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PROMET&O PROJECT: OBJECTIVE/SUBJECTIVE BINOMIUM IN INDOOR ENVIRONMENTAL MONITORING. A FOCUS ON THE METROLOGICAL CHARACTERIZATION

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Abstract

The topic of Indoor Environmental Quality (IEQ) monitoring, meant as the sum of the four environmental domains (thermal, visual, acoustic, and air quality), is becoming increasingly relevant, mainly in tertiary-use spaces. The reason is to be found both in a growing interest in personal well-being, comfort, and productivity and in the advent of inexpensive and easy-to-use devices, the low-cost sensors. However, it is not possible to trace the clinical picture of the indoor environment based on the numerical quantity expressed by the sensor. It is necessary to combine these objective data with the subjective data of the user's Indoor Environmental Comfort (IEC). The PROMET&O (PROactive Monitoring for indoor EnvironmenTal quality & cOmfort) project, developed by a multidisciplinary team at the Polytechnic of Turin, composed of experts in building physics, electronic and computer engineering, fits into this perspective. One of the project goals is to produce an accurate, innovative, and low-cost continuous monitoring system in terms of both IEQ and IEC. For this purpose, a low-cost multi-sensor designed and built at the Polytechnic is used, for the acquisition of objective data (Air temperature, Relative Humidity, Sound pressure level, Carbon Dioxide (CO_2), Carbon Monoxide (CO), Particulate Matter 2.5 and 10 (PM2.5, PM10), Formaldehyde, Nitrogen Dioxide (NO_2), Total Volatile Organic Compounds (TVOC), Illuminance), and an ad hoc questionnaire, for the collection of subjective user feedbacks, correlating them with the objective ones, and returning them graphically on the graphical interface, which can be consulted by the user. Thus, it is an innovation that can reconcile the objective/subjective binomium in terms of indoor environmental quality.

The present thesis work is presented as a continuation of previous work, with a focus on the metrological characterization of the individual sensors that make up the internal organs of the multisensor. The accuracy of the entire multisensor in simultaneously monitoring all parameters and physical quantities depends on that of the individual sensors in the ranges of interest.

After an outline of the fundamental concept of uncertainty and it's calculation, the calibration and calibration verification, the reference standards dictating the conditions for performing a metrological characterization (for each of the four domains) were investigated. Next, a literature review was conducted on the topic of low-cost sensor calibration that answered some basic questions, namely, what reference standards and procedures were used, and whether the results were similar to those obtained for PROMET&O.

After that, the metrological characterization process performed by comparison with an accurate reference instrument was described generically. First, a calibration verification was performed since manufacturers already provide the nominal accuracy value of the sensor in the data sheets. In case it met the metrological requirements, imposed at the design stage following standards and guidelines, the actual accuracy value of the sensor has been verified by comparison with the reference instrument. If, on the contrary, the nominal accuracy of the sensor already exceeded the requirements at the beginning, a preliminary adjustment using Matlab software has been performed, and then a proper calibration check.

Finally, the settings, procedures, and results, in numerical and graphical form, for each test conducted are reported. So far, the sensors tested have been those of Temperature, Relative Humidity, Illuminance, Carbon Dioxide, and Sound Pressure Level.

SUMMARY

1. OBJECTIVE/ SUBJECTIVE BINOMIUM IN MONITORING THE QUALITY OF AN INDOOR ENVIRONMENT

Most of the scientific literature on the monitoring of indoor environmental quality focuses on the collection and subsequent analysis of objective data. These are sampled using increasingly cheap and user-friendly instruments, mainly low-cost sensors. They can be single or clustered to form a multi-sensor capable of analyzing several physical quantities simultaneously. Yet it has been shown that although the indoor environment meets performance requirements and thresholds imposed by law, its objective environmental quality is not synonymous with subjective personal comfort. Therefore, subjective data from occupants of designed spaces should also be taken into account for the definition of the quality of the indoor environment. Quality and comfort should therefore not be thought of as self-excluding elements but as part of a unicum. The next two paragraphs aim at highlighting the differences between the concept of quality and comfort in the four environmental domains, which are too often considered synonymous in daily life.

1.1 OBJECTIVE: INDOOR ENVIRONMENTAL QUALITY

The word "quality" defines a property characterizing a thing or situation, or a whole of them, as a specific mode of being, especially in relation to particular aspects and conditions, activities, functions and uses. Thus, it can be defined as a tangible and objective aspect. Specifically, in the complex topic of Indoor Environmental Quality (IEQ), it takes the form of the physical parameters that influence its 4 domains:

1. Thermal Quality
2. Visual Quality
3. Air Quality
4. Acoustic Quality

In general, indoor environmental conditions acceptable to most of the occupants are dictated by national and international standard, as EN, ISO or ASHRAE, in order to evaluate and design the indoor environment of buildings.

Even if it is necessary to consider simultaneously all the environmental quality parameters, often, standards deal with domain requirements one at the time.

ASHRAE and ISO, for example, succeeded in including both thermal and IAQ (Indoor Air Quality) requirements. Instead, lighting and acoustic requirements are discussed into separate standards.

1.1.1 Thermal Quality

The main requirements in term of thermal environmental quality are expressed in 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”.

Moderate environment is one of the three types of thermal environments, that are conventionally defined:

1. Moderate environments are those that require moderate intervention of the human thermoregulation system. They are characterized by:
   - homogeneous environmental conditions with reduced variability over time,
   - absence of large localized heat exchanges between the subject and the environment,
   - modest physical activity,
   - substantial uniformity of the clothing worn by the various operators.
2. Hot severe environments are characterized by:
   - non-homogeneous environmental conditions with considerable variability over time,
   - high operating temperature in relation to the activity performed and the clothing worn,
   - unevenness of the activities performed and the clothing worn by different operators,
   - the body's thermoregulation system intervenes considerably, through the mechanisms of vasodilation and sweating, to prevent the body from overheating excessively.

3. Severe cold environments are defined as those environments that require considerable intervention of the human internal thermoregulation system through vasoconstriction and shivering. They are characterized by:

    - homogeneous environmental conditions with little variability over time
    - low operating temperature values (<10°C)
    - uniformity of the activities performed and of the clothing worn by different operators.

Moreover ISO 7730-2005 allows to analytical determinate and interpretate thermal comfort through PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) and local thermal comfort criteria. In the end it provides with environmental conditions considered acceptable for general thermal comfort as well as those causing local thermal discomfort.

According to the standard, the thermal environmental quality is function of six parameters. Four of them are physical quantities, two are personal factors:

- Air Temperature (T_a)

  Air temperature, or more specifically dry bulb temperature, is the temperature measured in degrees Celsius (°C) by a common bulb thermometer. The measurement of this temperature is absolutely independent of the relative humidity of the air.

- Relative Humidity (RH)

  It is defined as the ratio between the amount of water vapor contained in a mass of air and the maximum amount of water vapor that the same mass of air can contain under the same temperature and pressure conditions while still in the aeriform phase but under saturated conditions. Relative humidity, whose synonym is "hygrometric grade", is measured in percent (%). When the relative humidity is 100 %, the moisture content in the air is the maximum compatible with that thermodynamic state. Introducing more vapor into the environment causes part of the water mass to condense, with its passage into a liquid phase. The amount of vapor that can be contained by a mass of air decreases as the temperature decreases (it becomes zero at about -40 °C).

Thermal comfort is particularly influence by this parameter. In moderate environment (Ta < 26°C and moderate activity level < 2 met), RH has a modest impact on thermal sensation. An increase of 10 % RH is perceived to be as warm as a 0.3°C increase in the operative temperature. The higher is the temperature and activities, the more is the RH influence.

- Mean Radiant Temperature

The mean radiant temperature can be defined as the temperature of a thermally uniform fictitious environment that would exchange the same radiant heat power with humans as is exchanged in the real environment. This quantity is measured in °C.

- Air Velocity

It is defined as the rate of motion of air in a given direction.

Air velocity is responsible for the sensation of movement that produces 'thermal effects' even without a change in temperature. An increase in air velocity promotes heat dissipation through the surface of the epidermis in the following ways:

1. Increase in heat dissipation by convection, as long as the air temperature remains lower than that of the epidermis.

2. Acceleration of evaporation and thus production of physiological cooling.

At low relative humidities (< 30 %) this effect is irrelevant as there is already intense evaporation even with still air; at high relative humidities (> 80 %) evaporation is in any case limited and air movement has little cooling effect. Evaporation can, on the other hand, be considerably accelerated at medium humidity (40-50 %): if the air is still, the layer closest to the epidermis quickly becomes saturated, preventing further evaporation; air movement, on the other hand, can ensure a change of air and thus continuous evaporation.

In summer, to counteract rising temperatures, air velocity can be increased following the next graph. The combinations of air velocity and temperature defined by the lines in this figure result in the same total heat transfer from the skin. The benefits on thermal sensation depend on clothing, activities and skin temperature.

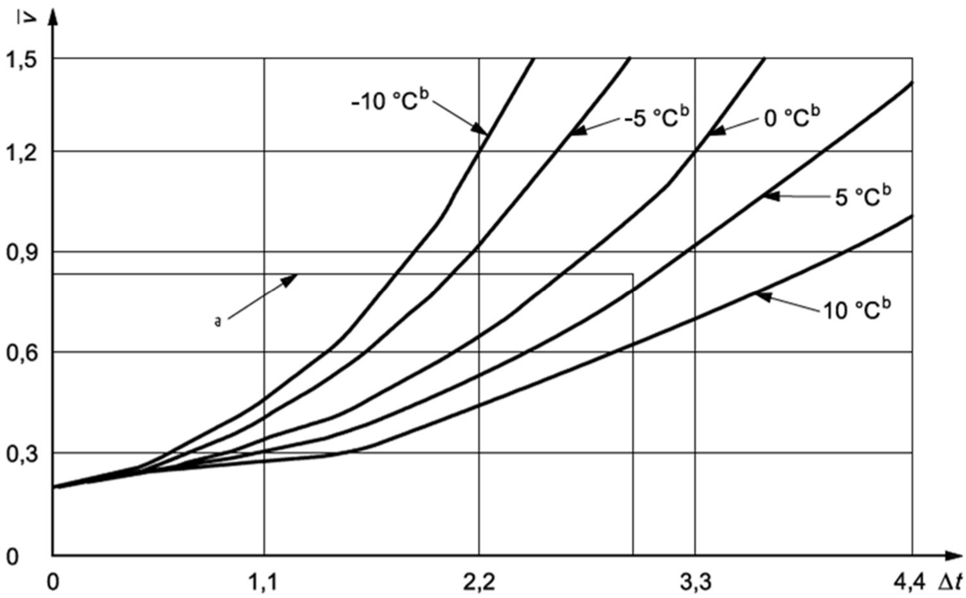


Fig. 1 Air velocity required to offset increased temperature. Taken from ISO 7730-2005.

- Clothing insulation

The thermal resistance of clothing is conventionally measured through the incoherent unit called clo. Like energy metabolism, thermal resistance is also usually measured by means of suitable tables. The thermal resistance of clothing is expressed in (m^2K) / W or, as is more frequently the case, in the incoherent unit clo. [1 clo = 0.155 (m^2 - K) / W]. 1 clo corresponds to the average resistance of winter clothing; summer clothing offers a thermal resistance of approximately 0.6 clo.

Table 1 Thermal insulation for typical combinations of garments

Work clothing	I_{cl}		Daily wear clothing	I_{cl}	
	clo	m²·K/w		clo	m²·K/w
Underpants, boiler suit, socks, shoes	0.70	0.110	Panties, T-shirt, shorts, light socks, sandals	0.30	0.050
Underpants, shirt, boiler suit, socks, shoes	0.80	0.125	Underpants, shirt with short sleeves, light trousers, light socks, shoes	0.50	0.080
Underpants, shirt, trousers, smocks, socks, shoes	0.90	0.140	Panties, petticoat, stockings, dress, shoes	0.70	0.105
Underwear with short sleeves and legs, shirt, trousers, jacket, socks, shoes	1.00	0.155	Underwear, shirt, trousers, socks, shoes	0.70	0.110
Underwear with long legs and sleeves, thermo-jacket, socks, shoes	1.20	0.185	Panties, shirt, trousers, jacket, socks, shoes	1.00	0.155
Underwear with short sleeves and legs, shirt, trousers, jacket, heavy quilted outer jacket and overalls, socks, shoes, cap, gloves	1.40	0.220	Panties, stockings, blouse, long skirt, jacket, shoes	1.10	0.170
Underwear with short sleeves and legs, shirt, trousers, jacket, heavy quilted outer jacket and overalls, socks, shoes	2.00	0.310	Underwear with long sleeves and legs, shirt, trousers, V-neck sweater, jacket, socks, shoes	1.30	0.200
Underwear with long sleeves and legs, thermo-jacket and trousers, Parka with heavy quitting, overalls with heave quilting, socks, shoes, cap, gloves	2.55	0.395	Underwear with short sleeves and legs, shirt, trousers, vest, jacket, coat, socks, shoes	1.50	0.230

- Work rate / metabolic heat

Energy metabolism, often referred to as metabolic expenditure, metabolic rate, metabolic heat energy, is divided into

  - Basal energy metabolism, which is necessary for the functioning of vital organs, and is that measured in a subject at physical and mental rest, under conditions of thermal neutrality (it counts approximately 45 W/m^2).
  - Activity-related energy metabolism, in particular tends to increase with physical and mental effort. For energy metabolism, it is customary to use an inconsistent unit of measurement, the met. Conventionally, 1 met = 58.2 W/m^2.

Metabolism is the complex of chemical and physical processes that take place in the human body (transformation of food, conversion of oxygen into CO_2, modification, growth and regeneration of the body's cells, physiological functions and motor functions and activities. Metabolic rate or energy metabolism (M) is the average difference in the unit of time between administered energy (food, drink and oxygen) and expelled energy. The metabolic rate is not constant over time; it depends on diet, external environmental conditions and the activity a person performs.

The human body, so that its internal energy and temperature do not vary, gives up energy to its surroundings: by convection with the air, by radiation with surrounding surfaces, by evaporation of water (from the skin and lungs). If the energy released is greater than the metabolic rate, the average body temperature decreases until a new steady state condition is reached. The body reacts to any imbalance by triggering complex thermoregulation mechanisms.

A table with metabolic rate values is provided by the regulations:

Table 2 Metabolic rates

Activity	Metabolic rate	
	W/m²	W/m²
Reclining	46	0.8
Seated, relaxed	58	1.0
Sedentary activity (office, dwelling, school, laboratory)	70	1.2
Standing, light activity (shopping, laboratory, light industry)	93	1.6
Standing, medium activity (shop assistant, domestic work, machine work)	116	2.0
Walking on level ground:		
2 km/h	110	1.9
3 km/h	140	2.4
4 km/h	165	2.8
5 km/h	200	3.4

The UNI EN ISO 7730-2005 contains also "Examples of thermal comfort requirements for different categories of environment and types of space" (Annex A). Here, the standard for identifying a Class A environment requires a PMV between -0.2 < PMV < 0.2. For a Class B environment, it requires a PMV between -0.5 < PMV < 0.5, and for a Class C environment a PMV between -0.7 < PMV < +0.7.

Table 3 Categories of thermal environment

Category	Thermal state of the body as a whole		Local discomfort			
	PPD %	PMV	DR %	PD %		
				Caused by		
				Vertical air difference temperature	Warm or cool floor	Radiant asymmetry
A	<6	-0.2<PMV<+0.2	<10	<3	<10	<5
B	<10	-0.5<PMV<+0.5	<20	<5	<10	<5
C	<15	-0.7<PMV<+0.7	<30	<10	<15	<10

The Minimum Environmental Criteria (CAM) in paragraph 2.3.5.7 'Thermo-hygrometric comfort' state that "conditions conforming to at least Class B according to ISO 7730-2005 in terms of PMV (Predicted Mean Vote) and PPD

(Predicted Percentage of Dissatisfied) must be guaranteed”. Furthermore, “compliance with the requirements set out in UNI EN 13788 pursuant to Ministerial Decree of 26 June 2015 must also be ensured with regard to all thermal bridges”.

Until now, the subject of “thermal comfort” has been dealt with, neglecting that UNI EN ISO 7730-2005 also indicates the main types of local discomfort. This term refers the sensation of thermal discomfort in one part of the body. For example, draughts can create discomfort at the neck level or cold floors can create discomfort at the foot level.

Four main local thermal discomfort are described by the standard:

1. Vertical air temperature difference

   Vertical temperature gradients can occur in the room, as warmer air tends to stratify upwards due to its lower density. This event, as well as implying higher energy consumption during the heating period, can produce discomfort sensations (hot to the head, cold to the feet). The UNI EN ISO 7730-2005 standard, in its previous version which did not consider adaptive comfort, stipulated that this temperature difference DT, at 0.1 m and 1.1 m (seated subject), should not exceed 3°C. This is equivalent to accepting a maximum percentage of dissatisfaction of 5%. Today, the model for determining the percentage of dissatisfied due to vertical air temperature differences is valid for temperature differences between head and feet of less than 8°C. The following graph shows that as the temperature difference increases, the percentage of dissatisfied also increases non-linearly.

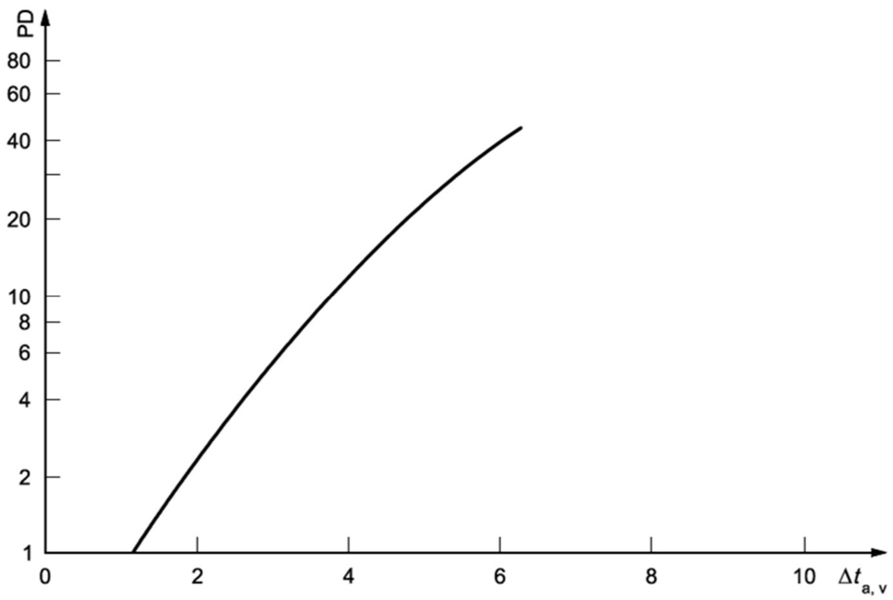


Fig. 2 Local discomfort caused by vertical air temperature difference. Taken from ISO 7730-2005

2. Warm and cool floors

This discomfort is caused by heat exchange between body and floor through the feet. Factors influencing this are the temperature of the floor, the thermal conductivity and heat capacity of the material from which the floor is covered, the type of footwear worn, and the time spent on it.

The model for determining the percentage of dissatisfaction with hot and cold floors in UNI EN ISO 7730-2005 was derived from studies of people standing and/or in a sedentary state wearing footwear.

