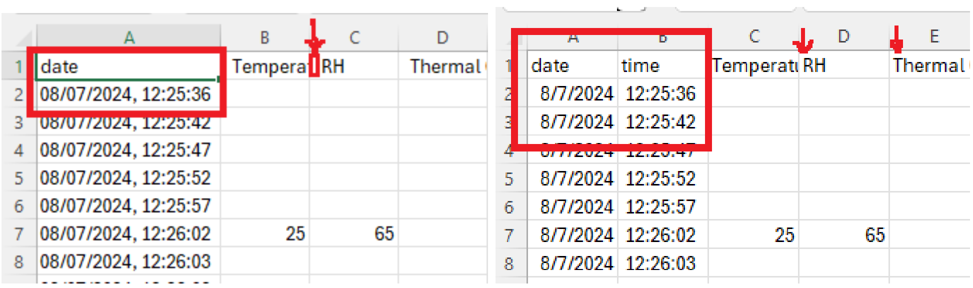


	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	date	Tempera	RH	Thermal	E	SPL	TVOC	CO2	PM 10	PM 2.5	IEQ	Air Quali	Visual Cc	Acoustic	Thermal	Acoustic	Visual cc	Air qualit	IEQ sbj	NO2
2	08/07/2024, 12:25:36					62														
3	08/07/2024, 12:25:42					50														
4	08/07/2024, 12:25:47					50														
5	08/07/2024, 12:25:52					60														
6	08/07/2024, 12:25:57					58														
7	08/07/2024, 12:26:02	25	65																	
8	08/07/2024, 12:26:03					51														
9	08/07/2024, 12:26:08					50														
10	08/07/2024, 12:26:13					42														
11	08/07/2024, 12:26:18					48														
12	08/07/2024, 12:26:24					52														
13	08/07/2024, 12:26:29					53														
14	08/07/2024, 12:26:31				753					9										
15	08/07/2024, 12:26:32						1		9											
16	08/07/2024, 12:26:33	25						1062												
17	08/07/2024, 12:26:34		65			51														
18	08/07/2024, 12:26:39					54														
19	08/07/2024, 12:26:44					56														
20	08/07/2024, 12:26:49					56														

Fig. 33. Figure of the excel file for data collected from grafana dashboard for sensor 1

It is noticeable from the data that the response times vary for each sensor and each parameter. This variation indicates that different sensors have differing sensitivities or data acquisition rates, which can affect how quickly they respond to changes in the measured parameters. Understanding these discrepancies is important for accurately interpreting the data and ensuring that all measurements are considered in the context of their specific response characteristics.

After collecting the data, I undertook a preparation step to ensure it could be accurately read by the Python script for the data analysis step. This process was crucial due to the script's sensitivity to various formatting details, including space, date and time formats, and the case of letters. To facilitate smooth data processing, I standardized all collected data from the multi-sensors, adjusting these elements to meet the script's requirements. This preparation process was repeated for all data sets to ensure consistency and accuracy in subsequent analysis.



	A	B	C	D
1	date	Tempera	RH	Thermal
2	08/07/2024, 12:25:36			
3	08/07/2024, 12:25:42			
4	08/07/2024, 12:25:47			
5	08/07/2024, 12:25:52			
6	08/07/2024, 12:25:57			
7	08/07/2024, 12:26:02	25	65	
8	08/07/2024, 12:26:03			

	A	B	C	D	E
1	date	time	Temperatu	RH	Thermal
2	8/7/2024	12:25:36			
3	8/7/2024	12:25:42			
4	8/7/2024	12:25:47			
5	8/7/2024	12:25:52			
6	8/7/2024	12:25:57			
7	8/7/2024	12:26:02	25	65	
8	8/7/2024	12:26:03			

Fig. 34. Figure of the DATA file preparation for upcoming data analysis

In addition to the data collected from the Grafana dashboard, we also gathered data from the illuminance device and the sound level meter device.

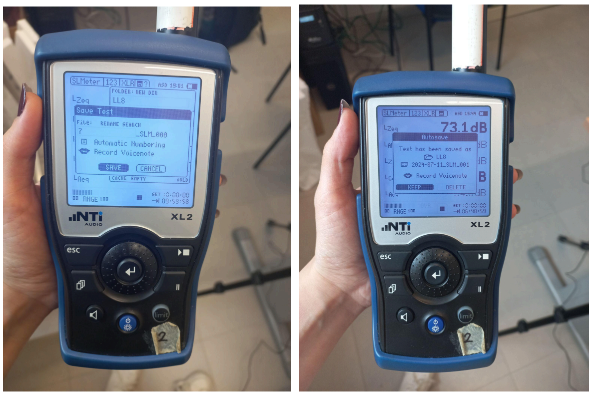
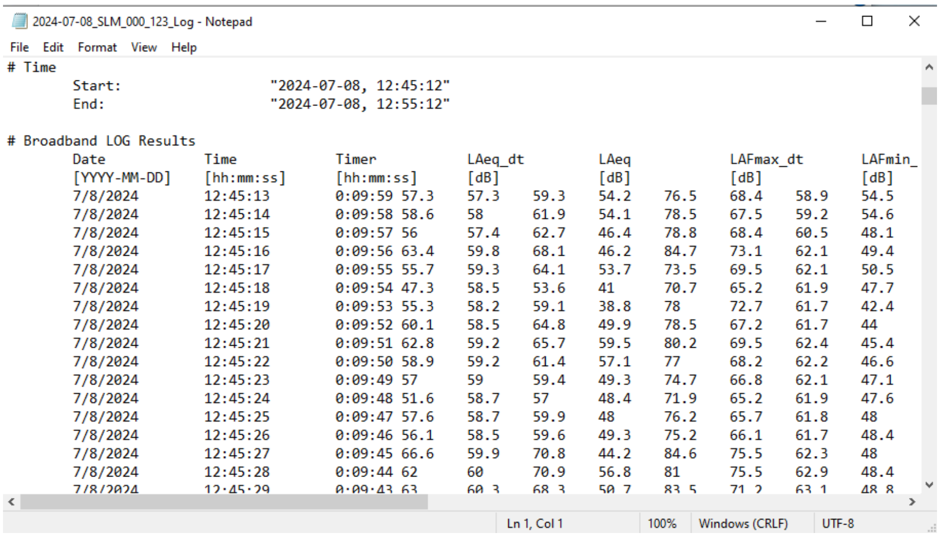


Fig. 35. Data collection process from Sound level meter device

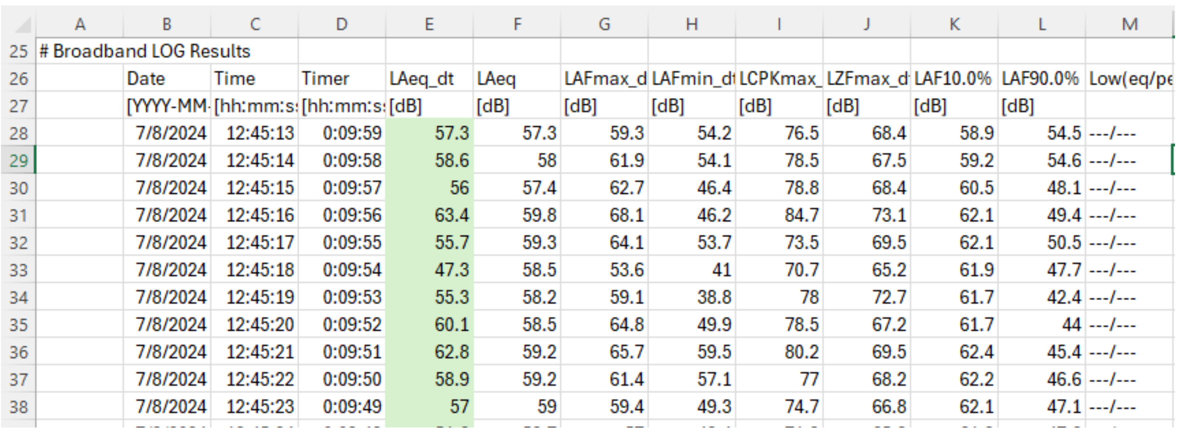


```
2024-07-08_SLM_000_123_Log - Notepad
File  Edit  Format  View  Help
# Time
        Start:                  "2024-07-08, 12:45:12"
        End:                    "2024-07-08, 12:55:12"

# Broadband LOG Results
        Date            Time            Timer           LAeq_dt         LAeq            LAFmax_dt       LAFmin_
        [YYYY-MM-DD]    [hh:mm:ss]      [hh:mm:ss]      [dB]            [dB]            [dB]            [dB]
        7/8/2024        12:45:13        0:09:59 57.3    57.3    59.3    54.2    76.5    68.4    58.9    54.5
        7/8/2024        12:45:14        0:09:58 58.6    58      61.9    54.1    78.5    67.5    59.2    54.6
        7/8/2024        12:45:15        0:09:57 56      57.4    62.7    46.4    78.8    68.4    60.5    48.1
        7/8/2024        12:45:16        0:09:56 63.4    59.8    68.1    46.2    84.7    73.1    62.1    49.4
        7/8/2024        12:45:17        0:09:55 55.7    59.3    64.1    53.7    73.5    69.5    62.1    50.5
        7/8/2024        12:45:18        0:09:54 47.3    58.5    53.6    41      70.7    65.2    61.9    47.7
        7/8/2024        12:45:19        0:09:53 55.3    58.2    59.1    38.8    78      72.7    61.7    42.4
        7/8/2024        12:45:20        0:09:52 60.1    58.5    64.8    49.9    78.5    67.2    61.7    44
        7/8/2024        12:45:21        0:09:51 62.8    59.2    65.7    59.5    80.2    69.5    62.4    45.4
        7/8/2024        12:45:22        0:09:50 58.9    59.2    61.4    57.1    77      68.2    62.2    46.6
        7/8/2024        12:45:23        0:09:49 57      59      59.4    49.3    74.7    66.8    62.1    47.1
        7/8/2024        12:45:24        0:09:48 51.6    58.7    57      48.4    71.9    65.2    61.9    47.6
        7/8/2024        12:45:25        0:09:47 57.6    58.7    59.9    48      76.2    65.7    61.8    48
        7/8/2024        12:45:26        0:09:46 56.1    58.5    59.6    49.3    75.2    66.1    61.7    48.4
        7/8/2024        12:45:27        0:09:45 66.6    59.9    70.8    44.2    84.6    75.5    62.3    48
        7/8/2024        12:45:28        0:09:44 62      60      70.9    56.8    81      75.5    62.9    48.4
        7/8/2024        12:45:29        0:09:43 63      60.3    68.3    50.7    83.5    71.2    63.1    48.8
Ln 1, Col 1    100%    Windows (CRLF)    UTF-8
```

Fig. 36. Collected data sheet from Sound level meter device

After downloading the data from the SPL device, I prepared the files for future data analysis by standardizing formats and ensuring compatibility with our analysis tools.



	A	B	C	D	E	F	G	H	I	J	K	L	M
25	# Broadband LOG Results												
26		Date	Time	Timer	LAeq_dt	LAeq	LAFmax_d	LAFmin_dt	LCPKmax_	LZFmax_d	LAF10.0%	LAF90.0%	Low(eq/pe
27		[YYYY-MM-	[hh:mm:s	[hh:mm:s	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	
28		7/8/2024	12:45:13	0:09:59	57.3	57.3	59.3	54.2	76.5	68.4	58.9	54.5	---/---
29		7/8/2024	12:45:14	0:09:58	58.6	58	61.9	54.1	78.5	67.5	59.2	54.6	---/---
30		7/8/2024	12:45:15	0:09:57	56	57.4	62.7	46.4	78.8	68.4	60.5	48.1	---/---
31		7/8/2024	12:45:16	0:09:56	63.4	59.8	68.1	46.2	84.7	73.1	62.1	49.4	---/---
32		7/8/2024	12:45:17	0:09:55	55.7	59.3	64.1	53.7	73.5	69.5	62.1	50.5	---/---
33		7/8/2024	12:45:18	0:09:54	47.3	58.5	53.6	41	70.7	65.2	61.9	47.7	---/---
34		7/8/2024	12:45:19	0:09:53	55.3	58.2	59.1	38.8	78	72.7	61.7	42.4	---/---
35		7/8/2024	12:45:20	0:09:52	60.1	58.5	64.8	49.9	78.5	67.2	61.7	44	---/---
36		7/8/2024	12:45:21	0:09:51	62.8	59.2	65.7	59.5	80.2	69.5	62.4	45.4	---/---
37		7/8/2024	12:45:22	0:09:50	58.9	59.2	61.4	57.1	77	68.2	62.2	46.6	---/---
38		7/8/2024	12:45:23	0:09:49	57	59	59.4	49.3	74.7	66.8	62.1	47.1	---/---

Fig. 37. Formatted data file in excel for SPL to be ready for data analysis phase

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
25	# Broadband LOG Results																	
26		Date	Time	Timer	LAeq_dt	LAeq	LAFmax_d	LAFmin_dt	LCPKmax_	LZFmax_d	LAF10.0%	LAF90.0%	Low(eq/pe	Overload	Pause			
27		[YYYY-MM-	[hh:mm:s:	[hh:mm:s:	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]						
28		7/8/2024	12:45:13	0:09:59	57.3	57.3	59.3	54.2	76.5	68.4	58.9	54.5	---/---					
29		7/8/2024	12:45:14	0:09:58	58.6	58	61.9	54.1	78.5	67.5	59.2	54.6	---/---				AVERAGE	
30		7/8/2024	12:45:15	0:09:57	56	57.4	62.7	46.4	78.8	68.4	60.5	48.1	---/---				42.4	
31		7/8/2024	12:45:16	0:09:56	63.4	59.8	68.1	46.2	84.7	73.1	62.1	49.4	---/---					
32		7/8/2024	12:45:17	0:09:55	55.7	59.3	64.1	53.7	73.5	69.5	62.1	50.5	---/---					

Fig. 38. Average calculated data file in excel for SPL to be ready for data analysis phase

For the illuminance measurements, we connected each illuminance device individually to the designated PC, launched the X2000-9 software and saved logger data in a txt format.

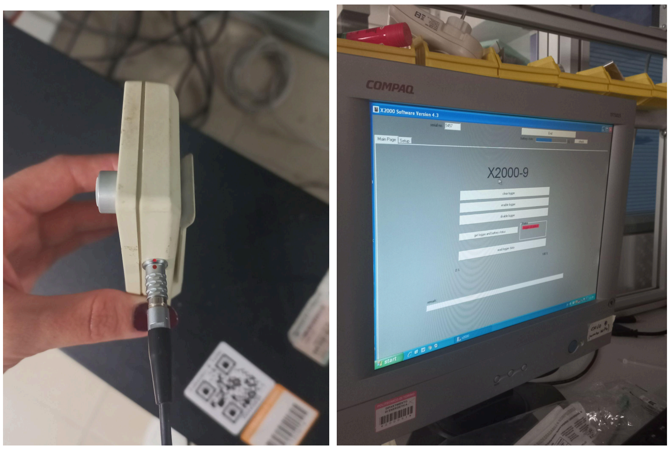


Fig. 39. Data collection process from Gigahertz-optik devices

1_8-15_LUGLIO2024 - Notepad

File Edit Format View Help

```
time / minutes    Kanal 1 / W/m? V(1) / lx       temperature internal / ?C       temperature external / ?C
logger enabled 08.07.2024 12:08:05
logger started 08.07.2024 12:08:05
000     0.000000E+00    1.272461E+00    24.9    11.5
005     0.000000E+00    9.240820E+01    25.1    11.6
010     0.000000E+00    6.576562E+02    25.5    11.6
015     0.000000E+00    4.895156E+02    25.4    11.6
020     0.000000E+00    1.010500E+03    25.4    11.6
025     0.000000E+00    1.723281E+03    25.4    11.6
030     0.000000E+00    1.619750E+03    25.3    11.6
035     0.000000E+00    1.732062E+03    25.3    11.6
040     0.000000E+00    1.616000E+03    25.4    11.6
045     0.000000E+00    1.496969E+03    25.6    11.6
050     0.000000E+00    1.068344E+03    25.7    11.6
055     0.000000E+00    1.699438E+03    25.9    11.6
060     0.000000E+00    1.964406E+03    26      11.6
065     0.000000E+00    1.712812E+03    26.2    11.6
070     0.000000E+00    1.456062E+03    26.4    11.6
075     0.000000E+00    1.513250E+03    26.6    11.6
080     0.000000E+00    1.859375E+03    26.8    11.6
085     0.000000E+00    1.452000E+03    26.9    11.6
090     0.000000E+00    1.711031E+03    27.1    11.6
095     0.000000E+00    1.850656E+03    27.2    11.6
100     0.000000E+00    1.760688E+03    27.3    11.6
```

Ln 1, Col 1 | 100% | Windows (CRLF) | UTF-8

Fig. 40. Collected data sheet from Gigahertz-optik device

After downloading the data from the illuminance devices, I prepared the files for future data analysis by standardizing formats and ensuring compatibility with our analysis tools. Including adding a new column and transforming the time data into a format reflecting actual timing, with intervals set at every 5 minutes from the initial measurement start time. Additionally, I began calculating averages using the AVERAGE formula in Excel, applying this to the defined timing for each day to facilitate a more comprehensive analysis of the data.

	time / minutes	TIME	Kanal 1 / W/m?	V(l) / lx	V(l) / lx	temperatu	temperatu
2	logger enabled 08.07.2024 12:08:05						
3	logger started 08.07.2024 12:08:05						
4	0	12:08:05	0.00E+00	1.27E+00	1.27	24.9	11.5
5	5	12:13:05	0.00E+00	9.24E+01	92.41	25.1	11.6
6	10	12:18:05	0.00E+00	6.58E+02	657.66	25.5	11.6
7	15	12:23:05	0.00E+00	4.90E+02	489.52	25.4	11.6
8	20	12:28:05	0.00E+00	1.01E+03	1010.50	25.4	11.6
9	25	12:33:05	0.00E+00	1.72E+03	1723.28	25.4	11.6
10	30	12:38:05	0.00E+00	1.62E+03	1619.75	25.3	11.6
11	35	12:43:05	0.00E+00	1.73E+03	1732.06	25.3	11.6

Fig. 41. Formatted data file in excel for Gigahertz-optik to be ready for data analysis phase

	time / minutes	TIME	Kanal 1 / W/m?	V(l) / lx	V(l) / lx	temperatu	temperatu	serialnumber:2904						
2	logger enabled 08.07.2024 12:08:05													
3	logger started 08.07.2024 12:08:05													
4	0	12:08:05	0.00E+00	1.27E+00	1.27	24.9	11.5			average				
5	5	12:13:05	0.00E+00	9.24E+01	92.41	25.1	11.6			1541.8	E (12-15)	8th		
6	10	12:18:05	0.00E+00	6.58E+02	657.66	25.5	11.6			1643.1	E (15-18)	8th		
7	15	12:23:05	0.00E+00	4.90E+02	489.52	25.4	11.6			1592.5	E (12-18)			
8	20	12:28:05	0.00E+00	1.01E+03	1010.50	25.4	11.6							
9	25	12:33:05	0.00E+00	1.72E+03	1723.28	25.4	11.6			1175.6	E (09-12)	9th		
10	30	12:38:05	0.00E+00	1.62E+03	1619.75	25.3	11.6			1265.0	E (12-15)	9th		
11	35	12:43:05	0.00E+00	1.73E+03	1732.06	25.3	11.6			1220.3	E (09-15)			
12	40	12:48:05	0.00E+00	1.62E+03	1616.00	25.4	11.6			1619.9	E (15-18)	9th		

Fig. 42. Average calculated file in excel for Gigahertz-optik to be ready for data analysis phase

I followed the same process for collecting data from the Audio Space Lab (A.S.L) as we did for the Living Lab. This involved deploying and managing the measurement devices with careful attention to detail, including connecting them properly, ensuring accurate data capture.

	date	Tempera	RH	Thermal	E	SPL	TVOC	CO2	PM 10	PM 2.5	IEQ	Air Quali	Visual Cc	Acoustic	Thermal	Acoustic	Visual cc	Air qualit	IEQ sbj
2	07/18/2024, 04:57:21â€¯PM					32													
3	07/18/2024, 04:57:26â€¯PM					32													
4	07/18/2024, 04:57:32â€¯PM					32													
5	07/18/2024, 04:57:37â€¯PM					32													
6	07/18/2024, 04:57:40â€¯PM	32	45																
7	07/18/2024, 04:57:42â€¯PM					32													
8	07/18/2024, 04:57:47â€¯PM					33													
9	07/18/2024, 04:57:52â€¯PM					35													
10	07/18/2024, 04:57:57â€¯PM					33													
11	07/18/2024, 04:58:03â€¯PM					32													
12	07/18/2024, 04:58:08â€¯PM					33													
13	07/18/2024, 04:58:09â€¯PM				36				7	7									
14	07/18/2024, 04:58:10â€¯PM						1	923											
15	07/18/2024, 04:58:11â€¯PM	32	45																
16	07/18/2024, 04:58:13â€¯PM					32													
17	07/18/2024, 04:58:18â€¯PM					32													
18	07/18/2024, 04:58:23â€¯PM					32													
19	07/18/2024, 04:58:28â€¯PM					32													
20	07/18/2024, 04:58:34â€¯PM					32													

3-All data-A.S.L

Fig. 43. Figure of the excel file for data collected from grafana dashboard for sensor 3 in A.S.L

7.4 Data Analysis

For data analysis, I encountered challenges due to the different response times of the assembled multi-sensors compared to each individual sensor. To address this, I decided to use Python for processing the data and generating comprehensive analysis graphs.

I began by writing a script to read each data file and produce dot plots for individual parameters. These plots visually represented the entire measurement process for each day and sensor, allowing for a clear overview of the data collection. Next, I developed another script to identify and document instances where sensors failed to transmit data for specific parameters. This step was crucial for pinpointing any gaps or inconsistencies in the data.

I moved on creating histogram graphs to analyze the average levels of the data more effectively. To achieve this, I wrote a script that generated histograms within selected timeframes for each parameter, facilitating a deeper understanding of data trends and variations. I then combined all the files into a unified dataset, allowing me to read and process the data simultaneously. This integration enabled me to produce graphs with the requested modifications, including the addition of threshold lines and highlighted threshold regions to indicate significant data points.

Following further instructions from the professor, I incorporated uncertainty levels into each graph to account for variability and measurement errors. Lastly, I defined the start and finish points for each parameter, ensuring that the analysis accurately reflected the data collection periods and provided a comprehensive evaluation of the results.

For the data analysis presented in Appendix 11.1 and Appendix 11.2, I utilized PyCharm as the integrated development environment (IDE) for executing and managing the Python script. Its built-in terminal and interactive Python console were instrumental in running scripts and testing individual components of the code. PyCharm's comprehensive code inspection and error-checking capabilities ensured that the analysis was both accurate and optimized, ultimately contributing to the successful generation of the graphs and data insights documented in the appendix.

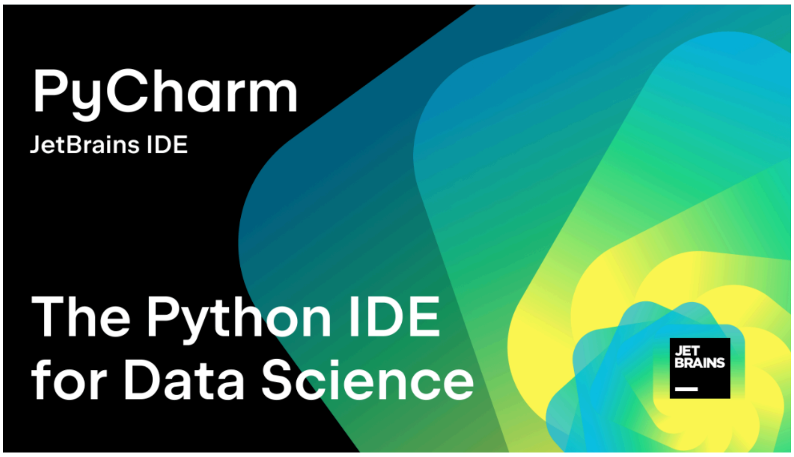


Fig. 44. Figure of the Pycharm environment (Adapted from grafana https://www.jetbrains.com/pycharm/)

For data analysis, I created different pycharm files that include all timing for all the sensors and all the parameters recorded by the multi-sensors. To ensure a systematic and thorough analysis, I approached the data day by day and parameter by parameter. For instance, on the first day, I focused on the data from the 10 multi-sensors, analyzing one parameter at a time. On subsequent days, I concentrated on the main sensors and additional parameters we put in place. This methodical approach allowed for detailed comparisons and insights. Each parameter was given its unique file for each day, and graphs were used to create visual comparisons and identify trends and patterns in the data.

7.4.1 Politecnico di Torino Living Lab

In this section, I will provide a detailed breakdown of the data analysis conducted using Python for the graphs presented in Appendix 11.1, which pertains to the data analysis of the Living Lab experiment. The analysis process involved several key steps: first, data was extracted from the dashboard, each corresponding to different sensors and measurement parameters. We defined specific time ranges to segment the data, ensuring a focused analysis on relevant periods. Each parameter was analyzed according to predefined thresholds (Fissore et al., 2024) and reference values to assess compliance and performance. Here's a step-by-step explanation of the Python script and how it works:

Import Necessary Libraries

```
import pandas as pd
import matplotlib.pyplot as plt
import os
```

In this section, I import the essential libraries required for the analysis. The pandas library is used for data manipulation and analysis, matplotlib.pyplot provides tools for creating a variety of plots and visualizations, and OS allows for interaction with the operating system to handle file paths and directories.

Define File Paths and Colors

```
file_paths = {
   'C:\\Users\\West\\Desktop\\1_All data.csv': ('red', 'Sensor 1'),
 }
```

In this step, I defined the file paths and associated colors for each sensor's data files.

Define time ranges

```
time_ranges = {
   '12-15 PM (8th)': ('2024-08-07 12:00:00', '2024-08-07 15:00:00'),
   }
```

In this step, I defined the time ranges for segmenting the data. This segmentation allows for a focused analysis of data collected during specific intervals and facilitates comparisons across different periods.

Define Threshold for each parameter

```
thresholds = {
  'temperature': {'low': 23, 'high': 26, 'unit': '°C', 'uncertainty': 0.5},
}
```

In this section, I defined the thresholds and uncertainty level for each parameter based on the paper published recently (Fissore et al., 2024). The thresholds dictionary specifies acceptable ranges or limits for various environmental metrics. Each parameter is associated with specific threshold values, units of measurement, and uncertainties.

Define box legend including the uncertainty level on each bar

```
box_legend = {
   'temperature': 'uncertainty ±0.5 °C',
}
```

In this analysis, the box legend defines the uncertainty levels associated with each parameter on the bar charts (Fissore et al., 2024).

Define reference values for different parameters from reference devices

```
reference_values = {
    'pm 2.5': {
        '12-15 PM (8th)': 9.51,
} # add other references
```

The reference values are established to provide baseline measurements for comparison across different time periods and parameters. These reference values serve as benchmarks to assess the performance and compliance of the monitored parameters (Fissore et al., 2024).

Define the process_file and plot_graphs functions: The process_file function reads and filters data from CSV files based on a specified parameter and time range, loading the data into a DataFrame and standardizing column names to ensure relevant data is extracted for analysis. The plot_graphs function generates and saves visualizations for the specified parameter by creating a bar chart with overlaid box plots to show the parameter's average levels across different time periods. The final plot is then saved with the given file name.

Define the threshold rectangles

```
if parameter == 'temperature':
    ax.axhspan(23, 26, facecolor='green', alpha=0.05, label=f'Temperature Range 23-26 °C')
```

Defining threshold rectangles adds horizontal shaded areas to the plot to indicate acceptable ranges or limits for different parameters. For temperature, a range of 23-26 °C is shaded green to indicate the acceptable temperature range.

Plot the bars and boxes on top of each bar: for plotting graphs code involves creating bar charts and overlapping box plots to represent data distributions visually. Box plots are added on top of the histogram bars to show the data distribution for each time period, using a smaller width for clear overlay.

Define the X and Y axis limits: the X-axis is labeled with the time ranges, while the Y-axis label and plot title are set according to the specified parameters.

Define to add reference values if provided: to incorporate reference values, the script first checks if any reference data is available. If so, it prints the reference values for the parameter in question, then calculates the y-values for the reference bars based on the provided data. These reference bars are plotted with a distinct color for clarity and positioned offset from the main data bars.

Define the threshold lines for each parameter: To enhance the clarity of the data visualization, the threshold lines for each parameter (Fissore et al., 2024) are defined and added to the plot.This approach helps in visually assessing whether the data falls within the acceptable ranges.

Define the legend plot: To effectively differentiate between parameters in the plot, a legend is added to describe the associated with each parameter.

Define the processing files for each time range and calculate average levels for each parameter: To process each file for the specified time ranges and calculate the average levels for each parameter, the script first initializes an average_values dictionary to store the results. This dictionary is structured to hold average values for each parameter across all defined time ranges.

Define to plot all the graphs for each parameter: To plot all the graphs for each parameter, the script iterates through each parameter defined in the thresholds dictionary. The plot is titled to reflect the parameter and the date range being analyzed, and the y-axis label is updated to indicate the unit of measurement for the parameter. Additionally, if reference values are provided for the parameter, they are included in the plot for comparison. This process ensures that detailed and informative graphs are produced for each parameter based on the collected data.

To generate plots that display history time for each parameter based on timing, I adjusted the script to define the entire hours of measurement for a single day rather than specifying a particular period. This allows the X-axis to represent the full hour measurement period, providing a comprehensive view of the data collected throughout the day, as can be seen below.

```
start_datetime = pd.to_datetime('2024-07-08 12:30:00')
end_datetime = pd.to_datetime('2024-07-09 15:30:00')
```

Additionally, I set the X-axis to display tick marks at one-hour intervals to enhance the clarity of the plots. A significant number of changes were made to finalize the script and ensure it produced the exact graphs we needed.

```
max_hours = (end_datetime - start_datetime).total_seconds() / 3600
plt.xlim([0, max_hours])
ax.xaxis.set_major_formatter(FuncFormatter(format_func))

tick_positions = range(0, int(max_hours) + 1)
plt.xticks(ticks=tick_positions, rotation=45)
```

In summary, to ensure a comprehensive analysis of the data collected in the Living Lab, the script was developed to read multiple CSV files and consolidate them into a single DataFrame. Each CSV file represents data recorded from different sensors deployed across the lab environment. The script combines the 'date' and 'time' columns into a unified datetime column, facilitating accurate data processing, sorting, and filtering based on specific time intervals.

For this analysis, several essential libraries are imported to handle data manipulation, visualization, and system interaction. The ***pandas*** library is utilized for efficient data management and analysis, allowing for the restructuring and processing of large datasets. ***Matplotlib.pyplot*** is employed to create a variety of visualizations, including time plots and histograms, which are crucial for interpreting the sensor data. Additionally, the ***os*** **library** ensures smooth interaction with the operating system, enabling automatic handling of file paths and directories.

A sample graph representing Day 1 in the Living Lab, including histograms and a tick time plot, is included here. Additional graphs are provided in **Appendix 1, Section 11.1**, where further comparisons between sensor readings, reference devices, and thresholds are illustrated.

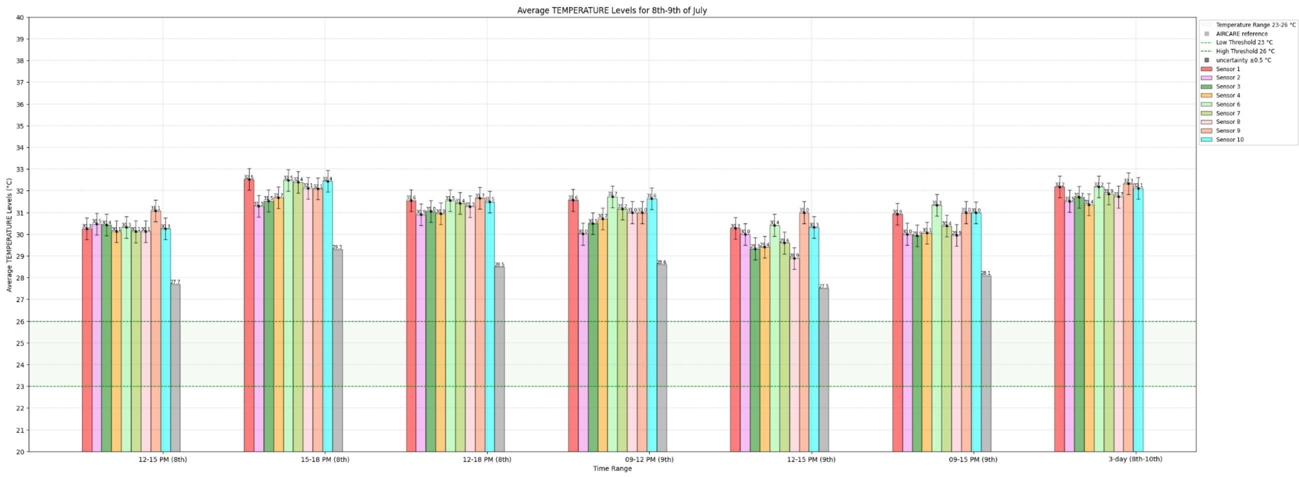


Fig. 45. Figure of the Temperature histogram graph for day one in Living Lab

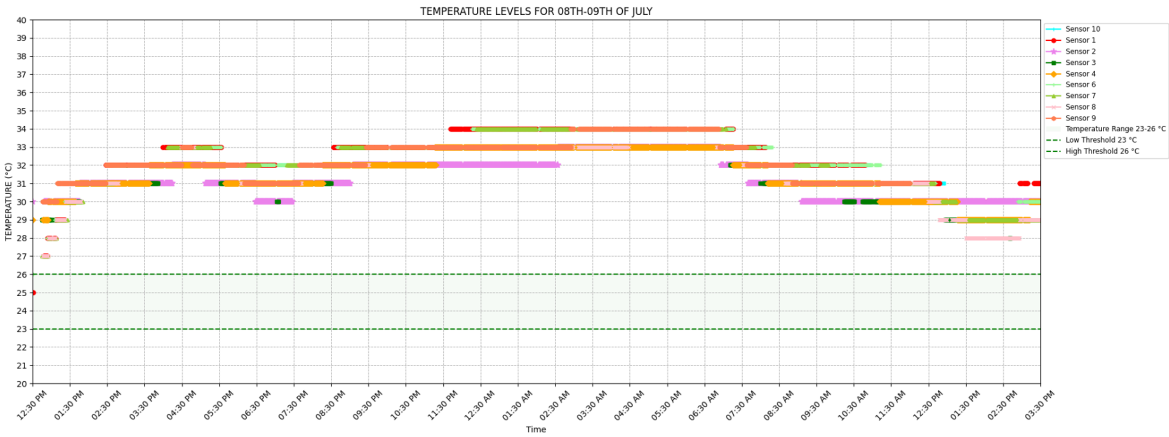


Fig. 46. Figure of the Temperature tick time graph for day one in Living Lab

To effectively interpret these graphs, start by examining the title, which provides an overview of the data presented. The legend outlines the different elements of the graph: colored bars and lines represent various sensors. The threshold range is highlighted with shaded light green rectangles, while the acceptable ranges for each parameter are marked with green dashed lines. The Y-axis displays the measured parameter levels, and the X-axis shows the time range under which measurements were taken. Additionally, the uncertainty level for each bar is indicated on top, providing insight into the variability of the measurements. Reference devices, if involved, are noted to offer context for comparison. By cross-referencing the legend, threshold markers, uncertainty levels, and axis labels, we can accurately assess how each sensor's readings compare to the thresholds and reference values.