The UNI 7730-2005 states that a floor temperature (T_{pav}) between 19°C and 26°C is suitable for not causing discomfort, also related to blood circulation problems. The upper limit is instead 29°C, only in the case of underfloor heating systems. This limit is equivalent to accepting a maximum percentage of dissatisfaction, PD, of 10%. For the summer season, there are no limits. For barefoot people, the floor temperature limits are slightly different: in this case, it is necessary to refer to ISO/TS 13732-2 (Methods for the assessment of human responses to contact with surfaces - Part 2: Human contact with surfaces at moderate temperature).

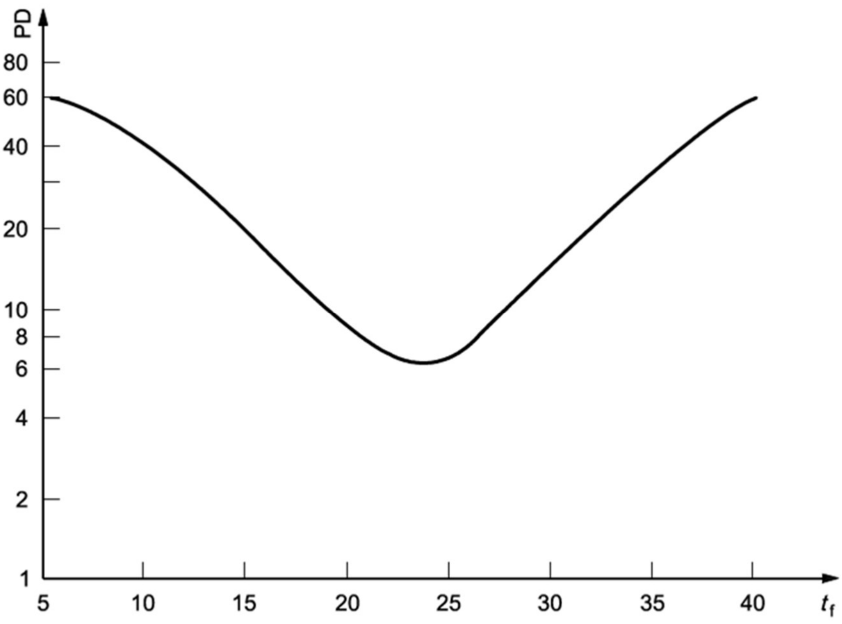


Fig. 3 Local thermal discomfort caused by warm or cold floors. Taken from ISO 7730-2005

3. Draughts

Often, air currents that hit the person produce feelings of localized thermal discomfort in that area of the body. UNI EN ISO 7730-2005 defines a coefficient, DR (Draft Risk, i.e. risk from air currents), which represents the percentage of discomfort from air currents. This model is applicable to people performing light, mainly sedentary activities with global thermal sensation close to neutral. Previously, draught discomfort was considered to depend only on air speed; in the new index, DR, however, the influence of air temperature (T_{amb}) and turbulence intensity (T_u) is also considered. It is necessary that the air velocity, at human height, does not exceed 0.15 m/s. UNI EN ISO 7730-2005 proposes for Class B a dissatisfaction rate of less than 20%.

4. Radiant asymmetry

Humans exchange energy by radiation with surfaces in their environment. Discomfort due to radiant asymmetry can result from the presence of surfaces with a temperature different from the ambient temperature, such as windows, uninsulated walls, machinery, hot or cold panels on walls, or ceilings. There are different rates of dissatisfaction (PD_{rad}) depending on the type of situation. UNI EN ISO 7730-2005 proposes four models to cover all cases of discomfort from radiant asymmetry:

- Warm ceiling, valid for asymmetric radiant temperature <23°C
- Cold wall, valid for asymmetric radiant temperature <15°C
- Cold ceiling, valid for asymmetrical radiant temperature <15°C
- Warm wall, valid for asymmetrical radiant temperature <35°C

These models depend solely on the value of the asymmetric radiant temperature, which is defined as the difference between the planar radiant temperature of two opposite surfaces. The planar radiant temperature is the temperature coming from the direction perpendicular to the measurement surface.

Moreover, UNI EN ISO 7730-2005 proposes for Class B a dissatisfaction rate of less than 5%.

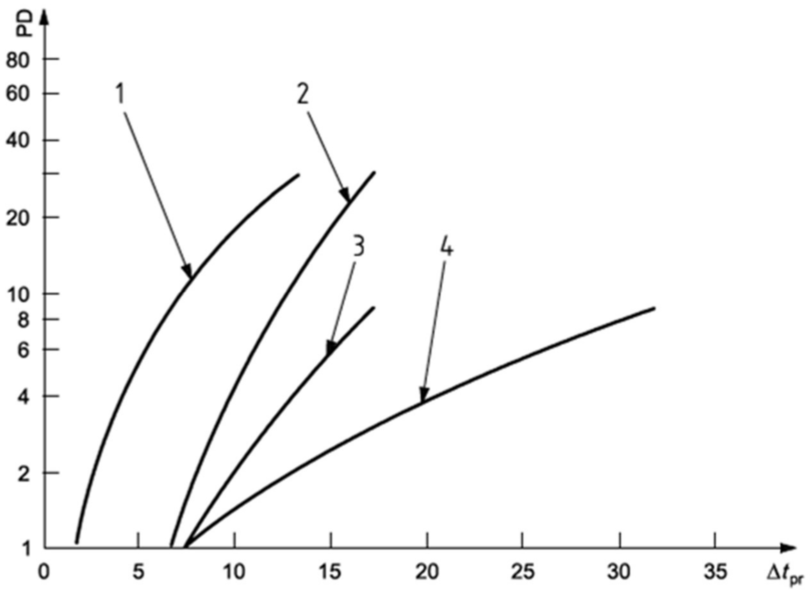


Fig. 4 Local thermal discomfort caused by radiant temperature asymmetry. Taken from ISO 7730-2005

ANSI/ASHRAE Standard 55-2017, Thermal Environmental Conditions for Human Occupancy, is another benchmark in terms of thermal quality. Briefly, it define both the indoor thermal environmental parameters (temperature, thermal radiation, humidity, and air speed) and personal factors (activity and clothing) whose coexistence makes the environment thermally acceptable to a majority of the occupants. The standard suggests to respect all the criteria (temperature, thermal radiation, humidity, air speed, activity and clothing) simultaneously, as indoor environmental quality is defined by the interaction of them. Moreover, it is specifically focused on thermal aspects, making negligible the influence of air quality, acoustics, and illumination parameters on comfort and health.

Finally, BS EN 16798-1:2019 "-Energy performance of buildings Ventilation for buildings" states the thermal, indoor air quality, visual and acoustic requirements for the indoor environment. Its focus is on the design of building systems with satisfactory energy performances. Moreover, this standard deals with design criteria for local thermal discomfort.

In the Italian legislative panorama, reliance is placed on D.lgs. 9 aprile 2008, n. 81, 'Testo Unico Sulla Salute E Sicurezza Sul Lavoro'.
in particular, annex IV of Tit. II deals with the topic of micro-climate.

The micro-climatic standards, in terms of thermal environment, can be summarized as follow:

- Microclimate conditions must not cause discomfort to workers.
- The temperature in the workplace must be appropriate to the human body during working time, taking into account the working methods applied and the physical efforts of the workers.
- The influence of the degree of humidity and concomitant air movement must be taken into account.
- Windows, skylights, and glazed walls must be such to avoid excessive sunlight in the workplace.
- When it is not convenient to change the temperature of the whole room, workers must be protected against excessively high or low temperatures by localized technical measures or personal means of protection.

- The equipment in the workplace must not produce excessive heat that can be a source of discomfort for workers.

1.1.2 Visual Quality

Visual quality in work environments is guaranteed if required illuminances are accomplished, as well as further qualitative and quantitative needs:

1. Visual comfort, reached if occupants feel satisfied with the luminous environment (see paragraph 1.2.5)
2. Visual performance, if occupants can accomplish their visual task, in any condition and during long time.
3. Safety (see paragraph 1.2.5).

The photometric quantities used to outline visual comfort are:

- Luminance distribution

Luminance is the ratio of the luminous flux emitted or reflected by a surface, per unit solid angle in a given direction, to the emitting surface projected onto a plane perpendicular to that direction [cd/m^2]. It affects the adaption level of the eyes, and thus task visibility. A satisfactory luminance distribution may increase:

  - visual acuity
  - contrast sensitivity
  - efficiency of the ocular functions

This parameter also influence visual comfort. It is important to remind that an excessive luminance increase the risk of glare and it causes eyes fatigue due to constant re-adaption, as well as, not enough luminance makes the working environment less stimulating.

Table 4 Luminance value for environmental component (EN 12464-1)

Environmental component	Luminance [cd/m²]
Floors	10-100
Walls	50-200
Roofs	100-300
Windows	200-500
Equipment	200-1000
Task area	30-100
Surrounding area	L≥1/3 L task area

- Illuminance

Illuminance is the ratio of the luminous flux incident on a surface to the surface itself [lx]. Illuminance and its distribution over the visual task area and surrounding area have a great influence on how quickly, safely and comfortably people perceive and perform the visual task.

EN 12464-1:2021 defines the average maintained illuminance (E_m) to ensure visual comfort and performance in an office.

The values of the average maintained illuminance refer to usual visual conditions and take into account the following factors:

- psycho-physiological aspects
- visual task requirements
- ergonomics of vision
- practical experience
- safety
- economy

If visual conditions differ from the assumed norm, the illuminance value may be varied by at least one step on the illuminance scale.

The standard recommends increasing the average illuminance maintained when:

- the visual task is critical;
- errors are costly to correct;
- accuracy and high productivity are very important;
- the worker's visual capabilities are lower than normal;
- the details of the visual task are exceptionally small or with low contrast;
- the visual task must be performed for exceptionally long periods.

Conversely, the average illuminance maintained may be reduced when:

- the details of the visual task are exceptionally large or with high contrast;
- the visual task is to be performed for an exceptionally short time.

Table 5 Illuminance value for environmental component (EN 12464-1:2021)

Type of space	Average illuminance level [lx]
Entrances and corridors	50-100-150
Hall	100-150-200
Operations office	200-300-350
Executive office	300-500-750
Conference rooms	200-300-500
Auditorium	150-200-300

- Glare

Glare is the visual sensation produced by surfaces with high luminance within the visual field and can be perceived as discomfort (or direct) or disability (or reflected) glare. EN-12464-1:2021 specifies that the disturbing glare produced by luminaires must be evaluated using the CIE tabular method of the Unified Glare Rating (UGR), based on the following formula:

$$UGR = 8 \cdot \log_{10}\left(\frac{0.25}{L_b} \sum \frac{L^2 * \omega}{p^2}\right)$$

Where

L_b; L = luminances of the background and luminous parts of the luminaires

ω = solid angle subtended by the luminaires

p = Guth position index

The standard reference values of the UGR are between 10 (no glare) and 30 (considerable physiological glare) spaced by 3 units (10, 13, 16, 19, 22, 25 and 28), to be found in the two directions of view (transverse and longitudinal to the luminaire): the lower the value, the less direct glare.

In the following table the maximum UGR value for each type of environment is indicated:

Table 6 Glare index for type of environment (EN 12464-1:2021)

Type of environment	Glare Index [UGR]
Entrances and corridors	25
Hall	22
Operations office	13-19
Executive office	19
Conference rooms	22
Auditorium	25

In order to reduce or limit reflected glare it is possible to make particular design choices, such as:

- appropriate arrangement of luminaires and workplaces,
- surface finish (matt surfaces),
- reduction of luminaire luminance,
- increasing the luminous area of the luminaire,
- bright walls and ceilings

- Directional lighting of visual tasks

The right balance of diffuse lighting and directional lighting, i.e. coming from a specific direction, can enhance a specific visual task. This can highlight objects, and make the working environment more comfortable and stimulating.

- Colour appearance of the light

The colour appearance of a lamp refers to the apparent colour (chromaticity) of the emitted light. It is defined by its correlated colour temperature (T_{cp}).

This parameter arises from a comparison with the light variations of a heated black body. As the temperature increases, the black body gradually changes from red to orange, to yellow, to white, to bluish-white. The colour temperature of a light source is precisely the temperature, expressed in Kelvin (K), at which the colour of the black body will correspond exactly to that of the light source.

Table 7 Correlated colour temperature and its appearance

Colour appearance	Correlated colour temperature (T_{cp}) [K]
Warm	< 3300
Neutral	3000-5300
Cool	> 5300

- Colour rendering

Colour rendering is an index that defines how well a luminaire is able to render colours and the human skin as illuminated by sunlight. The colour rendering index (R_a or CRI for Colour Rendering Index) ranges from 0 to 100 and decreases as the quality of colour rendering decreases. UNI EN 12464-1 recommends not using lamps with an index below 80 in workplaces where people stay and/or work for long periods. An index of less than 80 is permitted as an exception if the room to be illuminated is very high, but in any case, lighting with a higher colour rendering index must be ensured at fixed workplaces that are continuously occupied and where the colours of safety signs must be recognized.

- Flicker and stroboscopic effects

The flicker phenomenon is defined as the perception of visual instability induced by a light stimulus whose luminance, or spectral distribution, fluctuates over time, for a static observer in a static environment (CIE publication TN 006:2016). This phenomenon occurs when, under static conditions, it is perceived that light does not remain constant in time and tends to flicker or flicker.

The stroboscopic effect is in fact defined as a change in the perception of the movement of an object, induced by a light stimulus, the luminance or spectral distribution of which appears to fluctuate over time for a static observer in a non-static environment (CIE publication TN 006: 2016).

All light sources powered by electricity emit a flicker. Normally flickers below 70Hz are not perceived by the human eye and therefore do not cause any discomfort.

If, on the other hand, they reach higher frequencies they can cause distraction, discomfort, and headaches and suffer the stroboscopic effect if they exceed 100Hz. Stroboscopic effects can lead to dangerous situations due to an altered perception of the movement of rotating or reciprocating machinery.

EN 12464-1 recommends the design of lighting systems that limit flickering and stroboscopic effects as much as possible.

1.1.3 Air Quality

Many world organizations have pronounced themselves on the concept of "acceptable Indoor Air Quality". Today the most reliable definition is expressed by the standard ASHRAE 62/2016: "air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction". This definition includes both the concept of safety (the air must not cause damage to health) and the ergonomic concept of comfort (the air must be fresh, pleasant, non-irritating,...).

Italian Ministry of Health, indeed, defines "Indoor pollution" as "the modification of the normal composition or physical state of the indoor atmospheric air, due to the presence in it of one or more substances in such quantity and with such characteristics as to alter the normal environmental and health conditions of the air itself, and such as to constitute a danger, or direct or indirect damage to human health".

The WHO (World Health Organization) itself has also recognized that indoor pollution constitutes a major environmental risk, the main causes of which lie in a large number of polluting sources in living and working environments on the one hand, and in reduced ventilation rates on the other, generally linked to energy-saving reasons (massive insulation and increasingly airtight windows).

In the last decades even more researchers have been focused on this topic, in order to find out minimum optimal requirements and thresholds. As sample, in a study by Cumo et al.(Cumo et al., 2006), a global IAQ index is proposed as the product of specific indices for individual pollutant families (e.g. chemical, radioactive, electromagnetic), calculated as the difference between the concentration value measured in the environment and the maximum admissible value deduced from scientific literature or sector standards. The result represents the global index of indoor air quality, varying between 0 and 1, where 0 represents an unacceptable environmental condition from the IAQ point of view, and the unit value represents the uncontaminated environment.

It is important to remind that outdoor air is polluted itself. It is mainly affected by:

- nitrogen oxides (NO_x: NO, NO_2, NO_3)
- sulphur oxides (SO_x)
- carbon oxides (CO, CO_2)
- volatile organic compounds (VOC)
- airborne particulates (dust)
- ozone (O_3)
- microbiological contaminants (bacteria, viruses).

Thus, when outdoor air infiltrates inside the building, both outdoor and indoor pollutants worsen the Indoor Air Quality of the environment.

Indoor sources of pollution may be divided into three categories:

- chemical agents;
- physical agents;
- biological agents.

Chemical agents such as nitrous oxide and nitrogen dioxide, sulfur oxides, carbon monoxide, ozone, atmospheric particulate matter, benzene, volatile organic compounds, formaldehyde, polycyclic aromatic hydrocarbons, asbestos, are produced by multiple indoor sources, primarily occupants and activities, as well as building materials and air conditioning systems.

Physical agents responsible for poor indoor air quality include radon (a radioactive noble gas that is harmful in high concentrations) and electromagnetic fields.

Biological agents include microorganisms (fungi, bacteria, viruses, parasites, protozoa), indoor allergens (dust mites, plant and animal allergens) and molds. The health risks associated with exposure to these pollutants can be classified into three types:

- infectious,
- toxic,
- allergic.

The effects may manifest themselves with different intensity depending on various factors, such as the physical condition and susceptibility of each individual.

Table 8 Air pollutants and sources where they come from (Taken from: Ministero della salute)

SOURCES	POLLUTANT
Gas or coal combustion processes for heating and/or cooking, wood-burning fireplaces and stoves, flue gas vehicles.	Combustion products (CO, NO_x, SO_2, particulate matter)
Building materials and insulation	Asbestos, man-made glass fibers, particulate matter, radon; biological agents (due to presence of moisture and/or dust)
Coating materials and carpeting	Formaldehyde, acrylates, VOCs, and biological agents (due to the presence of moisture and/or dust)
Furniture	Formaldehyde, VOCs and agents biological (due to the presence of moisture and/or dust)
Cleaning liquids and products	Alcohols, phenols, ammonia, VOCs
Photocopiers	Ozone (O_3), toner dust, volatile hydrocarbons (VOCs)
Cigarette smoke	Polycyclic hydrocarbons, VOC formaldehyde, CO, fine particulate matter
Air conditioning systems	CO_2 and VOCs (due to poor hourly turnover or excessive recycling); biological agents

	(due to lack of cleaning/maintenance)
Dust	Biological agents (indoor allergens: mites)
People	CO_2 and biological agents (bacteria, viruses, etc.)
Animals	Indoor allergens (hair, etc.)
Outdoor air	Smog, etc.

The crux of the matter is to define a maximum concentration level for the main pollutants of the indoor environment, that has not to be overcome in order to avoid serious health consequences.

WHO was the first to point out some guidelines in 1987. Their most recent update was in 2021. In this report the guidelines became even more strict than the one in 2005, based on review on scientific literature.

Also other organizations introduced their own guidelines. EPA (Environmental Protection Agency) published National Ambient Air Quality Standards (NAAQS) in 1990, to set the threshold for six principal pollutants (Carbon monoxide, Lead, Nitrogen Dioxide, Ozone, Particle pollution, Sulfur Dioxide). It defines two categories of standards: Primary standards for public health protection; Secondary standards for public welfare protection, also for animals, vegetation and buildings. Furthermore these standards are periodically revised.

LEED, Leadership in Energy and Environmental Design, one of most popular and adopted green building rating system, presents its air quality assessment standards in 2014, as well.

The following table (Tab 9) shows a comparison between the aforementioned standards.

Table 9 Comparison between IAQ standards

POLLUTANT	LEED		EPA		WHO		
	MAXIMUM CONCENTRATION	AVERAGE TIME	MAXIMUM CONCENTRATION	AVERAGE TIME	MAXIMUM CONCENTRATION		AVERAGE TIME
					2005	2021	
PM 10	50 µg/m³	n.r.	150 µg/m³	24 h	50 µg/m³	45 µg/m³	24 h

PM 2.5	15 µg/m³	n.r.	35 µg/m³	24 h	25 µg/m³	15 µg/m³	24 h
OZONE (O_3)	0.075 ppm	n.r.	0.070 ppm	8 h	100 µg/m³	100 µg/m³	8 h
CARBON MONOXIDE (CO)	9 ppm	n.r.	9 ppm	8 h	n.r.	4 mg/m³	24 h
FORMALDEHYDE	27 ppb	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.
TVOC	500 µg/m³	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.
LEAD	n.r.	n.r.	0.15 µg/m³	3 months	n.r.	n.r.	n.r.
NITROGEN DIOXIDE (NO_2)	n.r.	n.r.	100 ppb	1 h	n.r.	25 µg/m³	24 h
SULFUR DIOXIDE (SO_2)	n.r.	n.r.	75 ppb	1 h	20 µg/m³	40 µg/m³	24 h

The most common and affective indoor pollutants are:

- Carbon monoxide (CO)
  it is an odourless, colourless, flammable and very toxic gas produced by incomplete combustion reactions of carbon compounds. Taken up by the body by inhalation, it has the ability to bind firmly to red blood cells and is exchanged for oxygen causing hypoxia, fatigue, drowsiness, migraine headaches, and difficulty breathing, leading to death.

- Nitrogen dioxide (NO_2)
  It is a red-brown gas with a strong, pungent odor, highly toxic and irritating, produced by all high-temperature combustion processes (heating plants, vehicle engines, industrial combustion, power plants, etc.). Being denser than air, it tends to remain at ground level. It is responsible for the formation of photochemical smog as it is the intermediate for the production of dangerous secondary pollutants such as ozone, nitric acid and nitrous acid. These, once formed, can be deposited on the ground by wet (e.g., acid rain) or dry means causing damage to vegetation and buildings. The effects on human health are mainly acute (respiratory dysfunctionality and

bronchial reactivity (mucosal irritation), or chronic (impaired respiratory function and increased cancer risk).

- PM2.5 and PM10

  Atmospheric particulate matter refers to the set of solid and liquid particles, with a wide variety of chemical, and physical characteristics, dispersed in the atmosphere for sufficiently long times to undergo diffusion and transport phenomena, whose main components are sulfate, nitrate, ammonia, sodium chloride, carbon, and mineral dust. PM10 is the fraction of particles collected by a sorting system for an aerodynamic diameter of 10 μm. Similarly for PM2.5.

  Sources can be natural or anthropogenic, primary or secondary (as a result of chemical and physical transformations).

  The risk for the human organism consists of the possibility of the smallest particles penetrating deep into the respiratory system. The toxicity of particulate matter can be amplified by its ability to absorb gaseous substances and heavy metals (some of which are potent carcinogens).

- Total volatile organic compounds (TVOCs)

  Volatile organic compounds, collectively referred to as total volatile organic compounds, are chemical compounds of different natures that are characterized by volatility in the environment. The indoor environment has multiple sources of VOCs:
    - the occupants themselves,
    - cleaning products and cosmetics,
    - heating devices,
    - glues, paint, solvents,
    - cigarette smoke,
    - work tools such as printers and copiers,
    - building materials,
    - furnishings,
    - outside air.

The emissions of these compounds can be:

- primary, meaning VOCs are present in the material,
- secondary, when VOCs are formed in the installed material, slower than primary.

The rate of emission depends on both the diffusion of VOCs into the product and their evaporation.

Harmful effects on human health range from simple discomfort to central nervous system effects.

In the Italian regulatory environment, measures and directives have been taken to regulate indoor TVOC concentrations:

- Directive 2006/161 -Legislative Decree No. 161 of March 27, 2006 on: Limitation of emissions of VOCs due to the use of organic solvents in certain paints and varnishes (2006). It makes the placing on the market of paints and coatings used in construction subject to a different maximum VOC content for each category, specific labeling requirements.

Table 10 Limitation of emissions of VOCs due to the use of organic solvents in certain paints and varnishes (D.M. 161/06)

Products	Base	Limits (g/l)	
		2007	2010
Interior opaque wall and ceiling paints.	water	75	30
	solvent	400	30
Wood paints and impregnates for interior and exterior finishes.	water	150	130
	solvent	500	400

- EU Directive 2004/42 - Limitation of emissions of volatile organic compounds due to the use of organic solvents in certain paints and varnishes and vehicle refinishing products.
- EU Directive 2010/79 - Limitation of emissions of volatile organic compounds. Adaptation to technical progress of Annex III of Directive 2004/42 with Definition of measurement methods.

- Decreto Italia 11/01/2017 - CAM: Minimum environmental criteria for green public procurement for interior furniture, construction and textile products.

Table 11 VOC concentration values in relation to possible health effects

Concentration range (μg/m³)	Effects
< 200	Comfort
200-3000	Possible occurrence of Various diseases
3000-25000	Discomfort
>25000	Toxicity

- Formaldehyde

  It is a colorless volatile organic compound with a pungent odor and high irritant power. By reacting with urea, it can develop highly toxic VOCs. Therefore, its effects on human health also include serious diseases, e.g. occurrence of cancer. Emissions of this gas are continuous and last for years. It is in fact mainly absorbed by carpets and fabrics, and then gradually released into the environment. The main items at risk of formaldehyde emission are:
  - plywood panels
  - honeycomb panels
  - Chipboard panels
  - technical foams
  - carpets
  - curtains

  In the Italian regulatory framework, DM 10/10/2008 stipulates for the wood-furniture sector and, in particular, wood-based panels, the obligation to comply with at least class E1. It stipulates that formaldehyde (HCHO) emissions must be less than 0.1 ppm (0.124 μg/m³).

  In European legislation, however, there are multiple regulations governing formaldehyde emissions:

- UNI EN 13986:2015- Wood-based panels for use in construction - Characteristics,

conformity assessment and marking, which provides for classes E1plus, E1,E2.

- UNI EN 717-1:2014 - Wood-based panels Determination of formaldehyde release - test chamber method.
- UNI EN ISO 12460-3:2015 - Gas analysis method - Determination of the release accelerated formaldehyde from coated and uncoated wood-based panels, focusing on periodic production control testing.
- UNI EN ISO 12460-5:2016 - Extraction method, that provides:
    - "Drilling" method used to determine the formaldehyde content in panels made of unlaminated and uncoated wood-based
    - periodic production control tests.

It is possible to obtain an improvement of the IAQ through:

1. Pollutant removal at the source, that can be achieved if pollutant production occurs in a limited space.
2. Pollutant dilution, that is the physical mechanism by which ventilation reduces the concentration of pollutants.

   From the mass balance on an environment results in:

$$\dot{Vo} = \frac{\dot{q}}{Ci - Co}$$

$\dot{Vo}$ =[m^3/s] is the outdoor air flow rate

$\dot{q}$ =[m^3/s] is the pollutant flow rate produced in the room

Ci = [m^3 pollutant/m^3 air] is the concentration of pollutant in indoor air in the area occupied by people (indoor)

Co =[m^3 pollutant/m^3 air] is the concentration of pollutant in the outdoor air (outdoor)

To determine the flow rate of outside air to be introduced into the room a reference standard is EN 15251:2007, updated as 16798-1:2019, which for nonresidential buildings provides three criteria:

1. Criterion 1 (performance): a criterion based on the concept of dilution of each individual pollutant. It stipulates that the required airflow rate is the sum of that needed to dilute bio effluents from people (share proportional to the number of occupants) and that needed to dilute contaminants emitted by building components (share proportional to the building area).

Table 12 Design ventilation rates for sedentary, adults, non-adapted persons for diluting emissions (bio effluents) from people for different categories

Category	Expected percentage dissatisfied	Airflow per non-adapted person l/s (per person)
I	15	10
II	20	7
III	30	4
IV	40	2.5

2. Criterion 2 (prescriptive): the required airflow rate is given in terms of flow rate per person or per square meter of floor area and contributes to the dilution of contaminants emitted by both people and building components.

Table 13 Default design CO_2 concentrations above outdoor concentration assuming a standard CO_2 emission of 20 L/(h per person)

Category	Corresponding CO_2 concentration above outdoors in PPM for non-adapted persons
I	550 (10)
II	800 (7)
III	1350 (4)
IV	1350 (4)

3. Criterion 3 (ventilation on demand): the required air flow rate is determined from the dilution equation based on the maximum allowable difference between indoor and outdoor CO_2 concentrations.

Table 14 Default predefined design ventilation air flow rates for an office (non-adapted person)

Category	Total design ventilation air flow rate for the room	
	l/s (per person)	l/(s*m^2)
I	20	2
II	14	1.4
III	8	0.8
IV	5.5	0.55

Indeed The ASHRAE 62.1 standard helps in designing and controlling a HVAC system. Tab 15 shows the methodology to calculate outdoor air flow rate in office buildings, according to the minimum ventilation requirements. It is based on type of zone, floor area and occupancy density. The main concept is to let enough outdoor air to dilute indoor pollutants.

Table 15 Minimum ventilation rates in office building (The ASHRAE 62.1)

Occupancy category		People outdoor air rate	Area Outdoor air rate	Default values	
				Occupant density	Combined outdoor air rate
		m^3/h Person	m^3/h m^2	#/100 m^2	m^3/h Person
Office building	Break rooms	2.5	0.6	50	3.5
	Office space	2.5	0.3	5	8.5
	Reception areas	2.5	0.3	30	3.5
	Main lobbies	2.5	0.3	10	5.5

Finally, the Italian standard D.lgs 81/08, in chapter 1.9.1 “Microclima”, deals with the topic of Ventilation of enclosed workplaces. It states that: “In enclosed workplaces, it is necessary to ensure that taking into account the methods of work and physical exertion to which workers are subjected, they have sufficient healthy air obtained preferably by natural openings and when this is not possible, by ventilation facilities. If an aeration system is used, it must be kept in working order at all times. Any failure must be reported by a control system when this is necessary to safeguard the health of workers".

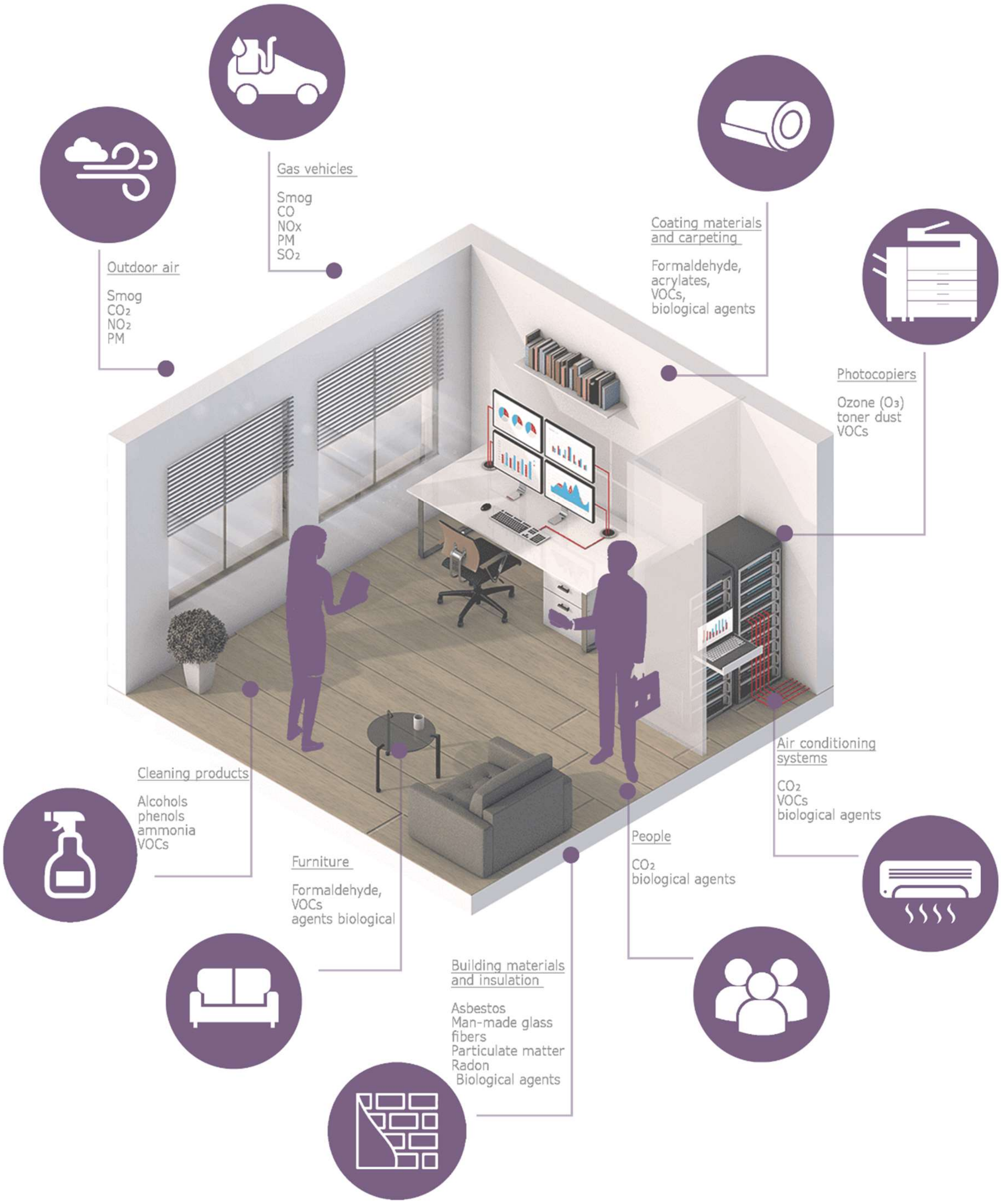


Figure 1 Representation of pollutants generated by sources inside an office.

1.1.4 Acoustic Quality

Acoustic quality is a fundamental element in the design of rooms and depends mainly on their geometry, the type of materials they are made of, and their arrangement with respect to sound sources, sound reverberation, and total background noise level.

On the other hand, for proper acoustic design of a room, it is necessary to define the intended use. As sample, open plan office design is one of the most challenging type in terms of acoustic quality. Lot of people perform different activities, more or less noisy, in the same space. Such a large number of scenarios in the same environment requires a special attention to acoustic aspects as well, in order to enable everyone using the same space to maintain high concentration and productivity.

The balance of the acoustic set-up must allow, for example:

1. That communication and listening levels remain optimal among members of a group, while not precluding to ensuring the privacy of their conversations.
2. That people engaged in video conferencing and telephone calls or who are simply socializing do not disturb those who are working.
3. The best compromise between absence of background noise and an excessive level of background noise.

It is necessary a brief introduction on the concept of acoustic and sound.

First of all, sound is characterized by the propagation of pressure waves in an elastic medium due to the rapid succession of compressions and expansions of the medium itself. For the phenomenon to occur and propagate, the presence of a sound source and an elastic medium that allows its propagation is necessary, and it is because sound cannot spread in a vacuum. The sound source consists of a vibrating element that transmits its motion to particles in the surrounding medium, which oscillate around their equilibrium position. When the front of a sound wave strikes a wall, three phenomena generally occur, that contribute in different ways to the redistribution of the energy carried by the wave: part of this energy is reflected according to the laws of classical mechanics; part is dissipated within the material of which the wall is made; and a third part passes through the material and proceeds freely beyond.

Some of the main parameters that characterizes sound are:

- Wave amplitude

The amplitude of sound pressure fluctuations is the characteristic that allows to distinguish loud sounds from soft ones. The human ear is a pressure sensor. Normally, however, the amplitude of sound pressure fluctuation expressed in Pa (pascals) is not used to measure human-perceived sound sensation. Instead it is converted to the logarithmic scale of dB (decibels), thus defining the sound pressure level (SPL).

- Frequency (f)

The perceived pitch of sounds depends on the frequency (f), that is, the number of oscillations that occur in a given time (one second). The more numerous they are, the sharper the sound.

Frequency is measured in "Hertz" [Hz]. This term refers to the name of the German physicist who first studied these phenomena.

One Hertz corresponds to one complete oscillation in one second. The human ear can only hear sounds between 20 and 20,000 Hz.

$$f = \frac{\omega}{2\pi} \text{ [Hz]}$$

- Period (T)

A period is defined as the time required to complete one cycle complete, also referred to as the inverse of frequency.

$$T = \frac{1}{f}$$

- Sound Intensity (I)

Sound Intensity is the parameter for evaluating the flow of energy that passes through a given surface, in the direction normal.

- Sound Power

Describes the sound-emitting capacity of a source and is measured in watts (W). Power cannot be measured directly, but requires special methods for its determination.

This parameter is an objective quantity independent of the environment in which the source is placed.

- Sound Pressure level (SPL)

The sound pressure level is the most adopted indicator for acoustic wave strength. As everyone perceives in a different way the sound level (how loud a sound is), SPL has been used to get an objective measurement, that create a link with human loudness perception. To better understand the concept of Sound Pressure Level, it has to be bear in mind the concept of Sound pressure, defines as is the average variation in atmospheric pressure caused by the sound. Its unit of measurement is Pascal (Pa). Sound pressure level is the pressure level of a sound, as well, but expressed in Decibel (dB). It is defined as the ratio of the absolute sound pressure against a reference level of sound in the air.

$$LP = 10log\frac{p^2}{p_{ref}^2}$$

Where

P= rms sound pressure (Pa)

P_{ref} = reference pressure ($2x10^{-5}$ Pa)

Decibels are useful for measuring sound because they can represent the wide range of levels that the human ear perceives with an easier-to-manage scale.

The following table shows some of the sound pressure levels generated by representative sources.

Noise level in dB	Common Environment	Your conversation would be...
120	Jet engine nearby	
110	Police siren nearby	IMPOSSIBLE
100	Inside subway train	
90	Using hair drier	DIFFICULT
80	Truck passing by	LOUD VOICE REQUIRED
70	Street with car traffic	
60	Normal conversations at office	
50	Moderate rainfall	
40	Quiet residential area	EASY
30	Whispering	
20	Rustling leaves	
10	Breathing	

Figure 2 SPL generated by representative sources

The lowest sound pressure level has the value of 0 dB (the hearing threshold) while the pain threshold has the value of approximately 120 dB. The sound pressure required for a sound to be audible to the human ear varies with the frequency of the sound. For example, a sound of 1,000 Hz is audible at "0 dB," while going down to 30 Hz requires a sound pressure level of at least 60 dB for the sound to be audible. Prolonged exposure to sound pressure levels above 85 dB can cause severe discomfort or even permanent deafness.

Many standards have been thought in order to assess the acoustic quality of open plan offices at best.

- 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.