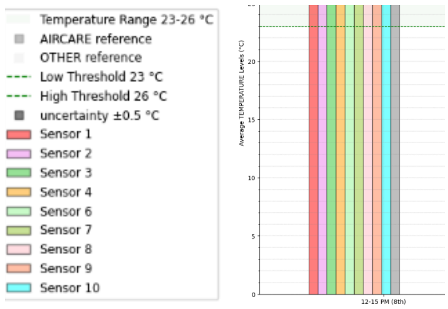


Fig. 47. Figure of the representation of legend, X axis and Y axis

Histograms are instrumental in summarizing and analyzing the average data for each sensor and parameter by providing a clear picture of the data distribution across different intervals. When used to aggregate data from multiple sensors, histograms help visualize the frequency of different average values within specified ranges. This visualization allows for the comparison of distributions across different sensors, highlighting variations in performance or conditions captured by each sensor. By understanding these distributions, analysts can gain insights into sensor accuracy, identify anomalies, and make decisions to optimize sensor calibration or address potential issues in the measurement process. In summary, histograms are essential for transforming raw data into meaningful insights, facilitating a comprehensive understanding of sensor data across various parameters.

Overlaying a box plot on top of histogram bars offers a powerful way to visualize the range and distribution of data, enhancing the analysis of uncertainty levels. By superimposing a box plot onto each histogram bar, it is possible to see the range of values within each bin and how they relate to the bar.

Summary of Environment:

- Artificial light was turned on, and there is a fixed window without shading in the room.
- No one was present in the room during the measurement.
- The door was closed during measurement.
- Microphones recorded a peak every hour, possibly due to the fan inside the multi-sensors.
- All multi-sensors recorded very low values for TVOC.

Summary of Multi-Sensors:

- All sensors recorded higher than the reference device for temperature. Sensors 1, 6, and 10 overestimate the value in comparison to the reference device and other sensors.
- Sensors 2, 4, and 6 underestimate the value in comparison to the reference device and other sensors for relative humidity.
- Sensor 1 overestimates illuminance in comparison to other sensors at different timings.
- Sensors 2 and 10 overestimate the SPL in comparison to other sensors and the reference.
- Sensor 8 underestimates $PM_{2.5}$ in comparison to other sensors, and sensor 10 overestimates it in comparison to other sensors.
- Sensor 3 overestimates the value for CO_2, and sensors 6, 7, and 10 underestimate in comparison to the reference device.
- All multi-sensors recorded an over-threshold value for CO, and multi-sensor 10 overestimates in comparison to other sensors.
- All multi-sensors recorded very close values for TVOC.
- Sensors 1, 3, 6, and 10 noticeable underestimate in comparison to others for formaldehyde.
- All multi-sensors recorded a zero value for NO_2.

7.4.2 Politecnico di Torino A.S.L.

Same as the previous section, in this section, I will provide a short breakdown of the data analysis conducted using Python for the graphs presented in Appendix 11.2, which pertains to the data analysis of the Audio Space Lab experiment. I defined specific time ranges to segment the data, ensuring a focused analysis on relevant periods. Each parameter was analyzed according to predefined thresholds (Fissore et al., 2024) and reference values to assess compliance and performance. I used histogram graphs and box plots on each graph. These visualizations display average parameter levels across different time periods, with threshold lines indicating acceptable ranges and reference values providing context for comparison. The script for analyzing the A.S.L. data is largely similar to the one used for the Living Lab, with a few modifications.

Sensor 11, which did not send any data during the Living Lab measurement due to a technical issue, was successfully fixed and fully operational for the ASL experiment. It was present in the ASL setup.

```
'C:\\Users\\West\\Desktop\\11-All data-Asl.csv': ('yellow', 'Sensor 11')
```

We had the reference devices available in the lab for a short period, so we decided to focus on the timeframe from 16:30 to 18:00 of 18th of July. To accommodate this, I updated the script to specifically define this timing for our analysis.

```
time_ranges = { '16:30-18 PM (18th)': ('2024-07-18 16:30:00', '2024-07-18 18:00:00')}
```

The reference values recorded in the lab were incorporated into the final script to ensure accurate visualization. Since we had three reference values for the illuminance parameter, the script was adjusted to account for this. For other parameters with only one reference value, these were set as "none" in the script to avoid displaying them as zero values on the graph.

Note: It is important to note that the reference value was calculated manually from the reference data collected, averaging the values over the exact same timing as the sensors.

The script consolidates multiple CSV files into a single DataFrame, merging 'date' and 'time' into a unified datetime column for accurate analysis. It evaluates the data within specified time ranges and parameters, generating visualizations to compare against thresholds and reference values. Here is a sample for the Audio Space Lab of the histograms and tick time plot; additional graphs are available in Appendix 1, 11.2.

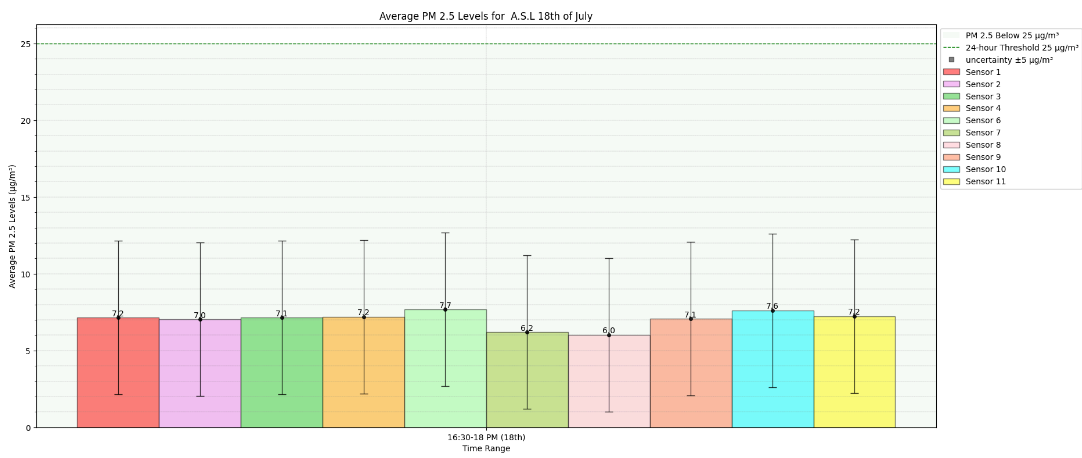


Fig. 48. Figure of the PM 2.5 graph for A.S.L measurement

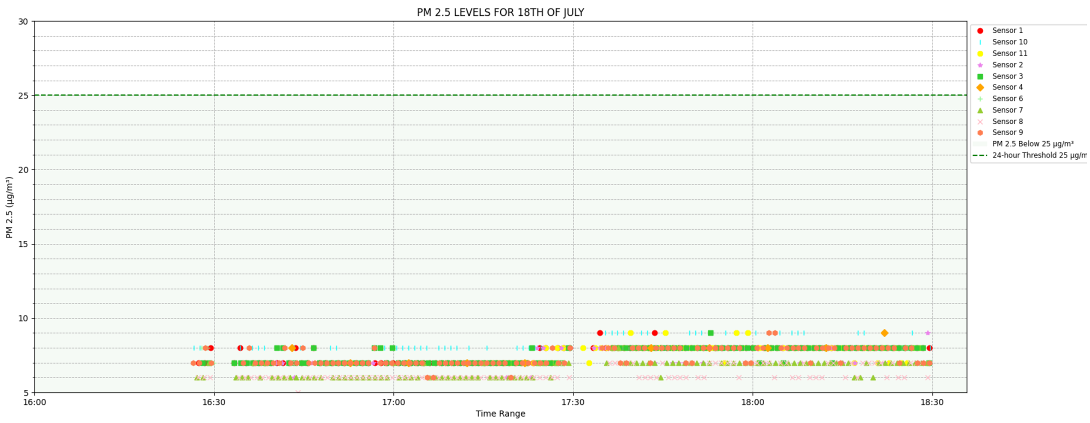


Fig. 49. Figure of the PM 2.5 tick time graph for A.S.L measurement

Threshold ranges are indicated with light green rectangles, while acceptable ranges are marked with green dashed lines. The Y-axis shows measured levels and the X-axis shows the time range. Uncertainty levels are displayed on top of each bar, and reference devices are noted for context.

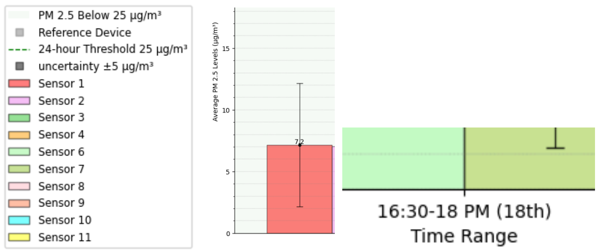


Fig. 50. Figure of the representation of legend, X axis and Y axis

Summary of environment:

- The door was closed and the light was turned off during the measurement period.
- No one was present in the room during the measurement period.

Summary of multi-Sensors:

- Temperature: multi-sensors recorded values close to the threshold level; multi-sensor 6 had a lower value; all sensors recorded higher temperatures than the reference device.
- Relative humidity: all multi-sensors recorded lower values compared to the reference device.
- Illuminance: all multi-sensors recorded higher values compared to the reference devices.
- Sound Pressure Level: all multi-sensors recorded higher values compared to the reference device; multi-sensors 2, 10, and 11 overestimated SPL.
- $PM_{2.5}$: all multi-sensors recorded very close values.
- PM_{10}: all multi-sensors recorded very close values.
- CO_2: multi-sensor 3 overestimated CO_2 values; multi-sensors 6, 7, and 10 underestimated CO_2 values.
- CO: all multi-sensors recorded higher values than the threshold; multi-sensor 10 recorded a very high value; the reference device recorded zero CO.
- Total Volatile Organic Compounds: all multi-sensors recorded very low values.
- NO_2: all multi-sensors recorded zero values.

References Chapter 7

1. Putty. (n.d.). Putty: A Free SSH and Telnet Client. Retrieved from https://www.putty.org
2. Grafana Cloud. (n.d.). Retrieved from https://grafana.com/products/cloud/ Promet*o Platform. (2024)
3. JetBrains. (2024). *PyCharm* (Version 2024.2) [Computer software]. https://www.jetbrains.com/pycharm/
4. Astolfi, A., & Fissore, V. I. (2024). Multi-sensor device for traceable monitoring of indoor environmental quality. *Sensors, 24*(9), 2893. https://doi.org/10.3390/s24092893
5. Microsoft Corporation. (2021). *Microsoft Excel* (Version 16.0) [Software]. Includes AVERAGE formula for statistical analysis. https://www.microsoft.com/en-us/microsoft-365/excel
6. Politecnico di Torino et al. (2023). *Set up and preliminary validation of a small spatial sound reproduction system for clinical purposes*. Forum Acusticum 2023, Frontiers in Audiology. https://doi.org/10.61782/fa.2023.0698
7. Politecnico di Torino. (n.d.). *Politecnico di Torino*. Retrieved September 7, 2024, from https://www.polito.it/
8. Python help assistant, OpenAI. (2024). *ChatGPT* (Aug 25 version) [Large language model]. https://www.openai.com/chatgpt

IN-FIELD EXPERIMENT

COMPANY

8. In-Field Application of PROMET&O system in the company open-space offices

Understanding the relationship between environmental conditions and employee well-being in office settings is crucial for optimizing productivity and comfort. In this chapter, I will delve into the detailed process of in-field measurement conducted at the open-space company offices, where PROMET&O multi-sensors were deployed to monitor and analyze the office environment. This approach combines cutting-edge sensor technology, collecting objective data from sensors.

The primary goal of this study is to provide a comprehensive evaluation of the workplace conditions and their impact on the occupants, ultimately informing strategies to enhance both comfort and productivity in office environments. The data collected will be used to refine the sensors and inform future improvements in environmental monitoring technology.

8.1 In-field application

We selected PROMET&O multi-sensor 2, 4, 6, 7, 8, 9 to be placed in the open space company offices.

Implementation Process of Multi-Sensor Systems in the open-space Company Measurement: (2nd of August from 14:00 - 18:00) and next several days from (3rd to 8th of August from 09:00 - 18:00) and (9th of August from 09:00 - 15:00).

Upon arrival at the company, we positioned the sensors in the two designated offices—the smaller office (n.1) and the larger office (n.2). For this experiment, we selected and deployed sensors 2, 4, and 6 in the office n.1, and sensors 7, 8, and 9 in the office n.2.

Finally, we checked the dashboard to confirm that all sensors were operating correctly and that data was being transmitted as expected. This setup and engagement with the office staff were crucial for ensuring the collection of accurate environmental data. The distinction between the smaller office (n.1), housing seven employees, and the larger office (n.2), accommodating over ten individuals, provided an opportunity to compare environmental conditions and their impact across different settings within the same workplace. By collecting objective data, we aim to draw meaningful correlations that will help optimize office environments for comfort, productivity, and overall well-being.

Note 1: The measurements in the company continued over the next several days with the same sensor settings and positioning, remaining unchanged. Data was collected during three time intervals: 9:00-12:00 PM, 12:00-15:00 PM, and 15:00-18:00 PM.

Note 2: We conducted the measurements from August 2nd at 14:00 to August 9th at 15:30.

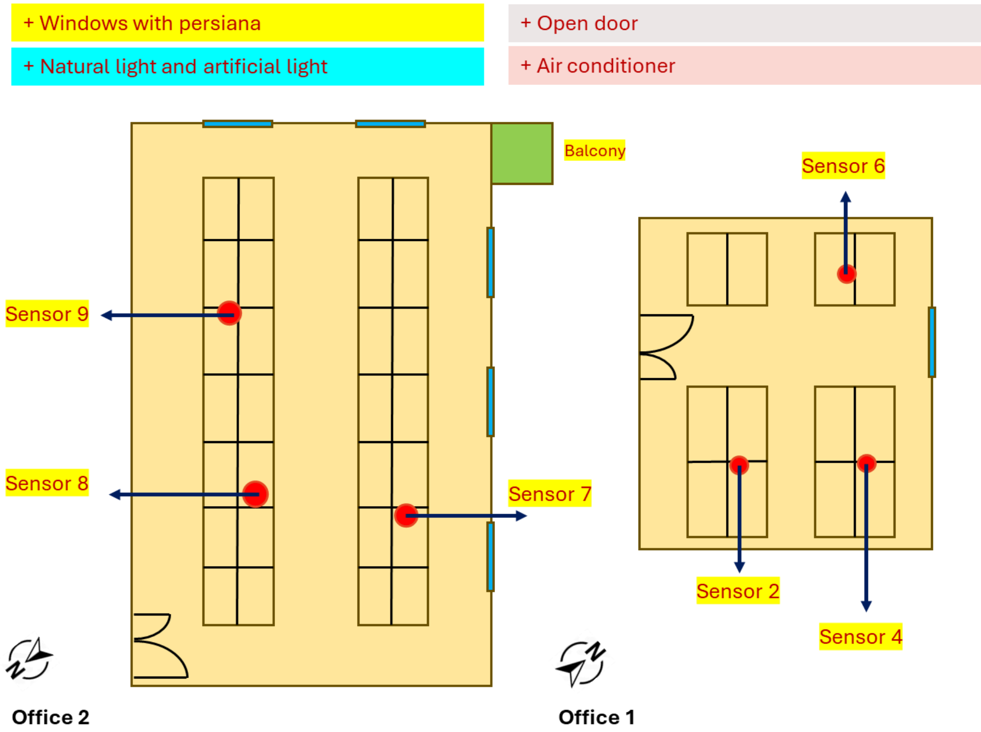


Fig. 1. Figure representing the positioning of the sensors in office settings

8.2 Data collection and preparation

In the company's data collection process, we follow the same procedures as those used in our Living Lab, ensuring consistency and accuracy in measuring quantifiable environmental parameters. We accessed the Grafana dashboard for monitoring and downloading data from each sensor and to view real-time data and historical trends for all the sensors deployed in the offices. Here is the visualization of the Grafana dashboard, which displays the data graph and associated metrics for sensor 4 located in office n.1 in the company.

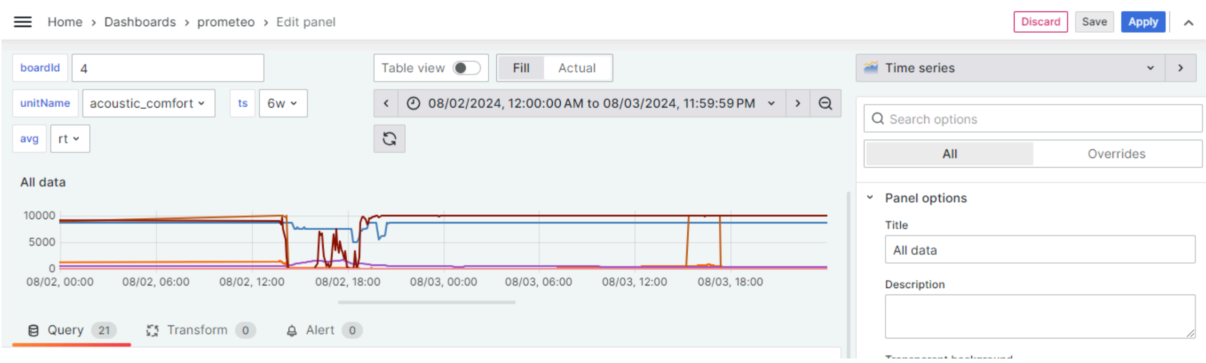


Fig. 2. Interface of grafana showing the data for sensor 4 (Adapted from grafana)

This visual representation includes various IEQ parameters such as temperature, humidity, CO_2 levels, and particulate matter concentrations, captured in real-time over the monitoring period. This file illustrates how these parameters fluctuate throughout the day.

After collecting the data, I undertook a preparation step to ensure it could be read by the Python script for the data analysis step. This process was crucial due to the script's sensitivity to various formatting details, including space, date and time formats, and the case of letters. This preparation process was repeated for all data sets to ensure consistency and accuracy in subsequent analysis.

8.3 Data Analysis

In this section, I will provide a short breakdown of the data analysis conducted using Python for the graphs presented in Appendix 11.3, related to the Company experiment. The analysis process involved several crucial steps: initially, data was extracted from the grafana dashboard, corresponding to sensors 2,4,6,7,8,9. Specific time ranges were defined to segment the data, ensuring a focused examination of relevant periods (we considered 9-18 for the office setting). The script for analyzing the company data is largely similar to the one used for the Living Lab and A.S.L, with a few modifications.

The selection of sensors for the measurements was informed by the data analyzed from the Living Lab. As a result, we deployed sensors 2, 4, 6 in one office and sensors 7, 8, 9 in another. To enhance visualization in the graphs, I assigned different color tones to each group: a red tone for sensors 2, 4, and 6, and a blue tone for sensors 7, 8, and 9. Additionally, I modified the script to ensure consistent color application across the sensors in each office, making it easier to read and compare the data.

```
file_paths = {

   'C:\\Users\\West\\Desktop\\2-All data-C.csv':('firebrick', 'Sensor 2'),
```

Here is a sample graph of the company histograms and tick time plot; additional graphs are available in Appendix 1, 11.3.

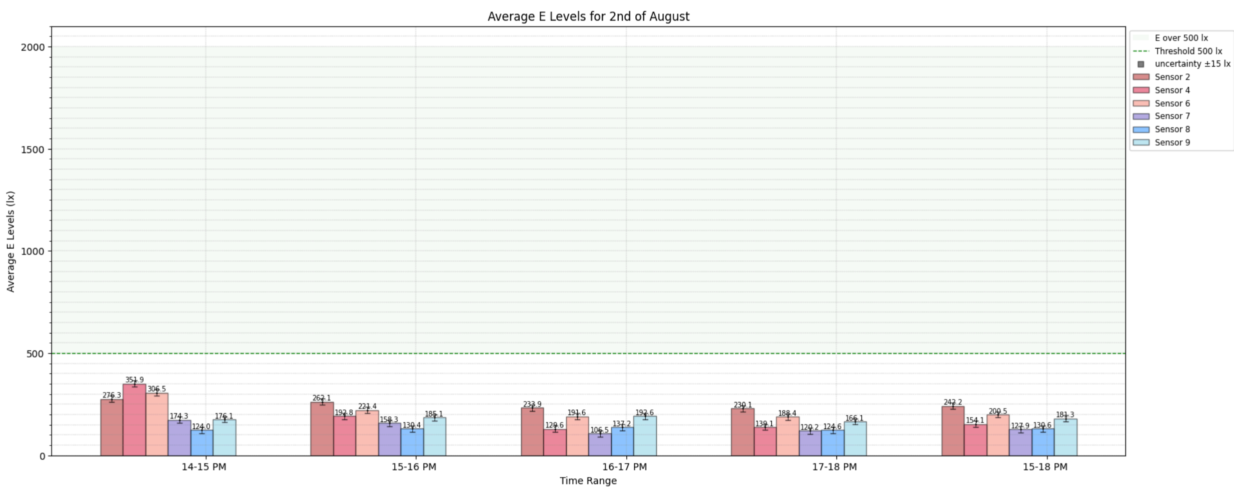


Fig. 3. Figure of the illuminance graph for company measurement

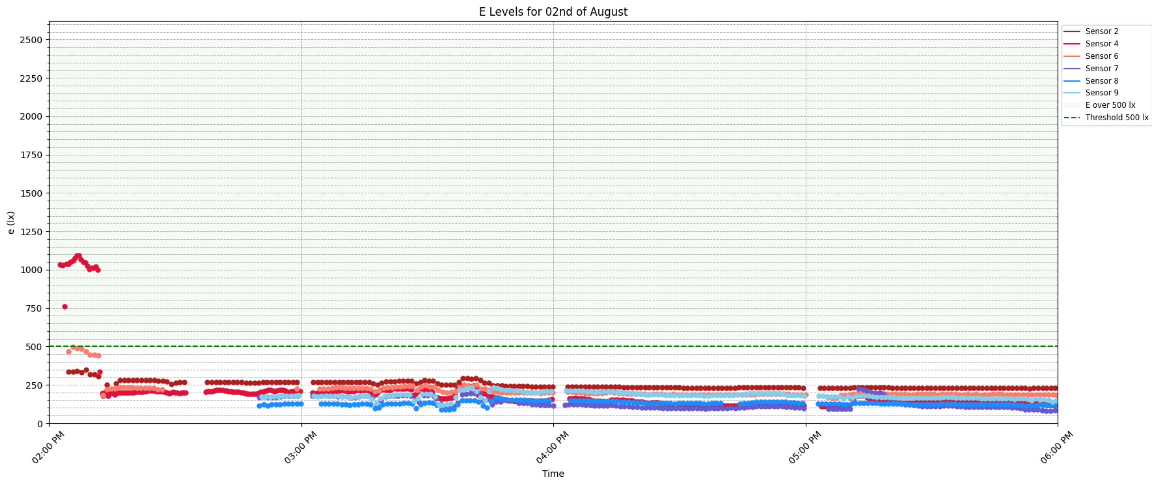


Fig. 4. Figure of the illuminance tick time graph for company measurement

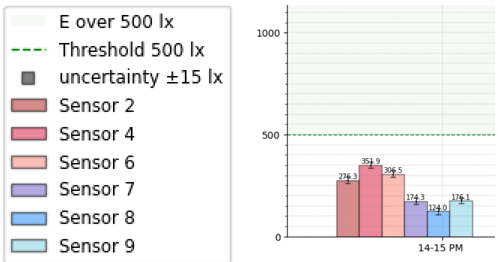


Fig. 5. Figure of the representation of legend, X axis and Y axis

Summary of Multi-Sensors:

- Temperature: Office 1 had consistently higher temperatures than Office 2, notable that offices have different orientation and different number of occupants.
- Relative Humidity: Office 2 had higher relative humidity than Office 1, notable that offices have different orientation and different number of occupants.
- Illuminance: Office 1 had higher illuminance, with sensor 4 showing irregular behavior.
- Sound Pressure Level: SPL readings presented higher levels in Office 2.
- $PM_{2.5}$ and PM_{10}: most sensors reported similar PM levels, but sensor 9 in Office 2 showed higher values.
- Carbon dioxide: CO_2 levels were higher in Office 2, particularly in the late afternoon as there are more occupants there.
- Carbon monoxide: CO levels were above the threshold in both offices, due to a malfunction of the sensors, as noticed during the Living Lab and ASL measurements.
- Formaldehyde: Sensor 4 in Office 1 showed higher formaldehyde levels while in Office 2, sensor 7 showed lower values.
- Total Volatile Organic Compounds: TVOC levels were consistently low in both offices.

References Chapter 8

1. Grafana Cloud. (n.d.). Retrieved from https://grafana.com/products/cloud/
2. Promet*o Platform. (2024)
3. JetBrains. (2024). *PyCharm* (Version 2024.2) [Computer software]. https://www.jetbrains.com/pycharm/
4. Astolfi, A., & Fissore, V. I. (2024). Multi-sensor device for traceable monitoring of indoor environmental quality. *Sensors, 24*(9), 2893. https://doi.org/10.3390/s24092893
5. Microsoft Corporation. (2021). *Microsoft Excel* (Version 16.0) [Software]. Includes AVERAGE formula for statistical analysis. https://www.microsoft.com/en-us/microsoft-365/excel
6. Python help assistant, OpenAI. (2024). *ChatGPT* (Aug 25 version) [Large language model]. https://www.openai.com/chatgpt

UNIVERSITY RESIDENCE ROOM

9. In-Field Application of PROMET&O System in a university residence room

In this chapter, I will explore the detailed process of conducting in-room measurements using PROMET&O multi-sensors 2 and 6 in a room serving as workspace and bedroom. The focus will be on gathering objective data to assess environmental conditions. This involves specific tasks like lighting a candle to observe changes in certain parameters, adjusting the curtains to measure variations in illuminance, and opening or closing the window to evaluate airflow and sound pressure levels. Additionally, I will examine the impact of turning the fan on and off to observe airflow changes, and switching artificial lights on and off to monitor variations in light levels.

The goal is to compare data with the ones from other experiments to assess the functionality and accuracy of the readings, keeping in mind that this experiment was conducted without a reference device.

9.1 In-field application

I positioned the sensors in the room at **21:30 on August 9th,** for a round of night measurements ensuring they were set up for comprehensive in-field measurement under controlled conditions.

- **Room Location**: south orientation allows natural light to enter by opening the curtain, rendering artificial light unnecessary during the day for a specific period.
- **Curtains**: The curtain is dark, effectively blocking external light when closed, which is useful for conducting nighttime measurements.
- **Window**: The window is double-glazed, which impacts the sound pressure levels recorded by the sensors when closed at night.

I began the initial measurement period at **21:30 on August 9th and continued until midnight on August 11th.**

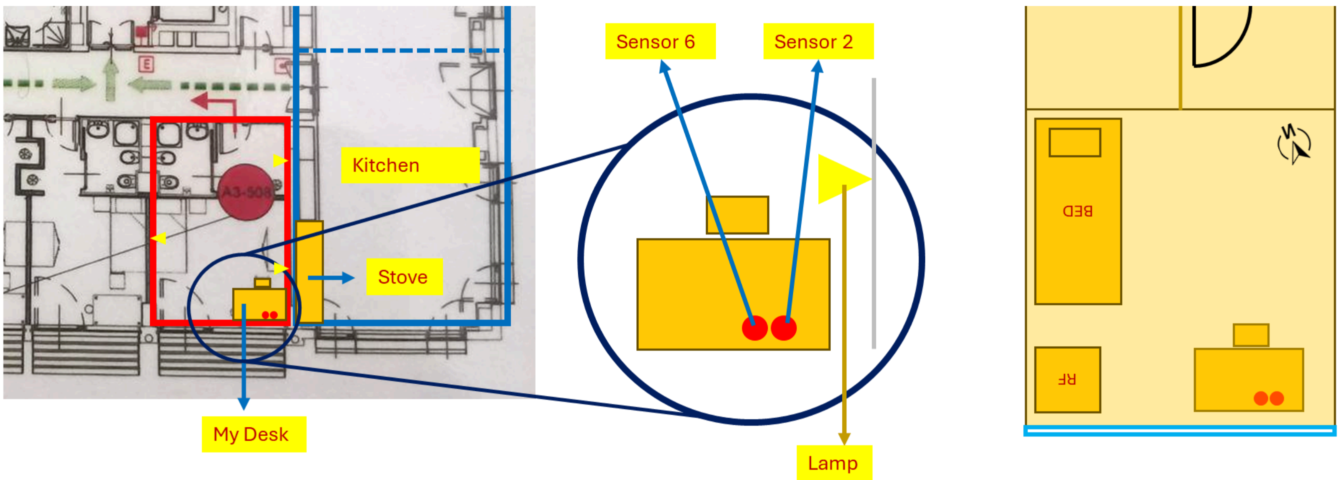


Fig. 1.Room plan and sensors positioning

+ Close door

+ Portable fan

+ Window with dark curtain and shading

+ Natural light + Artificial light

Fig. 2. Room environment conditions

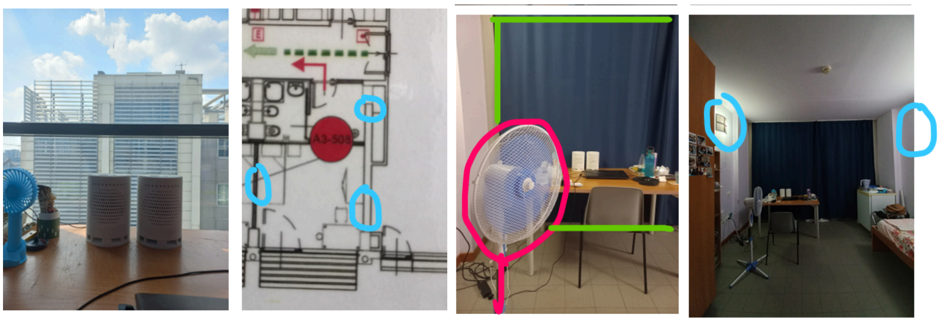


Fig. 3. Room environment 1

Fig. 4. Room environment 2

Fig. 5. Location of the portable fan in the afternoon and at night

Fig. 6. Day 1 sensors arrangements on 9th-11th of August

As the process continued for room measurements, I created a table for each day to document any changes made, specifically regarding the window, curtains, portable fan, and artificial light. This record allowed me to track environmental adjustments and correlate them with the data collected by the sensors.

9-Aug-24 to 11-Aug-24	21:00-00:00	00:00-03:00	03:00-06:00	06:00-09:00	09:00-13:00	13:00-15:00	15:00-18:00	18:00-21:00	21:00-00:00
Curtain	Closed	Closed	Closed	Closed	Open	Closed	Closed	Closed	Closed
Window	Open	Closed	Closed	Closed	Open	Open	Open	Open	Open
Portable fan	On	On	On	On	Off	On	On	On	On
Atrificial light	On	Off	Off	Off	Off	Off	Off	On	On

Fig. 7. Day 1 Table that showcase changes in room for 9th-11th of August

Day 2 of in-room measurement:

On the following day, starting at midnight, I rotated **both sensors 90 degrees clockwise** to observe how this adjustment affected the results. This rotation aimed to evaluate the impact of sensor orientation on the collected data. Additionally, I conducted a short **CO_2 test** on day 2 by burning a smudge near the sensors for 10 minutes to assess their response to elevated CO_2 levels and air quality parameters.