  This standards provides some indoor noise criteria according to the space function. Tab. 16 shows the main criteria:

Table 16 Indoor system noise criteria of come spaces and buildings. Taken from EN 16798-1:2019

Building	**Type of space**	**Equivalent Continuous Sound Level $L_{Aeq,nT}$ [dB(A)]**		
		I	II	III
Residential	Living-room	≤ 30	≤ 35	≤ 40
	Bedrooms	≤ 25	≤ 30	≤ 35
Places of assembly	Auditoriums	≤ 24	≤ 28	≤ 32
	Libraries	≤ 25	≤ 30	≤ 35
	Cinemas	≤ 24	≤ 28	≤ 32
	Museums	≤ 28	≤ 32	≤ 36
Commercial	Retail Stores	≤ 35	≤ 40	≤ 45
	Department stores, Supermarkets	≤ 40	≤ 45	≤ 50
Hospitals	Bedrooms	≤ 25	≤ 30	≤ 35
	Wards	≤ 32	≤ 36	≤ 40
	Operating theatres	≤ 35	≤ 40	≤ 45
Hotels	Hotel rooms	≤ 25	≤ 30	≤ 35
	Reception, Lobbies	≤ 30	≤ 35	≤ 40
Offices	Small offices	≤ 30	≤ 35	≤ 40
	Landscaped offices	≤ 35	≤ 40	≤ 45
	Conference rooms	≤ 30	≤ 35	≤ 40
Restaurants	Cafeterias	≤ 35	≤ 40	≤ 45
	Bars, Dining rooms	≤ 32	≤ 36	≤ 40
	Kitchens	≤ 45	≤ 50	≤ 55
Schools	Classrooms	≤ 30	≤ 34	≤ 38
	Gymnasiums	≤ 35	≤ 40	≤ 45
Sport	Covered sport facilities	≤ 35	≤ 40	≤ 45
General	Service rooms, Corridors	≤ 35	≤ 40	≤ 45
	Toilets	≤ 35	≤ 45	≤ 55

- BS EN ISO 3382-3:2022_Acoustics–Measurement of room acoustic parameters_Part 3: Open plan offices, Whose scope is to provide a methos for measuring room acoustic parameters in unoccupied open-plan offices, underlining procedures, instruments, method of data evaluation.

  Annex A introduces some useful concept and parameters for understanding better the critical aspects of this office layout and how to deal with them.

  As previous mentioned, speech is one of the most annoying sound source. Particularly, in open plan offices, cognitively demand tasks can be performed worst because of intelligible speech. So lower speech intelligibility and higher speech privacy are preferred between workstations. Some studies have shown a significant reduction on verbal or mathematical tasks with perfectly intelligible speech (STI > 0,5), compared to absence of speech (ST=0). STI varies a lot within the same open-plan office according to the room acoustic quality and the distance between the speaker and the listener. The standard shows a curve attesting that when the ST is below 0,5, the negative effects of speech decrease quickly. This is the reason why the distraction distance r_D is the distance from the speaker where STI falls below 0,5.

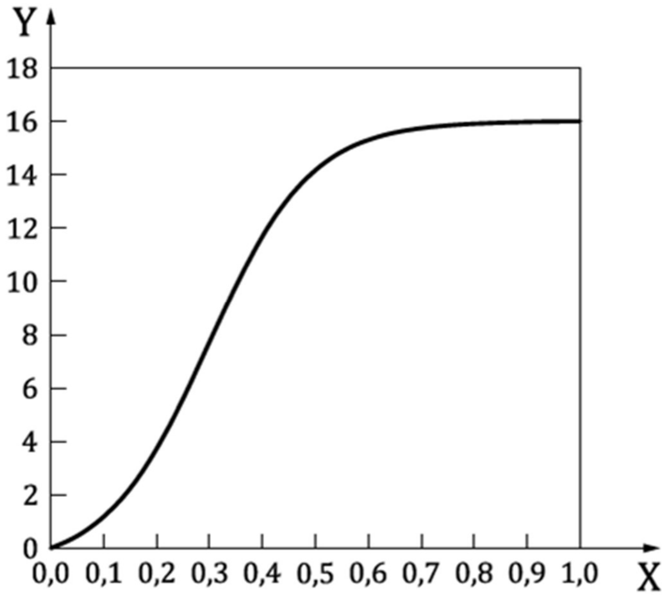


Figure 3 Effect of STI of irrelevant speech on cognitive performance. Taken from BS EN ISO 3382-3:2022

Two important parameters defined by the standard are comfort distance and distraction distance. The former shows the result of spatial attenuation in the office, without taking into account speech privacy, background noise level, or sound masking.

Confort distance r_c is calculated using the following formula:

$$rc = 2^{(L_{p,A,S,4m} - 45 + 2 \cdot D_{2,S})/D_{2,S}}$$

Where

$L_{p,A,S,4m}$= speech level at 4 m distance (A-weighted SPL of speech in decibels at the distance of 4,0 m from the middle point of the omnidirectional sound source)

$D_{2,S}$= spatial decay rate of speech (dB) (the rate of spatial decay of A-weighted sound pressure level (SPL) of speech per distance doubling in decibels)

$D_{2,S}$ describes how fast the A-weighted SPL of speech attenuates in the open-plan office when the distance to OSS increases. Large value means strong room acoustic attenuation. In free field, $D_{2,S}$ = 6 (dB).

If $L_{p,A,S}$ < 45 dB at the nearest workstation to the OSS (first measurement position), r_C will be smaller than the distance between the first measurement position and the OSS. It happens generally in high ceiling offices with large sound absorption and high screens to divide workstations. Instead, if $L_{p,A,S}$ > 45 dB even in the farther position , r_C wil be larger than the distance between the farther position and the OSS. This situation happens in a very reverberant open-plan office.

Distraction distance r_D (m), is an index to predict the objective speech privacy of the open-plan office, considering both background noise level and spatial attenuation. r_D is calculated by interpolation the linear distance to the OSS (x axes) and the speech transmission index (STI) (y axes).

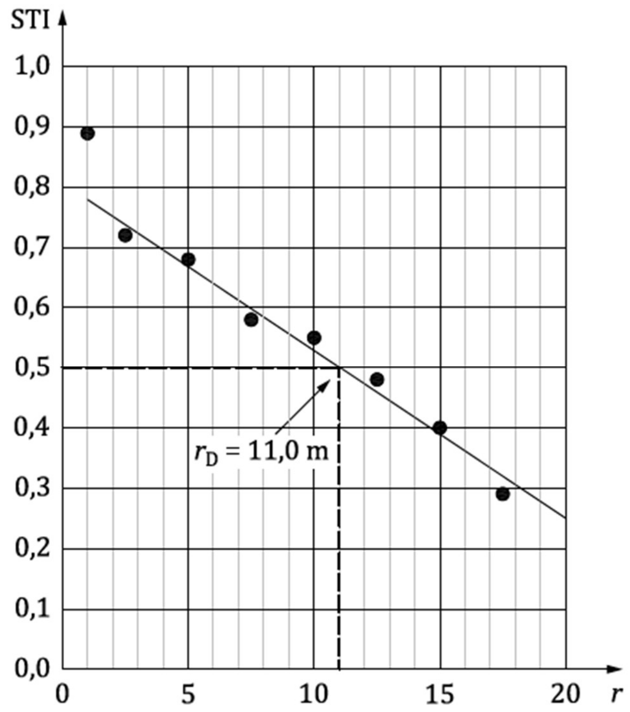


Figure 4 Determination of rD. Linear fitting includes positions located beyond 1 m from the OSS

- BS ISO 22955:2021_Acoustics — Acoustic quality of open office spaces, whose scope is to provide some guidelines to reach acoustic quality of open plan offices, for six “space type”:
    - Space type 1: activity not known yet – vacant floor plate;
    - Space type 2: activity mainly focusing on outside of the room communication (by telephone/audio/video);
    - Space type 3: activity mainly based on collaboration between people at the nearest workstations;
    - Space type 4: activity based on a small amount of collaborative work;
    - Space type 5: activity that can involve receiving public;
    - Space type 6: combining activities within the same space.

For example space type 4 describes a typical office situation that involve mainly individual work and short discussions. The space requires high level of concentration, so that the standard suggest to provide some areas for private speeches. The acoustic challenge in this space is to provide high level of intelligibility at the workstation, and reduce it as much as possible among them. The standard also provide a table (Tab.17) required values according to the position.

Table 17 Acoustic indicators and value- Activity mainly based on a small amount of collaborative work. Taken from BS ISO 22955:2021

Interaction	Acoustic challenges	Description, criterion	Target values	Required values
Workstation	High level of intelligibility at workstation	Low ambient noise Intelligibility good to excellent when speaking at normal level	$L_{Aeq,T} \leq 48$ dB [a]	
Between workstations	Need for discretion among workstations Average intelligibility among workstations	High level of attenuation		Attenuation $D_{A,S} \geq 6$ dB
On floorplate	Reducing disturbance from conversations in other services	Attenuating amplification inherent to room as much as possible by reducing reverberation Reducing noise in room by doubling distance		$T_r \leq 0{,}5$ s [b] $T_r \leq 0{,}8$ s at 125 Hz $D_{2,S} \geq 7$ dB $L_{p,A,S,4m} \leq 47$ dB

[a] During activity (see Annex E).
[b] Arithmetic mean of times for octave bands centred on 250 Hz to 4 000 Hz.

Where *T*r indicates the reverberation time. It is the time, in seconds, required for the existing noise level inside a room to decrease by 60 dB, when the noise source is instantly interrupted.

- NF S31-080:2006 "Acoustique - Bureaux et espaces associés - Niveaux et critères de performances acoustiques par type d'espace. The French standard deals with the acoustic quality of offices and collective spaces (individual offices, collective offices, open spaces, meeting rooms, restaurant rooms and circulations) and that, in relation to the use and intended use of the rooms, proposes three different levels of acoustic performance: standard level (corresponds to a functional performance that does not guarantee any conditions of acoustic comfort), high level (corresponds to a functional performance that guarantees conditions of acoustic comfort favorable to the performance of work activities), very high level (corresponds to a functional performance that guarantees the best conditions of acoustic comfort). These levels of acoustic performance are associated with objective and measurable acoustic indicators (external and internal insulation, reverberation time, sound level and sound decay). Table 18 shows the values suggested by this standard for individual offices.

Table 18 Standards for different levels of acoustic performance (NF S31-080:2006)

Descriptor	Standard level	High level	Very high level
Total sound level of:	L_{50} ≤ 55 db(A)	40<L_{50}<45 dB(A)	40<L_{50}<45 dB(A)
- External noise	$D_{nT,A,tr}$ ≥ 30 dB	$D_{nT,A,tr}$ ≥ 30 dB & L_{50}<35 dB(A)	$D_{nT,A,tr}$ ≥ 30 dB et L_{50}<30 dB(A)
- Equipment noise	L_{Aeq} ≤ 45 dB (A)	NR 35<Lp<NR 40	Lp<NR33 (permanent) & L_{max}≤35dB(A) (intermittent)
Impact noise	L'_{nTw} ≤ 62 dB	L'_{nTw} ≤ 60 dB	L'_{nTw} ≤ 58 dB
Reverberation (Vol< 250 m^3)	T_r ≤ 0,8 s	0,6 < T_r < 0,8 s	T_r ≤ 0,6 s
Spatial decay (Vol > 250 m^3)	2 dB(A)/double Or T_r ≤ 1,2 s	3 dB(A)/double Or T_r ≤ 1 s	4 dB(A)/double Or T_r ≤ 0,8 s
Insulation to the indoor airborne noise	$D_{nT,A}$ ≥ 30 dB	$D_{nT,A}$ ≥ 35 dB	$D_{nT,A}$ ≥ 40 dB

1.2 SUBJECTIVE: INDOOR ENVIRONMENTAL COMFORT

By definition, the word *comfort* defines a pleasant and satisfying feeling of being physically or mentally free from pain and suffering, or something that provides this feeling. For this reason, the concept of Indoor Environmental comfort (IEC) may be considered as a subjective one. It is related to human perception and satisfaction with their surrounding environment.

As people spend approximately 90% of their time indoor, designers have to be focused on occupants' perception of the environment in order to guarantee a status of comfort. This is a real challenge as objective IEQ, subjective IEC and energy efficiency should be taken into account in the act of designing. Some design choices may affect the others, positively but also negatively. As sample, in the study by Allen et al.(Allen et al., 2016), less ventilated building has been built in order to achieve energy regulations, even more focused on lower greenhouses emissions and energy costs. This layout seems to make the building more cost-efficient. Moreover, to increase real estate profit returns, spaces with reduced dimension accommodate several people. These combined factors lead to a worsening of the indoor environmental quality.

Each occupant has his own perception of the surroundings. It depends on several personal factors, such as gender, age, origins, but also psychological factor, as personality aspects. In the last years even more researchers have been focused on personal comfort systems through simulation tools. The consciousness that users want to interact and independently control the indoor space, in order to reach their own comfort, has emerged (Haldi & Robinson, 2011a; Rijal et al., 2009a).

The overall perception of indoor environmental comfort depends on 4 domains:

1. Thermal comfort
2. Air quality perception
3. Visual comfort
4. Acoustic comfort

So objective physical quantities, such as air quality, temperature, relative humidity, illuminance and sound pressure level, impact on quality of life, but at different intensities. The co-existence and the interaction of these physical, chemical and biological indoor factors establish, on one side, the concept of Indoor environmental quality (IEQ)(Steinemann et al., 2017a). On the other side, occupants may be physical or psychological affected by these factors, known also as environmental stressors (Fisk, 2000), influencing the concept of Indoor environmental Comfort (IEC). Thus it is not possible to consider IEQ and IEC as two different and self-excluding entities.

1.2.1 Occupant's Perception and Factors Of Influence

As previously mentioned, individual needs, comfort state and environmental stress are different among users. Several studies have shown a strong correlation between subjective factors such as attitudes, gender, age, country of origin and occupants' perception of the indoor environmental quality (Awada et al., 2023a).

Different environmental perception occur among different age groups. For instance, older occupants feel more comfortable in higher temperature environments, as they have a lower metabolic rate and activity level (Hoof & Hensen, 2006). On the other hand, younger occupants experience more psychological stress during a heat stress period. Also the perception of high illumination levels is felt completely different. Young users perceive this environmental condition as a relaxing one, while older users feel it like an awaking condition (Chou & Chen, 2013). Moreover an higher color temperature, expressed as a white-blue light, is able to raise old occupants' cortisol levels (Schatz & Bowers, 2005), indicating higher levels of stress.

Country of origins is a subjective feature that can modify the perception of the indoor thermal environment. It has been shown that occupants coming from cold countries get used to cold indoor environments more quickly (Luo et al., 2016).

As well known, also clothing level influences the thermal perception (Awada et al., 2023a).

Even if body response to cold and hot environments is linked to the percentage of body fat and the surface-to-mass ratio, it has been shown that women have a lower pulse rate when exposed to cold, while men's pulse rate remains invariable despite temperature changes (Chaudhuri et al., 2018). Women are also more sensitive to noise levels increase than men (Abbasi et al., 2022). Gender also affect the effects of lighting on the body. A research demonstrated that a sample of women standing in a room with an illuminance of 325 lux and a color temperature of 3400 K have lower heart rate levels, thus they are more stressed (Kuijsters et al., 2015).

According to a research by Tang et al. (Tang et al., 2022), the acoustic environment had a greater impact on females than males, while the IAQ had a greater impact on males.

Often objective and subjective features are discerned. It is a wrong approach as the former may influence the latter, and vice versa. For example, a design choice, as the use of a specific material, may affect the user, physically or psychologically (colors, healthiness). Moreover the use of certain materials can be unhealthy. Some of them release pollutants in the environment, such as formaldehyde or VOCs, while degrading or if they are exposed to high relative humidity conditions (see paragraph 1.2.6).

So that, among the well-known aspect that can influence the quality of an indoor environment, it is important to take into account also other factors influencing occupants' perception. Some examples could be the spatial layout of the office, where the building is located, the accessible public/private services connection, but also if the occupant has the possibility to connect with the nature outside, or if he reaches enough natural light.

Finishing material and furniture are also responsible of workers' environmental level stress. Several studies, as sample, have shown how workers feel less tired and stressed while working in a wood paneled environment (Sakuragawa et al., 2005) and how their heart rate and heart rate variability is lower, indicating a more easygoing state (Zhang et al., 2017). Also salivary cortisol concentration is reduced for people working in wood furnished offices (Burnard & Kutnar, 2020).

Also office interior color can affect workers' stress and humor. As sample, a worker may experiences an higher level of stress and anxiety inside a red office, instead of a blue one (Kwallek et al., 1989).

Office layout is one of the design choices having a direct influence on workers' well-being. Open-plan offices may intensify workers' environmental stress levels, as they are often related to less privacy, higher noise levels, and difficulties in control the indoor environment (Kim & de Dear, 2013). It has been proved that open-plan offices turn down workers' well-being, if it is compared to a private office(Sander et al., 2021). Concentration loss, higher stress levels, and consequently lower productivity, come from the inability to control visual and physical work in open-plan offices (Rashid et al., 2009) and the distraction sources (Haapakangas et al., 2018).

Access to natural view and nature integration in office spaces, are two ways to lessen workers' stress levels and facilitate the stress recovery (Ulrich et al., 1991).

In conclusion, there is not a general setting for occupant comfort, as each person has a different perception (al Horr et al., 2016).

1.2.2 Workers' performance and productivity

In order to achieve a reliable and complete evaluation of a building, it is unsatisfactory to take into account just its operating and rent costs or its operating parameters' performance. A fulfilling way is to involve an analysis about the worker productivity and the occupants' health benefits. Indeed, it has been discovered that these factors can mean up to 92% annual investment (Seppänen & Fisk, 2006a).

For this reason, in the last years, an increasing number of companies started to invest on office even more environmentally comfortable. They realized how an adequate IEQ may be cost-effective. It has been shown that financial investments in enhancing IEQ are refunded in less than two years (Seppänen & Fisk, 2006a). Actually, business operating costs can be split in 80-90% of employee expenses, 1-3% of energy costs, 8-11% others (Clements-Croome, 2004; Alker et al., 2014). Furthermore, a reduced workers productivity, caused by inadequate IEQ in offices, involves expenses that can exceed energy costs by two orders of magnitude

(Steinemann et al., 2017b). Some studies have proved that, if the productivity of workers is reduced because of illnesses attributable to a lack in supplying fresh air, a financial loss can affect the company. Fisk et al., have estimated a loss of 15 billion pounds for UK and 38 billion dollars for USA (Fisk et al., 2012; Centre for Mental Health, 2011).

Even more focus on workers conditions are evidenced, among others, by the development of a specific language. For example, in 2010 the term “presenteeinsm” has been adopted to describe a worker who doesn’t reach the maximum productivity at work due to health issues or other kind of distractions (Centre for Mental Health, 2011).

One of the strategy to enhance IEQ in offices, and thus IEC, can be the use of personal control systems (PCS). Personal control on the indoor environment may encourage people to counteract negative environmental stimuli. A work environment where users can adjust and choose their own settings, has benefits in terms of workers’ psychological stress, performance, environmental satisfaction, group collaboration, physical health problems (Huang et al., 2004; Samani et al., 2015; Thea, 1989). PCSs allow to achieve optimal work performance through thermal personal control. Also international sustainable rating tools (LEED, BREEAM, Green Star…) started to recognize more credits to building designed with higher level of Personal Environmental Control (PEC). Several types of personal control system exist: from an elementary thermostat control, to laborious personalized ventilations systems (Bauman et al., 1998). A further value of these kinds of systems is the possibility to save on energy consumption, up to 30% referring to conventional centralized HVAC systems. In addition to this, an higher thermal and IAQ comfort is guarantee, with the possibility to reach the 100% satisfaction (R. J. de Dear et al., 2013; Oh et al., 2014). Furthermore, comparing a LEED-rated building with a standard office, the average productivity can raise up to 2.86 work hours more each month, because of a reduction in environmental stress (Singh et al., 2011).

By adopting PEC it may be avoided a decrease performance by 10%, because of discomfort perception (Steinemann et al., 2017b). It has been shown that work cognitive performance may decrease in the range of 2.4% and 14,8% when occupants are exposed to thermal, acoustic or lighting discomfort situations. Sometimes they are indirectly affected, feeling less motivated and focused (Lamb & Kwok, 2016).

Another strategy to increase IEQ and IEC is to ensure an higher ventilation rate and thermal comfort. They have a good impact on workers' ordinary tasks, such as text-typing, reading, memorization and mathematical calculation (Steinemann et al., 2017b).