Fig. 8. Day 2 Test for CO_2 with same sensors arrangements

Fig. 9. Day 2 sensors arrangements on 11th-12th of August in room

11-Aug-24 to 12-Aug-24	00:00-02:00	02:00-06:00	06:00-09:00	09:00-11:00	11:00-13:00	13:00-15:00	15:00-18:00	18:00-21:00	21:00-00:00
Curtain	Closed	Closed	Closed	Closed	Open	Closed	Closed	Closed	Closed
Window	Open	Closed	Closed	Open	Open	Open	Open	Open	Open
Portable fan	On	On	On	On	On	On	On	On	On
Atrificial light	On	Off	Off	Off	Off	Off	Off	On	On

Fig. 10. Day 2 Table that showcase changes in room for 11th-12th of August

Day 3 of in-room measurement:

For the subsequent days, I continued with the same setup but rotated the **sensors 90 degrees clockwise** each day to further assess the impact of sensor orientation on the measurements.

Fig. 11. Day 3 sensors arrangements on 12th-13th of August in room

12-Aug-24 to 13-Aug-24	00:00-03:00	03:00-06:00	06:00-09:30	09:30-13:00	13:00-15:00	15:00-18:00	18:00-21:00	21:00-00:00
Curtain	Closed	Closed	Closed	Open	Closed	Closed	Closed	Closed
Window	Closed	Closed	Closed	Open	Open	Open	Open	Open
Portable fan	On	On	On	Off	Off	Off	On	On
Atrificial light	Off	Off	Off	Off	Off	Off	On	On

Fig. 12. Day 3 Table that showcase changes in room for 12th-13th of August

Day 4 of in-room measurement:

Fig. 13. Day 4 sensors arrangements on 13th-14th of August in room

13-Aug-24 to 14-Aug-24	00:00-03:00	03:00-06:00	06:00-10:00	10:00-11:00	11:00-15:00	15:00-18:00	18:00-21:00	21:00-00:00
Curtain	Closed	Closed	Closed	Open	Closed	Closed	Closed	Closed
Window	Closed	Closed	Closed	Open	Open	Open	Open	Open
Portable fan	On	On	On	Off	Off	On	On	On
Atrificial light	Off	Off	Off	Off	Off	Off	On	On

Fig. 14. Day 4 Table that showcase changes in room for 13th-14th of August

Day 5 of in-room measurement:

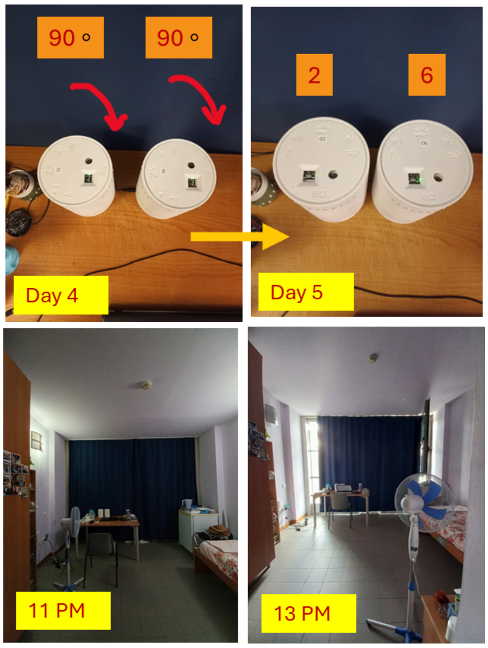


Fig. 15. Day 5 sensors arrangements on 14th-15th of August in room

14-Aug-24 to 15-Aug-24	00:00-03:00	03:00-06:00	06:00-09:00	09:00-12:00	12:00-15:00	15:00-18:00	18:00-21:00	21:00-00:00
Curtain	Closed	Closed	Closed	Open	Open	Open	Closed	Closed
Window	Closed	Closed	Closed	Open	Open	Open	Open	Open
Portable fan	On	On	On	Off	Off	Off	Off	Off
Atrificial light	Off	Off	Off	Off	Off	On	On	On

Fig. 16. Day 5 Table that showcase changes in room for 14th-15th of August

After reviewing the data and collections we decided to conduct an additional **CO_2 test** using a candle with the window closed to further investigate the sensors' responses. The test was carried out **from 23:36 on August 21st to 00:10 on August 22nd, lasting 30 minutes**. During the first 15 minutes, both sensors were positioned as they were on the initial measurement day to establish a baseline for comparison. Following this period, the **second 15 minutes I rotated Sensor 6 for 90 degrees clockwise** to examine how this change affected the measurements, especially in relation to its proximity to the candle. This adjustment aimed to determine how sensor orientation influences CO_2 detection. The results from this test will help us understand the impact of sensor positioning on data accuracy.

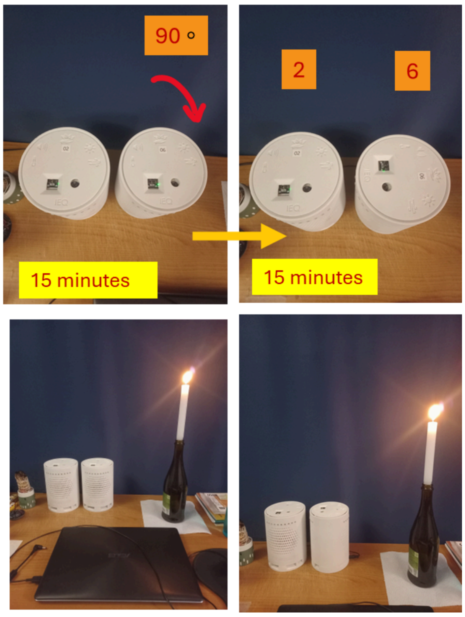


Fig. 17. Additional CO_2 test on 21st-22nd of August in room

Fig. 18. Condition after turning off the candle for the test on 21st-22nd of August in room

9.2 Data collection and preparation

I followed the same process for this experiment as I did for the others, collecting data for Sensors 2 and 6 from the Grafana dashboard. This approach ensured consistency in how data was retrieved and analyzed, allowing for accurate comparisons across different experiments.

Here is the visualization of the Grafana dashboard, which displays both the data graph and associated metrics for sensor 2 and 6 located in the room.

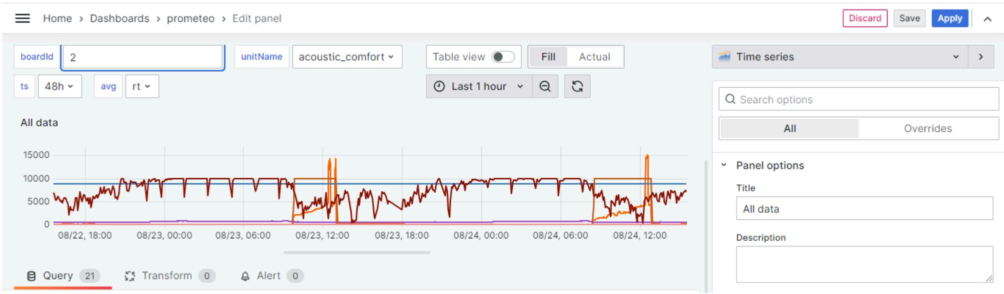


Fig. 19. Interface of grafana showing the data for sensor 2 (Adapted from grafana)

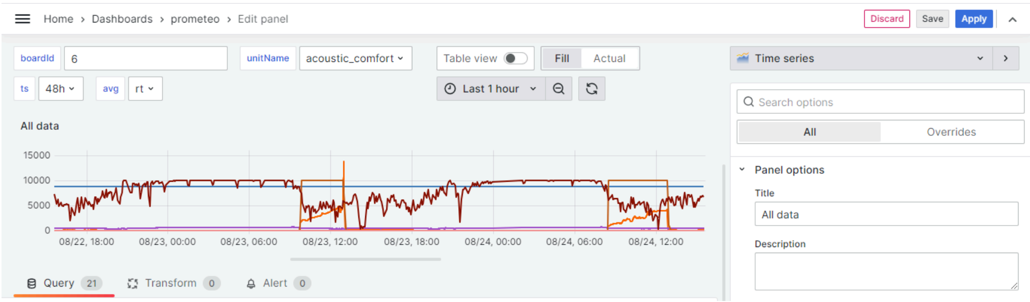


Fig. 20. Interface of grafana showing the data for sensor 6 (Adapted from grafana)

I created a daily table as part of the data collection process to document any changes made to the window, curtains, portable fan, and artificial light.

9-Aug-24 to 11-Aug-24	21:00-00:00	00:00-03:00	03:00-06:00	06:00-09:00	09:00-13:00	13:00-15:00	15:00-18:00	18:00-21:00	21:00-00:00
Curtain	Closed	Closed	Closed	Closed	Open	Closed	Closed	Closed	Closed
Window	Open	Closed	Closed	Closed	Open	Open	Open	Open	Open
Portable fan	On	On	On	On	Off	On	On	On	On
Atrificial light	On	Off	Off	Off	Off	Off	Off	On	On
11-Aug-24 to 12-Aug-24	00:00-02:00	02:00-06:00	06:00-09:00	09:00-11:00	11:00-13:00	13:00-15:00	15:00-18:00	18:00-21:00	21:00-00:00
Curtain	Closed	Closed	Closed	Closed	Open	Closed	Closed	Closed	Closed
Window	Open	Closed	Closed	Open	Open	Open	Open	Open	Open
Portable fan	On	On	On	On	On	On	On	On	On
Atrificial light	On	Off	Off	Off	Off	Off	Off	On	On

Fig. 21. Daily report Table that showcase changes in room from 9th-12th of August

12-Aug-24 to 13-Aug-24	00:00-03:00	03:00-06:00	06:00-09:30	09:30-13:00	13:00-15:00	15:00-18:00	18:00-21:00	21:00-00:00
Curtain	Closed	Closed	Closed	Open	Closed	Closed	Closed	Closed
Window	Closed	Closed	Closed	Open	Open	Open	Open	Open
Portable fan	On	On	On	Off	Off	Off	On	On
Atrificial light	Off	Off	Off	Off	Off	Off	On	On
13-Aug-24 to 14-Aug-24	00:00-03:00	03:00-06:00	06:00-10:00	10:00-11:00	11:00-15:00	15:00-18:00	18:00-21:00	21:00-00:00
Curtain	Closed	Closed	Closed	Open	Closed	Closed	Closed	Closed
Window	Closed	Closed	Closed	Open	Open	Open	Open	Open
Portable fan	On	On	On	Off	Off	On	On	On
Atrificial light	Off	Off	Off	Off	Off	Off	On	On
14-Aug-24 to 15-Aug-24	00:00-03:00	03:00-06:00	06:00-09:00	09:00-12:00	12:00-15:00	15:00-18:00	18:00-21:00	21:00-00:00
Curtain	Closed	Closed	Closed	Open	Open	Open	Closed	Closed
Window	Closed	Closed	Closed	Open	Open	Open	Open	Open
Portable fan	On	On	On	Off	Off	Off	Off	Off
Atrificial light	Off	Off	Off	Off	Off	On	On	On

Fig. 22. Daily report Table that showcase changes in room from 12th-15th of August

9.3 Data Analysis

In this section, I will provide a short breakdown of the data analysis conducted using Python for the graphs presented in Appendix 1, 11.4, related to in-room experiment. The analysis process involved several crucial steps: initially, data was extracted from the grafana dashboard, corresponding to sensors 2 and 6. Specific time ranges were defined to segment the data, ensuring a focused examination of relevant periods (we considered all day including office timing from 9-18 and also night measurements considering the possibility of having control on the window, lighting, curtain and portable fan). Histogram graphs and box plots were employed to visualize the data, displaying average parameter levels across different time periods.

The selection of sensors for the measurements was guided by the data analyzed from the Living Lab, A.S.L, and the company. Consequently, we chose sensors 2 and 6 for an in-room experiment. To improve visualization in the graphs, I used different color tones for each day of measurement. Furthermore, I adjusted the script to ensure the new dates, times, and sensors csv file, making the data easier to read and compare.

Note: This experiment was conducted without the use of reference devices.

The time range for the in-room experiment was set from 9:30 PM on the first day until midnight. For the subsequent days, measurements were taken from midnight to midnight, ensuring a full 24-hour period for each day.

The rest of the script is almost the same as for the other experiments, with few modifications made to the X and Y axis depending on the measured data for each specific day.

Here is a sample graph of ROOM histograms and tick time plot; additional graphs are available in Appendix 1, 11.4.

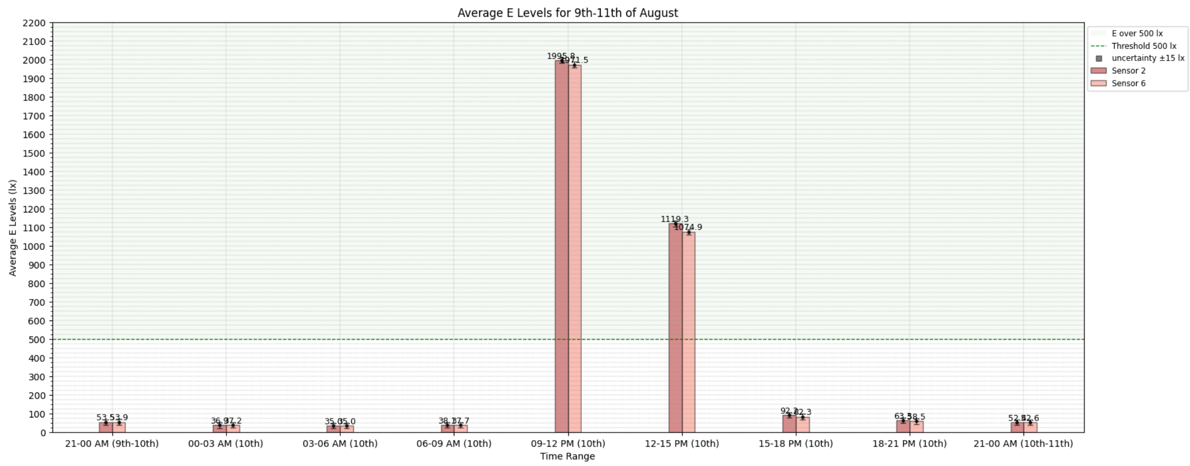


Fig. 23. Figure of the illuminance graph for day 1 room measurement

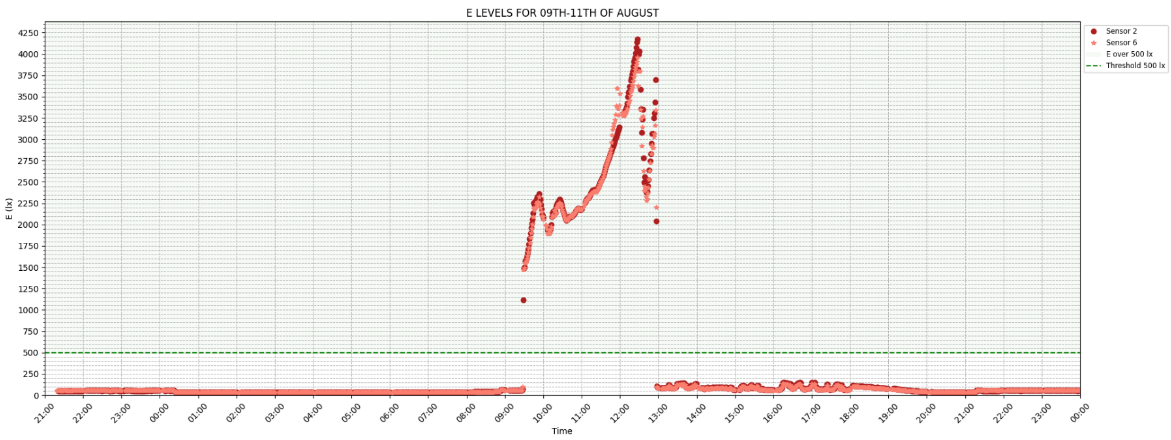


Fig. 24. Figure of the illuminance tick time graph for day 1 room measurement

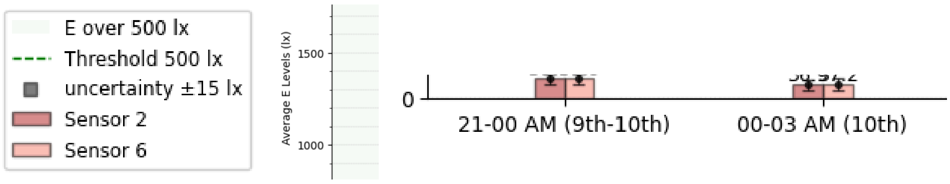


Fig. 25. Figure of the representation of legend, X axis and Y axis

Summary of Environment:

- Window is double glazed and blocks outside noise when it's closed.
- Curtain is navy blue and blocks light from outside when it's closed.
- Artificial lights are on during nighttime and are turned off during morning and afternoon.
- When the curtain is open and in the presence of natural light, both sensors record a value in the threshold range.
- When the curtain is closed and in the presence of artificial light, sensors indicate there is not sufficient light in the room.
- When the window is open, SPL is higher: road traffic and people chatting are the main noise sources.
- During the night time the window was closed and the PM level was lower.
- During the night time the window was closed and CO_2 level was higher.
- When the window is closed at nighttime, formaldehyde is higher in the room.

Summary of Multi-Sensors:

- Temperature recorded by multi-sensors are very close.
- Multi-sensor 2 recorded a lower value than multi-sensor 6 for relative humidity.
- Multi-sensors recorded very close values for illuminance. When the window was open, sensor 6 recorded a higher value.
- SPL value has a peak every hour, probably caused by the fan running in the multi-sensor.
- Both multi-sensors recorded close values for $PM_{2.5}$ and PM_{10}.
- Multi-sensors recorded different values for CO_2; sensor 2 recorded higher than sensor 6.
- Both multi-sensors recorded very high values for CO, indicating they are not functioning well.
- Multi-sensors recorded close or different values at different times for formaldehyde.
- Both multi-sensors recorded low values for TVOC at different times.
- Both multi-sensors recorded zero values for NO_2 at different times.

- **References Chapter 9**

1. Grafana Cloud. (n.d.). Retrieved from https://grafana.com/products/cloud/
2. Promet*o Platform. (2024)
3. JetBrains. (2024). *PyCharm* (Version 2024.2) [Computer software]. https://www.jetbrains.com/pycharm/
4. Astolfi, A., & Fissore, V. I. (2024). Multi-sensor device for traceable monitoring of indoor environmental quality. *Sensors, 24*(9), 2893. https://doi.org/10.3390/s24092893
5. Microsoft Corporation. (2021). *Microsoft Excel* (Version 16.0) [Software]. Includes AVERAGE formula for statistical analysis. https://www.microsoft.com/en-us/microsoft-365/excel
6. Python help assistant, OpenAI. (2024). *ChatGPT* (Aug 25 version) [Large language model]. https://www.openai.com/chatgpt

CONCLUSION

10. Discussion & Conclusion

In this chapter, the thesis approach is concluded by summarizing the key findings and their implications for future work. Firstly, the designed wireframe for the mobile application, which has been developed to provide a user-friendly interface and intuitive navigation, will be handed over to the computer engineering science team that will code the application, ensuring it is robust and adaptable for future developments. This initial prototype will serve as the foundation for future iterations, allowing for continuous refinement and enhancement.

Secondly, the findings from various experiments have provided significant insights into the behavior of PROMET&O multi-sensors in different measurement settings. These experiments have been crucial in understanding how individual sensors perform under varying environmental conditions and how multiple sensors can be integrated to provide comprehensive monitoring solutions. For example, it was observed that the CO sensor in multi-sensor 10 consistently recorded significantly higher levels compared to other sensors, indicating a potential issue with calibration or coding that needs further investigation. Additionally, multi-sensor 3 exhibited higher CO_2 levels across different experiments, suggesting that this sensor may be more sensitive or a potential issue with calibration or coding occured. These observations guide the next phase of debugging and development, allowing for targeted improvements to both single sensors and assembled multi-sensor configurations.

Moreover, it was noted that the sound pressure level sensor consistently showed peaks every hour, which could be an indication of a sound generated by the multisensor itself. This finding suggests that there may be mechanical or electronic noise within the sensor assembly, which could affect the accuracy of sound measurements. Identifying and addressing these issues is crucial for ensuring the reliability of the sensor data.

Overall, these findings underscore the importance of thorough testing and experimentation in the development of sensor technology. By identifying specific behaviors and anomalies, we can better tailor our solutions to meet the unique challenges presented by different settings. The next steps will involve refining the sensor calibration processes and enhancing the overall system integration to ensure accurate and reliable data collection.

1. Living Lab experiment summary: the data collected from the multi-sensors in the Living Lab study provides an in-depth analysis of environmental conditions using multi-sensors, revealing notable deviations in temperature, humidity, and air quality measurements compared to reference devices. It is notable that the window is fixed and without a curtain.

Actions can be taken for multi-sensors improvement from Living Lab results:

- The temperature sensor in the multi-sensors needs to be checked. Sensors 1, 6, and 10 to avoid overestimation, and sensors 2 and 4 to avoid underestimation.
- The relative humidity sensor in all multi-sensors should be checked, as they record lower values than the reference device.
- Sensors 1 and 10 consistently overestimate illuminance and should be checked.
- Recalibrate sensor 3 to lower the CO_2 readings, and sensors 6, 7, and 10 to increase their readings for accurate results.
- Sensors 2 and 10 overestimated SPL compared to reference devices and should be checked.

- Sensor 10 overestimated $PM_{2.5}$, while sensor 8 underestimated $PM_{2.5}$.
- All sensors generally recorded values close to the Aircare reference for PM_{10}.
- The CO sensor in all multi-sensors should be checked, as they are not functioning correctly.
- Sensors 1, 3, 6, and 10 consistently underestimate formaldehyde and need to be checked.

Conclusion for Living Lab experiment: the Living Lab's environmental monitoring using multi-sensors revealed consistent deviations in temperature, CO_2, and particulate matter readings compared to reference devices. Additionally, the discrepancies in SPL and illuminance values across different sensors highlight the dynamic nature of the living lab environment, emphasizing the need for cross-referencing of sensor data to maintain data accuracy and reliability. Results can be found in appendix 11.1.

2. Audio Space Lab experiment Summary: The data collected from the multi-sensors in the Audio Space Lab reveals several key observations about the environmental conditions.

Actions can be taken for multi-sensors improvement from Audio Space Lab results:

- The temperature sensor in multi-sensor 6 should be calibrated as it records lower values than the others.
- The relative humidity sensor in all multi-sensors should be calibrated, as they record lower values than the reference device.
- The illuminance sensor in all multi-sensors should be calibrated, with sensor 11 overestimating compared to the reference device.
- The SPL sensor in all multi-sensors should be calibrated, as they record higher values than the reference device, with multi-sensors 2, 10, and 11 overestimating SPL levels.
- The CO_2 sensor in multi-sensor 3 should be calibrated for overestimating CO_2 levels, while multi-sensors 6, 7, and 10 need calibration for underestimating values.
- The CO sensor in all multi-sensors requires debugging, particularly sensor 10, which is overestimating readings.

Conclusion for Audio Space Lab experiment: the environmental monitoring data from the Audio Space Lab highlights several discrepancies between the multi-sensors and reference devices, particularly concerning temperature, illuminance, CO levels. These inconsistencies may be due to sensor placement, calibration issues, or external environmental factors affecting the readings. Additionally, the high CO levels detected by the multi-sensors, despite the reference reading zero, suggest that there might be sensor malfunctions that need to be addressed. Overall, the findings call for a review of sensor calibration and placement strategies to ensure reliable monitoring of environmental conditions. Results can be found in appendix 11.2.

3. Company experiment Summary: based on the data collected over five days from experiments conducted in the offices for company experiments, several key trends and observations emerged regarding the performance of the multi-sensors across different environmental parameters.

Conclusion for company experiment: there are notable differences between the two environments in terms of room orientation, number of occupants that can cause different temperature, humidity, and air quality, with the n.2 office generally recording higher humidity, particulate matter, and sound levels. The variability in sensor readings suggests the need for further investigation into sensor calibration, and debugging to ensure accurate monitoring. Future developments should focus on addressing these inconsistencies and optimizing sensor configurations for more reliable and precise environmental monitoring. Results can be found in appendix 11.3.

4. In-Room experiment Summary: the room experiment aimed to evaluate the environmental conditions using two multi-sensors over several days, with a focus on temperature, humidity, air quality, and the impact of variables such as natural light, artificial light, and a candle test. The findings reveal consistent trends in sensor readings and significant changes under specific conditions, highlighting the dynamics of indoor air quality and environmental parameters.

Conclusion for In-Room experiment: the room experiment demonstrates the variability and sensitivity of indoor environmental conditions to different factors such as window position, light exposure, and activities like burning a candle. The discrepancies between sensor readings, particularly for CO_2, PM, and CO, underline the importance of using multiple sensors for a comprehensive assessment of air quality. The results emphasize the need for proper ventilation and monitoring to maintain healthy indoor air conditions, especially in scenarios where environmental thresholds are exceeded. Results can be found in appendix 11.4.

Conclusion for Candle test in particular: During the candle test, several parameters showed significant changes in both multi-sensors, primarily in particulate matter levels, CO_2, and formaldehyde:

Summary of the environment condition for in-room **candle test**:

- Candle test was at night timing from 23:36 to 00:30.
- Window was closed during the test. (Double glazed window)
- Curtain was completely closed.
- Portable fan was turned off.
- Both multi-sensors were close to the candle but sensor 6 was closer
- After 15 minutes of turning on the candle, I turned the sensor 6 for 90 degrees clockwise.
- I was present in the room during the candle test.

Summary of the data analysis for in-room **candle test**:

- Both multi-sensors recorded an increase in $PM_{2.5}$ and PM_{10} values.
- CO_2 levels for both multi-sensors increased gradually.
- Both multi-sensors recorded an unchanged value for CO during the candle test while they did not function well.
- Formaldehyde level increased slightly in multi-sensor 2 during the test and after turning off the candle.
- Both multi-sensors recorded unchanged values for TVOC during the test and after turning off the candle.

Overall, the candle test demonstrated a notable increase in particulate matter, highlighting the impact of burning a candle on indoor air quality. CO_2 levels also rise, although carbon monoxide and TVOC levels did not show any significant changes during this test. Results can be found in appendix 11.4.

Project executive summary and final actions for multi-sensors and environments improvements:

Investigating and optimizing sensor calibration and configurations will enhance the accuracy of environmental monitoring and ensure better management of air quality and comfort conditions. Using multiple sensors ensures a comprehensive assessment of IEQ, and adjustments to ventilation and monitoring systems will help maintain healthy indoor air conditions.

Actions can be taken for multi-sensors improvement from all the experiments results:

- **Temperature:** calibrate temperature sensors to address both overestimation (sensors 1, 6, 10) and underestimation (sensors 2, 4, and 6).
- **Relative Humidity:** calibrate relative humidity sensors in all multi-sensors to ensure they reflect accurate values, as they consistently record lower readings than reference devices.
- **Illuminance:** calibrate sensors 1, 10, and 4 to correct overestimation issues, and recalibrate sensor 11 for accuracy.
- **Sound Pressure Level**: calibrate multi-sensors 2, 10, and 11 to bring readings in line with the reference levels.
- **$PM_{2.5}$:** calibrate sensor 10 for overestimation and sensor 8 for underestimation of $PM_{2.5}$ levels.
- **CO_2:** calibrate multi-sensor 3 to reduce overestimation, and sensors 6, 7, and 10 to correct underestimation of CO_2 levels.
- **CO:** calibrate all CO sensors, as they are frequently malfunctioning. Pay special attention to sensor 10 for overestimation issues.
- **Formaldehyde:** calibrate sensors 1, 3, 6, and 10 to correct underestimation, and ensure sensor 4 is properly calibrated to avoid overestimation.
- **TVOC:** check all TVOC sensors against a reference device, as they consistently record low values.

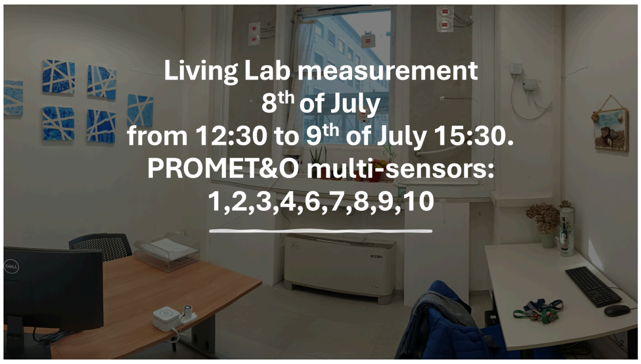
11. Appendix 1

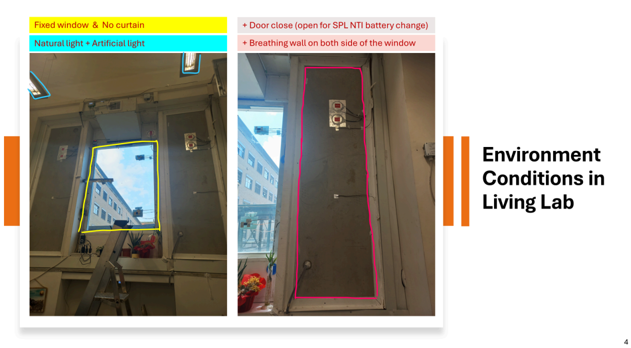
In this appendix, I provide a comprehensive overview of the data analysis conducted throughout the experiments, encompassing detailed spatial and temporal considerations. This chapter includes the mapping of all experiment locations, specifying office and room settings, as well as the strategic placement of multi-sensors and reference devices. For each day of the experiments, we meticulously document the reference devices used, accompanied by their specific characteristics. The analysis is further segmented into daily time intervals, with a focused examination of office settings during the 9-12, 12-15, and 15-18 hours. Additionally, a distinct analysis is provided for night measurements conducted in the room setting. Special attention is given to specific tests, including the controlled increase of CO_2 levels by lighting a candle, to better understand the environmental dynamics under these conditions. This detailed analysis serves to ensure the robustness and replicability of our findings.

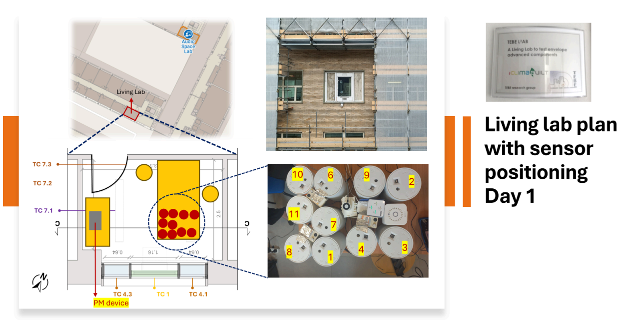
11.1 Politecnico di Torino Living Lab measurements graphs

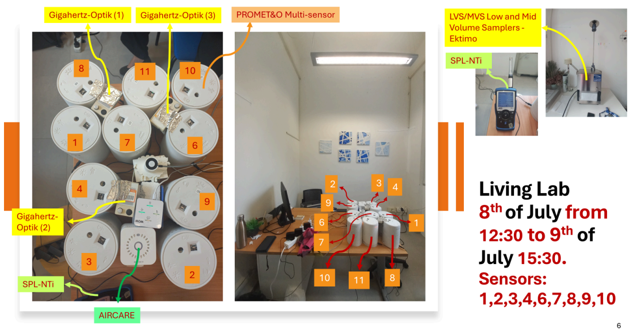
Here is the full representation of the graphs for the Living Lab.

Day 1 Living Lab measurement:









LVS/MVS Low and Mid Volume Samplers – Ektimo
Particulate matter measurement device

Gigahertz-Optik
Illuminance Measuring

SPL-Nti Audio XL2 M2230
Sound Pressure level Measuring

PROMET&O Multi-sensor
IEQ Measuring
LOW-COST device
Developed by Politecnico di Torino
DUT (Device under test)

AIRCARE
IAQ Measuring device

Reference Devices and DUT

7

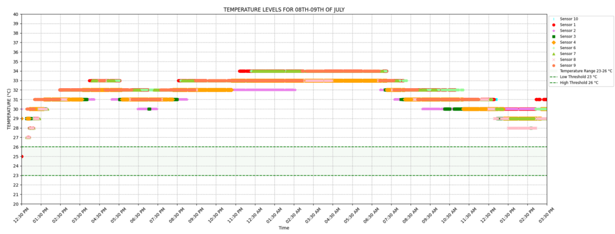
Time step of acquisition for sensors + reference devices

- T: 30 s
- RH: 30 s
- SPL: 5 s
- TVOC: 60 s
- CO_2: 60 s
- $PM_{2.5}$: 60 s
- PM_{10}: 60 s
- NO_2: 60 s
- CO: 60 s
- CH_2O: 60 s

- Gigahertz-Optik: 5 min
- Testo 400: 30 min
- AIRCARE: 5 min
- SPL NTi: 1 s
- LVS/MVS (PM): 2 min

8

Temperature



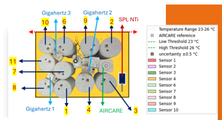
8th of July from 12:30 to 9th of July 15:30.