Even if it is extremely difficult to attribute a percentage of influence to each comfort domain, thermal comfort has been indicated as the most influent environmental one of the perception of IEQ. A research demonstrated how participants thermally unsatisfied felt more dissatisfaction also with air quality, noise and lighting. The workers who perceived thermal environment as "neutral" or "slightly cool" were the most productive ones (Geng et al., 2017).

1.2.3 Well-being and Sick Building Syndrome (SBS)

The World Health Organization rated "stress" as the epidemic of the 21st century. It is defined as a physical and psychological human response to certain situation, changes and circumstances. Every external stimulus can be a source of stress, but nowadays, it has been assumed that the main cause of stress is work and job. This is the reason why even more companies are focus on the need to ensure to their workers an healthier, pleasant, stress-free office. Several studies have been carried out about this topic. Rashid and Zimring, as sample, give a definition of "environmental stress", that is not a synonym for "work stress". The former takes place when personal comfort and health is restricted by the workspace. The authors states that office workers' stress level is strongly influenced by two classes of physical environmental parameters: 1) Indoor environmental conditions (e.g., noise, lighting, ambient temperature, and air quality), 2) interior design parameters (e.g., layout, access to view, colors, furnishing,…). Basically, environmental stress increase with the decrease of indoor environmental quality and bad designed spaces. It leads to elevated work stress (Rashid & Zimring, 2008).

Workers' level of stress is a condition that should not be underestimated, as it has clear health repercussions.

1930s a first definition of stress has made by the Austrian doctor, Selye: "stress is a non-specific response of the body to any demand". He set up a three-stage stress model, the General Adaption Syndrome (GAS), to describe the reactions of human body to stressors. After a first stage (alarm reaction), when body deal with a stressor, increasing its heart rate, cortisol and adrenaline release, in the second stage (resistance), the body attempt to get over the stress shock. If the stressful situation continue, the third stage (exhaustion) occurs, the body is not able to restore pre-stress function level. If this condition persists longer, it can drain all body's physical, emotional and cognitive resources (Saturday & Selye, 1950).

According to its duration, the stress can be: 1) acute, short-term stress whose effects are emotional pain, irritation, muscular tension, headaches, back pain, 2) episodic stress when acute stress in repeated, producing headaches, hypertension, heart disease, 3) chronic stress if the inputs are constant, bringing to digestive and sleeping problems, low concentration, but also cardiovascular disease and type 2 diabetes (Madhu et al., 2019; Shalev, 2002).

Among the impacts on people health, Sick building syndrome (SBS) is one of the most studied since 1980's.

Sick building syndrome (SBS) indicates a well-defined symptomatologic picture, which manifests itself in a large number of occupants of modern or recently renovated buildings equipped with mechanical ventilation and global air conditioning systems (without fresh air intake from outside) mainly used as offices, schools and hospitals. Clinical manifestations are non-specific, occurring after a few hours in a building and usually resolving rapidly, within a few hours or a few days (in the case of skin symptoms) after leaving the building.

Numerous researches in buildings where health or comfort problems were reported, showed that the prevailing problem (in almost half of the cases) was inadequate ventilation (Fisk et al., 2009).

Besides chemical and biological contaminants, and inadequate ventilation rate, also psychological factors, as excessive work stress or dissatisfaction, not enough and inappropriate lighting with absence of daylight, poor acoustics, and high relative humidity may contribute to SBS (Joshi et al., 2008).

Many chemical compounds in indoor air are known or suspected to cause irritation or stimulation of the sensory system and can give rise to sensory discomfort and other symptoms commonly found in so-called BSS. Studies conducted on offices and other public buildings in several countries have revealed a frequency of discomfort among occupants of between 15% and 50%.

1.2.4 Thermal Comfort

Thermal comfort is defined by the ASHRAE in 2017 as a subjective feeling of well-being with the thermal environment. It is evaluate subjectively (ASHRAE55-Version2017, 2017).

According to ASHARAE standards, there are six main parameters responsible for thermal comfort: dry bulb air temperature, relative humidity of the air, air velocity, mean radiant temperature, human metabolism, and clothing level. As it can be noticed, the first four parameters are objective, collectable by instruments. Human metabolism and clothing level are different for each person, and they have to be taken into account during the design phase of the building. To project the indoor comfort is a challenge as the designer has to bear in mind also secondary factors that have effects on thermal comfort. Among them, local discomfort, outdoor climatic condition, age, sex and visual stimulation, have the greatest impact (ASHRAE55-Version2017, 2017).

The subjective nature of personal comfort is strongly underlined by some studies that have shown just a weak correlation between objective IEQ data, such as air temperature, relative humidity, CO_2 concentration level, and subjective thermal comfort (Cheung et al., 2017). Furthermore, it has to be taken into account that different office tasks correspond to distinct optimal temperatures, thus enhanced productivity (al Horr et al., 2016).

To be at the peak of their productivity, workers have to operate in a thermally comfortable environment (R. J. de Dear et al., 2013). It has shown that the best thermal setting for an office ranges between 21°C and 25°C. Cognitive processes, that link physical, physiological and psychological factors, help a person to reach his own comfort perception. Contrary to the expectations, if the temperature exceeds the former limit, the productivity decrease. Precisely for each 1°C more, it is observed a loss in workers' production of 2% (Seppänen & Fisk, 2006b). The requirement of different thermal condition depend on sex, age and body mass index. It has demonstrated that women, for example, are more sensible to temperature changes in a controlled environment. Moreover they have less tolerance to cold conditions.

In the definition of thermal comfort, it does not have to be confused with "thermal sensation". While the former is a subjective perception, the latter is described as an objective state. It is the direction and intensity of a person's sensual perception of his indoor surroundings. Thermal feeling can be converted into numbers, associating a score to a judgment, on a 7 point scale. Precisely, the sensation of "Cold" is expressed with a numerical value of (-3), "Cool" with (-2), "Slightly Cool" with (-1), "Neutral with (0), "Slightly warm" with (+1), "Warm" with (+2), and "Hot" with (+3).

One of the first researcher in the field of thermal comfort was Fanger. The development of an analytical model for setting the thermal comfort for buildings with centrally controlled HVAC system. Using physical parameters of the room (air temperature, air flow rate, relative air humidity, globe temperature) but also human variable (level of dressing, activity), he found out a way to estimate the Predicted Mean Vote (PMV index). By definition it aims to predict the mean value of votes of a group of occupants on a seven-point thermal sensation scale. When an occupant's internal heat production is the same as its heat loss, thermal equilibrium is obtained. According to ASHRAE 55, if PMV is 80% or more thermal comfort may be achieved.

$$PMV = [0.303 \cdot e^{-0.036M} + 0.028] \cdot L$$

Where

M= metabolic heat output

L= thermal load

PMV is also important to determinate the percentage of dissatisfied occupant (PPD index), that gives the percentage of people predicted to experience local discomfort. PPD index has to be lower than 20% in each occupied point of the room in order to meet the standards.

$$PPD = 100 - 0.95 \cdot e^{(-0.03353 \cdot PMV^4 + 0.2179 \cdot PMV^2)}$$

The diagram in the figure (Fig. 6) shows that, even for PMV = 0, PPD = 5%, there are no environmental conditions that can satisfy 100% of the people. The maximum obtainable on a statistical basis is therefore the satisfaction of 95% of the people.

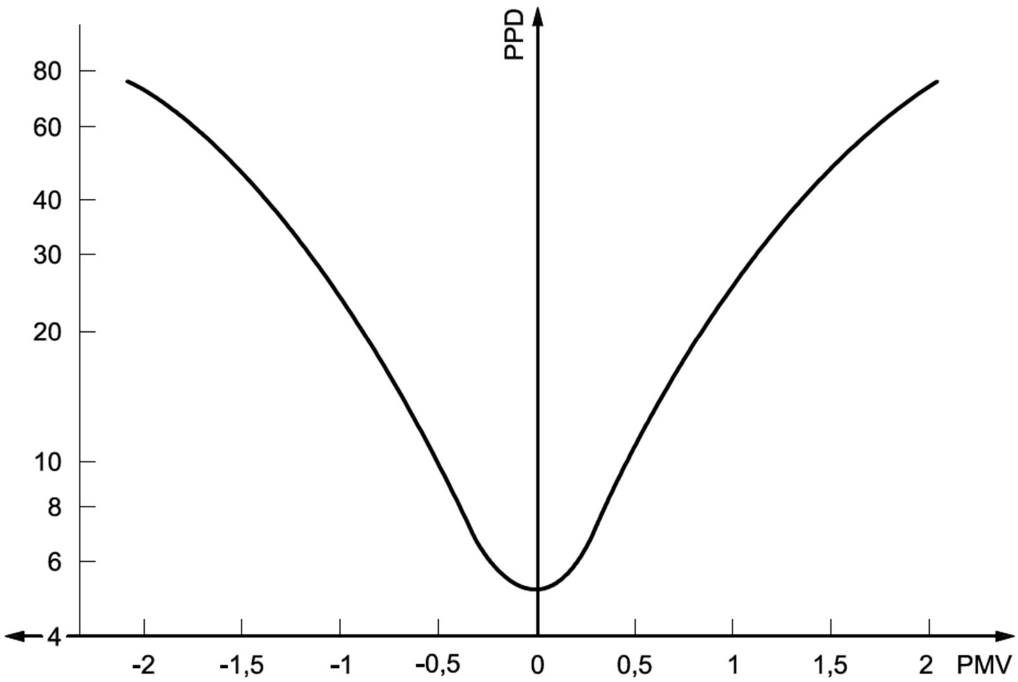


Figure 5 Graphical representation of PMV and PPD (BN ISO 7730-2005, pp. 5)

Fanger's comfort model is the most popular one, even if Dear and Brager have implemented the adaptive acceptance model, at the end of the 20th century. In comparison with Fanger's PMV/PPD model, the adaptive approach is more focused on the subjective side of the thermal comfort (Brager 'i, & de Dear ', 1998). The former was given as globally applicable, while the latter considered the occupants as a part of the overall comfort system. De Dear and Brager meant the adaptive process as a behavioral, physiological and psychological process. The main assumption was the capability of the occupants of natural ventilated building to assess easily a thermal comfort condition, compared with the ones occupying HVAC system ventilated buildings. Furthermore, it is established that man, if he is able to change the conditions of the environment in which he finds himself (changing clothing, opening or closing windows, switching systems on or off), is willing to accept conditions that are also less than ideal.

A common negative aspect of both the methodologies is the non-applicability for a small group of individuals. They can be successfully applied to estimate the comfort level for a big sample of users (Talon & Goldstein, 2015). Particularly, to collect personal input data (such as insulation properties of clothing or metabolic rate) is not that easy, bringing to inaccurate approximations (Auffenberg et al., 2015). Kim et al., in 2018, developed a new approach, called "personal comfort model". It is more focused on the individual perception of each occupant than on the average response of a large sample. To reach its aim, the methodology transform the real-world data, collected by feedbacks, into individuals' comfort requirements, through Internet of things and machine learning. This method seems to have 40% more accuracy than the conventional models. Personal comfort model could be a valuable ally in building energy saving, as it provide data to optimize the comfort level among occupants (Kim et al., 2018).

The new thermal comfort standards (ASHRAE Standard 55/2004, EN ISO 7730-2005, EN 15251) do not establish fixed comfort conditions, but differentiate them according to the type of system and the microclimate control pursued. In particular, for "fully-conditioned" environments, an approach linked to the Fanger theory is still retained. Where, however, the user is able to substantially modify the microclimate, there is greater acceptability of the environment.

- WELL-BEING EQUATION

The condition of thermal comfort is not only sensation and perception but also strictly depends on the body's physical mechanisms. The human organism needs to achieve the condition of homothermia, i.e. the mechanism that regulates the physiological response to environmental stresses in order to adapt to the surrounding environment and maintain a constant body temperature.

Therefore, the human body can be considered as a thermodynamic system on which it is possible to make an energy balance, referred to as the 'well-being equation':

$$S = M_{tot} - (W) - E_{sk} - R_{res} - C - R - C_k$$

Where:

S= change in internal energy of the human body in the unit of time [W].

M_{tot}= total metabolic flux [W].

W= mechanical power exchanged between the body and the environment (activity performed) [W].

E_{sk}= heat power lost through evaporation by skin (air hygrometric degree, air temperature, skin temperature, relative air speed, clothing, percentage of skin wet by sweat) [W].

R_{res}= heat power lost in respiration consisting of a share of latent heat and a share of sensible heat (activity performed, hygrometric air degree, air temperature) [W].

C= heat power exchanged through convection (temperature of the external surface of the dressed body, air temperature, relative subject-air velocity, clothing coefficient) [W].

R= heat power exchanged by radiation (external surface temperature of the clothed body, mean radiant temperature, clothing coefficient) [W].

C_k= heat power exchanged by conduction [W].

There are three possible scenarios:

1. S > 0: the body temperature tends to rise (metabolic activity is preponderant over energy release).

2. S < 0: body temperature tends to decrease, due to excessive energy release to the outside.

3. S = 0: the presence of thermal equilibrium and therefore of potential well-being, a necessary but not sufficient condition due to the self-regulation mechanisms of body temperature.

It is important to remember that the transfer of metabolic flux to the external environment occurs through two main mechanisms:

- Sensible heat exchange, forced by a temperature difference.
- Latent heat exchange, forced by a difference in partial vapor pressure.

Therefore thermal comfort conditions, or thermal neutrality, occurs when environmental and behavioral parameters, acting on the sensitive and latent energy exchanges of the human body, cancel out the sensations of heat or cold perceived by the occupant.

1.2.5. Visual Comfort

Visual comfort is defined in the European standard EN 12665 as "a subjective condition of visual well-being induced by the visual environment" . Physiology of the human eye, the amount of light and its distribution on surfaces, the spectral emission of the light source, are the main aspects that may affect visual comfort.

Personal needs and light environment are related by some factors, through which visual comfort can be studied (Carlucci et al., 2015):

- The amount of light: it has to be adequate in order to allow the users to accomplish his task.
- The uniformity of light: it should spread uniformly on the work plan, in order to avoid visual stress, and thus discomfort.
- The quality of light in rendering colors: as artificial light is not able to reproduce the whole spectrum, daylight should be preferred.
- The prediction of occupants' risk of glare: the occupant may experience disability glare, if his eyes is reached by an excessive amount of light, or discomfort glare if the luminance range is too wide in a given visual field.

As above mentioned, daylight should be preferred. It is the main regulator system for the human body. Moreover, it controls people circadian rhythm, providing physical and mental energy for the day. This is the reason why a well-designed illumination system, can really improve people quality of life. It has shown that people more exposed to daylight are more relaxed and joyful. Moreover, daylight is the best way to reach human visual comfort (Aries, 2005; D. H. W. Li, 2010). Offices with more affluence of natural light are considered more pleasant and they have good effects on workers' life: some companies report an "absenteeism" 15% lower and a presence up to 47% in offices where daylighting is maximized (Mujan et al., 2019). Even if the daylight spectrum can be emulated by some kinds of lighting, they cannot cover the entire spectrum, ad previously mentioned. This can modify the 24-h internal human clock, influencing physiological and psychological processes (Rea et al., 2002)and generate a perception of discomfort. It has also to be taken into account that artificial light intensity level are one decimal lower than daylight intensity, that is the responsible of an hormone called melatonin, the hormone that regulates the circadian rhythm (van Bommel & van den Beld, 2004).

Basically, overall productivity and health depend strongly on visual comfort. For this reason, the amount of artificial light should be limited in favor of an higher intake of natural light (Yun et al., 2012). This need can be extended to a wider discourse. About 33% of electricity consumption in building is caused by the use of artificial light. Commercial office buildings consume even more, reaching 40%. As known, the more is the energy consumption the more are the greenhouse gas emissions (Krarti et al., 2005). Thus, limiting artificial light in favor of natural light, is an ally to ensure visual comfort and more sustainable buildings.

1.2.6. Air Quality Perception

In literature is even more frequent to bump into researches about Indoor Air Quality and Comfort, and how much the business sector can be affected by it, as well. It has experimentally confirmed a strong link between IAQ and productivity on common tasks as math calculation, text typing or proofreading (Langer & Bekö, 2013; Ng et al., 2012; Ole Fanger, 2000; Wargocki, 2000). Moreover workers that feel dissatisfied of IAQ usually develop illnesses. Symptoms can vary from light respiratory problems to more serious problem such as Sick Building Syndrome (SBS) and even asthma. As explained before, SBS's most common symptoms are itching or burning of the eyes, nose irritation and sinus problems. More serious issues are respiratory system irritation, headache, lethargy and mental fatigue, even if they seem to be less frequent (Mendell & Smith, 1990; Ottoet al.,1992).

The theme of exchange air rate is a very sensitive subject and it may influence ones' air quality perception. Different researches have demonstrated a strong interrelation between Sick Building Syndrome (SBS) and insufficient air exchange, less than 10 l/s. Furthermore, if an office is well-ventilated, the workers' productivity exponentially increases (Fisk et al., 2009; Kosonen & Tan, 2004; Seppänen, 1999).

In the literature the most common air pollutants associated to a reduction of productivity are Volatile Organic Compounds (VOCs). Human activities, such as smoking or cooking, the degradation and the natural release of some construction materials, are the most common internal sources of VOCs. The effect of exposure to VOCs is mainly linked to respiratory sensitivity and irritation, but they can also impact on human psyche. Chemically and physically, VOCs presents different characteristics that make difficult their sampling and analysis, as well as their measurements.

A way to measure the internal sources has been developed by Fanger, who proposes the Olf and Decipol units. The former is used to measure the air pollution emission rate as the one of a standardized user. 0.1 to 0.2 Olf/m^2 is the range emission of the most common materials. Decipol represents the level of perceived air quality. For example, an occupant has a perceived air quality of 1 Decipol with a ventilation rare of 10 l/s. Then, implementing a deciphering function, it is possible to estimate a number of dissatisfied people (Fanger, 1988).

Air quality and thermal comfort data depends also on seasonal variation. For this reason some studies recommend to monitor at each changing season (Deng & Lau, 2019).

1.2.7. Acoustic Comfort

When the occupant experience satisfactory acoustical condition in an environment, and thus feel a status of well-being, he has reached his acoustic comfort (Vardaxis et al., 2018; Wang et al., 2015). It is influenced by two main kind of noise: structure-borne noise, or impact noise, and airborne noise. The former is generated by a physical impact or vibration of a building element (roof, floor, wall), while the latter is transmitted through the air (Hopkins, n.d.). Sound pressure level, noise frequency, noise source, noise duration and its temporal variation are the most influent parameters on acoustic comfort. Moreover, in order to predict comfort with airborne noise, equivalent sound pressure level (L_{eq}) is used, while for structure-borne noise maximum sound pressure level (L_{max}) is applied (Guski, 1999).

Besides these parameters, acoustic comfort remains an highly subjective topic. People may perceive differently the same noise source, with the same acoustical characteristics. In order to assess acoustic comfort, some personal features, such as noise sensitivity and attitude toward a noise source, have to be taken into account (Guski, 2002; Ouis, 1999).

A lack in acoustic comfort has evident psychological consequences on humans, including stress and de-concentration. Other studies have shown how higher blood pressure, higher production of stress hormones and anxiety, a reduction of the ability to remember and to focus on, are linked to elevated levels of noise (Evans et al., 1998).

Aware of this, some regional and international standards prescribe noise level limits, based on the effect noise on the user and the tasks performed. It has been noticed that the main effects generated by acoustic discomfort on office workers are communication issues, bad work performance, less productivity. Moreover it has been established that in open-plan offices the transmission index, distraction distance and privacy distance do not have to be underestimated (Delle Macchie et al., 2018). Nevertheless, individual differences and sensitivities are not fully considered. Most of the guidelines do not take into account temporal variation of noise, as well as variable noise (Laszlo et al., 2012). In fact, noise in offices mainly originates from internal sources, such as people chatting, operations of machines (for example typing on the keyboard, in offices), or office equipment (like printers) (Banbury & Berry, 2005).

To guarantee the acoustic comfort in an indoor space means to make it pleasant for its users, without modifying the original building's function and protecting people from noise. As all the others indoor environmental quality domains, also a perception of acoustic discomfort can influence occupants' operativeness, strongly relating acoustic comfort and the commercial sector (Landstriim et al., 1995). The different comfort domains are strictly connected. Indeed, a research carried out by Pellerin and Candas in 2004, revealed that an increase or decrease of 1°C from a comfort condition, produces the same result on thermal comfort as the increment in noise of 2.6 dB in short-term exposure and 2.9 dB in long-term exposure (Pellerin & Candas, 2004).

1.3 THE ISSUE OF INDOOR ENVIRONMENTAL QUALITY IN THE EUROPEAN SCENARIO

On March 14, 2023, the European Parliament approved the negotiating mandate on the European energy efficiency directive, the Energy Performance of Building Directive (EPBD). It is still an open negotiation, in which the first formal meeting between representatives of Parliament, the Council and the Commission was held on June 6 to reach mediation on a jointly agreed text in Brussels; the second will take place on August 31. The EPBD, which promotes the concept of a "green home," aims to renovate existing buildings that have high energy consumption, and thus belong to the latest energy classes, and to construct new energy-efficient buildings with near-zero greenhouse gas emissions. Specifically, the legislation aims:

- For residential properties, the achievement by 2030 of energy class E, which will evolve to D by 2033, with a 25% cut in energy consumption;
- For other buildings, it will be mandatory for them to be in class E from 2027, and in class D from 2030;
- From 2028, all new buildings will have to be 0-emissions.

The broader goal encompassing the directive is for the European Union to reduce emissions by 55 percent by 2030, compared to 1990 levels. It, therefore, requires each member state to submit its own national plan, as well as decide on the sanctions to be applied in case of non-compliance with the directive.

It also reads the possibility for EU countries to exempt certain building types from the application of the directive, such as:

- Those located in historic centers,
- Under Cultural Heritage constraints;
- Those whose architectural value could decrease;
- Second homes;
- Buildings of religion;
- Detached dwellings with an area of less than 50 square meters.

A number of countries, including Italy, voted against it, mainly highlighting the overly tight timeline, considering that much of Italy's building heritage was built at the turn of the 1970s and 1990s, thus before energy-saving regulations. As of today, ANCE (National Association of Building Contractors) data reveal that 9 million of Italy's 12.2 million residential buildings do not align with the required energy performance.

The directive also focuses on an aspect that transcends but at the same time stands as an integrated part of a wider concept of energy efficiency: indoor environmental quality (IEQ).

Article 2, dealing with definitions of the directive's main terms, defines "indoor environmental quality" as "a set of parameters related to a building, including indoor air quality, thermal comfort, lighting and acoustic quality that affect the health and well-being of its occupants." as well as "indoor thermo-hygrometric comfort" as "the indoor environment of a building that optimizes the health, comfort, and well-being of its occupants in line with specific performance levels, including those related to daylighting, indoor air quality, and thermal comfort, such as mitigating overheating and improving acoustic quality. ".

Proceeding, in Article 5 "Setting of minimum energy performance requirements," the EPBD stipulates that minimum energy performance requirements should take into consideration the thermo-hygrometric comfort of indoor environments.

In Article 7, "New buildings," it is stated that "Member States shall ensure by ...[date of transposition of this Directive] that new buildings have optimal indoor environmental quality levels, including air quality, thermal comfort a high capacity to mitigate and adapt to climate change through, inter alia, green infrastructure, adhere to fire safety and safety lighting standards, mitigate risks related to intense seismic activity and prioritize accessibility for persons with disabilities."

Article 11, "Technical building systems," expressly calls for the installation of devices that monitor and control environmental quality in zero-emission buildings, those newly constructed, those that have undergone major renovations, nonresidential buildings with a rated useful output of more than 70 kW for heating and cooling systems, and public buildings used for education, health, and social care. Effective monitoring of indoor environmental quality must therefore be ensured to preserve the health and safety of occupants.

There is even an entire article devoted to indoor environmental quality (Article 11a). According to this article, each member state is required to set up appropriate standards to maintain appropriate indoor environmental quality. IEQ indicators to be monitored are then listed, namely:

- the level of CO_2;
- the temperature and thermal comfort;
- the relative humidity
- the level of daylighting or appropriate levels of daylighting;
- the ventilation rate expressed in air changes per hour;
- indoor acoustic comfort, such as by controlling reverberation time, the level
- of background noise and intelligibility of speech.
- (Possibly) Particulate matter from indoor source emissions and target limits of pollutants from indoor sources on volatile organic compounds classified as carcinogenic, mutagenic or toxic, including formaldehyde.

As stated in Article 16, "Energy performance certificates," the energy performance certificate not only prescribes ways to optimize the cost of energy performance and reduce greenhouse gas emissions over the life cycle of the building, but also to improve indoor environmental quality. In fact, Annex V, Template for energy performance certificates, specifies that the certificate must have some additional indicators, namely:

- presence of fixed sensors that monitor levels of indoor environmental quality;
- presence of fixed controls that react to indoor environmental quality levels.

On this scenario that the will but also the need for designing a complete, innovative and low cost internal environmental monitoring system is born: PROMET&O.

2. HOW TO MERGE SUBJECTIVE AND OBJECTIVE: PROMET&O PROJECT

The previous chapter has underlined how objective and subjective aspects of the Indoor Environment have to co-exist in the comfort assessment. The more they go hand to hand, the easier is to ensure a comfortable indoor work space (Awada et al., 2023).

At the moment on-site monitoring of physical parameters of the four environmental domains and occupants' subjective feedback, collected mainly through questionnaires, are two interrelated approaches in assessing indoor environmental comfort (Loomans et al., 2020). Actually the monitoring campaigns detect more IEQ parameters than IEC ones, due to the use of wireless low-cost sensors and cloud software platforms, within the IoT framework (Duarte Roa et al., 2020).

Occupants' subjective feedback, instead, can be easy collected through smartphone, PC, Tablet or polling stations. Anyway it could be useful to assess a proper routine for collecting feedback, including the best methodology, device and the frequency of data collection. Furthermore all the personal, social, psychological and contextual variables, such as location, gender, age, country of origin and so on (see paragraph 1.2.1), have to be taken into account.

Even if standard requirements are fulfilled, occupants may be dissatisfied with the IEQ of their environment. It has been shown that their satisfaction increase with higher degree of personal control. It is able to enhance the occupant behavior and thus reduce energy consumptions (Haldi & Robinson, 2011b; Huang et al., 2004b; Rijal et al., 2009b; Samani et al., 2015b; Thea, 1989).

The most desirable enhancement would be a methodology able to embrace IEQ, IEC, Physiological, Personal, Behavioral, Contextual Variables (PPBCv) and energy consumptions (ECs). In the post-Covid 19 era, companies themselves have shown a growing interest in office design, safety, health and comfort. Thus it is necessary to develop a low-cost, accurate system to monitor IEQ and IEC, able to engage occupants with a proactive behavior and provide guidelines and best practices for potential stakeholders (occupants, chief executive officers, human resources managers, health and safety manager, energy and facility managers, investors, …).

In this perspective the project "PROMET&O – PROactive Monitoring for indoor EnvironmenTal quality & cOmfort" was born.

A first phase is made of preliminary investigations with the aim to define the physical quantities to monitor, the key performance indicators, the acquisition and representation methodologies.

2.1 AIM OF THE PROJECT AND WORFLOW

PROMET&O adopts a multidisciplinary approach, whose team consist of building physics, electronic and computer engineering experts. The main objects of the project can be reassumed as following:

Object 1: To produce an in-field monitoring system for Indoor Environmental Quality (IEQ) and Comfort (IEC) which is accurate, innovative and low-cost.

Objective 2: To encourage a proactive occupants' behavior, fostering them to provide feedback on their subjective IEC perception. In this phase PPBCv (Physiological, Personal, Behavioral, Contextual Variables) have to be taken into account. In order to achieve this result, multiple strategies has been adopted. Among them it is necessary to remind:

- the use of an attractive communication to engage occupants
- the administration of questionnaires on multiple-steps
- the promotion of the objective and subjective results to keep the occupants aware.

Objective 3: To supply stakeholders with best practice, gained by the "PROMET&O system" data elaboration. This interaction between Building Automation and Control System will promote a healthier work environment, thus benefits in terms of well-being, productivity, as well as a reduction of energy consumption.

PROMET&O project consists of some consequential and simultaneous phases. After the definition of the physical quantities to monitor, the sensor to use and their position, a subjective questionnaire to monitor IEQ and IEC has been developed. The electronical components of the multisensor have been assembled in order to make the first prototype that will be implemented during the entire project. In the meanwhile the sensors have undergone a calibration phase. Ten additional prototypes will be 3D printed and used to monitor IEQ and IEC in a real environment, i.e. Italgas offices in Turin.

2.2 PROMET&O AND COMPETITORS

Over the past 20 years the introduction of the Internet of Things (IoT), started a technological revolution. Generally IoT is a term used to describe an everyday object enclosing wireless sensor network (WSN), with the aim to reach a specific goal. Normally a WSN deploys a wide number of wireless sensing devices (nodes) around the studied phenomena, in order to get useful data (Akyildiz et al., 2001; Gubbi et al., 2013). The assembly line consists of:

1. A sensor to monitor the surrounding environment;
2. A microprocessor to generate usable data from the raw signal of the sensor;
3. A transmitter to send data.

Among the reason why these networks are even more adopted there is the fact that they are easy-to-deploy and low-cost. Moreover, wall-mounted sensors are not able to monitor the micro-environment in which every occupant performs.

In the recent years even more low-cost multisensors spread out on the market. For this reason, a benchmark analysis has been carried out to analyze the competitors more similar to PROMET&O. In the end, it has been shown that PROMET&O project makes a step forward the state of the art thanks to its capability to merge objective and subjective data. Subjective data acquisition, instead, involves a proactive behavior of occupants, keeping an high engagement level. The following tables (Tab. 19, 20) reassumes the performances comparison of PROMET&O and its two main competitors, SAMBA and AirCare.

Table 19 Comparison of the measured parameters for PROMET&O, AirCare and SAMBA. Taken from (Bevilaqua D. ,2023)

	PROMET&O	AirCare	SAMBA
Air temperature	✓	✓	✓
Globe temperature	✗	✗	✓
Air velocity	✗	✗	✓
Relative humidity	✓	✓	✓
Sound pressure level	✓	✓	✓
Carbon Dioxide	✓	✓	✓
Carbon monoxide	✓	✗	✓
PM 10	✓	✓	✗
PM2.5	✓	✓	✗
Formaldehyde	✓	✗	✓
Nitrogen Dioxide	✓	✗	✗
TVOC	✓	✓	✓
Atmospheric pressure	✗	✓	✗
Illuminance	✓	✓	✓
Electrosmog	✗	✓	✗

Table 20 Comparison among additional components. Taken from (Bevilaqua D. ,2023)

		PROMET&O	AirCare	SAMBA
Details	Single body	✓	✓	✗
	LED light	✓	✗	✗
	Vertical hook	✓	✓	✗
	Rubberised base	✓	✓	✓
	Rod hook	✓	✗	✗
Subjecting feedback reporting	IEC monitoring	✓	✗	✗

2.2.1 SAMBA

SAMBA has been developed by IEQ Lab at The University of Sydney as a low-cost solution for continuous, real-time measurements of Indoor environmental quality (IEQ) parameters in office buildings. The device is made by two different elements, whose main has 9x9x19 cm of dimensions, while the satellite is smaller (9.5x9.5x9.5 cm).

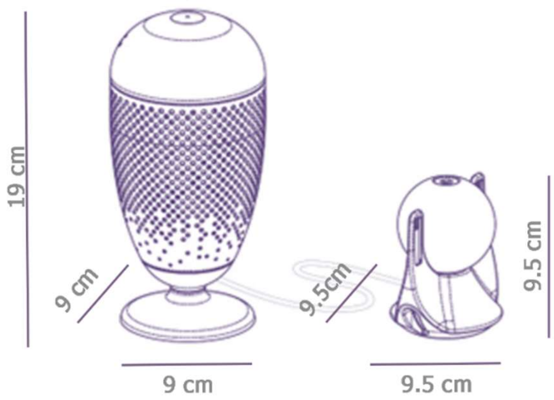


Figure 6 Dimensional features of SAMBA device. Personal rework from https://good-design.org

It integrates a low-cost sensors network, chosen for their performance, power requirements, output type and form factor, with a software platform where no-scientists have the possibility to visualize and understand the monitored data. Data sampled are both across building floor space and through day time. They are wirelessly transmitted to a web service, and graphically converted into a dashboard, generated using PHP and Javascript, that shows real time parameters and indices, to engage the occupants and let them interact. To achieve this goal also weekly reports to sum up the overall performance of the building are emailed to users every Monday morning. A performance index "IEQ Rating" is shown on the dashboard. There are three rating levels, based on the total number of hours in accordance with the standards:

1. Good (green), more than 80%
2. Fair (yellow), between 60% and 80%
3. Poor (red), less than 60%.

Moreover the four domains of IEQ are weighted in the assessment of overall IEQ rating. Specifically thermal comfort and indoor air quality have a 0.35 coefficient each, while Visual comfort and Acoustic comfort contribute 0.15 each (Parkinson et al., 2019a).

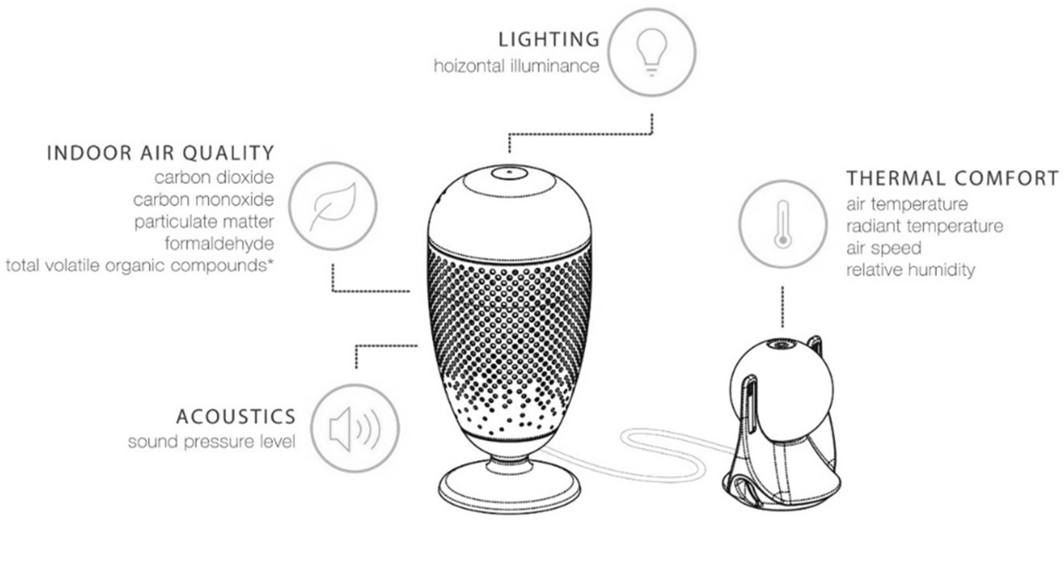
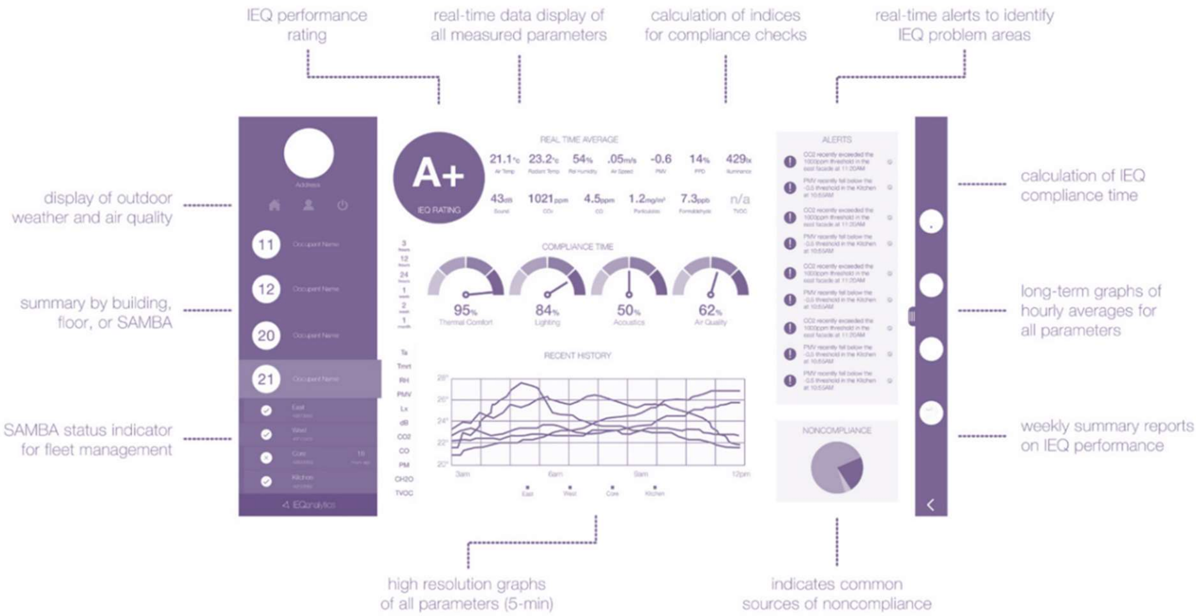


Figure 7 Sensors positioning in SAMBA device. Taken from https://good-design.org/projects/samba-indoor-environmental-quality-ieq-monitoring-platform/

Figure 8 Dashboard setting. Taken from https://good-design.org/projects/samba-indoor-environmental-quality-ieq-monitoring-platform/



According to Australias's NABERS, 10 parameters have been taken into account:

Parameter	Sensor Type	Range	Resolution
Air temperature	NTC thermistor	0-50°C	0.1°C
Relative humidity	Capacitive	5-95%	0.1%
Globe temperature	NTC thermistor	0-50°C	0.1°C
Air speed	Bi-directional thermal anemometer	0-1 m/s	0.01 m/s
Sound pressure level	Electret microphone	40 to 90 dBA	0.1 dBA
Illuminance	Broadband photodiode	0 to 20000 lx	1 lx
Carbon dioxide (CO_2)	Nondispersive infrared	0-5000 ppm	1 ppm
Carbon monoxide (CO)	Electrochimical	0-50 ppm	0.1 ppm
Formaldehyde (HCHO)	Electrochimical	0-2 ppm	0.01 ppm
Total volatile organic compounds (TVOC)	Photoionisation	10-2000 ppb	10 ppb

2.2.2 AirCare

AirCare is an Italian IoT device adopted for indoor environmental quality monitoring, in order to ensure people's well-being.