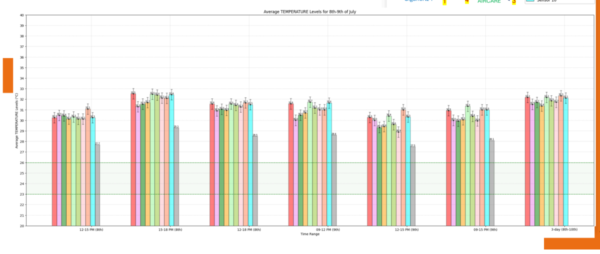
9

Temperature (T)

Threshold: (ISO 7730:2005)
Winter: (20–24) ∘C , Summer: (23–26) ∘C
Required uncertainty: ± 0.5 ∘C

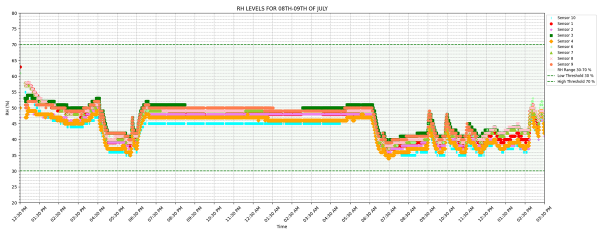
- Aircare is the reference device
- All sensors recorded higher then reference device
- Sensors 1,6 and 10 overestimate the value in compare to reference device and other sensors





10

Relative humidity



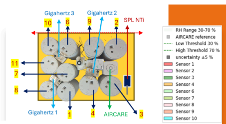
8th of July from 12:30 to 9th of July 15:30.

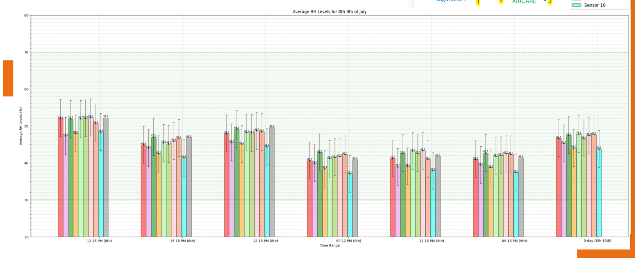
11

Relative humidity (RH)

Threshold: (ISO 7730:2005)
(30–70)%
Required uncertainty: ± 5 %

- Aircare is the reference device
- Sensors 2,4 and 6 underestimate the value in compare to reference device and other sensors

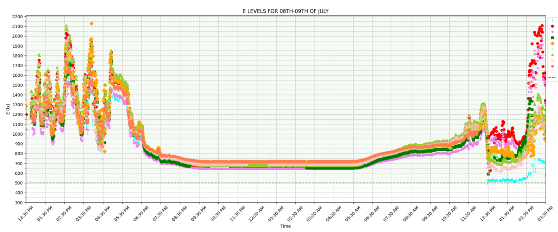




12

Illuminance

- Window is fixed and without shading.



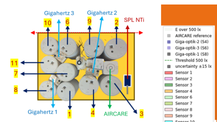
8th of July from 12:30 to 9th of July 15:30.

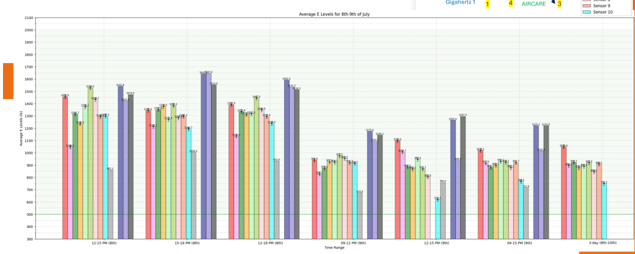
13

Illuminance (E_h)

Threshold: (EN 12464-1:2021) ≥500 lx
Required uncertainty: 15 lx

- Artificial light was turn on and there is a fixed window without shading in the room
- Air care and Gigahertz-optik are the reference devices and record different value
- Sensor 1 record higher value in compare to other sensors for different timings

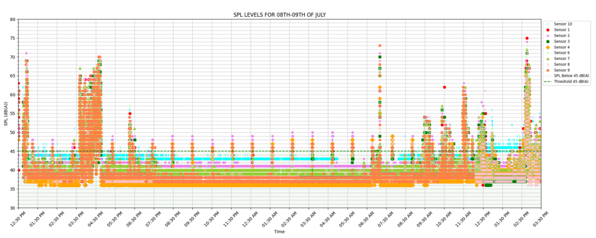




14

Sound Pressure Level

- Sensors record a peak every hour that can be for the fan inside the multi-sensors



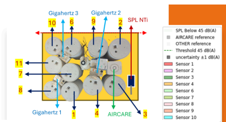
8th of July from 12:30 to 9th of July 15:30.

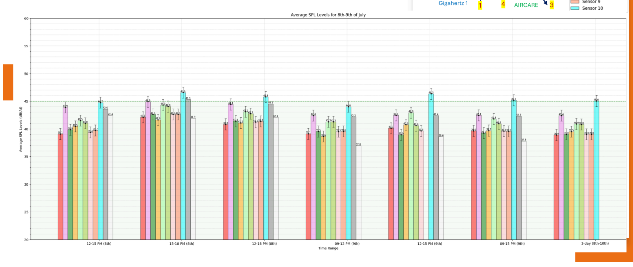
15

Sound Pressure Level (SPL)

Threshold: (NF S 31-080)
≤45 dB(A)
Required uncertainty: ± 1 dB

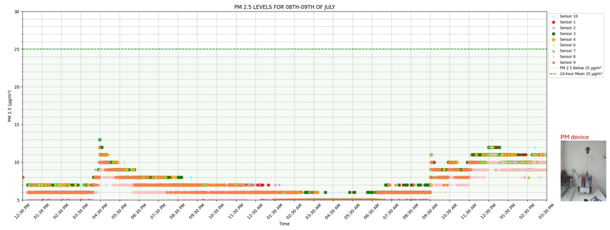
- Aiacare record higher value than SPL Nti device
- Sensor 2 and 10 are overestimate in compare to other sensors and references





16

Particulate Matter 2.5



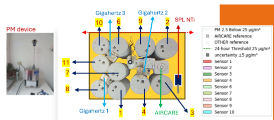
8th of July from 12:30 to 9th of July 15:30.

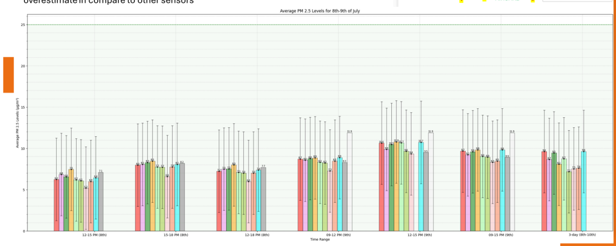
17

Particulate Matter ($PM_{2.5}$)

Threshold: (EN 16798-1:2019 (WHO guidelines))
24 h mean ≤ 25 μg/m³
Required uncertainty: ± 5 μg/m³

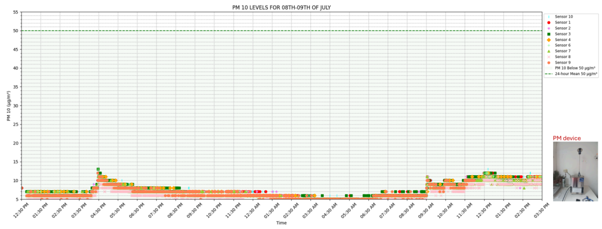
- Airecare and PM device record completely different value
- Sensors record value close to Aircare
- Sensor 8 underestimate in compare to other sensors and sensor 10 overestimate in compare to other sensors





18

Particulate Matter 10



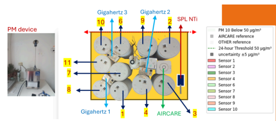
8th of July from 12:30 to 9th of July 15:30.

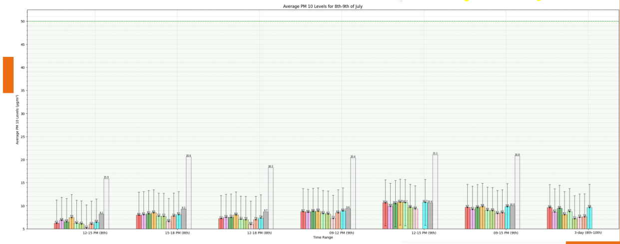
19

Particulate Matter (PM_{10})

Threshold: (EN 16798-1:2019 (WHO guidelines))
24 h mean ≤ 50 μg/m³
Required uncertainty: ± 5 μg/m³

- Aircare and PM device record completely different value
- Sensors record value close to Aircare
- Sensor 8 underestimate value in compare to other sensors and Aircare

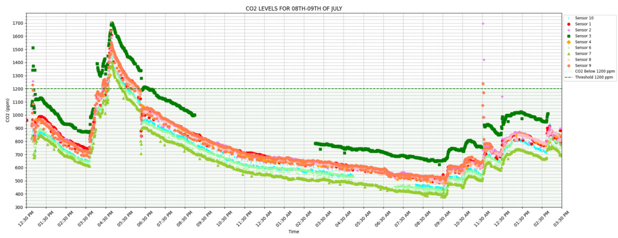




20

Carbon Dioxide

- No one was present in the lab during the measuring, every 3 hour one person enter the room
- Window is fixed and closed



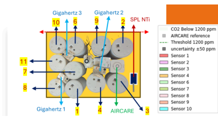
8th of July from 12:30 to 9th of July 15:30.

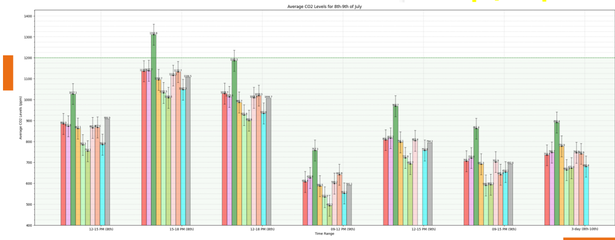
21

Carbon Dioxide (ΔCO_2)

Threshold: (EN 16798-1:2019) ≤1200 ppm
Required uncertainty: ± 50 ppm

- Aircare is the reference device
- Sensor 3 overestimate the value and sensors 6 ,7 and 10 underestimate in compare to reference device

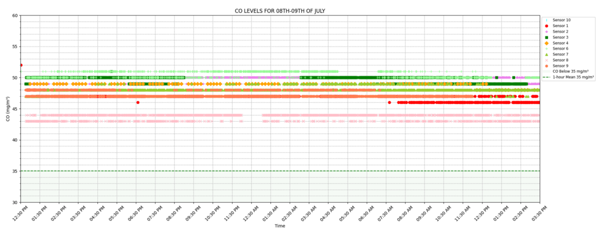




22

Carbon Monoxide

- No explanation for overestimated data



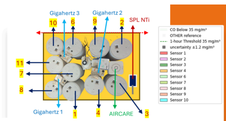
8th of July from 12:30 to 9th of July 15:30.

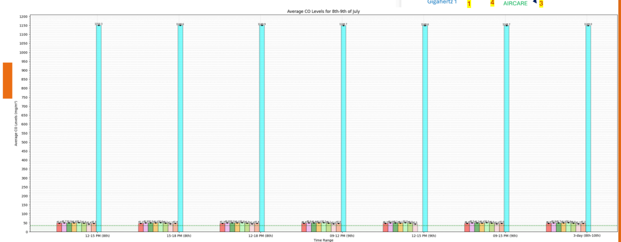
23

Carbon Monoxide (CO)

Threshold: (EN 16798-1:2019 (WHO guidelines))
1 h mean ≤ 35 mg/m³
Required uncertainty: ± 1.2 mg/m³

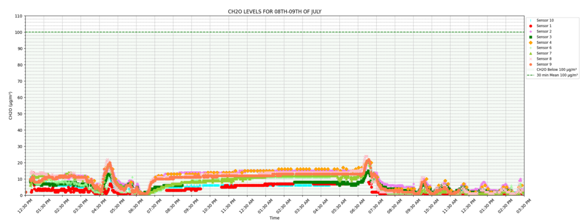
- Testo 400 is the reference device and record zero for CO level
- Sensors didn't meet the reference value and sensor 10 overestimate





24

Formaldehyde



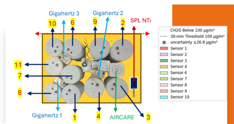
8th of July from 12:30 to 9th of July 15:30.

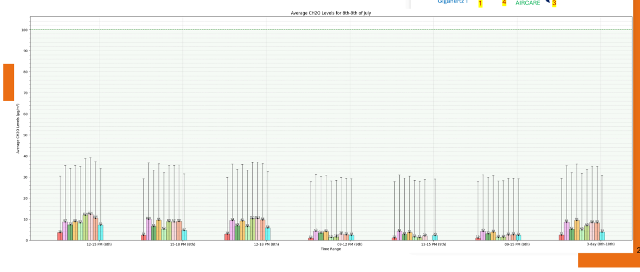
25

Formaldehyde (CH_2O)

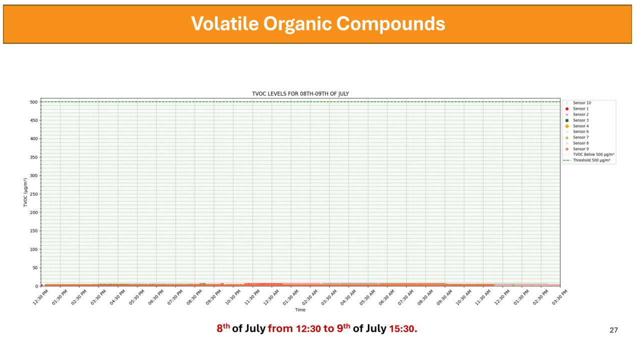
Threshold: (EN 16798-1:2019 (WHO guidelines))
30 min. mean ≤ 100 μg/m³
Required uncertainty: ± 26.8 μg/m³

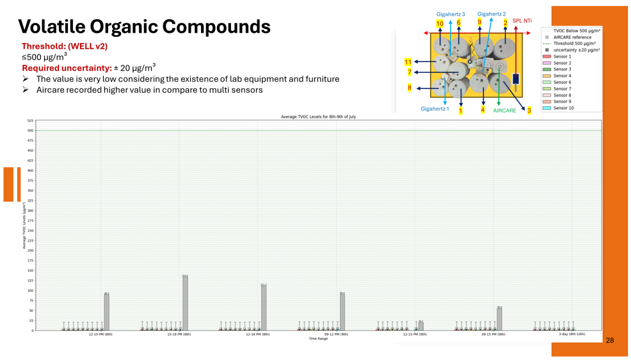
- Formaldehyde sensors record different value
- Sensors 1,3,6 and 10 recorded noticeable underestimate value in compare to others

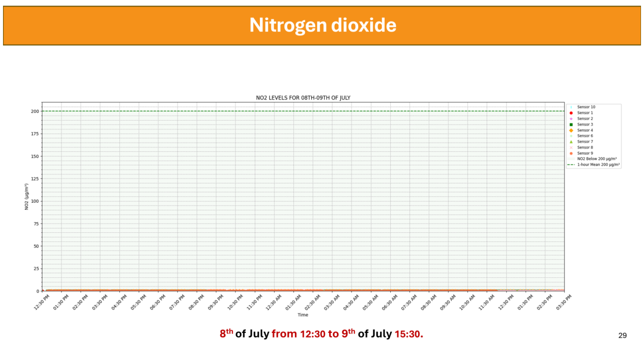


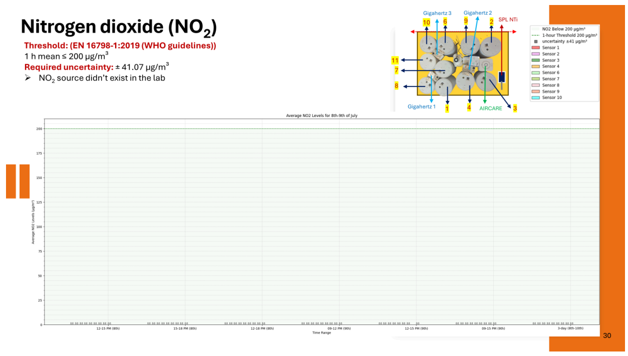


26

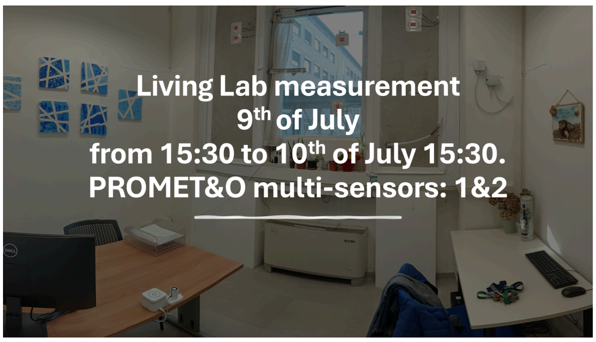


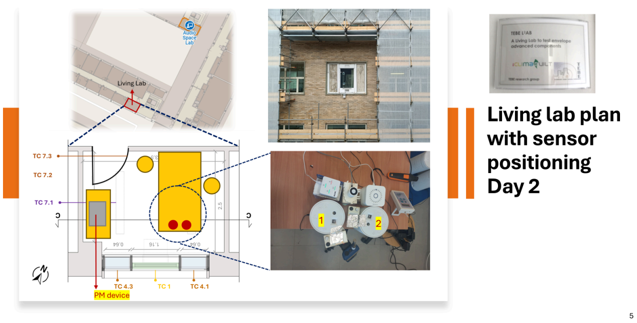


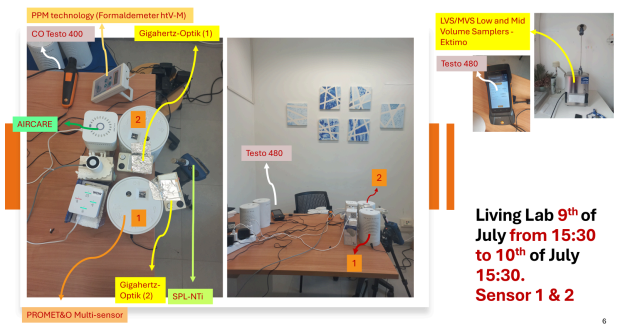




Day 2 Living Lab measurement:







PPM technology (Formaldemeter htV-M)
CH2O/RH/T measurement device

SPL-Nti Audio XL2 M2230
Sound Pressure level Measuring

Testo 400 KIT
CO Measuring

AIRCARE
IAQ Measuring device

LVS/MVS Low and Mid Volume Samplers – Ektimo
Particulate matter measurement device

Testo 480 KIT
CO2 Measuring

PROMET&O Multi-sensor
IEQ Measuring LOW-COST device
Developed by Politecnico di Torino
DUT (Device under test)

Reference Devices and DUT

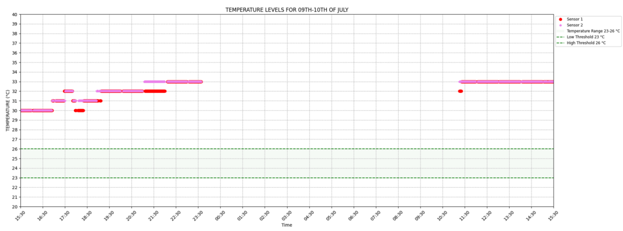
7

Time step of acquisition for sensors + reference devices

- T: 30 s
- RH: 30 s
- SPL: 5 s
- TVOC: 60 s
- CO_2: 60 s
- $PM_{2.5}$: 60 s
- PM_{10}: 60 s
- NO_2: 60 s
- CO: 60 s
- CH_2O: 60 s
- Gigahertz-Optik: 5 min
- Testo 400: 30 min
- Testo 480: 30 min
- AIRCARE: 5 min
- SPL NTI: 1 s
- LVS/MVS (PM): 2 min
- Formaldemeter: 30 min

8

Temperature



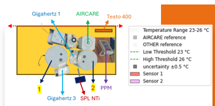
9th of July from 15:30 to 10th of July 15:30.

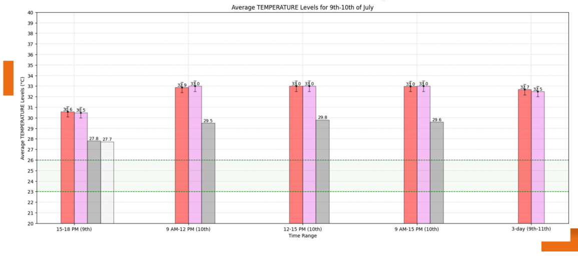
9

Temperature (T)

Threshold: (ISO 7730:2005)
Winter: (20–24) ∘C , Summer: (23–26) ∘C
Required uncertainty: ± 0.5 ∘C

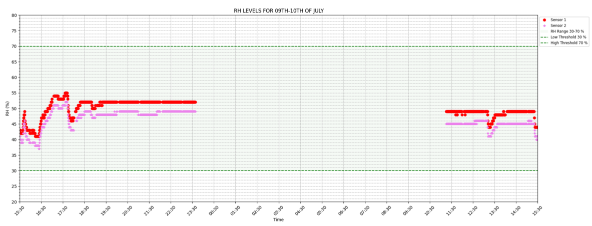
- Both sensors are higher then reference devices
- Reference devices measured very close value





10

Relative humidity



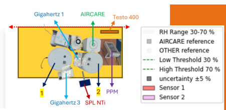
9th of July from 15:30 to 10th of July 15:30.

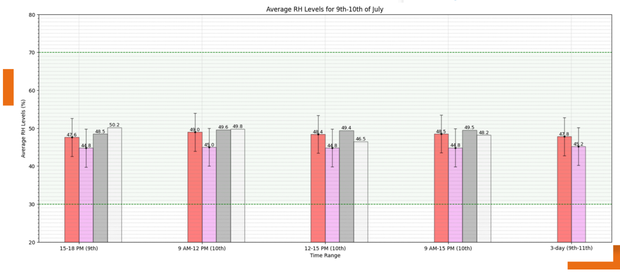
11

Relative humidity (RH)

Threshold: (ISO 7730:2005)
(30–70)%
Required uncertainty: ± 5 %

- Sensor 2 record lower value than reference devices
- Reference devices did not measured same value

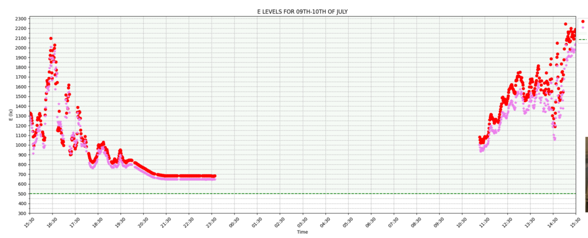




12

Illuminance

- Window is fixed and without shading.



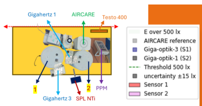
9th of July from 15:30 to 10th of July 15:30.

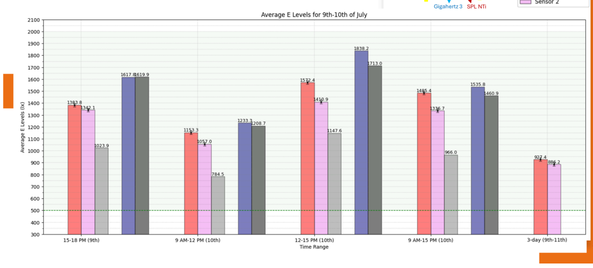
13

Illuminance (E_h)

Threshold: (EN 12464-1:2021) ≥500 lx
Required uncertainty: 15 lx

- Artificial light was turn on and door was closed
- Sensors value is lower than gigahertz but higher than Aircare
- Aircare record very low value in compare to gigahertz devices

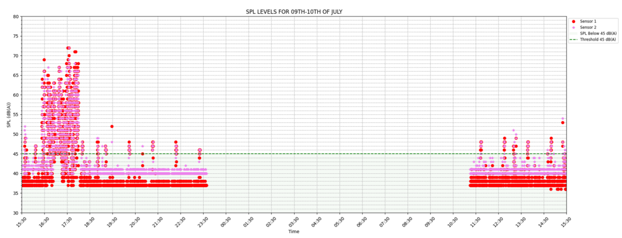




14

Sound Pressure Level

- Sensors record a peak every hour that can be for the fan inside the multi-sensors



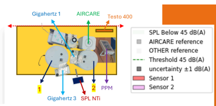
9th of July from 15:30 to 10th of July 15:30.

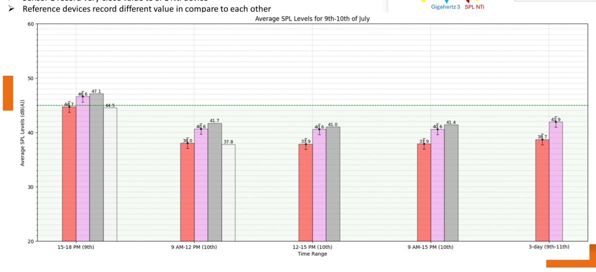
15

Sound Pressure Level (SPL)

Threshold: (NF S 31-080)
≤45 dB(A)
Required uncertainty: ± 1 dB

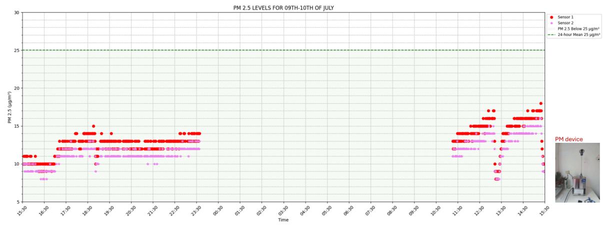
- Sensor 2 record very close value to Aircare device
- Sensor 1 record very close value to SPL Nti device
- Reference devices record different value in compare to each other





16

Particulate Matter 2.5

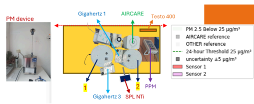


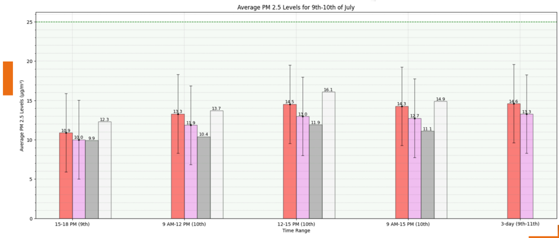
9th of July from 15:30 to 10th of July 15:30.

17

Particulate Matter ($PM_{2.5}$)

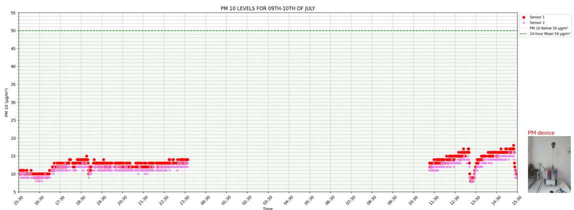
Threshold: (EN 16798-1:2019 (WHO guidelines))
24 h mean ≤ 25 µg/m³
Required uncertainty: ± 5 µg/m³
- Reference devices record different values, Aircare record lower than PM device





18

Particulate Matter 10

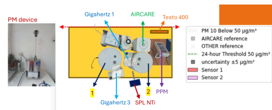


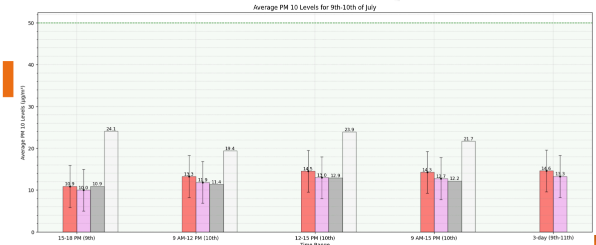
9th of July from 15:30 to 10th of July 15:30.

19

Particulate Matter (PM_{10})

Threshold: (EN 16798-1:2019 (WHO guidelines))
24 h mean ≤ 50 µg/m³
Required uncertainty: ± 5 µg/m³
- Refeence devices record different values, Aircare record lower than PM device
- Multi sensors value are close to Aircare device value

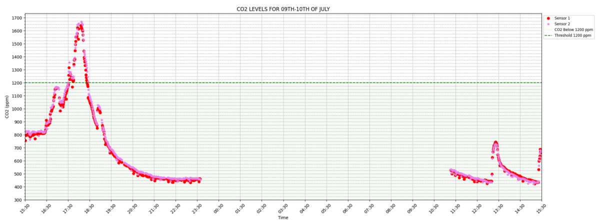




20

Carbon Dioxide

- No one was present in the lab during the measuring, every 3 hour one person enter the room
- Window is fixed and closed

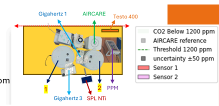


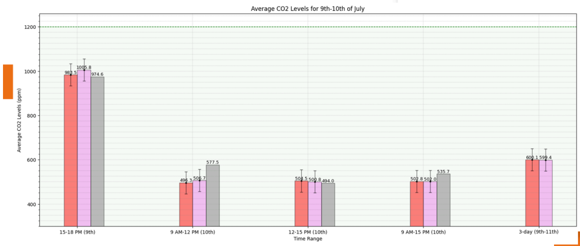
9th of July from 15:30 to 10th of July 15:30.

21

Carbon Dioxide (ΔCO_2)

Threshold: (EN 16798-1:2019) ≤1200 ppm
Required uncertainty: ± 50 ppm
- Aircare is the reference device
- No one was present in the lab during the measuring, every 3 hour one person enter the room
- Sensors measured close value but different from reference

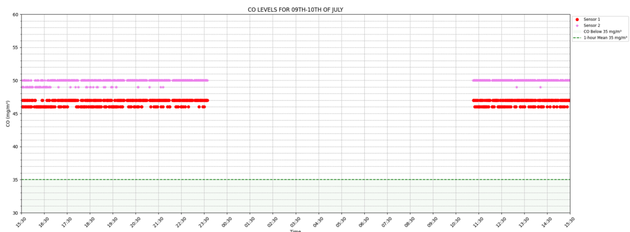




22

Carbon Monoxide

- No explanation for overestimated data

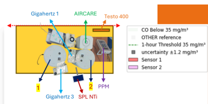


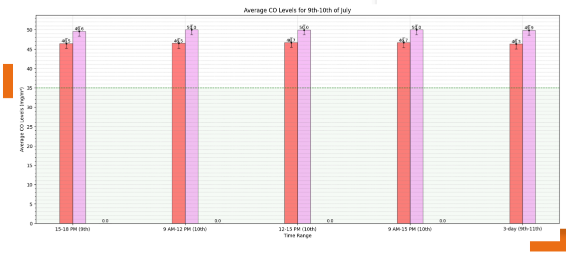
9th of July from 15:30 to 10th of July 15:30.

23

Carbon Monoxide (CO)

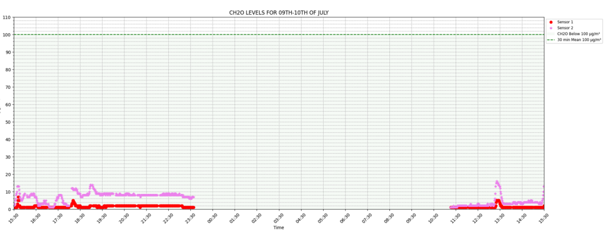
Threshold: (EN 16798-1:2019 (WHO guidelines))
1 h mean ≤ 35 mg/m³
Required uncertainty: ± 1.2 mg/m³
- Testo 400 is the reference device
- Sensors didn't meet the reference value and overestimate





24

Formaldehyde

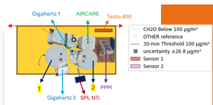


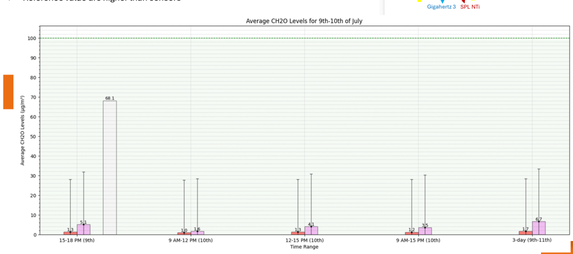
9th of July from 15:30 to 10th of July 15:30.