It measures:

1. Air quality parameters:
    a. Volatile Organic Compound
    b. Particulate matter (PM10, PM2.5)

    c. Air Quality Index
    d. Carbon Dioxide (CO_2)
    e. CO_2 equivalent

2. Environmental comfort
    a. Sound Pressure Level
    b. Temperature
    c. Humidity
    d. Ambient light
    e. Atmospheric pressure

3. Elettrosmog
    a. High frequency
    b. Low frequency
    c. Wifi (networks)
    d. Wifi (level)

Moreover this device has been scientifically validated by SIMA (Italian Society of Environmental Medicine) for PM2.5 and CO_2 measurements.

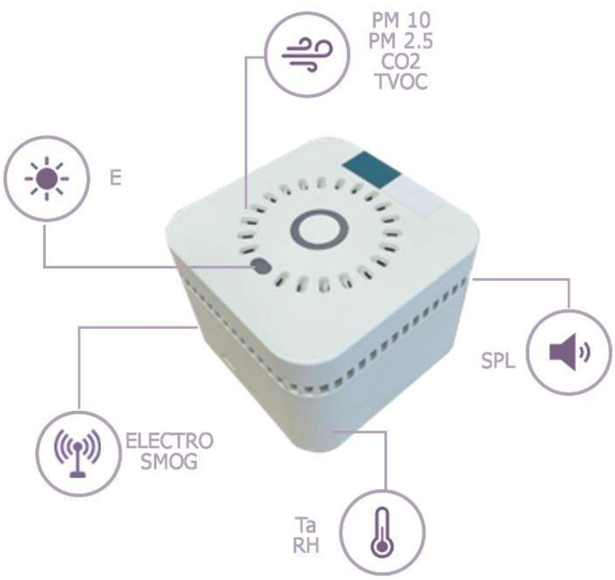


Figure 9 Sensors positioning in an AirCare device. Rework from https://www.aircare.it

From the case design point of view, the device shows up as a compact, linear white device, 10x10x7cm (Fig. 12, 13). It presents side openings in order to guarantee a continous ventilation and avoid an overheating of electronic components.

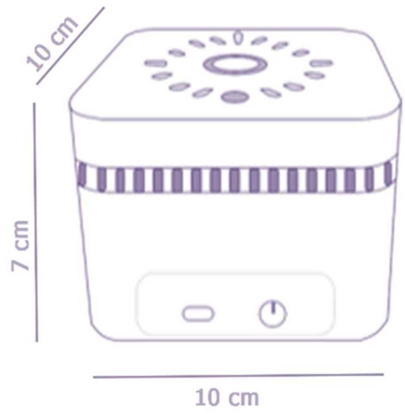


Figure 10 Dimensional features of a AirCare device. Rework from https://www.aircare.it

AirCare deploys some LED indicators on the upper surface. According to change of colors or illumination frequency it is possible to understand how the device is working. The data collected are through Wifi or Narrowband-IoT.

Also AirCare provide a Dashboard as user interface, in order to reach an higher occupants' engagement. Through it the user has the ability to control all the IoT devices and monitor the collected data. Moreover he can check Indoor Wellbeing, Air Quality and Comfort rating.

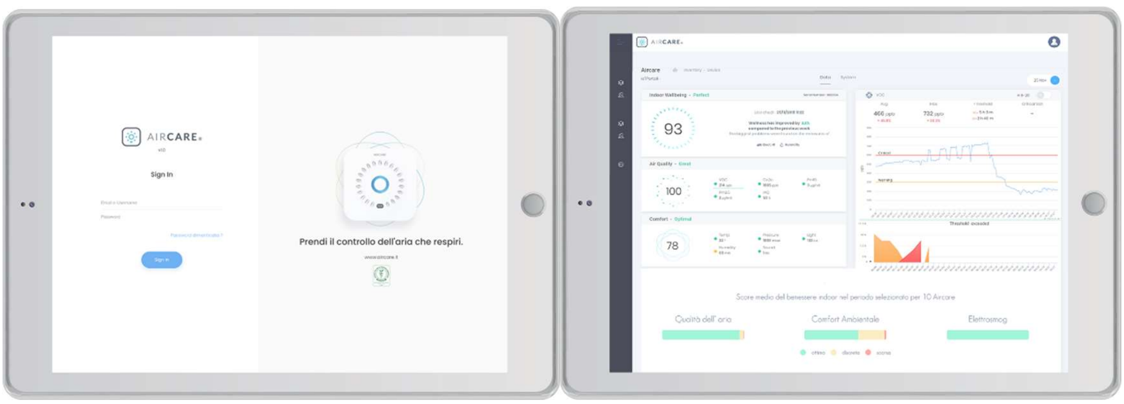


Figure 11 Dashboard user login and display. Taken from https://www.aircare.it

Using the platform it is possible to produce reports about the collected data and email it (Fig. 15). One example is attached below:

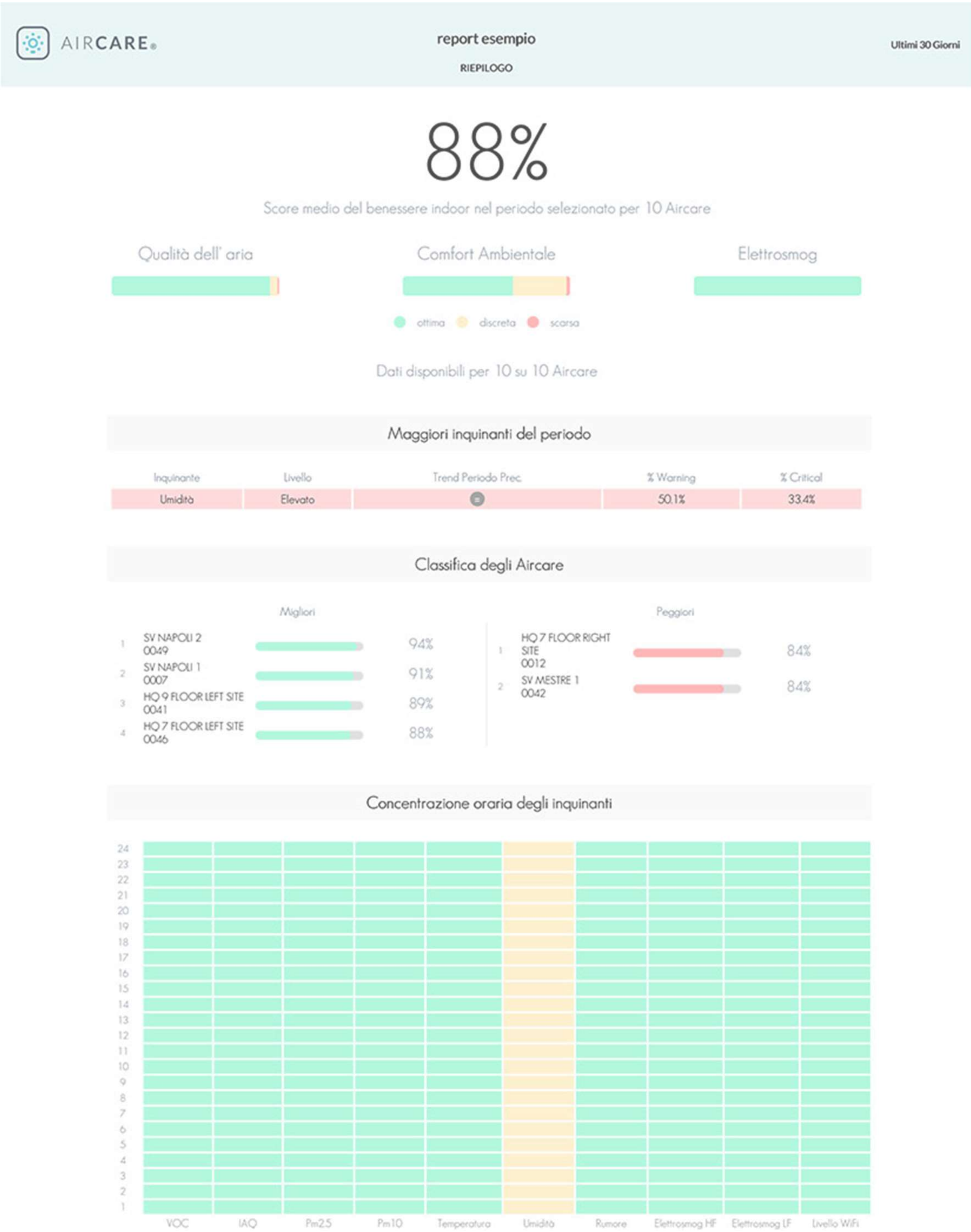


Figure 12 Example of report. Taken from https://www.aircare.it

Moreover it is possible to create analytical reports for critical conditions, when threshold are overcome. The peculiarity is the analysis of the possible origins and the suggested solutions (Fig. 16). An example is showed above:

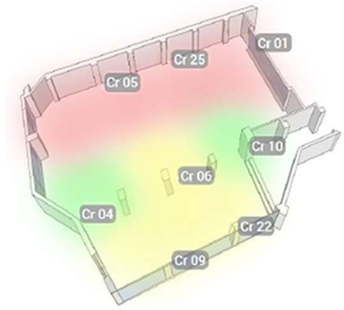
AIRCARE *Relazione monitoraggio ambientale*
Control Room – 1.3

5 Conclusioni

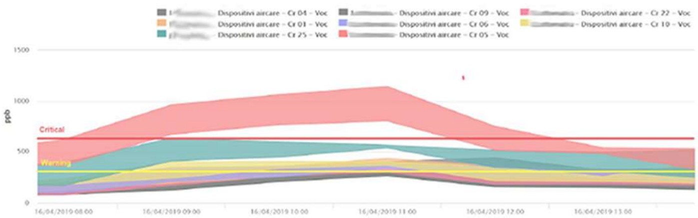
Come già esplicitato nei paragrafi precedenti per le singole misure, le rilevazioni effettuate hanno mostrato che l'area del locale che presenta una minore salubrità è la parete nord, ovvero quella monitorata tramite i device CR 05, CR 25 e CR 01.
Per comodità si riportano di seguito le misure per cui più frequentemente sono stati riscontrati dei problemi sui tre device sopra citati:

- IAQ
- PM 2.5
- Temperatura
- Umidità
- VOC

La motivazione è probabilmente da ritrovarsi nella lontananza dalle bocchette del ricircolo dell'aria e dall'elevato tasso d'occupazione in quella zona.
Le aree coperte dai dispositivi **CR 04** e **CR 10** risultano invece avere un livello di salubrità da prendere come esempio.



Nel dettaglio, il 16 aprile 2019 tra le 9 di mattina e le 12 gli otto device hanno registrato un evento particolarmente critico, dove addirittura è stata superata la soglia di **1000 ppb.**
La figura seguente mostra evidenza dell'evento.



Nello specifico si è notato una tendenza al superamento delle soglie in determinati orari della giornata, quali ad esempio:

- Mattina: **8-9**
- Pomeriggio: **15-17**

Questi risultati possono essere chiaramente visibili nelle immagini seguenti, dove si possono notare picchi elevati proprio in queste fasce orario.

Figure 13 Example of environmental monitoring report. Taken from https://www.aircare.i

2.3 PHYSICAL QUANTITIES TO MONITOR

Based on a thorough analysis of national and international standards, environmental sustainability protocols and review of scientific literature on the topic of Indoor Environmental Quality (IEQ), the physical quantities to be monitored in the indoor environment, and the most appropriate measuring instruments, were selected: air temperature (Ta), relative humidity (RH), illuminance (E), sound pressure level (SPL), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen dioxide (NO_2), particulate matter PM2.5 and PM10, volatile organic compounds (TVOC) and formaldehyde (CH_2O). A search was conducted for the most suitable sensor for monitoring each quantity, pursuing the goal of developing a low-cost and accurate multisensor. The following table (Tab.21) shows for each monitored parameter:

1. Sensor measuring range
2. Considered range (minimum and maximum value showed on y axes of the graph)
3. Threshold obtained from current standards
4. Temporal mean on graph
5. Current reference standards
6. Technical definition of the parameter

Table 21 Physical quantities to monitor

PARAMETER			SENSOR MEASUREMENT RANGE	RANGE ON ORDINATE AXIS OF THE GRAPH	THRESHOLD	TEMPORAL MEAN ON GRAPH	REFERENCE	DEFINITION
Air temperature	T_a	°C	-40-125 °C	10-40 °C	WINTER 20-24 °C	On all temporal graphs from 21/9 to 21/6	ISO 7730	Air temperature is the temperature of the air around the human body
					SUMMER 23-26 °C	On all temporal graphs from 21/6 to 21/9		
Relative Humidity	RH	%	0-100 %	25-95%	25-60%	All temporal graphs	EN 16798	The values giving the composition of the air in terms of water vapour in relation to the maximum amount it can hold at a given temperature characterize the relative humidity of the environment
Illuminance	E	lx	0.0072-120 000 lx	5-5000 lx	Writing, typing, reading, data processing ≥ 500 lx	All temporal graphs	EN 12464-1	Illuminance is the ratio between the luminous flux incident on an elementary surface and the area of the elementary surface itself
Carbon monoxide	CO	mg/m^3	0-1145.609 mg/m^3	0-200 mg/m^3	15 min. mean ≤ 100 mg/m^3	RT	EN 16798	Carbon monoxide (CO) is a colourless, non-irritant, odourless and tasteless toxic gas. It is produced by the incomplete combustion of carbonaceous fuels such as wood, petrol, coal, natural gas and kerosene.
				0-100 mg/m^3	1 h mean ≤ 35 mg/m^3	3h		
				0-50 mg/m^3	8h mean ≤ 10 mg/m^3	12h		
				0-50 mg/m^3	24 h mean ≤ 7 mg/m^3	24h-3d-1w-1m		

Carbon dioxide	CO_2	ppm	0-40 000 ppm	0-1000 ppm	≤ 800 ppm	All temporal graphs	EN 16798	Carbon dioxide is a colourless and odourless gas at atmospheric temperature and pressure. It is produced by the combustion of organic compounds
Nitrogen dioxide	NO_2	$\mu g/m^3$	0-9409 $\mu g/m^3$	0-500 $\mu g/m^3$	1 h mean ≤ 200 $\mu g/m^3$	RT-3h-12h-24h-3d-1w	EN 16798	Nitrogen dioxide in its gaseous form is volatile, reddish-brown in colour and heavier than air, and has a characteristic pungent odour perceptible from a concentration of 188 $\mu g/m^3$ (0.1 ppm). It is one of the principal nitrogen oxides associated with combustion sources.
				0-100 $\mu g/m^3$	Annual mean ≤ 20 $\mu g/m^3$	1m		
Particulate matter	$PM_{2.5}$	$\mu g/m^3$	0-1000 $\mu g/m^3$	0-100 $\mu g/m^3$	24 h mean ≤ 25 $\mu g/m^3$	RT-3h-12h-24h-3d-1w	EN 16798	Particulate matter is a mixture of solid particles and liquid droplets found in the air. $PM_{2.5}$: fine inhalable particles, with diameters that are 2.5 micrometers or smaller.
				0-50 $\mu g/m^3$	Annual mean ≤ 10 $\mu g/m^3$	1m		
Particulate matter	PM_{10}	$\mu g/m^3$	0-1000 $\mu g/m^3$	0-200 $\mu g/m^3$	24 h mean ≤ 50 $\mu g/m^3$	RT-3h-12h-24h-3d-1w	EN 16798	Particulate matter is a mixture of solid particles and liquid droplets found in the air. PM_{10} : inhalable particles, with diameters that are 10 micrometers or smaller
				0-100 $\mu g/m^3$	Annual mean ≤ 20 $\mu g/m^3$	1m		

Total volatile organic compounds	TVOC	µg/m³	0-10000 µg/m³	0-1000 µg/m³	≤ 500 µg/m³	All temporal graphs	WELL	Volatile organic compounds are organic chemical compounds whose composition makes it possible for them to evaporate under normal indoor atmospheric conditions of temperature and pressure. Are toxic by inhalation and exposition, with chronic or acute effects.
Formaldehyde	CH_2O	µg/m³	0-1228 µg/m³	0-200 µg/m³	30 min. mean ≤ 100 µg/m³	All temporal graphs	EN 16798	Formaldehyde is a colourless gas, flammable and highly reactive at room temperature. It is formed primarily by numerous natural sources and anthropogenic activities.
Sound Pressure Level	SPL	dB(A)	Acoustic overload point: 122.5 dB Frequency flat response: 100-10000 Hz	20-120 dB(A)	≤ 45 dB(A)	All temporal graphs	NF S 31-080	Logarithm of the ratio of a given sound pressure to the reference sound pressure. Sound pressure level in decibels is 20 times the logarithm to the base ten of the ratio.

2.4 LOW COST SENSORS SELECTION

The choice of sensors best suited to monitor the physical quantities shown in Tab.21 was dictated by multiple factors. Since this is a low-cost multi-sensor, one selection criterion was the cost of each individual sensor. In order for the case to be compact, an attempt was made to not exceed in size by choosing small sensors. In order to fabricate a scientifically valid instrument, sensors were chosen with accuracy and measurement range that met the reference standard or the WELL protocol, depending on the physical quantity. Since the entire project has tight deadlines, the market availability of the sensors was also considered. Finally, other selection criteria included the type of interface (analog or digital), response time, which is how long it takes the sensor to adapt to an abrupt alteration in the measured quantity, and current consumption, which, to avoid overheating problems, should be limited.

Based on the above considerations, a summary table of the characteristics of the specific sensors chosen is given (Tab.22), more fully discussed, in the following section. Overall, the cost of the sensors is about 203 €, per multi-sensor.

Table 22 List of chosen low cost sensors

PHYSICAL PARAMETER	PRODUCER PART NUMBER	MEASUREMENT RANGE	ACCURACY	DIMENSIONS WxLxH (mm)	INTERFACE	UNIT COST(€)
Air temperature Relative Humidity	Sensirion -SHT41	-40 °C - 125 °C / 0 % - 100 %	± 0.2 °C (tipica tra 0 °C e 60 °C) / ± 0.4 (max between 0 °C and 60 °C)	1.5 x 1.5 x 0.54	12 C	4.79
Illuminance	Vishay - VEML7700	0 - 120000 lux (max)	10 %	6.5 x 2.35 x 3	12 C	2.13
Carbon monoxide	Spec sensors - 3SP_CO_1000	0 - 1000 ppm	± 2.75 nA/ppm (sensitivity)	20 x 20 x 3.8	ANALOGIC	19.97
Carbon dioxide	Sensirion - SCD30	0 - 40000 ppm	± (30 ppm) ± 3 % range 400 - 10 000 ppm)	35 x 23 x 7	12 C	66.17
Nitrogen dioxide	Spec sensors - 3SP_NO2_5FP	0 - 5 ppm	± 10 nA/ppm (sensitivity)	20 x 20 x 3.8	ANALOGIC	19.97
Particulate matter	Sensirion - SEN54	0 - 1000 µg/m^3	PM2.5: ± 10 % PM10: ± 25 %	52.3 x 43.3 x 22.3	12 C	29.92
Total volatile organic compounds	SGX Sensortech – MiCS-VZ-89TE	0 - 1000 ppb (isobutylene equivalent)	not declared	22.9 x 14 x 3.15	12 C	5.37
Formaldehyde	Sensirion - SFA30	0 - 1 ppm	± 20 ppb or ± 20 %	42 x 24 x 5.5	UART	52.79
Sound Pressure Level	ST - IMP34DT05	Frequency response : 100 – 10000 Hz	not declared	3 x 4 x 1	12 S	2.49

2.4.1 Temperature and Relative Humidity Sensor

Figure 14(a) Assonometric view Sensirion-SHT41, (b) Technical drawing Sensirion-SHT41. Taken from https://www.mouser.it/

Among similar sensors, the Sensirion-SHT41 has been chosen for several reasons, such as:

- The accuracy meets the standards
- It measures Air Temperature and Relative humidity at the same time.