25

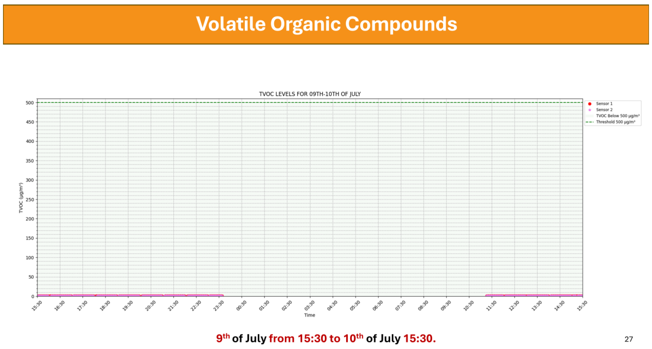
Formaldehyde (CH_2O)

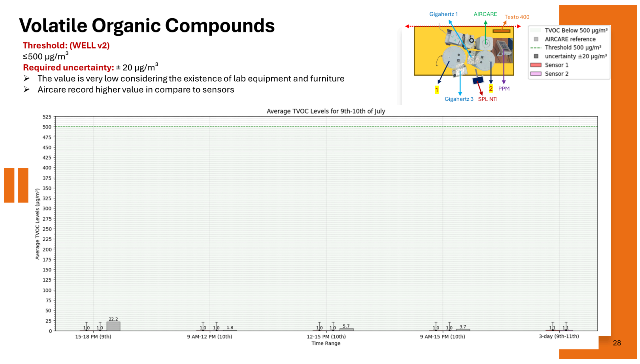
Threshold: (EN 16798-1:2019 (WHO guidelines))
30 min. mean ≤ 100 µg/m³
Required uncertainty: ± 26.8 µg/m³
- Formaldehyde sensors are not working correctly
- Reference value are higher than sensors

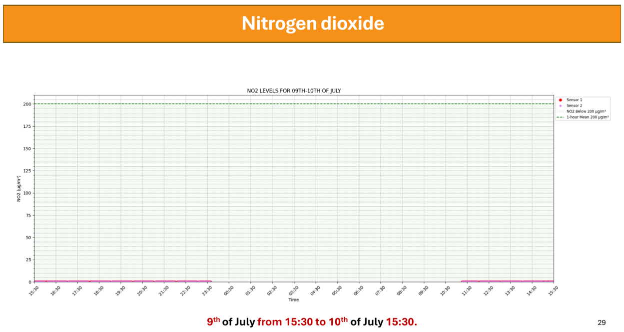


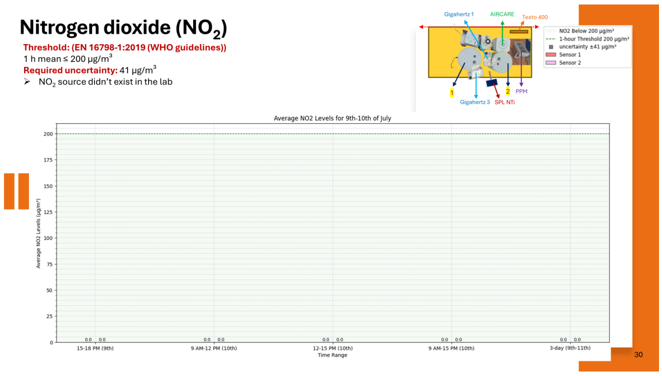


26

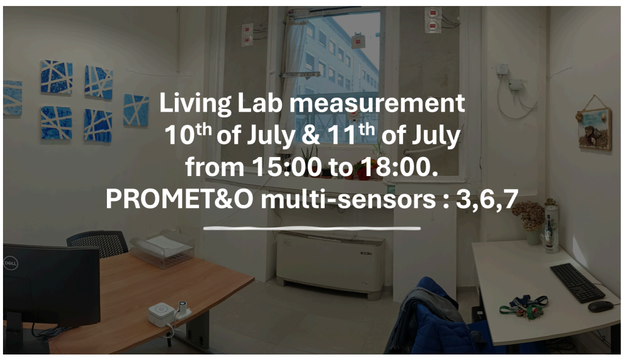


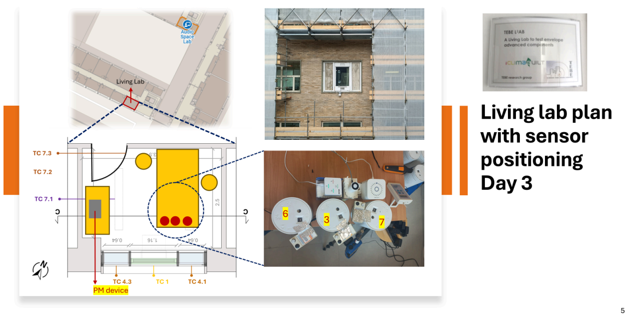


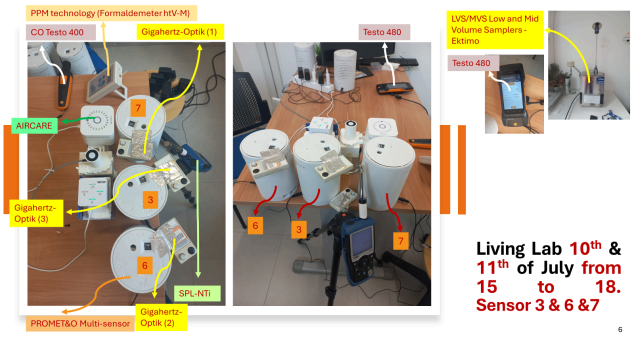




Day 3 Living Lab measurement:







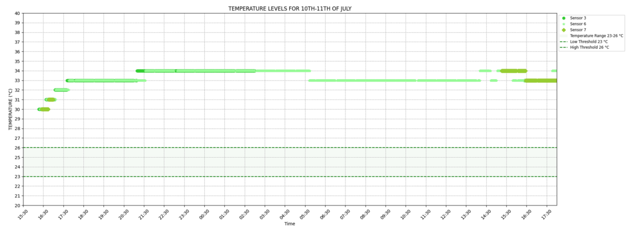
Reference Devices and DUT

Time step of acquisition for sensors + reference devices

- T: 30 s
- RH: 30 s
- SPL: 5 s
- TVOC: 60 s
- CO_2: 60 s
- $PM_{2.5}$: 60 s
- PM_{10}: 60 s
- NO_2: 60 s
- CO: 60 s
- CH_2O: 60 s

- Gigahertz-Optik: 5 min
- Testo 400: 30 min
- Testo 480: 30 min
- AIRCARE: 5 min
- SPL NTi: 1 s
- LVS/MVS (PM): 2 min
- Formaldemeter: 30 min

Temperature

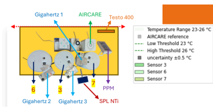


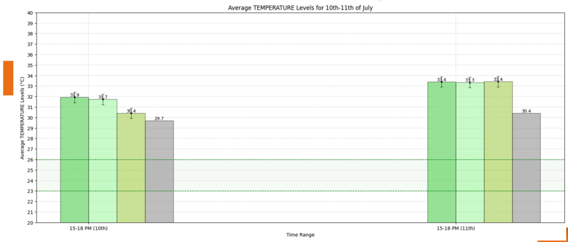
10th to 11th of July from 15 to 18.

Temperature (T)

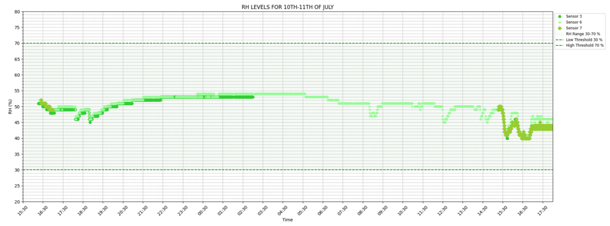
Threshold: (ISO 7730:2005)
Winter: (20–24) ∘C , Summer: (23–26) ∘C
Required uncertainty: ± 0.5 ∘C

- All sensors are higher then reference device





Relative humidity

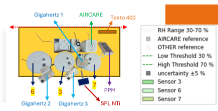


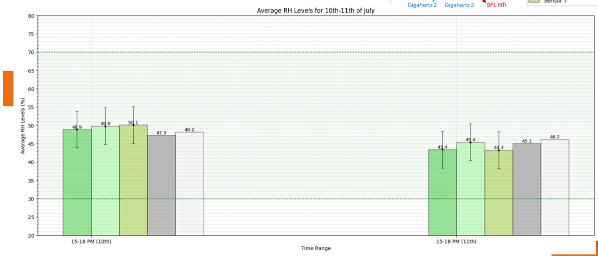
10th to 11th of July from 15 to 18.

Relative humidity (RH)

Threshold: (ISO 7730:2005)
(30–70)%
Required uncertainty: ± 5 %

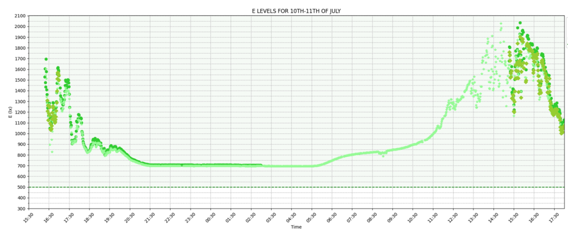
- Sensors value are close to reference values





Illuminance

- Window is fixed and without shading.

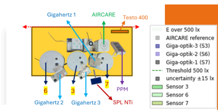


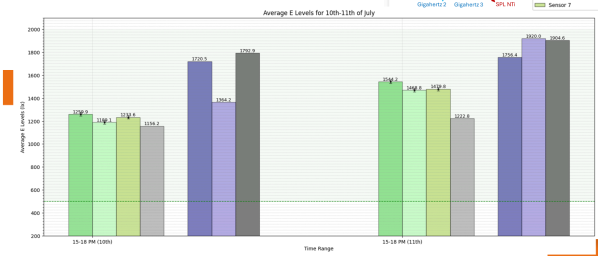
10th to 11th of July from 15 to 18.

Illuminance (E_h)

Threshold: (EN 12464-1:2021) ≥500 lx
Required uncertainty: 15 %

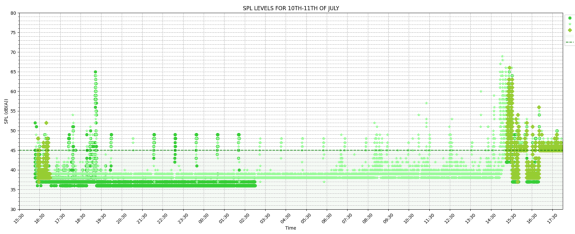
- Artificial light was turn on and door was closed
- Sensors didn't meet any reference devices
- AIRCARE record lower value than Gigahetrz devices





Sound Pressure Level

- Sensors record a peak every hour that can be for the fan inside the multi-sensors

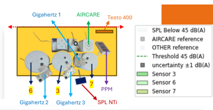


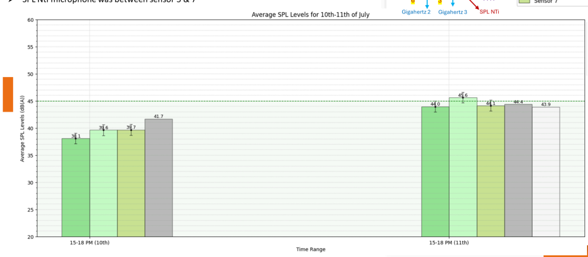
10th to 11th of July from 15 to 18.

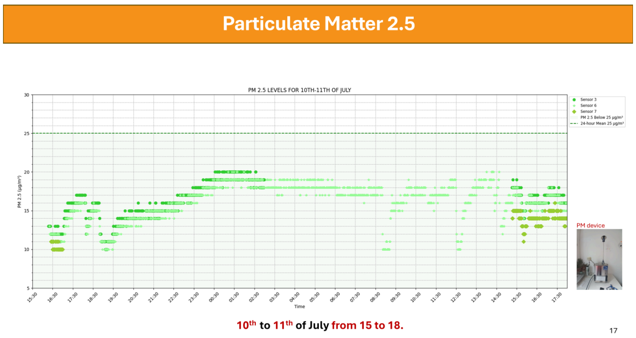
Sound Pressure Level (SPL)

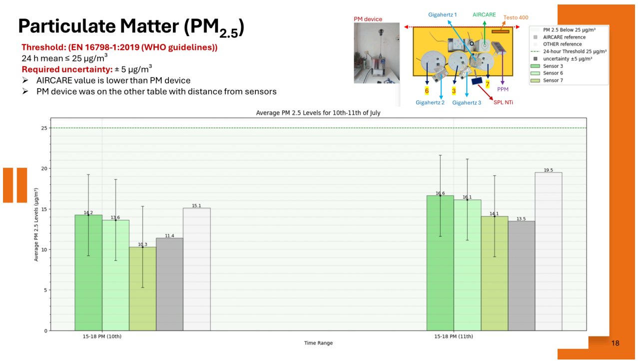
Threshold: (NF S 31-080)
≤45 dB(A)
Required uncertainty: ± 1 dB

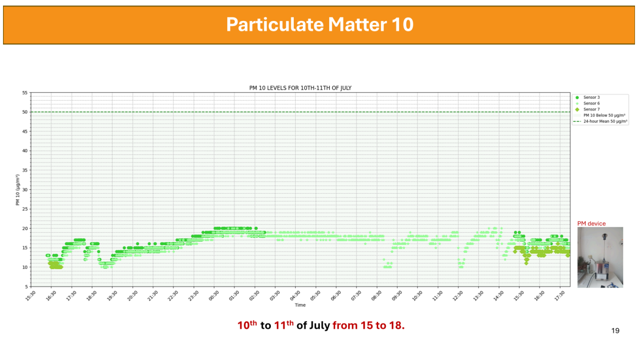
- All sensors value are close to reference devices
- SPL Nti microphone was between sensor 3 & 7

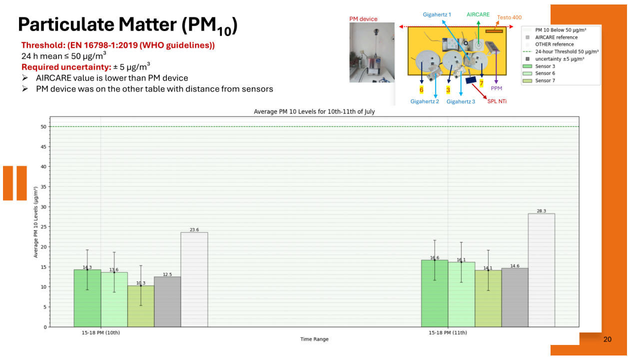


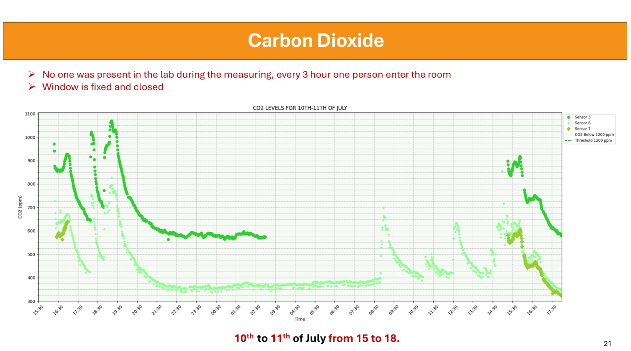


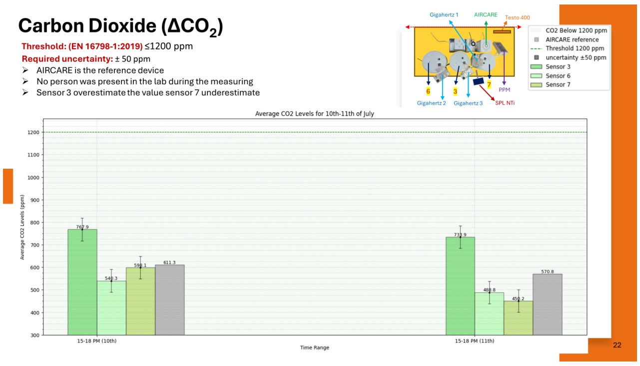

Particulate Matter 2.5
PM 2.5 LEVELS FOR 10TH-11TH OF JULY
PM device
10th to 11th of July from 15 to 18.
17

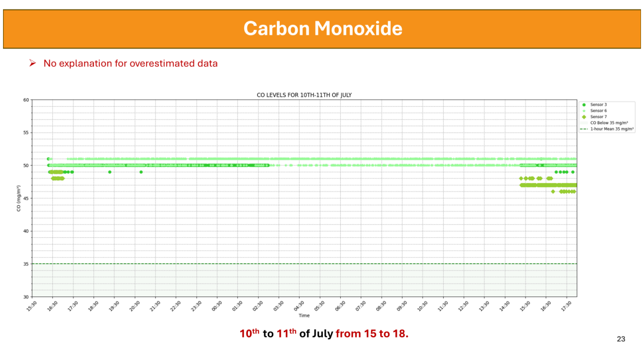

Particulate Matter (PM2.5)
Threshold: (EN 16798-1:2019 (WHO guidelines))
24 h mean ≤ 25 µg/m3
Required uncertainty: ± 5 µg/m3
AIRCARE value is lower than PM device
PM device was on the other table with distance from sensors
Average PM 2.5 Levels for 10th-11th of July
Time Range
18

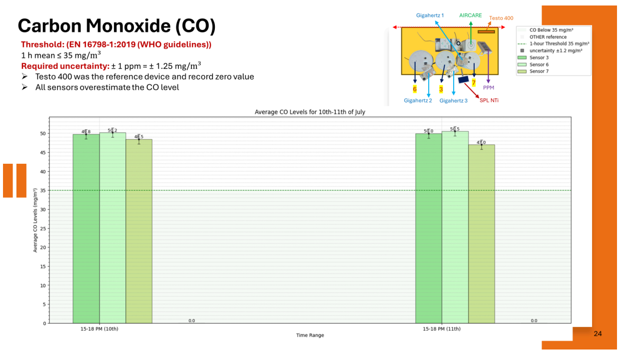

Particulate Matter 10
PM 10 LEVELS FOR 10TH-11TH OF JULY
PM device
10th to 11th of July from 15 to 18.
19

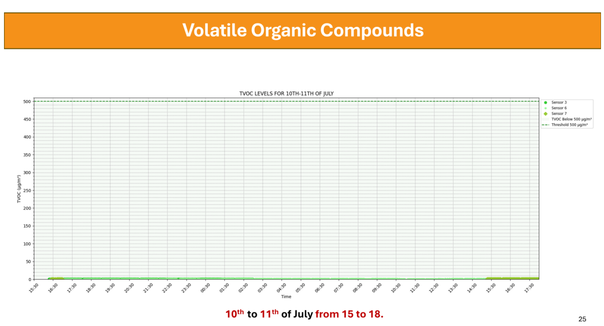

Particulate Matter (PM10)
Threshold: (EN 16798-1:2019 (WHO guidelines))
24 h mean ≤ 50 µg/m3
Required uncertainty: ± 5 µg/m3
AIRCARE value is lower than PM device
PM device was on the other table with distance from sensors
Average PM 10 Levels for 10th-11th of July
Time Range
20

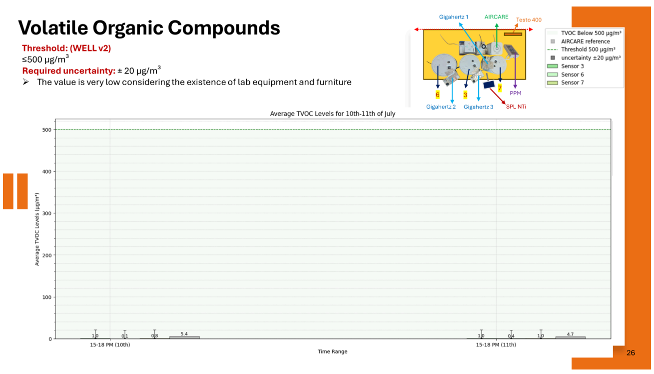

Carbon Dioxide
No one was present in the lab during the measuring, every 3 hour one person enter the room
Window is fixed and closed
CO2 LEVELS FOR 10TH-11TH OF JULY
10th to 11th of July from 15 to 18.
21


Carbon Dioxide (ΔCO2)
Threshold: (EN 16798-1:2019) ≤1200 ppm
Required uncertainty: ± 50 ppm
AIRCARE is the reference device
No person was present in the lab during the measuring
Sensor 3 overestimate the value sensor 7 underestimate
Average CO2 Levels for 10th-11th of July
Time Range
22

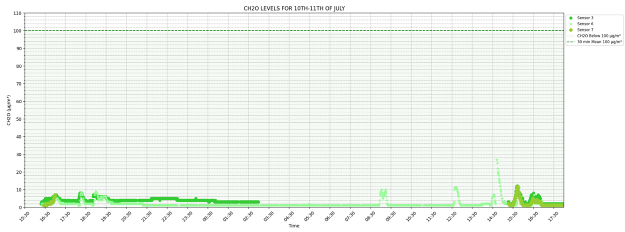

Carbon Monoxide
No explanation for overestimated data
CO LEVELS FOR 10TH-11TH OF JULY
10th to 11th of July from 15 to 18.
23


Carbon Monoxide (CO)
Threshold: (EN 16798-1:2019 (WHO guidelines))
1 h mean ≤ 35 mg/m3
Required uncertainty: ± 1 ppm = ± 1.25 mg/m3
Testo 400 was the reference device and record zero value
All sensors overestimate the CO level
Average CO Levels for 10th-11th of July
Time Range
24


Volatile Organic Compounds
TVOC LEVELS FOR 10TH-11TH OF JULY
10th to 11th of July from 15 to 18.
25


Volatile Organic Compounds
Threshold: (WELL v2)
≤500 µg/m3
Required uncertainty: ± 20 µg/m3
The value is very low considering the existence of lab equipment and furniture
Average TVOC Levels for 10th-11th of July
Time Range
26

Formaldehyde



10th to 11th of July from 15 to 18.

27

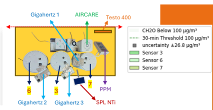
Formaldehyde (CH_2O)

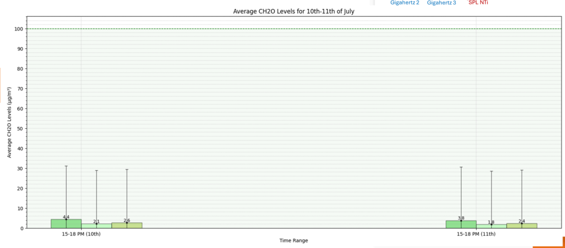
Threshold: (EN 16798-1:2019 (WHO guidelines))

30 min. mean ≤ 100 µg/m^3

Required uncertainty: 20 ppb = 26.79 µg/m^3

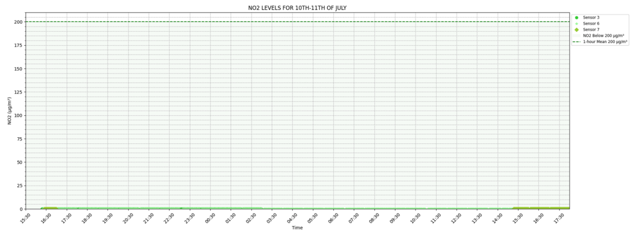
- Data was not recorded for this timing from reference device





28

Nitrogen dioxide



10th to 11th of July from 15 to 18.

29

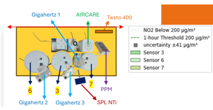
Nitrogen dioxide (NO_2)

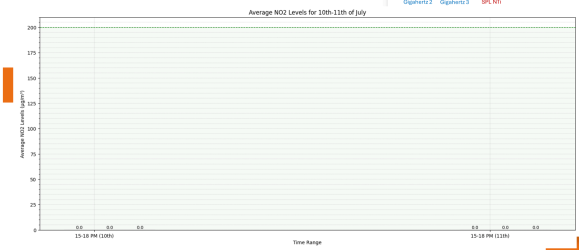
Threshold: (EN 16798-1:2019 (WHO guidelines))

1 h mean ≤ 200 µg/m^3

Required uncertainty: ± 20 ppb = 41.07 µg/m^3

- NO_2 source didn't exist in the lab

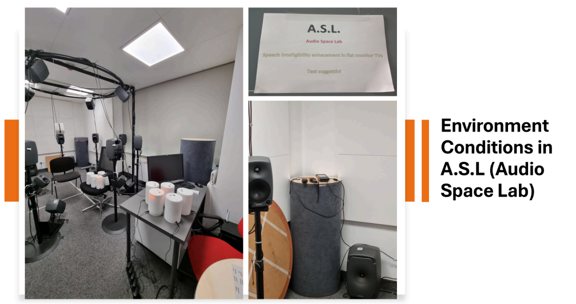


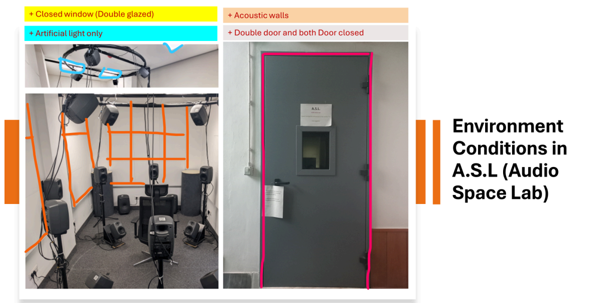


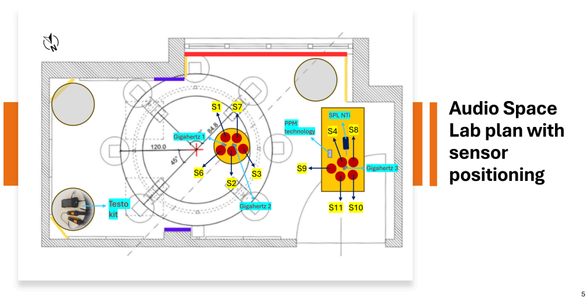
30

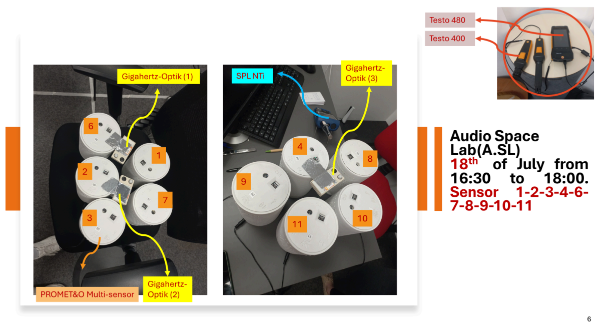
11.2 Politecnico di Torino Audio Space Lab (A.S.L.) measurements graphs

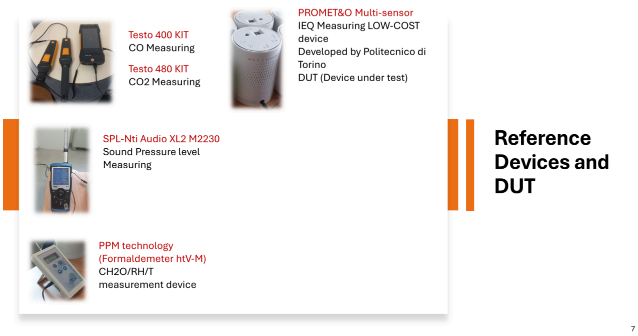
Here is the full representation of the graphs for the Audio Space Lab.

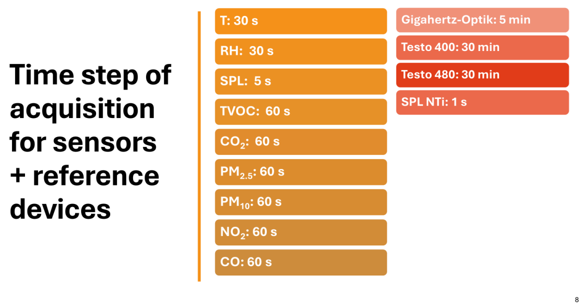






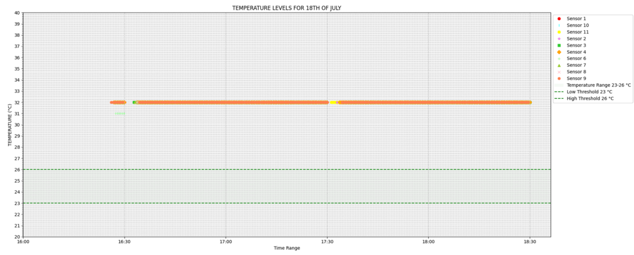






Temperature

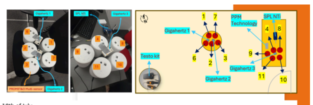
➢ Sensor 6 measured lower value in compare to others



18th of July from 16:30 to 18:00

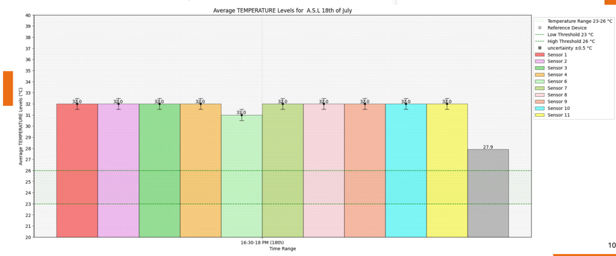
9

Temperature (T)



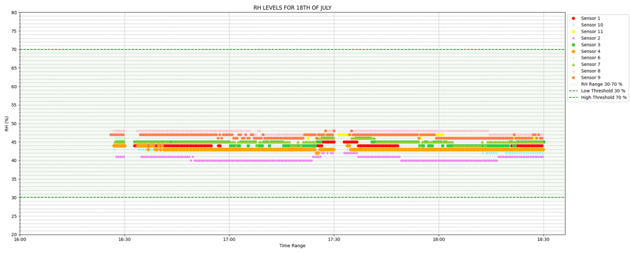
Threshold: (ISO 7730:2005)
Winter: (20–24) ◦C , Summer: (23–26) ◦C
Required uncertainty: ± 0.5 ◦C

➢ All sensors are higher then reference device
➢ Sensor 6 measured lower value in compare to others



10

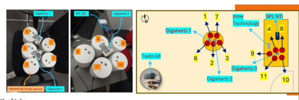
Relative humidity



18th of July from 16:30 to 18:00

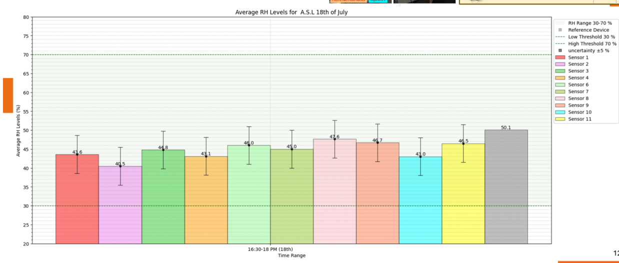
11

Relative humidity (RH)



Threshold: (ISO 7730:2005)
(30–70)%
Required uncertainty: ± 5 %

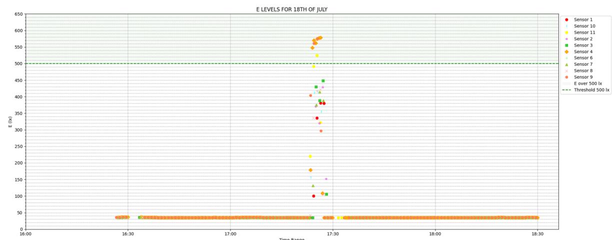
➢ Sensors value are close to reference value except for sensor 2 and 10



12

Illuminance

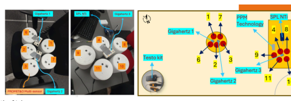
➢ Artificial light was turned on around 17:20 for taking the PPM device.



18th of July from 16:30 to 18:00

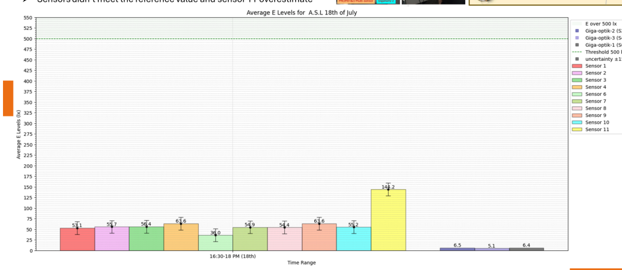
13

Illuminance (E_h)



Threshold: (EN 12464-1:2021) ≥500 lx
Required uncertainty: 15 lx

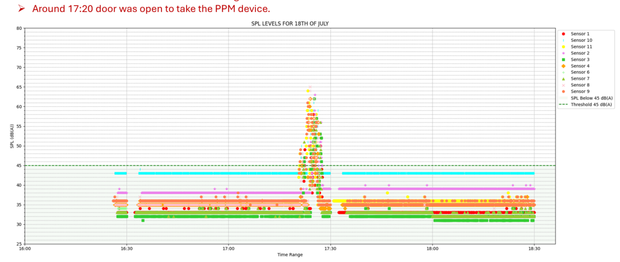
➢ Artificial light was turn off and door was closed. Light was turned on around 17:20 to take the PPM device.
➢ Sensors didn't meet the reference value and sensor 11 overestimate



14

Sound Pressure Level

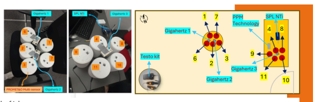
➢ Room is acoustic and door was closed during the measurement.
➢ Around 17:20 door was open to take the PPM device.



18th of July from 16:30 to 18:00

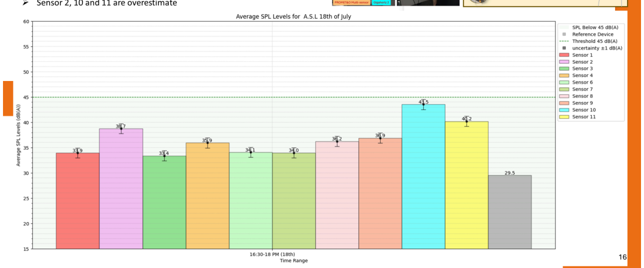
15

Sound Pressure Level (SPL)



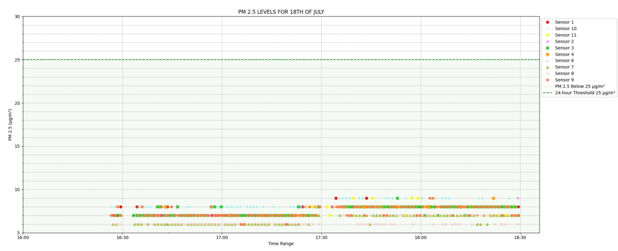
Threshold: (NF S 31-080)
≤45 dB(A)
Required uncertainty: ± 1 dB

➢ All sensors have higher value than reference device
➢ Sensor 2, 10 and 11 are overestimate



16

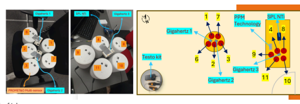
Particulate Matter 2.5



18th of July from 16:30 to 18:00

17

Particulate Matter ($PM_{2.5}$)

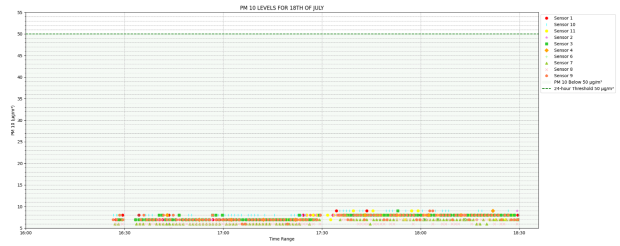


Threshold: (EN 16798-1:2019 (WHO guidelines))
24 h mean ≤ 25 µg/m³
Required uncertainty: ± 5 µg/m³

➢ No reference device available

18

Particulate Matter 10

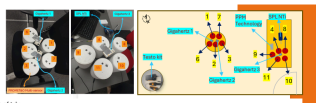


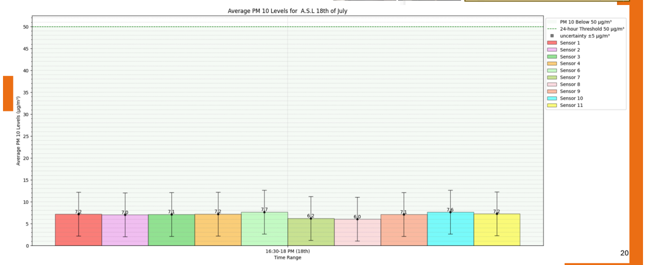
18th of July from 16:30 to 18:00

19

Particulate Matter (PM_{10})

Threshold: (EN 16798-1:2019 (WHO guidelines))
24 h mean ≤ 50 μg/m³
Required uncertainty: ± 5 μg/m³
- No reference device available

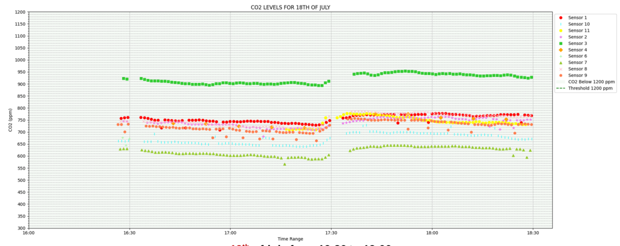




20

Carbon Dioxide

- Around 17:20 door was open and someone enter to take the PPM device.
- Sensor 3 overestimate the value sensor 7 underestimate

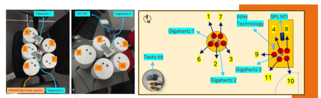


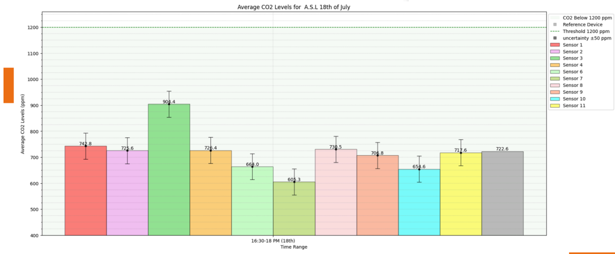
18th of July from 16:30 to 18:00

21

Carbon Dioxide (ΔCO_2)

Threshold: (EN 16798-1:2019) ≤1200 ppm
Required uncertainty: ± 50 ppm
- Testo 480 is the reference device
- No person was present in the lab during the measuring
- Sensor 3 overestimate the value sensor 7 underestimate

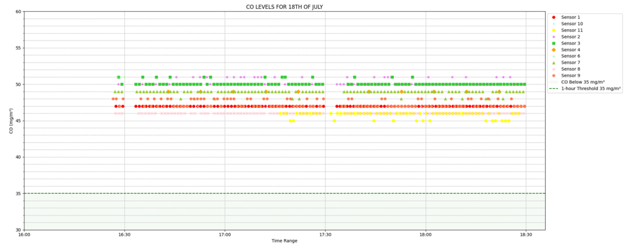




22

Carbon Monoxide

- Unexplainable result

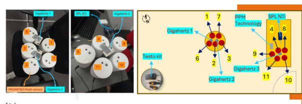


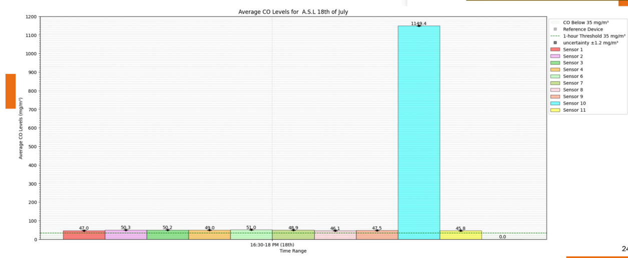
18th of July from 16:30 to 18:00

23

Carbon Monoxide (CO)

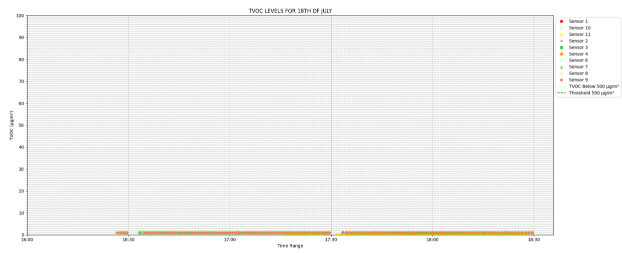
Threshold: (EN 16798-1:2019 (WHO guidelines))
1 h mean ≤ 35 mg/m³
Required uncertainty: ± 1.2 mg/m³
- Testo 400 is the reference device
- Sensors didn't meet the reference value and sensor 10 overestimate





24

Volatile Organic Compounds

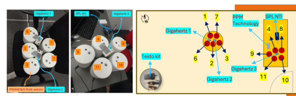


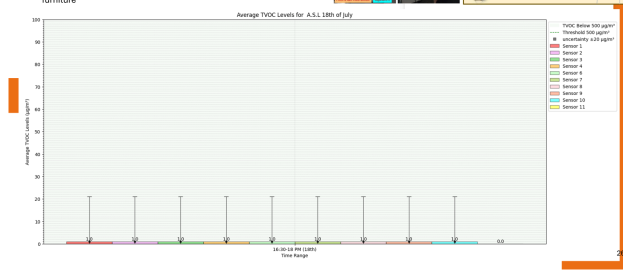
18th of July from 16:30 to 18:00

25

Volatile Organic Compounds

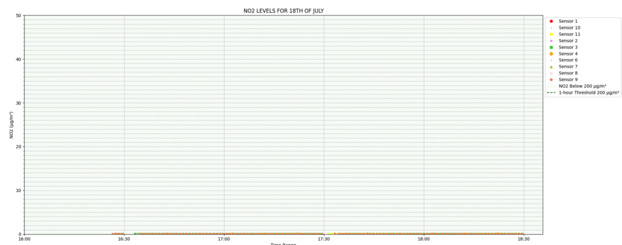
Threshold: (WELL v2)
≤500 μg/m³
Required uncertainty: ± 20 μg/m³
- The value is very low considering the existence of lab equipment and furniture





26

Nitrogen dioxide

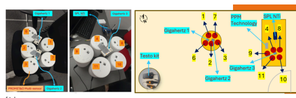


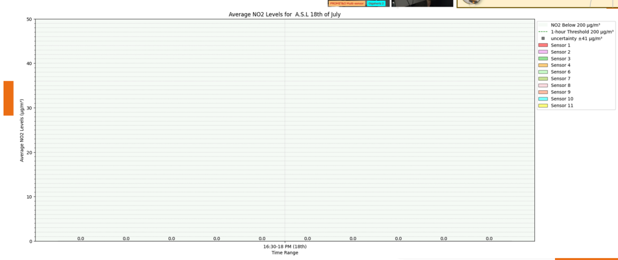
18th of July from 16:30 to 18:00

29

Nitrogen dioxide (NO_2)

Threshold: (EN 16798-1:2019 (WHO guidelines))
1 h mean ≤ 200 μg/m³
Required uncertainty: ± 41 μg/m³
- NO_2 source didn't exist in the lab

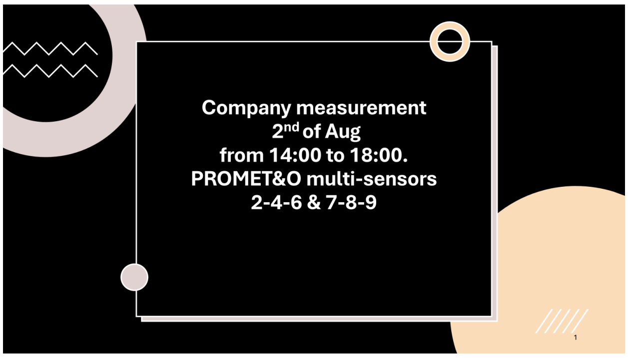


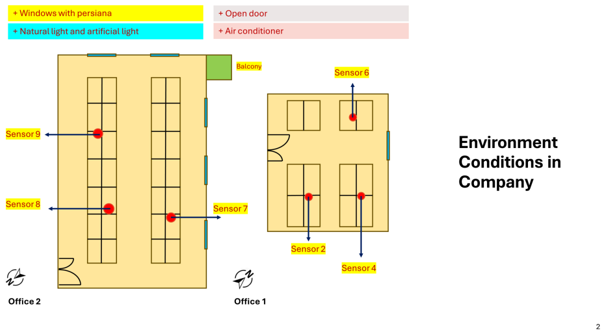


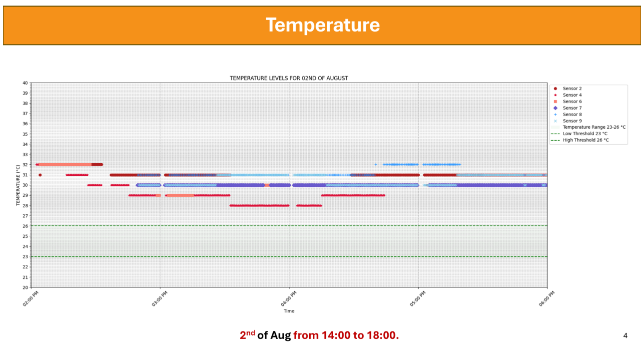
11.3 Company open-space offices measurements graphs

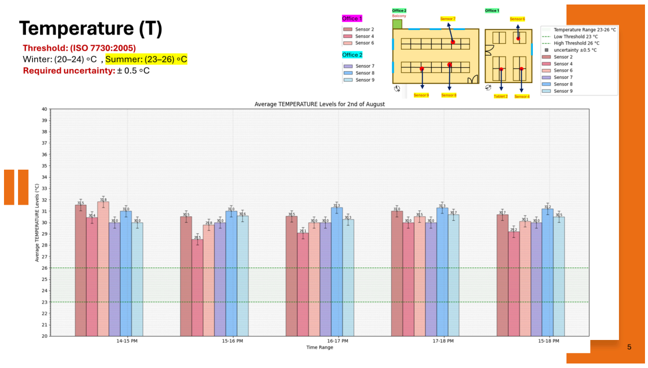
Here is the full representation of graphs for the open-space offices in the Company.

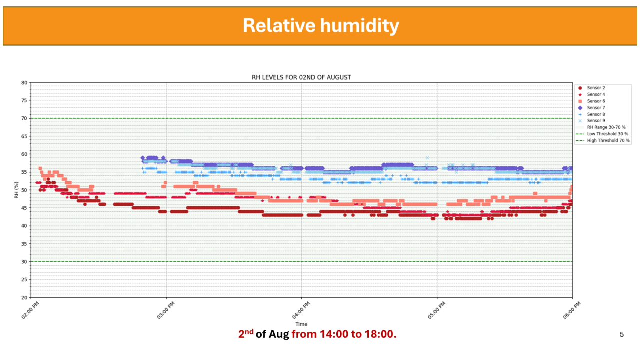
Day 1 Company measurement:

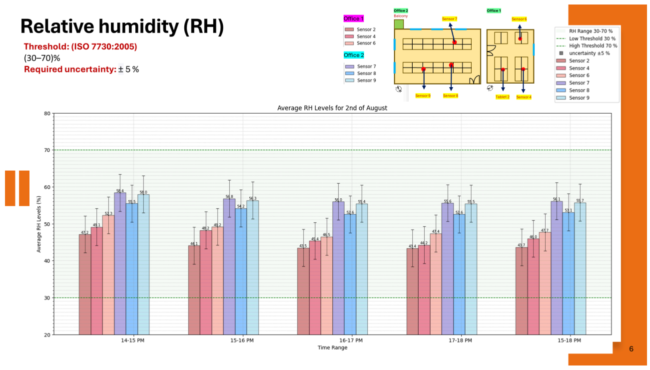


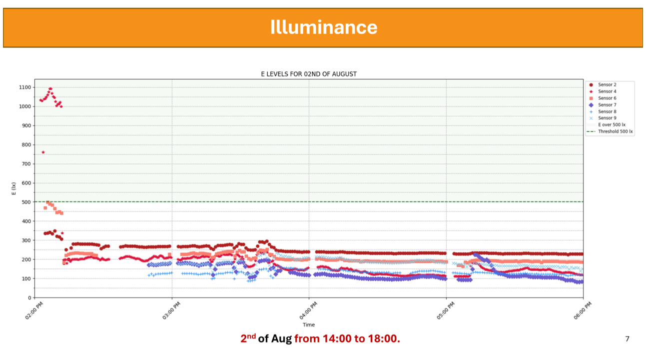


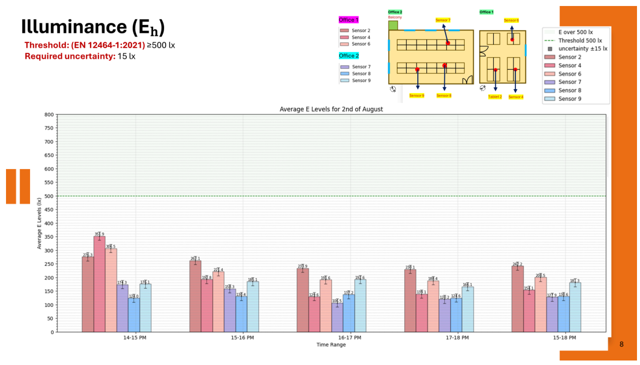




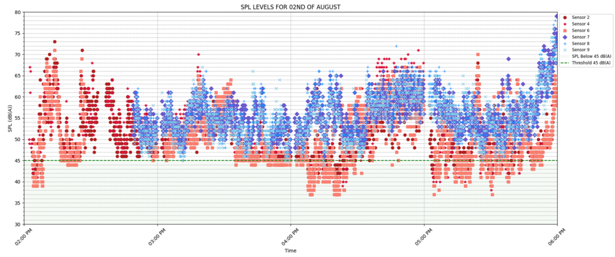








Sound Pressure Level

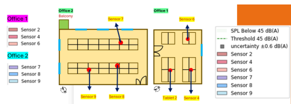


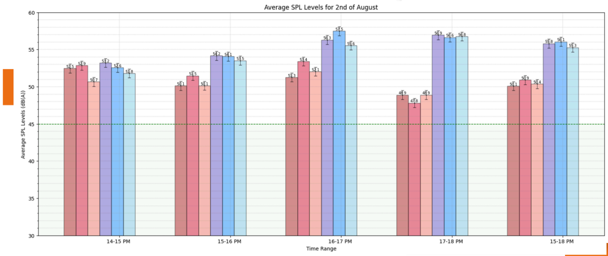
2nd of Aug from 14:00 to 18:00.

9

Sound Pressure Level (SPL)

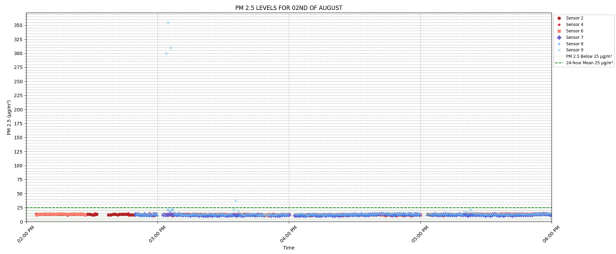
Threshold: (NF S 31-080)
≤45 dB(A)
Required uncertainty: ± 1 dB





10

Particulate Matter 2.5

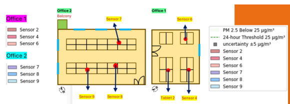


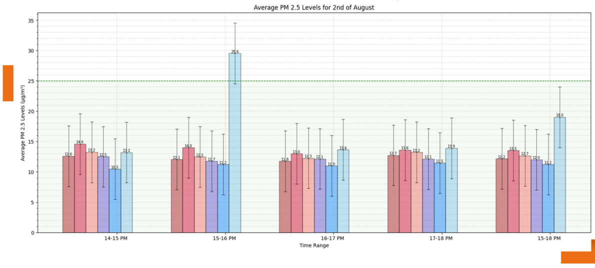
2nd of Aug from 14:00 to 18:00.

11

Particulate Matter ($PM_{2.5}$)

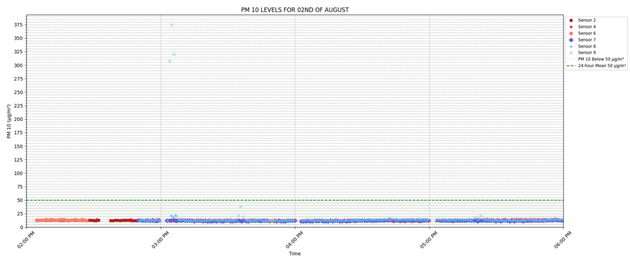
Threshold: (EN 16798-1:2019 (WHO guidelines))
24 h mean ≤ 25 µg/m³
Required uncertainty: ± 5 µg/m³
➢ Sensor 9 need to checked for this parameter





12

Particulate Matter 10

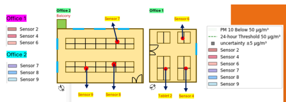


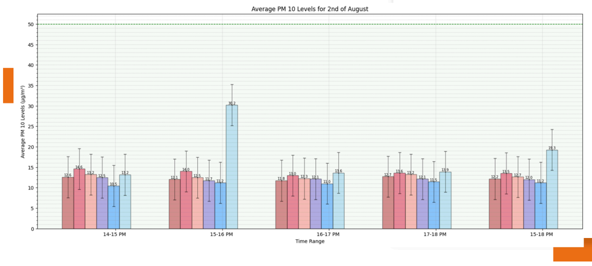
2nd of Aug from 14:00 to 18:00.

13

Particulate Matter (PM_{10})

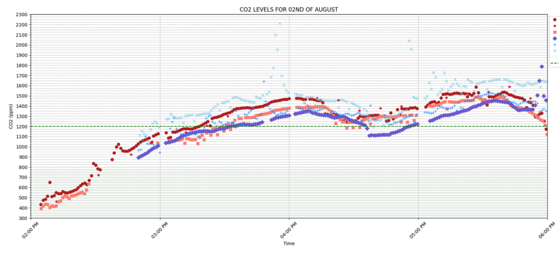
Threshold: (EN 16798-1:2019 (WHO guidelines))
24 h mean ≤ 50 µg/m³
Required uncertainty: ± 5 µg/m³





14

Carbon Dioxide

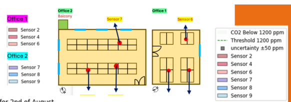


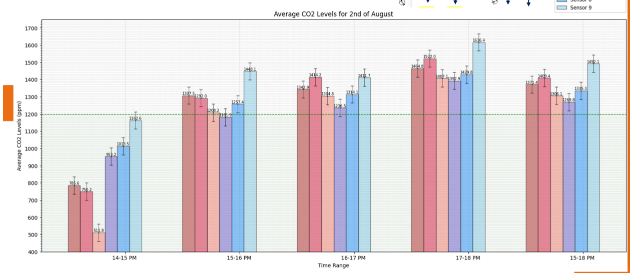
2nd of Aug from 14:00 to 18:00.

15

Carbon Dioxide (ΔCO_2)

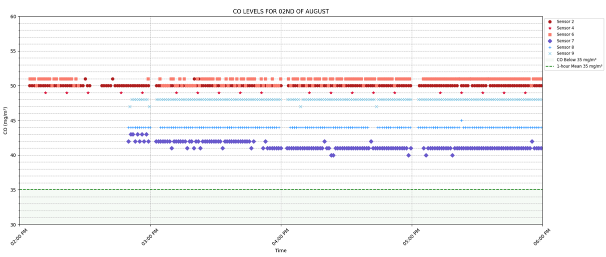
Threshold: (EN 16798-1:2019) ≤1200 ppm
Required uncertainty: ± 50 ppm





16

Carbon Monoxide

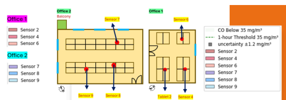


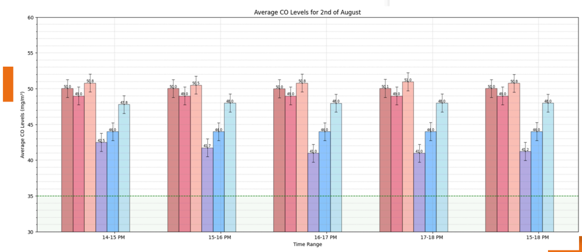
2nd of Aug from 14:00 to 18:00.

17

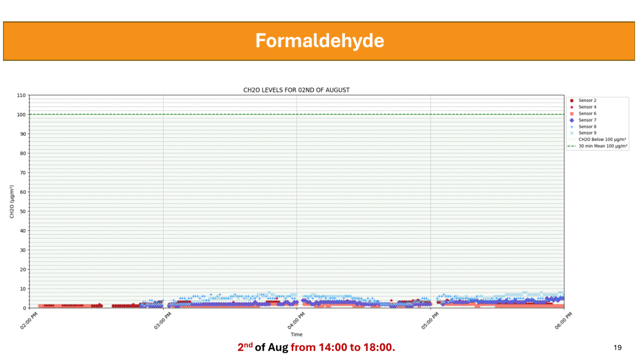
Carbon Monoxide (CO)

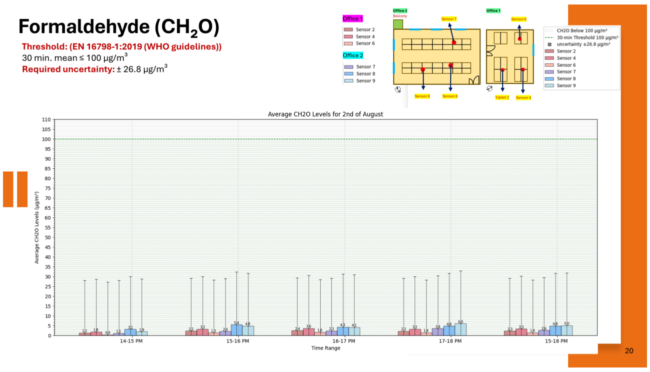
Threshold: (EN 16798-1:2019 (WHO guidelines))
1 h mean ≤ 35 mg/m³
Required uncertainty: ± 1.2 mg/m³

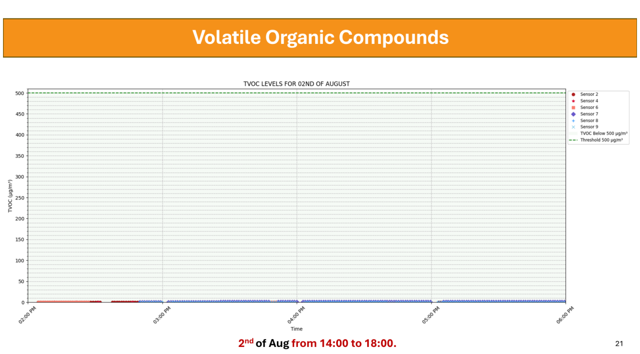


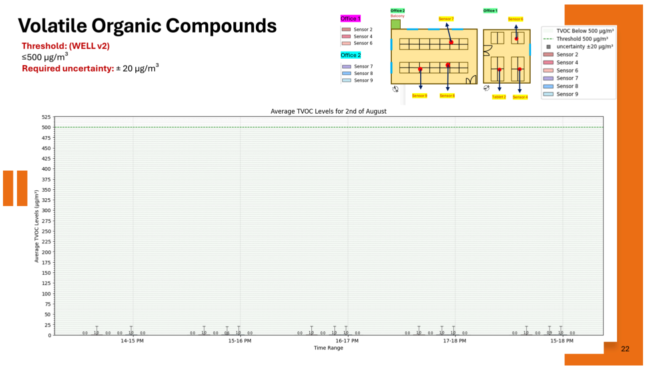


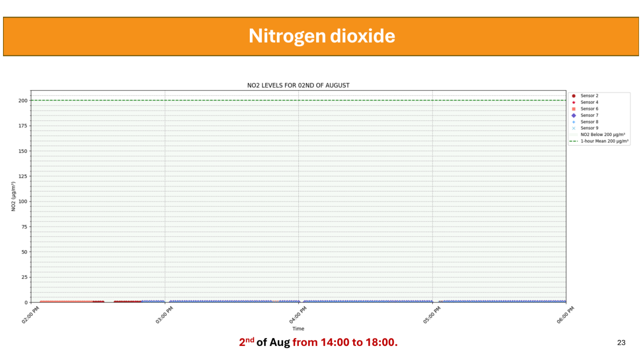
18

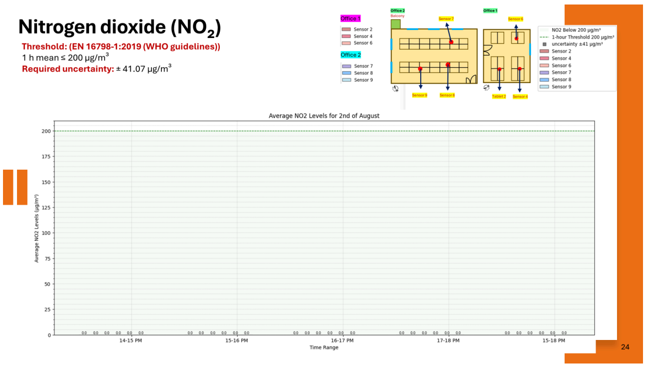




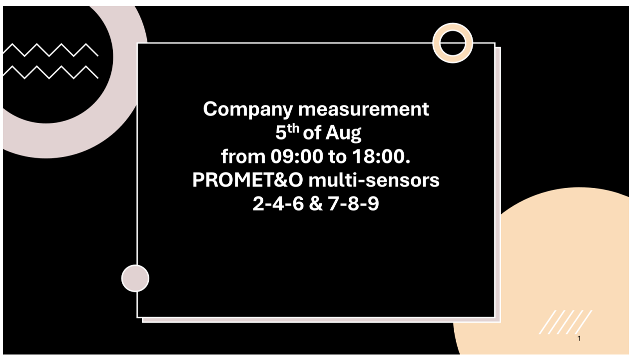


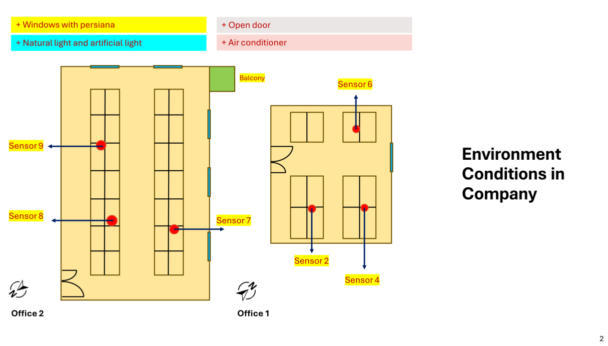


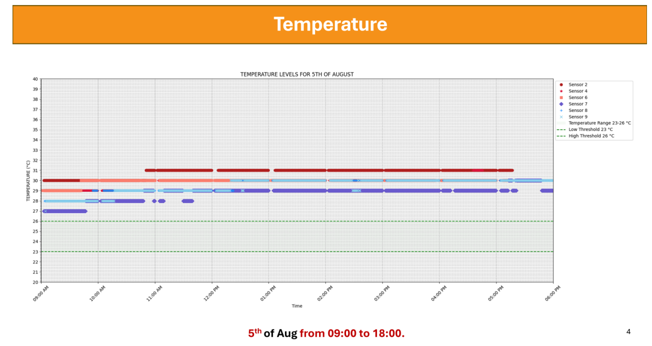


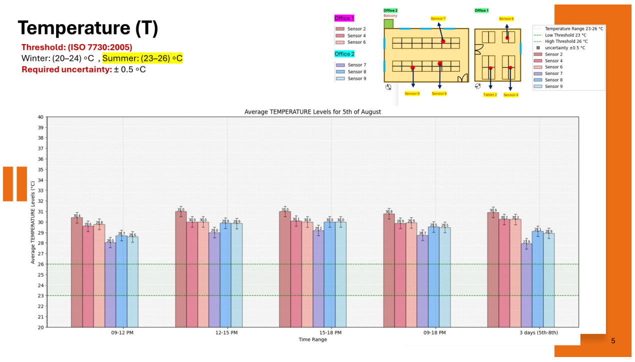


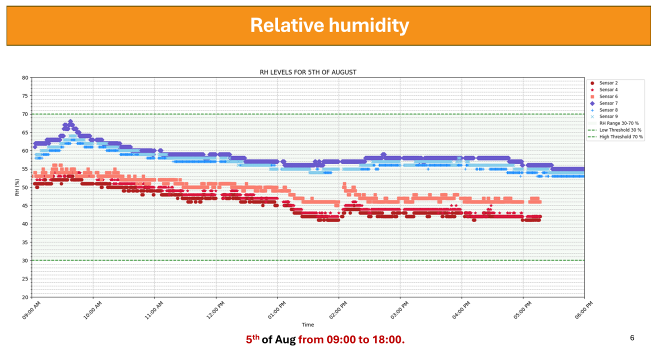
Day 2 Company measurement:

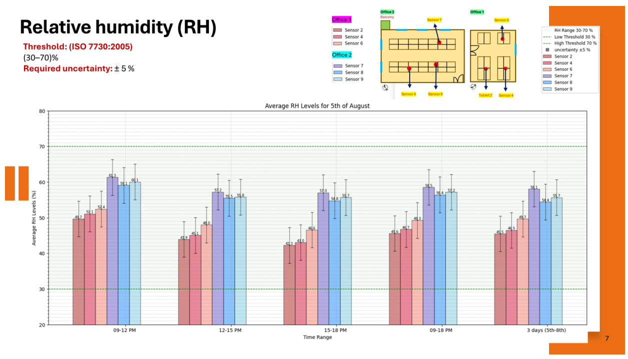


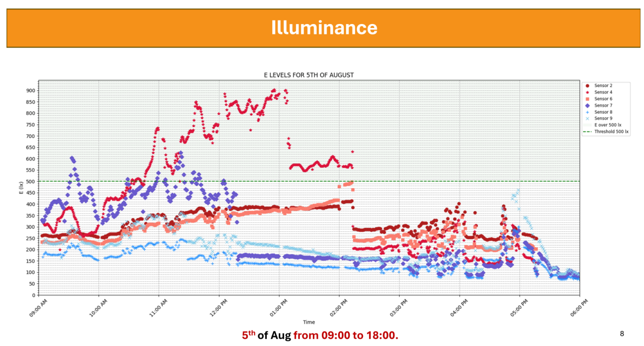


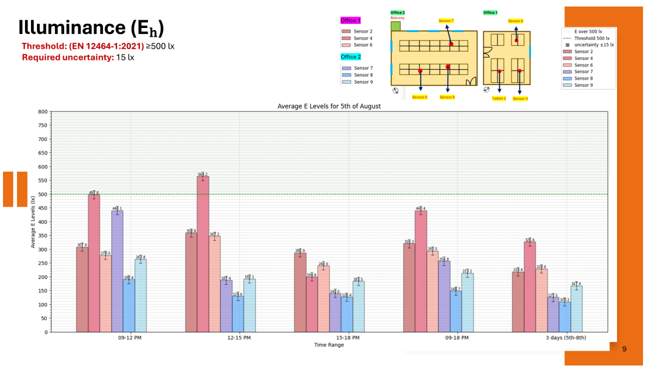

Temperature
TEMPERATURE LEVELS FOR 5TH OF AUGUST
5th of Aug from 09:00 to 18:00.
4

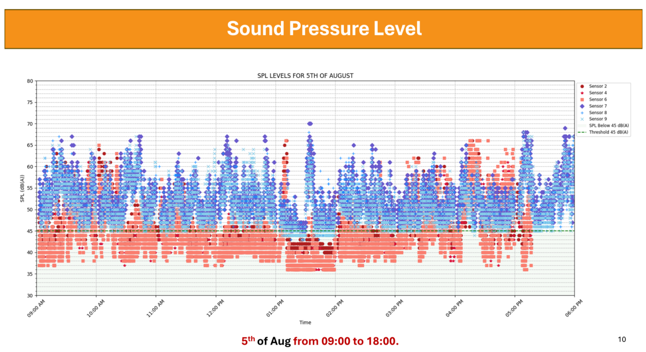

Temperature (T)
Threshold: (ISO 7730:2005)
Winter: (20–24) ᵒC , Summer: (23–26) ᵒC
Required uncertainty: ± 0.5 ᵒC
Average TEMPERATURE Levels for 5th of August
5

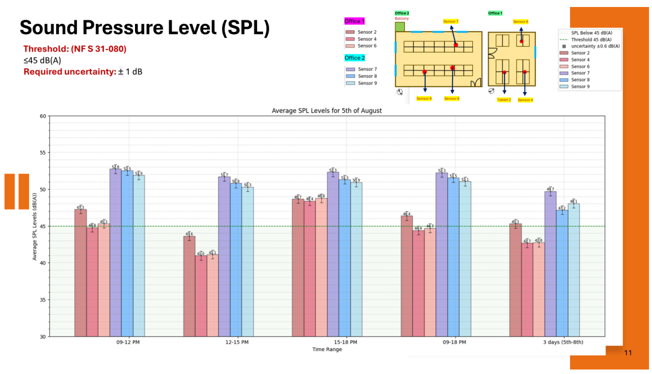

Relative humidity
RH LEVELS FOR 5TH OF AUGUST
5th of Aug from 09:00 to 18:00.
6

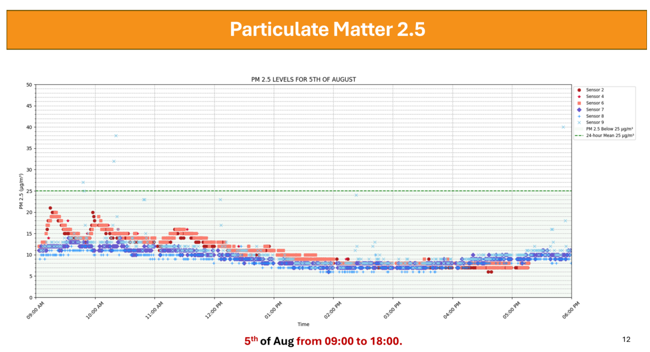

Relative humidity (RH)
Threshold: (ISO 7730:2005)
(30–70)%
Required uncertainty: ± 5 %
Average RH Levels for 5th of August
7

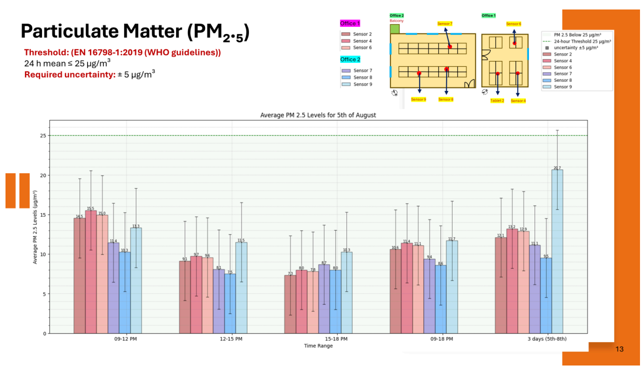

Illuminance
E LEVELS FOR 5TH OF AUGUST
5th of Aug from 09:00 to 18:00.
8


Illuminance (Eh)
Threshold: (EN 12464-1:2021) ≥500 lx
Required uncertainty: 15 lx
Average E Levels for 5th of August
9

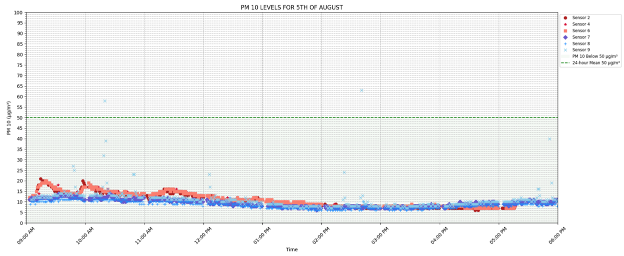

Sound Pressure Level
SPL LEVELS FOR 5TH OF AUGUST
5th of Aug from 09:00 to 18:00.
10


Sound Pressure Level (SPL)
Threshold: (NF S 31-080)
≤45 dB(A)
Required uncertainty: ± 1 dB
Average SPL Levels for 5th of August
11


Particulate Matter 2.5
PM 2.5 LEVELS FOR 5TH OF AUGUST
5th of Aug from 09:00 to 18:00.
12


Particulate Matter (PM2.5)
Threshold: (EN 16798-1:2019 (WHO guidelines))
24 h mean ≤ 25 µg/m3
Required uncertainty: ± 5 µg/m3
Average PM 2.5 Levels for 5th of August
13

Particulate Matter 10

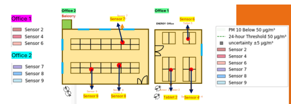


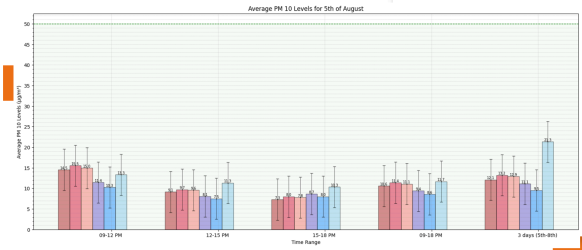
5th of Aug from 09:00 to 18:00.

14

Particulate Matter (PM_{10})

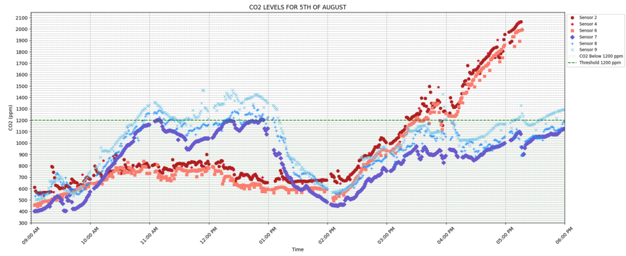
Threshold: (EN 16798-1:2019 (WHO guidelines))
24 h mean ≤ 50 µg/m^3
Required uncertainty: ± 5 µg/m^3





15

Carbon Dioxide

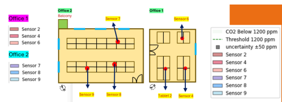


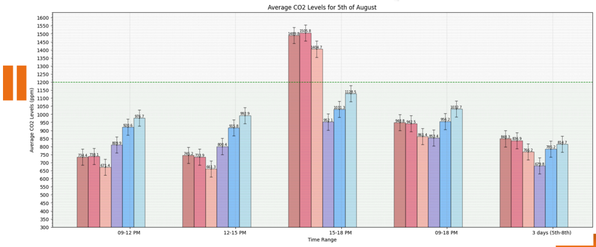
5th of Aug from 09:00 to 18:00.

16

Carbon Dioxide (ΔCO_2)

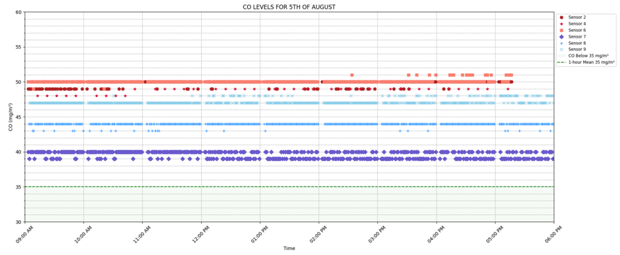
Threshold: (EN 16798-1:2019) ≤1200 ppm
Required uncertainty: ± 50 ppm





17

Carbon Monoxide

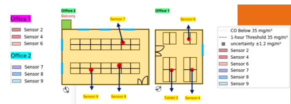


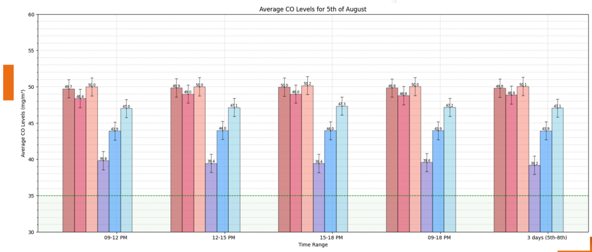
5th of Aug from 09:00 to 18:00.

18

Carbon Monoxide (CO)

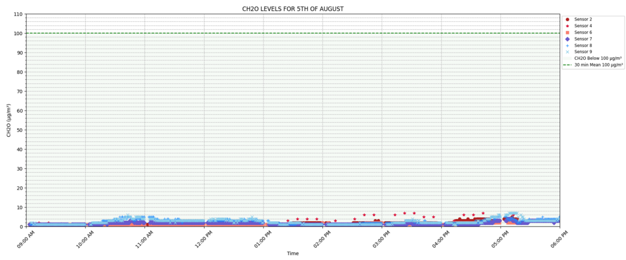
Threshold: (EN 16798-1:2019 (WHO guidelines))
1 h mean ≤ 35 mg/m^3
Required uncertainty: ± 1.2 mg/m^3





19

Formaldehyde

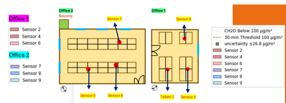


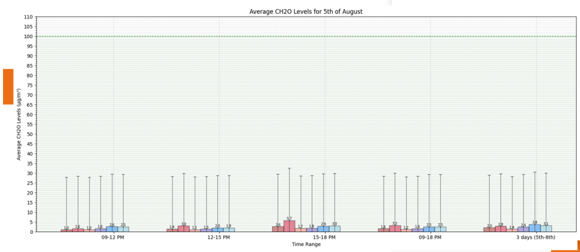
5th of Aug from 09:00 to 18:00.

20

Formaldehyde (CH_2O)

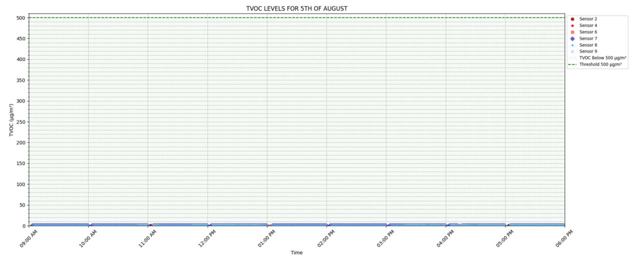
Threshold: (EN 16798-1:2019 (WHO guidelines))
30 min. mean ≤ 100 µg/m^3
Required uncertainty: ± 26.8 µg/m^3





21

Volatile Organic Compounds

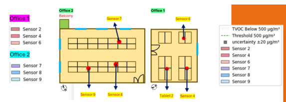


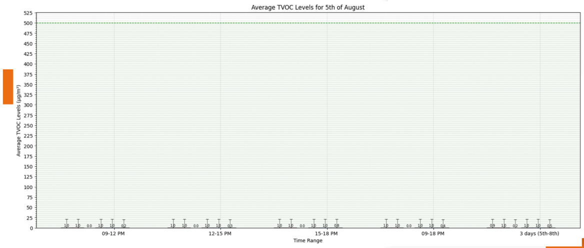
5th of Aug from 09:00 to 18:00.

22

Volatile Organic Compounds

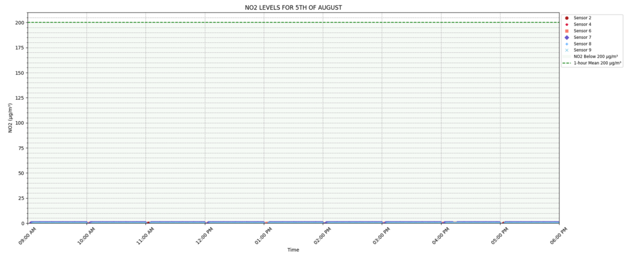
Threshold: (WELL v2)
≤500 µg/m³
Required uncertainty: ± 20 µg/m³





23

Nitrogen dioxide

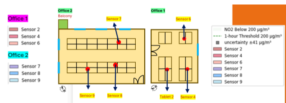


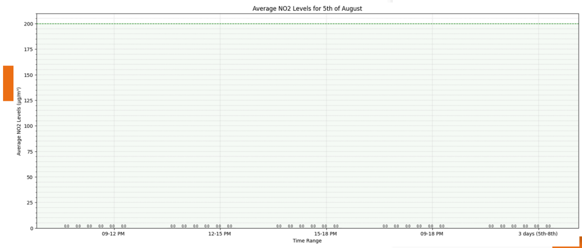
5th of Aug from 09:00 to 18:00.

24

Nitrogen dioxide (NO_2)

Threshold: (EN 16798-1:2019 (WHO guidelines))
1 h mean ≤ 200 µg/m³
Required uncertainty: ± 41.07 µg/m³





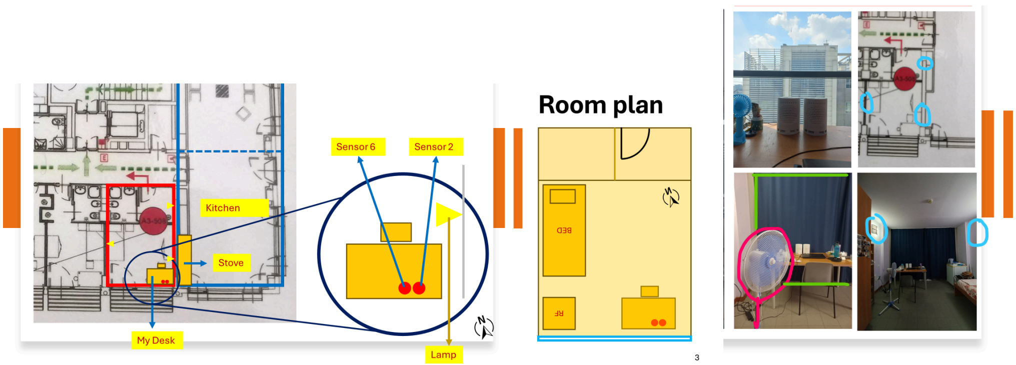
25

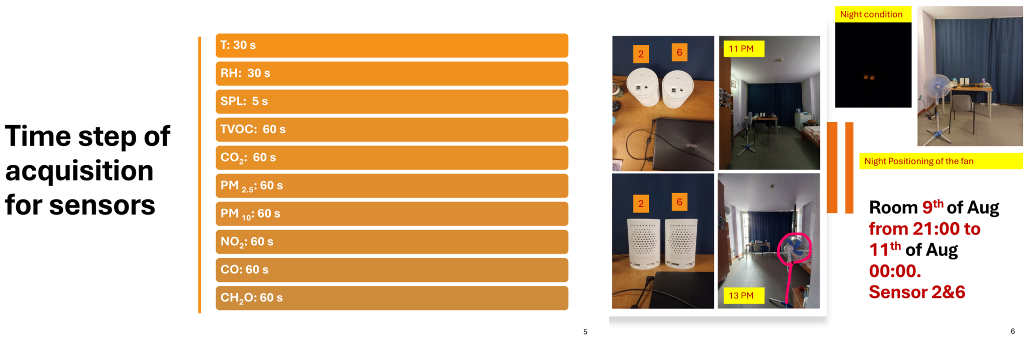
11.4 Bedroom in a university residence building measurements graphs

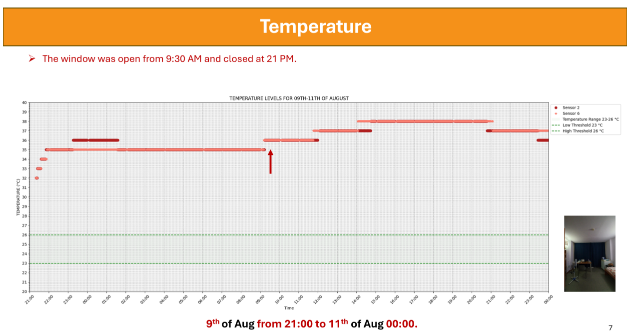
Here is the full representation of the graphs for in-room measurement.

Day 1 in-room measurement:

9-Aug-24 to 11-Aug-24	21:00-00:00	00:00-03:00	03:00-06:00	06:00-09:00	09:00-13:00	13:00-15:00	15:00-18:00	18:00-21:00	21:00-00:00
Curtain	Closed	Closed	Closed	Closed	Open	Closed	Closed	Closed	Closed
Window	Open	Closed	Closed	Closed	Open	Open	Open	Open	Open
Portable fan	On	On	On	On	Off	On	On	On	On
Atrificial light	On	Off	Off	Off	Off	Off	Off	On	On

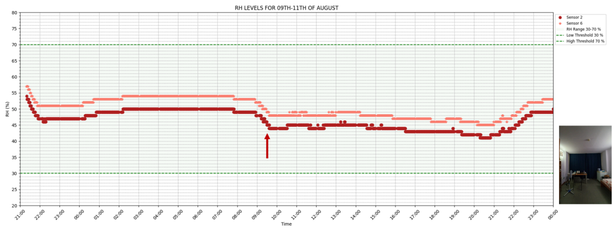






Relative humidity

➢ The window was open from 9:30 AM and closed at 21 PM.

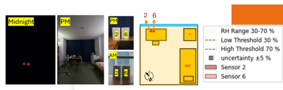


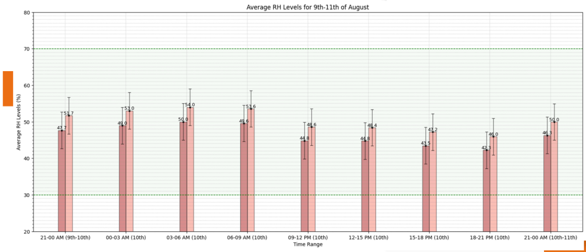
9th of Aug from 21:00 to 11th of Aug 00:00.

9

Relative humidity (RH)

Threshold: (ISO 7730:2005)
(30–70)%
Required uncertainty: ± 5 %
➢ The window was open from 9:30 AM and closed at 21 PM.

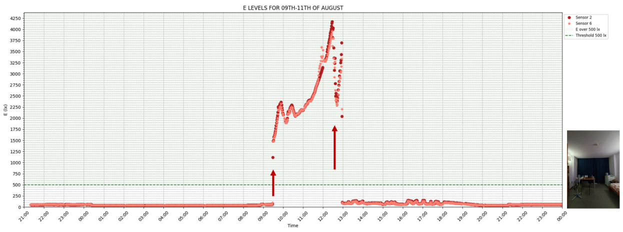




10

Illuminance

➢ The window was open from 9:30 AM and closed at 21 PM.
➢ Curtain was open from 9:30 AM to 13:00 and artificial light turn on from 18 PM.

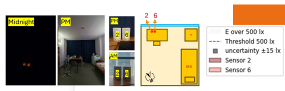


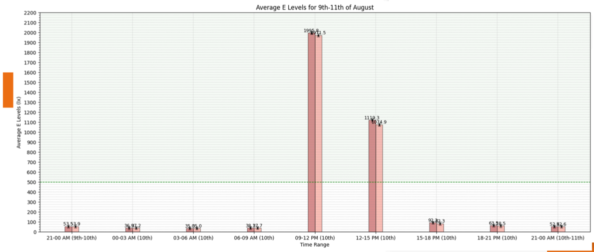
9th of Aug from 21:00 to 11th of Aug 00:00.

11

Illuminance (E_h)

Threshold: (EN 12464-1:2021) ≥500 lx
Required uncertainty: 15 lx
➢ The window was open from 9:30 AM and closed at 21 PM.
➢ Curtain was open from 9:30 AM to 13:00 and artificial light turn on from 18 PM.

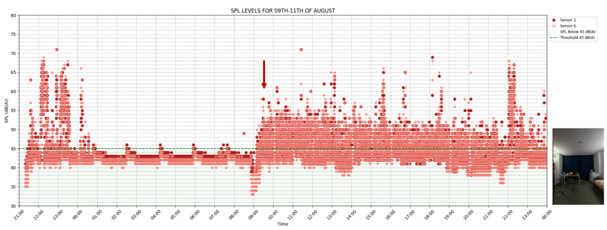




12

Sound Pressure Level

➢ The window was open from 9:30 AM and closed at 21 PM.
➢ Fan was turned on almost all day except from 9 AM to 13 PM.

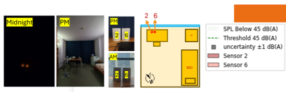


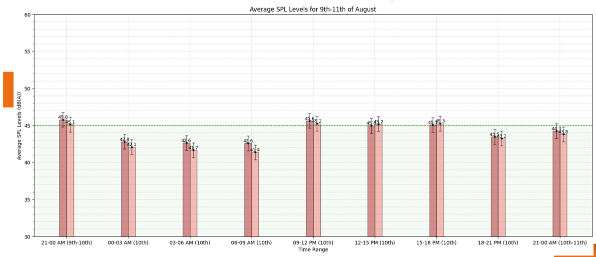
9th of Aug from 21:00 to 11th of Aug 00:00.

13

Sound Pressure Level (SPL)

Threshold: (NF S 31-080)
≤45 dB(A)
Required uncertainty: ± 1 dB
➢ The window was open from 9:30 AM and closed at 21 PM.
➢ Fan was turned on almost all day except from 9 AM to 13 PM.

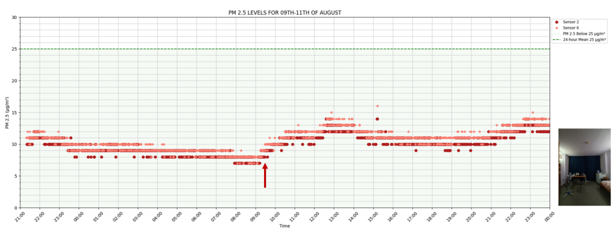




14

Particulate Matter 2.5

➢ The window was open from 9:30 AM and closed at 21 PM.

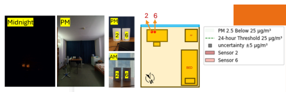


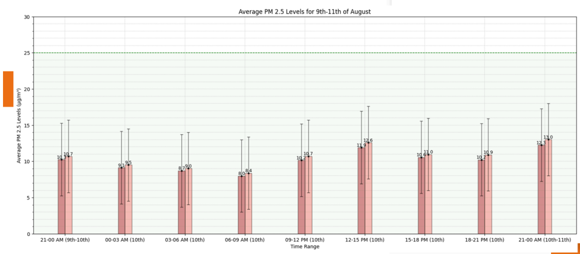
9th of Aug from 21:00 to 11th of Aug 00:00.

15

Particulate Matter ($PM_{2.5}$)

Threshold: (EN 16798-1:2019 (WHO guidelines))
24 h mean ≤ 25 μg/m³
Required uncertainty: ± 5 μg/m³
➢ The window was open from 9:30 AM and closed at 21 PM.

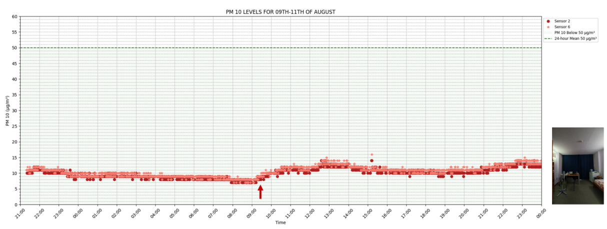




16

Particulate Matter 10

➢ The window was open from 9:30 AM and closed at 21 PM.

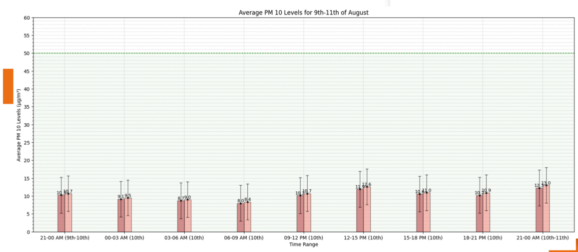


9th of Aug from 21:00 to 11th of Aug 00:00.

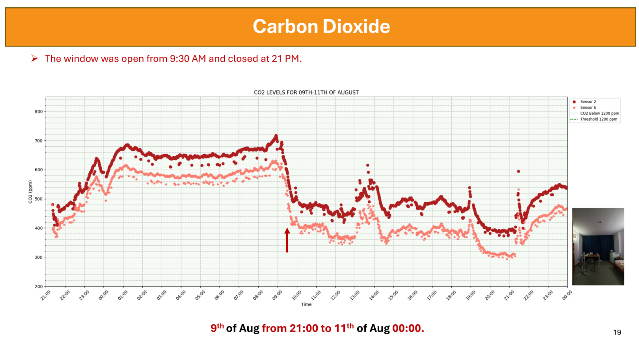
17

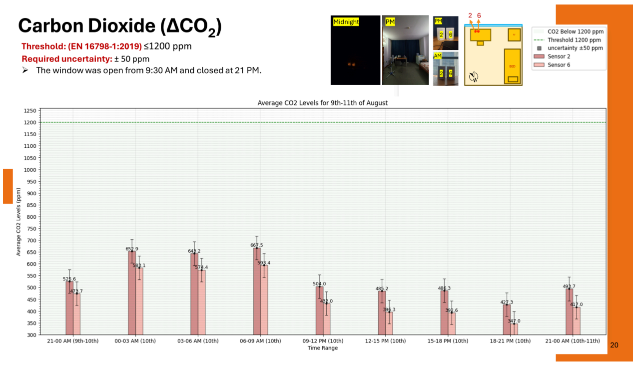
Particulate Matter (PM_{10})

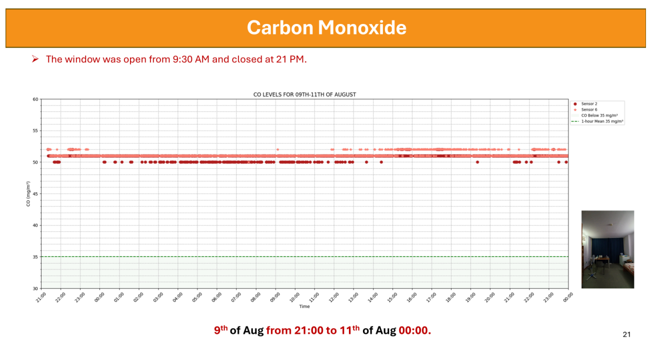
Threshold: (EN 16798-1:2019 (WHO guidelines))
24 h mean ≤ 50 μg/m³
Required uncertainty: ± 5 μg/m³
➢ The window was open from 9:30 AM and closed at 21 PM.

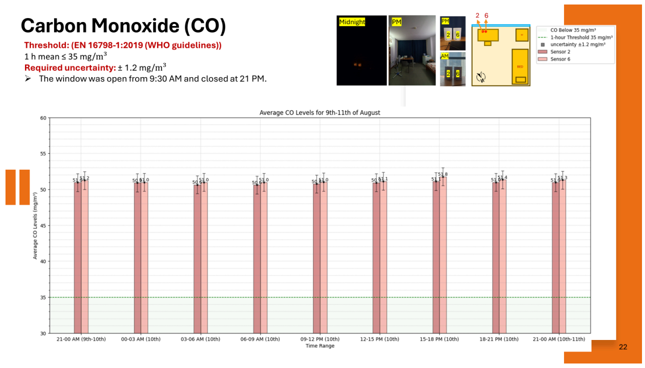


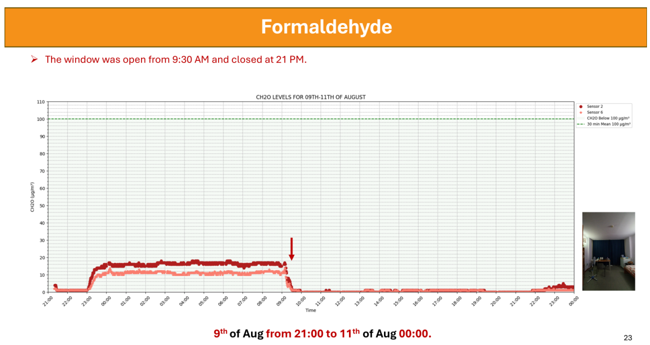
18

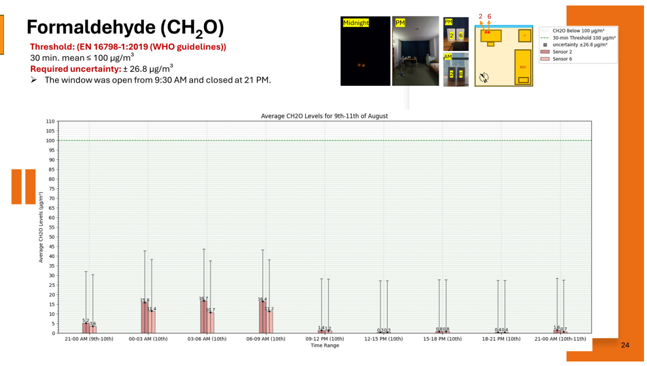

Carbon Dioxide
The window was open from 9:30 AM and closed at 21 PM.
CO2 LEVELS FOR 09TH-11TH OF AUGUST
9th of Aug from 21:00 to 11th of Aug 00:00.
19

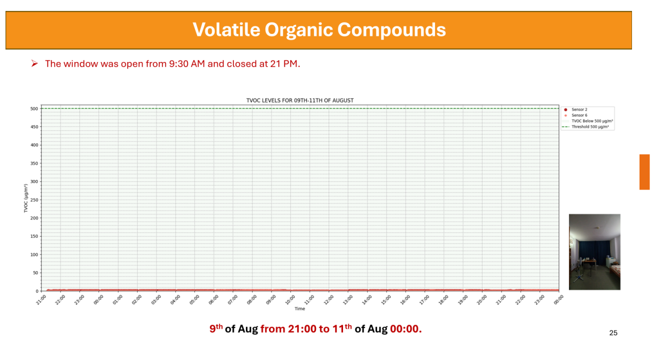

Carbon Dioxide (ΔCO2)
Threshold: (EN 16798-1:2019) ≤1200 ppm
Required uncertainty: ± 50 ppm
The window was open from 9:30 AM and closed at 21 PM.
Average CO2 Levels for 9th-11th of August
20

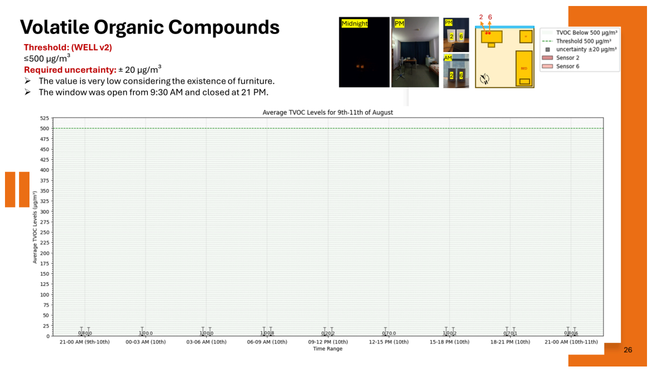

Carbon Monoxide
The window was open from 9:30 AM and closed at 21 PM.
CO LEVELS FOR 09TH-11TH OF AUGUST
9th of Aug from 21:00 to 11th of Aug 00:00.
21

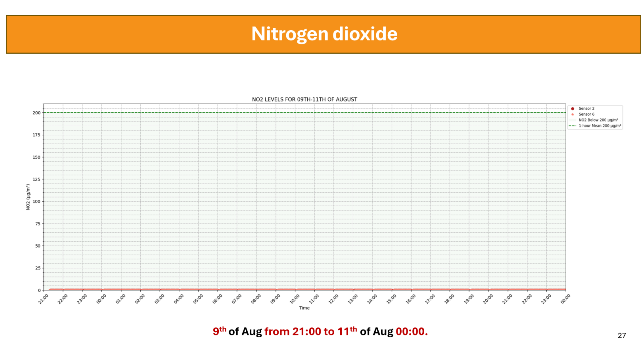

Carbon Monoxide (CO)
Threshold: (EN 16798-1:2019 (WHO guidelines))
1 h mean ≤ 35 mg/m3
Required uncertainty: ± 1.2 mg/m3
The window was open from 9:30 AM and closed at 21 PM.
Average CO Levels for 9th-11th of August
22

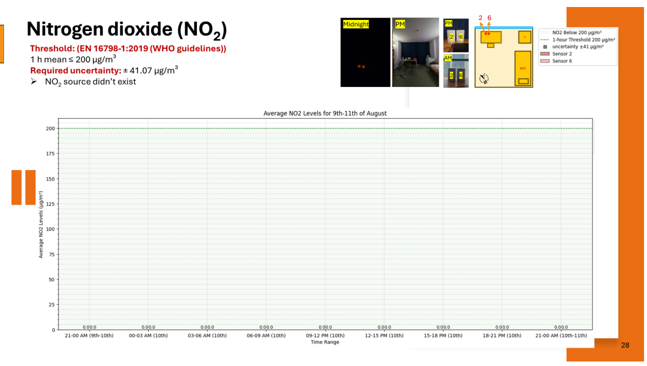

Formaldehyde
The window was open from 9:30 AM and closed at 21 PM.
CH2O LEVELS FOR 09TH-11TH OF AUGUST
9th of Aug from 21:00 to 11th of Aug 00:00.
23


Formaldehyde (CH2O)
Threshold: (EN 16798-1:2019 (WHO guidelines))
30 min. mean ≤ 100 µg/m3
Required uncertainty: ± 26.8 µg/m3
The window was open from 9:30 AM and closed at 21 PM.
Average CH2O Levels for 9th-11th of August
24


Volatile Organic Compounds
The window was open from 9:30 AM and closed at 21 PM.
TVOC LEVELS FOR 09TH-11TH OF AUGUST
9th of Aug from 21:00 to 11th of Aug 00:00.
25


Volatile Organic Compounds
Threshold: (WELL v2)
≤500 µg/m3
Required uncertainty: ± 20 µg/m3
The value is very low considering the existence of furniture.
The window was open from 9:30 AM and closed at 21 PM.
Average TVOC Levels for 9th-11th of August
26

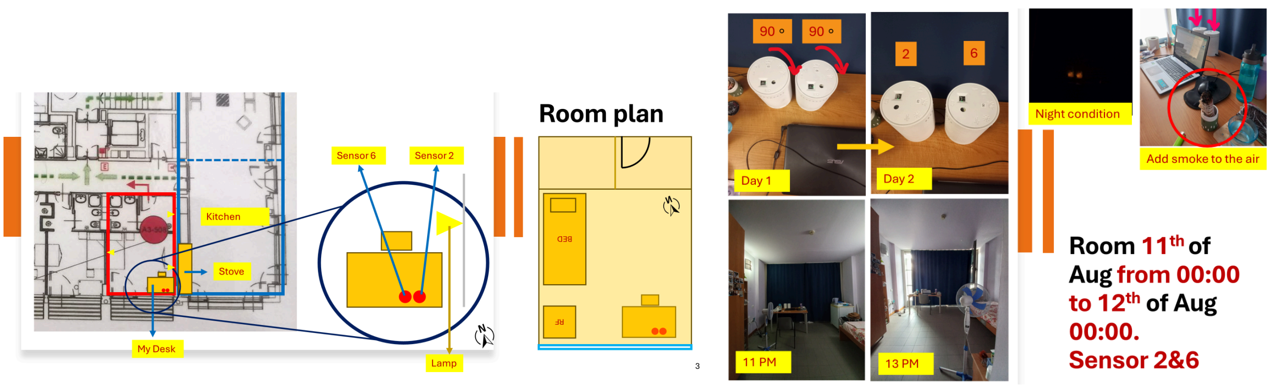

Nitrogen dioxide
NO2 LEVELS FOR 09TH-11TH OF AUGUST
9th of Aug from 21:00 to 11th of Aug 00:00.
27

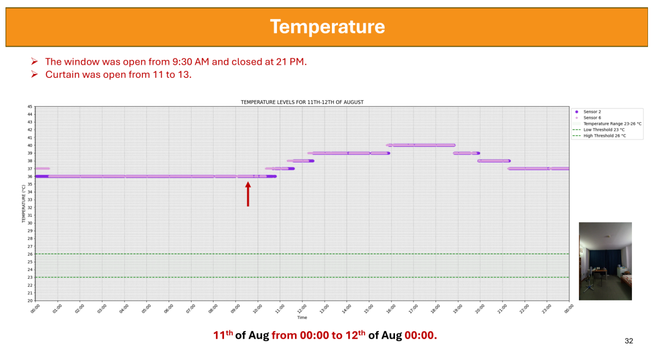

Nitrogen dioxide (NO2)
Threshold: (EN 16798-1:2019 (WHO guidelines))
1 h mean ≤ 200 µg/m3
Required uncertainty: ± 41.07 µg/m3
NO2 source didn't exist
Average NO2 Levels for 9th-11th of August
28

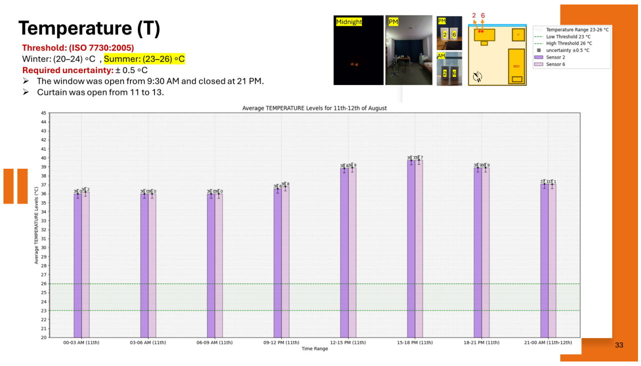
Day 2 in-room measurement:

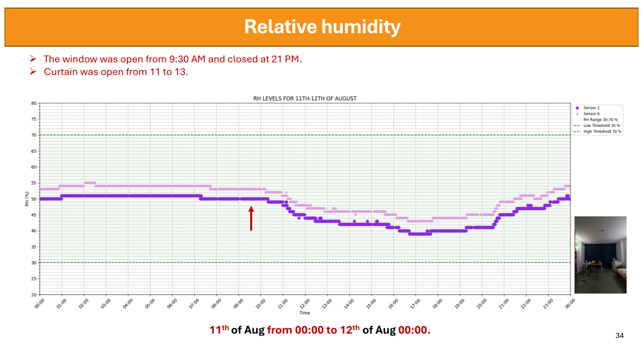
Here is the full representation of the graphs for day 2 in-room measurement.

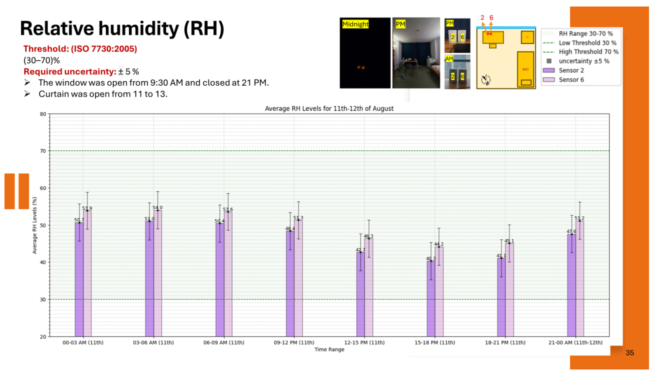
11-Aug-24 to 12-Aug-24	00:00-02:00	02:00-06:00	06:00-09:00	09:00-11:00	11:00-13:00	13:00-15:00	15:00-18:00	18:00-21:00	21:00-00:00
Curtain	Closed	Closed	Closed	Closed	Open	Closed	Closed	Closed	Closed
Window	Open	Closed	Closed	Open	Open	Open	Open	Open	Open
Portable fan	On	On	On	On	On	On	On	On	On
Atrificial light	On	Off	Off	Off	Off	Off	Off	On	On

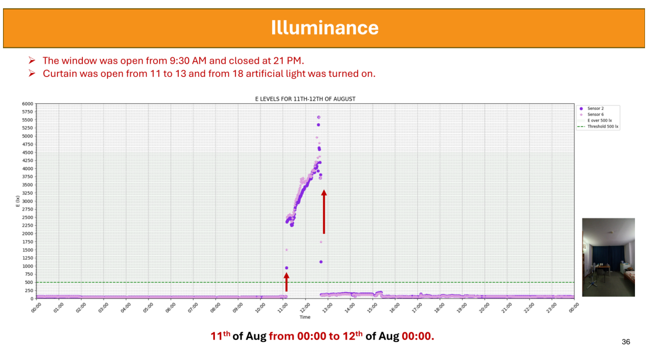


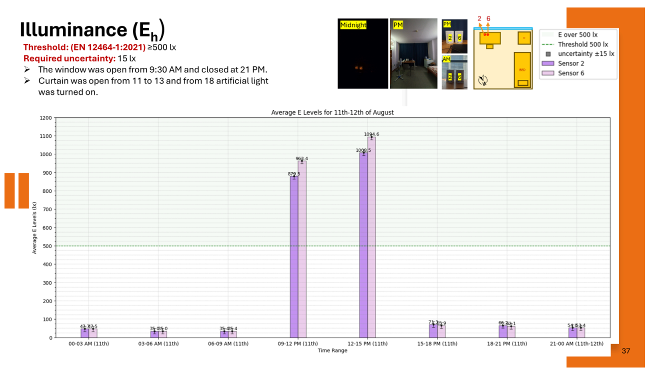






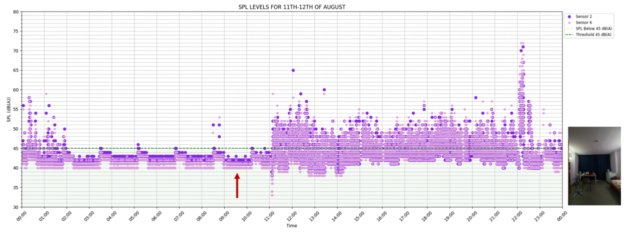






Sound Pressure Level

- The window was open from 9:30 AM and closed at 21 PM.
- Fan was turned on almost all day long.



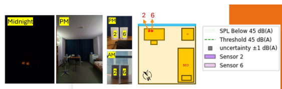
11th of Aug from 00:00 to 12th of Aug 00:00.

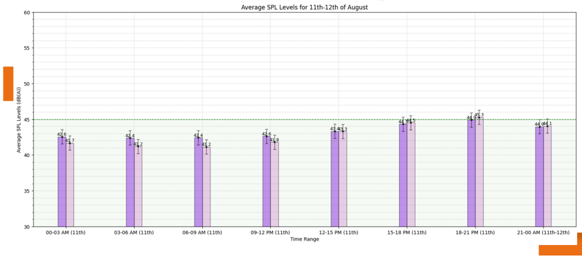
38

Sound Pressure Level (SPL)

Threshold: (NF S 31-080)
≤45 dB(A)
Required uncertainty: ± 1 dB

- The window was open from 9:30 AM and closed at 21 PM.
- Fan was turned on almost all day long.

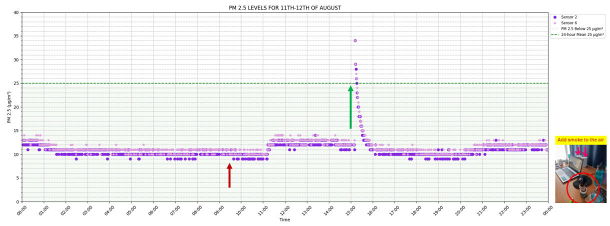




39

Particulate Matter 2.5

- The window was open from 9:30 AM and closed at 21 PM.
- Smudge test increased the PM 2.5 level in the room.



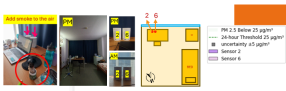
11th of Aug from 00:00 to 12th of Aug 00:00.

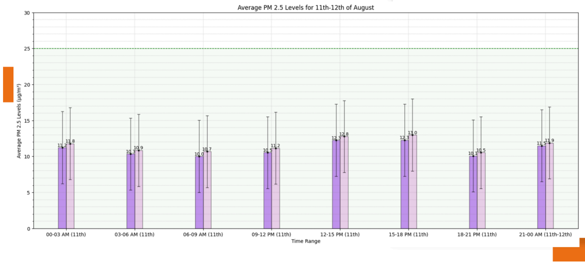
40

Particulate Matter ($PM_{2.5}$)

Threshold: (EN 16798-1:2019 (WHO guidelines))
24 h mean ≤ 25 µg/m³
Required uncertainty: ± 5 µg/m³

- The window was open from 9:30 AM and closed at 21 PM.
- Smudge test increased the $PM_{2.5}$ level in the room.

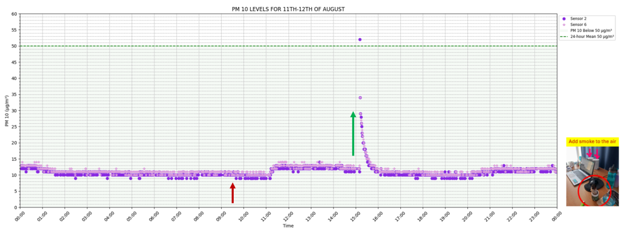




41

Particulate Matter 10

- The window was open from 9:30 AM and closed at 21 PM.
- Smudge test increased the PM 2.5 level in the room.



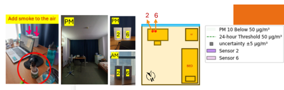
11th of Aug from 00:00 to 12th of Aug 00:00.

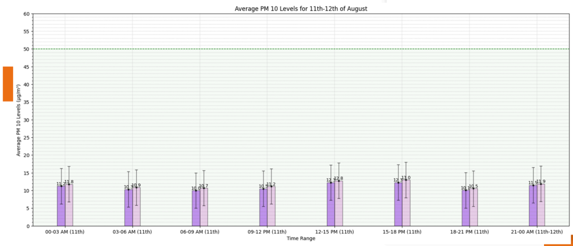
42

Particulate Matter (PM_{10})

Threshold: (EN 16798-1:2019 (WHO guidelines))
24 h mean ≤ 50 µg/m³
Required uncertainty: ± 5 µg/m³

- The window was open from 9:30 AM and closed at 21 PM.
- Smudge test increased the PM_{10} level in the room.

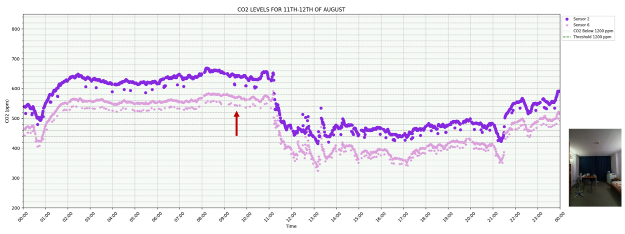




43

Carbon Dioxide

- The window was open from 9:30 AM and closed at 21 PM.



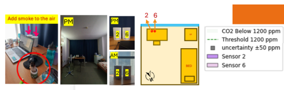
11th of Aug from 00:00 to 12th of Aug 00:00.

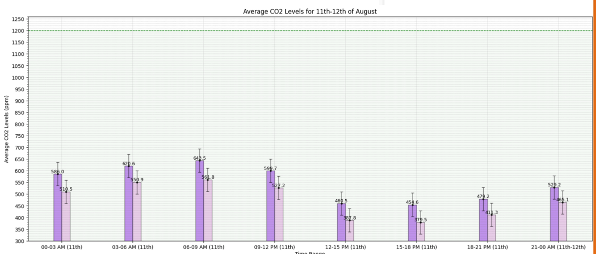
44

Carbon Dioxide (ΔCO_2)

Threshold: (EN 16798-1:2019) ≤1200 ppm
Required uncertainty: ± 50 ppm

- The window was open from 9:30 AM and closed at 21 PM.

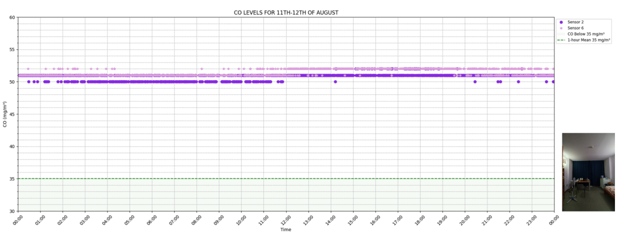




45

Carbon Monoxide

- The window was open from 9:30 AM and closed at 21 PM.



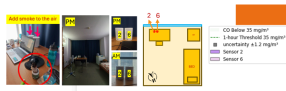
11th of Aug from 00:00 to 12th of Aug 00:00.

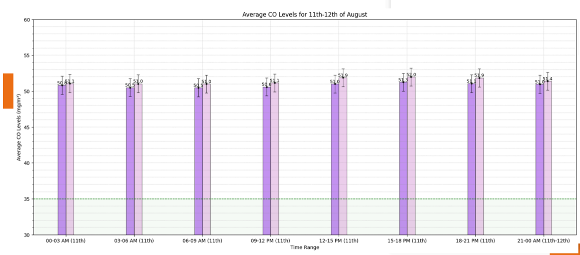
46

Carbon Monoxide (CO)

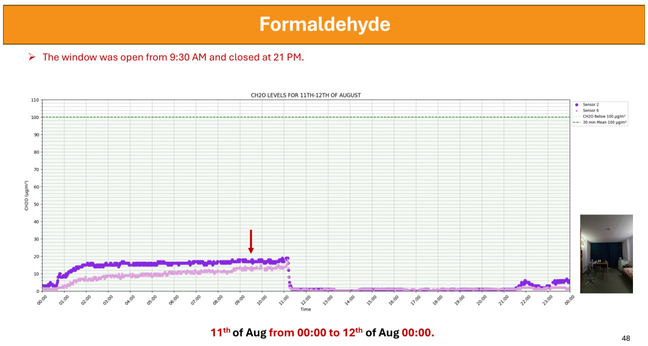
Threshold: (EN 16798-1:2019 (WHO guidelines))
1 h mean ≤ 35 mg/m³
Required uncertainty: ± 1.2 mg/m³

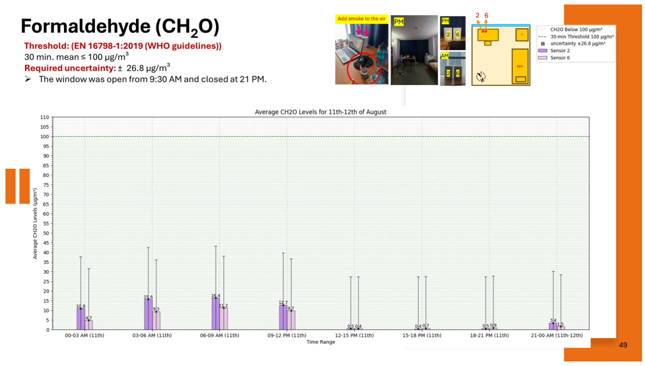
- The window was open from 9:30 AM and closed at 21 PM.

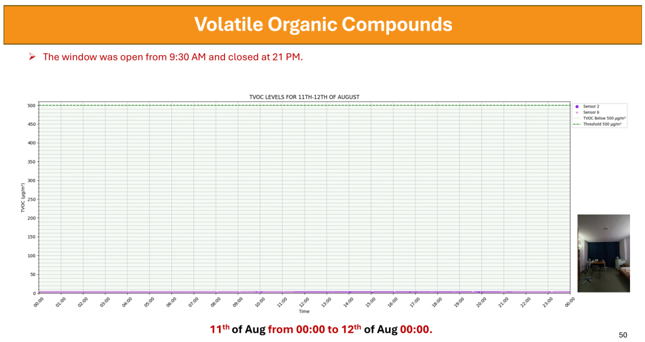


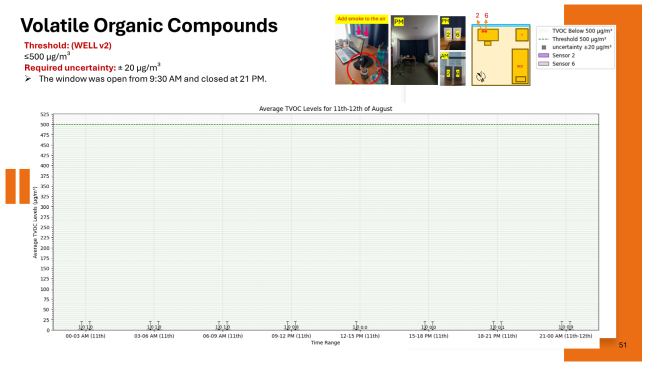


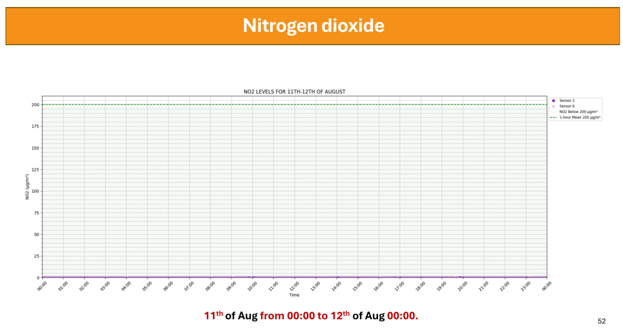
47

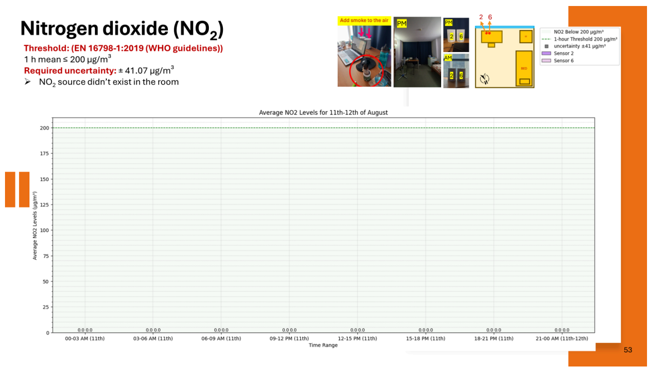

Formaldehyde
The window was open from 9:30 AM and closed at 21 PM.
CH2O LEVELS FOR 11TH-12TH OF AUGUST
Sensor 2
Sensor 6
CH2O Below 100 µg/m³
30-min Mean 100 µg/m³
Time
11th of Aug from 00:00 to 12th of Aug 00:00.
48


Formaldehyde (CH2O)
Threshold: (EN 16798-1:2019 (WHO guidelines))
30 min. mean ≤ 100 µg/m3
Required uncertainty: ± 26.8 µg/m3
The window was open from 9:30 AM and closed at 21 PM.
Add smoke to the air
PM
AM
BED
CH2O Below 100 µg/m³
30-min Threshold 100 µg/m³
uncertainty ±26.8 µg/m³
Sensor 2
Sensor 6
Average CH2O Levels for 11th-12th of August
Average CH2O Levels (µg/m³)
00-03 AM (11th)
03-06 AM (11th)
06-09 AM (11th)
09-12 PM (11th)
12-15 PM (11th)
15-18 PM (11th)
18-21 PM (11th)
21-00 AM (11th-12th)
Time Range
49

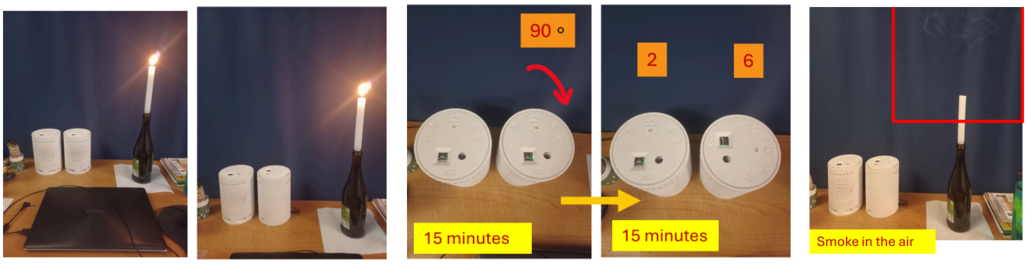

Volatile Organic Compounds
The window was open from 9:30 AM and closed at 21 PM.
TVOC LEVELS FOR 11TH-12TH OF AUGUST
Sensor 2
Sensor 6
TVOC Below 500 µg/m³
Threshold 500 µg/m³
Time
11th of Aug from 00:00 to 12th of Aug 00:00.
50

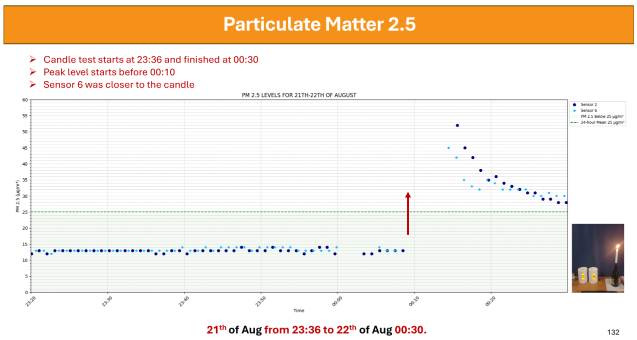

Volatile Organic Compounds
Threshold: (WELL v2)
≤500 µg/m3
Required uncertainty: ± 20 µg/m3
The window was open from 9:30 AM and closed at 21 PM.
Add smoke to the air
TVOC Below 500 µg/m³
Threshold 500 µg/m³
uncertainty ±20 µg/m³
Sensor 2
Sensor 6
Average TVOC Levels for 11th-12th of August
Average TVOC Levels (µg/m³)
00-03 AM (11th)
03-06 AM (11th)
06-09 AM (11th)
09-12 PM (11th)
12-15 PM (11th)
15-18 PM (11th)
18-21 PM (11th)
21-00 AM (11th-12th)
Time Range
51

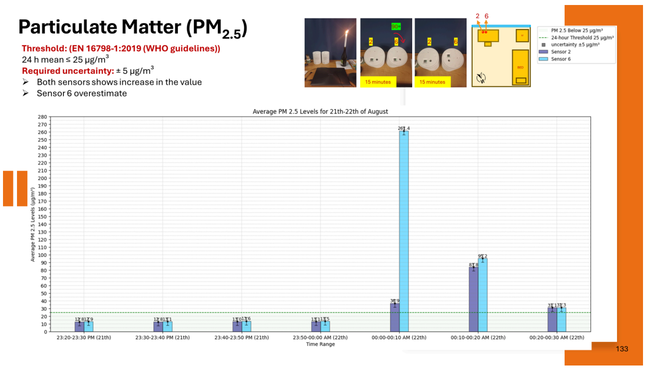

Nitrogen dioxide
NO2 LEVELS FOR 11TH-12TH OF AUGUST
Sensor 2
Sensor 6
NO2 Below 200 µg/m³
1-hour Mean 200 µg/m³
Time
11th of Aug from 00:00 to 12th of Aug 00:00.
52

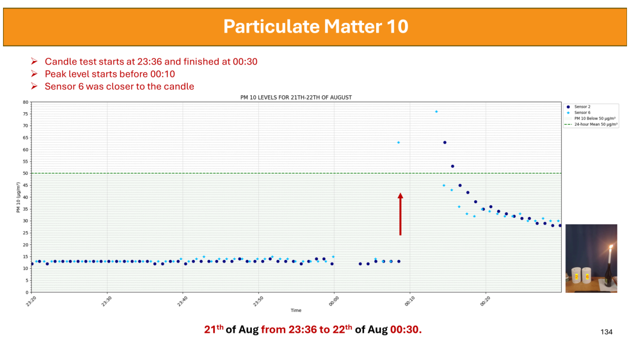

Nitrogen dioxide (NO2)
Threshold: (EN 16798-1:2019 (WHO guidelines))
1 h mean ≤ 200 µg/m3
Required uncertainty: ± 41.07 µg/m3
NO2 source didn't exist in the room
Add smoke to the air
NO2 Below 200 µg/m³
1-hour Threshold 200 µg/m³
uncertainty ±41 µg/m³
Sensor 2
Sensor 6
Average NO2 Levels for 11th-12th of August
Average NO2 Levels (µg/m³)
00-03 AM (11th)
03-06 AM (11th)
06-09 AM (11th)
09-12 PM (11th)
12-15 PM (11th)
15-18 PM (11th)
18-21 PM (11th)
21-00 AM (11th-12th)
Time Range
53

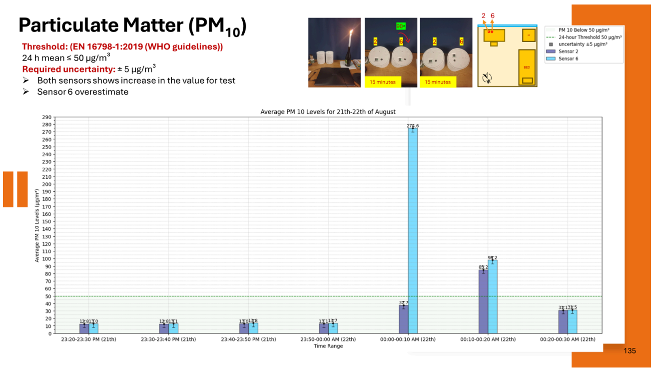
Candle test in-room measurement:

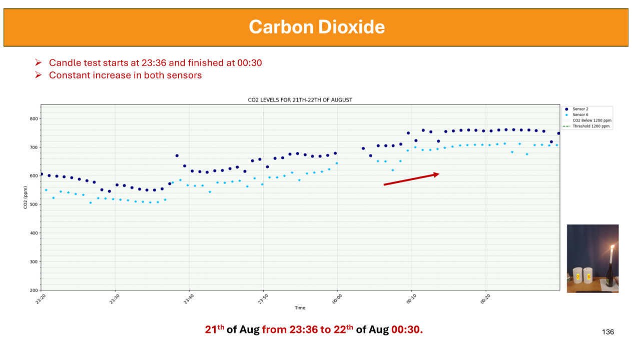


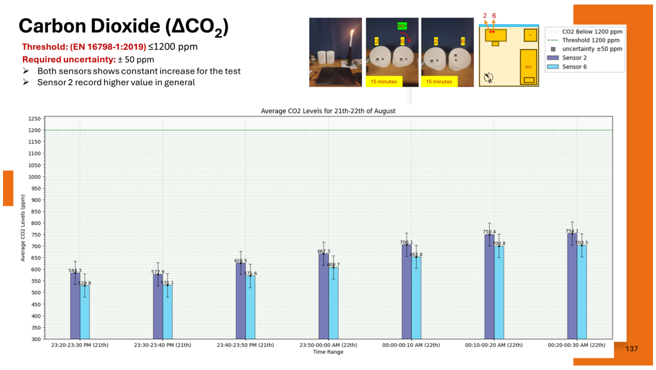






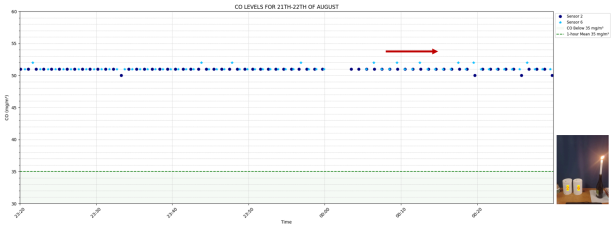






Carbon Monoxide

- Candle test starts at 23:36 and finished at 00:30
- No changes in the CO level



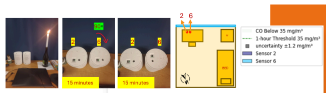
21th of Aug from 23:36 to 22th of Aug 00:30.

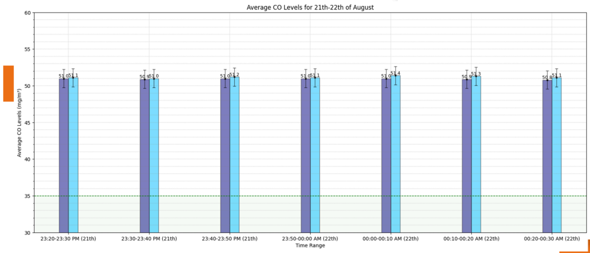
138

Carbon Monoxide (CO)

Threshold: (EN 16798-1:2019 (WHO guidelines))
1 h mean ≤ 35 mg/m^3
Required uncertainty: ± 1.25 mg/m^3

- Sensors did not show changes for the test
- The result are unexplainable

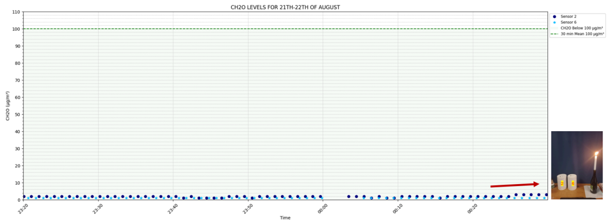




139

Formaldehyde

- Candle test starts at 23:36 and finished at 00:30
- Slight increase in both sensors after 00:20



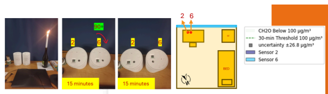
21th of Aug from 23:36 to 22th of Aug 00:30.

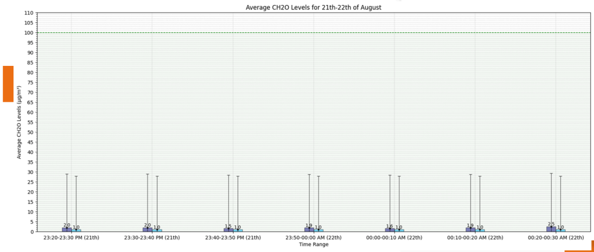
140

Formaldehyde (CH_2O)

Threshold: (EN 16798-1:2019 (WHO guidelines))
30 min. mean ≤ 100 µg/m^3
Required uncertainty: ± 26.8 µg/m^3

- Formaldehyde sensors show very slight increase for test





141

12. Methods and literature search

In this chapter, I will outline the methods and strategies used to gather and cite relevant literature for this thesis. A systematic approach to citation and literature search is crucial for ensuring the credibility and reliability of academic work.

Using the PICO (Patient/Problem, Intervention, Comparison, Outcome) framework, I systematically identified and selected pertinent studies, ensuring a comprehensive and focused review of the existing research.

In the pursuit of comprehensive and up-to-date scholarly resources for my thesis research, I utilized Scopus, Web of Science, and Elsevier ScienceDirect as primary tools to explore a wide array of academic literature. Leveraging their extensive databases spanning multiple disciplines, I conducted systematic searches using relevant keywords and Boolean operators to refine and tailor my inquiries. These platforms facilitated the efficient retrieval of a diverse range of research articles, conference papers, and other scholarly documents directly related to my thesis topic. Furthermore, the advanced search features and customizable alerts provided by Scopus, Web of Science, and Elsevier ScienceDirect proved invaluable in staying current with emerging research in my field of study.

PICO Framework:

- P (Patient/Problem): Define the patient group or problem.
- I (Intervention): Specify the intervention or exposure.
- C (Comparison): Determine the comparison group or alternative intervention.
- O (Outcome): Identify the outcomes of interest.

Using **Scopus** for research involves several steps to efficiently navigate the database and extract relevant information. Leveraging its extensive database spanning multiple disciplines, I conducted systematic searches using relevant keywords and Boolean operators to refine and tailor my inquiries. The PICO framework can be used to formulate research questions and identify relevant studies.

Web of Science is another powerful research database that provides access to multiple disciplines. Utilizing the PICO framework in Web of Science helps streamline the search process and enhance the relevancy of the results. The platform's advanced search features and filters further assisted in refining the search results, making it easier to identify studies.

Elsevier ScienceDirect is a leading full-text scientific database offering journal articles and book chapters. The PICO framework can be applied here to find specific and relevant literature efficiently. By structuring my searches around the PICO elements, I could narrow down the vast amount of available literature to those studies most relevant to my research questions. Additionally, the platform's advanced search options and customizable alerts helped me stay updated with the latest research developments in my field.

Integrated Method for Literature Search

- **Define Research Questions Using PICO Framework**
- **Conduct Searches in Scopus:**

    - Use relevant keywords and Boolean operators.
    - Apply the PICO framework to structure searches.
    - Refine and tailor inquiries using advanced search features.
- **Conduct Searches in Web of Science:**
    - Use the PICO framework to formulate research questions.
    - Utilize advanced search features and filters.
    - Conduct targeted searches to enhance relevancy.
- **Conduct Searches in Elsevier ScienceDirect:**
    - Apply the PICO framework to narrow down literature.
    - Use advanced search options for in-depth review.
    - Access full-text articles for comprehensive assessment.
    - Set up customizable alerts for latest research updates.

By following these steps, I was able to gather and evaluate a wide range of scholarly resources and focus the literature review for this thesis.