It is important to remind that each Sensirion sensor is manufacturer calibrated following the standards required by ISO/IEC 17025, as reference. In the technical datasheet the producer declare the accuracy of the sensor.

With regard to relative humidity, SHT41 RH typical uncertainty is ±1.8 %.

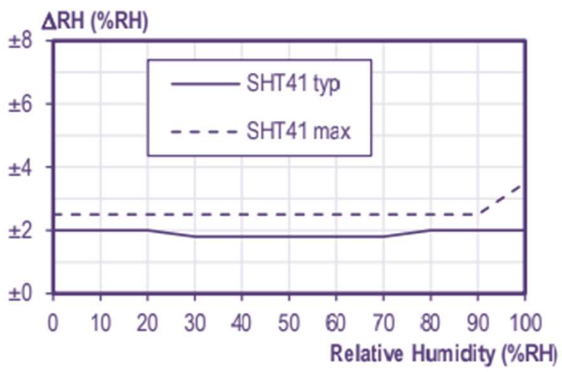


Figure 15 SHT41 typical and maximal relative humidity accuracy at 25°C.Taken from https://www.mouser.it/

The stated repeatability indicates how closely a series of measurements of the same quantity, made with the same sensor, yields the same or very close numerical value, regardless of whether it is correct. It is also a measure for the noise on the physical sensor output.

The term resolution in this context means the smallest change in the physical quantity that can be measured. It should not be confused with accuracy. The stated resolution is 0.01 %.

The specific range for which the humidity sensor specification is guaranteed is from 0 to 100%.

The time for achieving 63% of a humidity step function, measured at 25 °C and 1 m/s airflow (Response time) is 4 seconds.

Table 23 General relative humidity sensor specifications

Parameter	Conditions	Value	Units
SHT41 RH accuracy	typ.	±1.8	%RH
Repeatability	high	0.08	%RH
	medium	0.15	%RH
	low	0.25	%RH
Resolution	-	0.01	%RH
Hysteresis	At 25°C	±0.8	%RH
Specified range	extended	0 to 100	%RH
Response time	$\tau_{63\%}$	4	s
Long-term drift	typ.	<0.2	%RH/y

Regarding the monitoring of the air temperature, SHT41 has a declared accuracy of ±0.2 °C and a resolution of 0.01 °C.

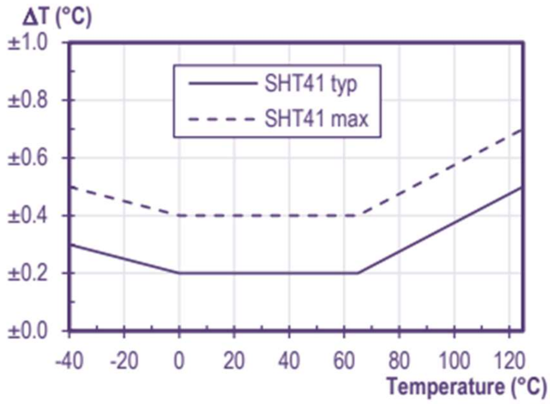


Figure 16 SHT41 typical and maximal temperature accuracy. Taken from https://www.mouser.it/

Instead, the specific range for which the temperature sensor is guaranteed is between -40°C and 125°C. In this case, the response time is 2 s, lower than the RH one. Temperature response time depends on heat conductivity of sensor substrate.

Table 24 General temperature sensor specifications. Personal elaboration from https://www.mouser.it/.

Parameter	Conditions	Value	Units
SHT41 RH accuracy	typ.	±0.2	°C
Repeatability	high	0.04	°C
	medium	0.07	°C
	low	0.1	°C
Resolution	-	0.01	°C
Specified range		-40 to +125	°C
Response time	$t_{63\%}$	2	s
Long-term drift	typ.	<0.03	°C /y

In order to ensure the best performance, the sensor should perform under temperature condition between 5°C-60°C, and relative humidity between 20%-80%. If this range are exceeded for a long time, especially at high RH, the RH signal may be temporarily offset.

Each Sensirion SHT41 is manufacturer calibrated performing a 3-point calibration. It is accredited by Swiss Accreditation service (SAS), according to ISO/IEC 17025:2017. The three temperature condition set up are t_1=-30°C, t_2=5°C, t_3=70°C.

2.4.2 Illuminance Sensor

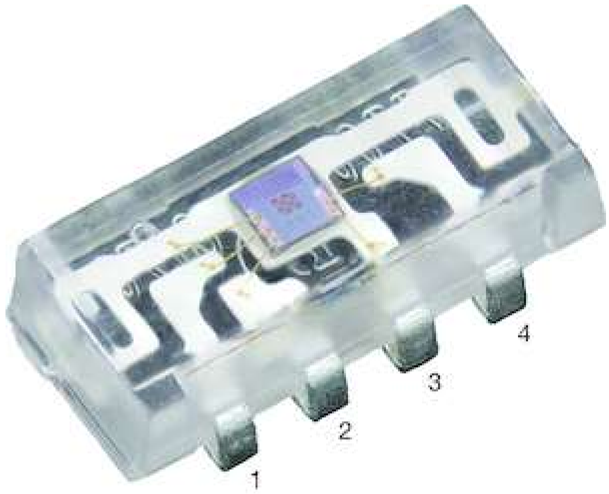


Figure 17 Assonometric view VISAY-VELM7700. Taken from https://www.mouser.it/

In choosing the illuminance sensor, the market analysis initially focused on a sensor with 5% accuracy. The lack of the same in the market, led to lowering the accuracy to 10%. Among the various options, the VISHAY-VELM7700 sensor was chosen for two main reasons:

- The spectral response of the sensor most closely approximates the visibility curve relative to the human eye (photopic vision);
- The measurement range is the most extensive.

The VELM7700 with its reduced dimensions of 6.8x2.35x3mm, includes a highly sensitive square shape photodiode (0.5mm), low-noise amplifier, 16-bit A/D converter, and supports an easy-to-use I^2C bus communication interface. The result monitored is a digital value. The range in which the photodiode can operate is between 0 lx and 120 klx, with a minimum resolution of 0.0036 lx/ct. This is the reason why the sensor may operate behind very dark cover glasses. This sensor may be also exposed to direct sunlight, up to 120 klx. The device should operate under thermal condition within the range of -25°C and +85 °C.

In order to calculate the lux level, starting from the digital result showed by the sensor, it is important to take into account the programmed gain and the integration time. Interpolating this two factors in the following table, provided by the manufacturer, the typical resolution is obtained. It is more sensitive if the gain is 2, while the integration time is 800 m/s. The result is the minimum resolution, i.e., 0.0036 lx/step. It is important to notice that by halving the integration time, the resolution value is doubled. Also the gain works in the same way. The lower is the light level, the higher is the integration time to be chosen. The lowest possible detectable illuminance is 0.007 lx.

Table 25 Resolution and maximum detection range. Taken from https://www.mouser.it/

RESOLUTION AND MAXIMUM DETECTION RANGE									
	GAIN 2	GAIN 1	GAIN 1/4	GAIN 1/8		GAIN 2	GAIN 1	GAIN 1/4	GAIN 1/8
IT (ms)	TYPICAL RESOLUTION					MAXIMUM POSSIBLE ILLUMINATION			
800	0.0036	0.0072	0.0288	0.0576		236	472	1887	3775
400	0.0072	0.0144	0.0576	0.1152		472	944	3775	7550
200	0.0144	0.0288	0.1152	0.2304		944	1887	7550	15 099
100	0.0288	0.0576	0.2304	0.4608		1887	3775	15 099	30 199
50	0.0576	0.1152	0.4608	0.9216		3775	7550	30 199	60 398
25	0.1152	0.2304	0.9216	1.8432		7550	15 099	60 398	120 796

The tolerance range is just ± 10 % with all kinds of light sources (LED light, fluorescent light, and normal daylight). Only halogen lamps with strong infrared content may reach ± 15 % (Fig. 21).

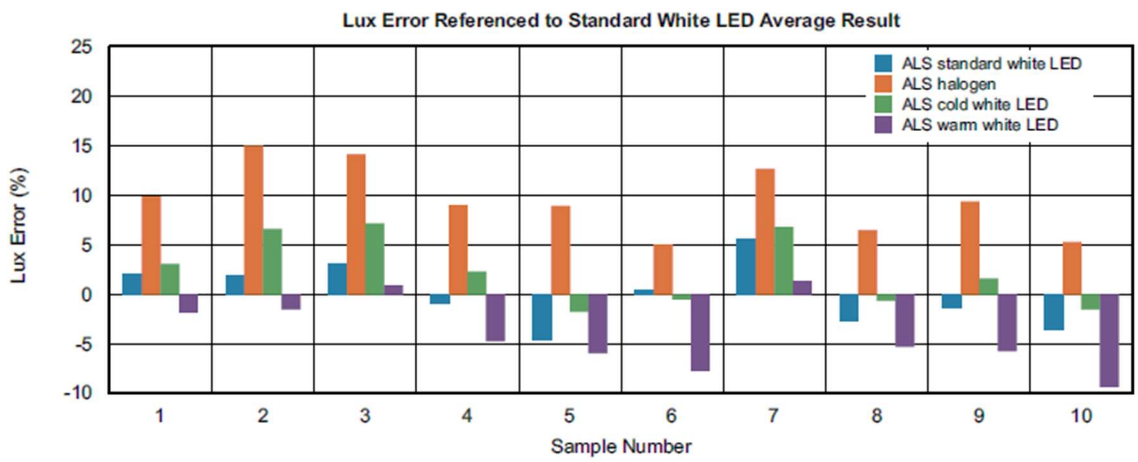


Figure 18 Tolerance for different light sources. Taken from https://www.mouser.it/

Despite most of the low-cost photodetectors, VELM7700 follows in a very exact way the v(λ) curve, so called "human eye curve". Its maximum deviation to nominal value is between ± 10 % (Fig. 22).

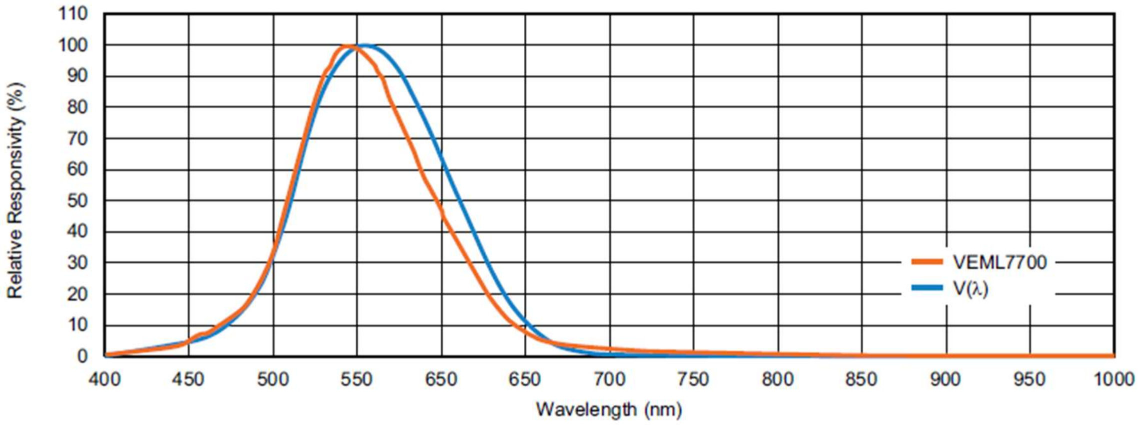


Figure 19 Spectral response ALS Channel. Taken from https://www.mouser.it/

The light sensitivity of a photo-detect diode varies according to the angle of the light source. The graph below (Fig.23) shows the ratio between Relative Radiant Sensitivity and Angular Displacement. As intuitable, if the incident light is perpendicular to the photodiode (0°), the sensitivity is at the maximum level (1.0). If the angle of incidence drops to 40°C, also the sensitivity is lower (0.75). This is the reason why the opening, or window, on the photodiode has to be large enough to maximize the incoming light. . The VEML7700 has an angle of half sensitivity of about ± 55°C.

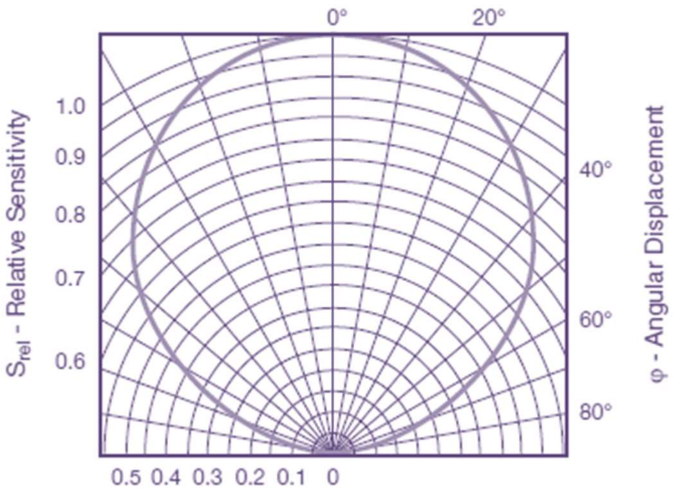


Figure 20 Relative Radiant Sensitivity vs. Angular Displacement. Taken from https://www.mouser.it/

Using the triangular rules, it is possible to calculate the window size of the case that embedded it. Knowing the distance between the upper surface of the photodiode and the window, and the angle below the latter, it is possible to calculate the total window width. The datasheet suggest graphically and numerically this procedure:

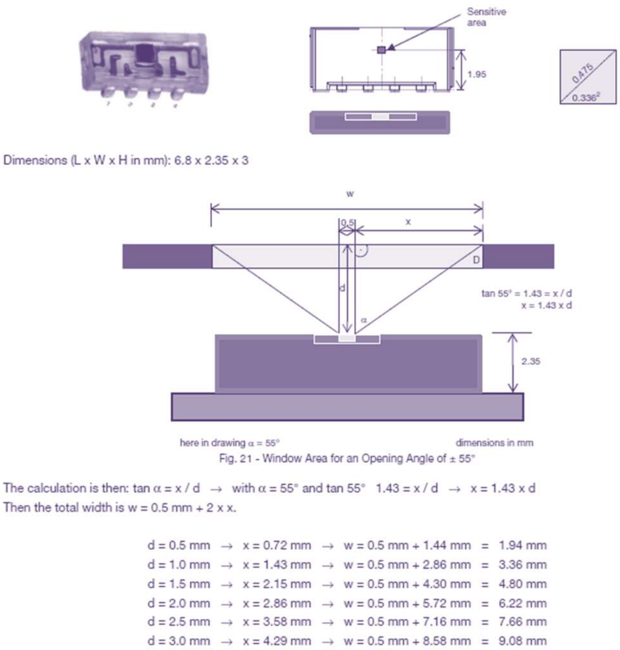


Figure 21 Window calculation for VELM7700. Taken from https://www.mouser.it/

2.4.3 Carbon Monoxide Sensor

Figure 22 Assonometric view SPEC SENSOR 3SP_CO_1000. Taken from https://www.mouser.it/

Sensors commonly used for monitoring carbon monoxide CO, are of the electrochemical type. They work by reacting with the gas of interest and producing an electrical signal proportional to the concentration of the gas. The sensors consist of two electrodes (a working electrode and a counter electrode), and a thin layer of electrolyte that can be passed through by charged molecules. This type is affected by temperature and the presence of other gases similar to the species of interest (cross-sensitivity).

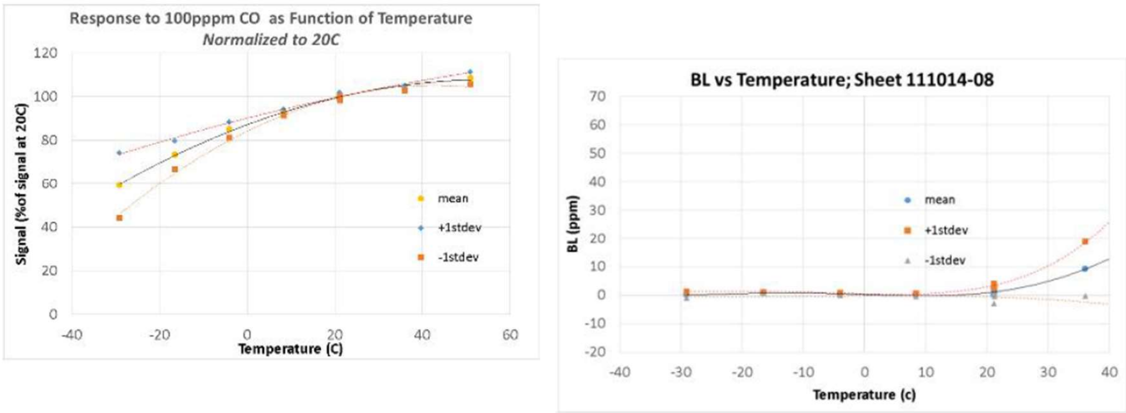
A Spec sensor 3SP_CO_1000 was chosen for CO monitoring, both for its lower cost than its competitors and for the known cross-sensitivity and temperature dependence parameters reported on the datasheet. They facilitated the metrological characterization work.

The main sensor characteristics are reported in the Table below (Tab.26):

Table 26 Sensor datasheet specifications. Personal elaboration from https://www.mouser.it/

SPECIFICATIONS	
Measurement range	0 to 1000 ppm
Detection Limit	0.5 ppm
Resolution	< 100 ppb
Repeatability	< ± 2% of reading
Response time- t90	< 30s
Sensitivity	4.75 ± 2.75 nA/ppm
Expected Operating Life	> 5 years
Operating Temperature Range	-30 to 55°C (recommended -20 to 40 °C)
Operating Humidity Range	15 to 95 %
Power consumption	10 to 50 uW

The sensor signal is affected by temperature fluctuation, easy to compensate. The datasheet shows the Temperature dependency of the 3SP_CO1000 under constant humidity of 40-50% (Fig.26).



Temperature Coefficient of Span ***(Typical)***	-20°C to 10 °C	0.9% / °C
	10°C to 40 °C	0.3% / °C
Zero shift (ppm/deg) ***(Typical)***	-20 to 0 °C	0.06 ppm/°C
	0 °C to 25 °C	0.4 ppm/°C
	25 to 40°C	1.4 ppm/°C

Figure 23 Sensor temperature dependency. Taken from https://www.mouser.it/

Cross-sensitivity to other gases is common for most of electrochemical sensors. The following table (Tab.27) lists the relative response of usual potential interfering gases, and the concentration at which the data was collected.

Table 27 Relative response of usual potential interfering gases. Taken from https://www.mouser.it/

Gas/Vapor	**Concentration**	**Typical Response PPM CO**
Carbon Dioxide	5,000 ppm	< 1
Hydrogen	100 ppm	17
Methane	3,000 ppm	< 1
Ammonia	100 ppm	< 1
Nitrogen Dioxide	10 ppm	< 1
Hydrogen Sulfide	25 ppm	< 1
Carbon Monoxide	400 ppm	400
Ozone	5 ppm	< 1
Sulfur Dioxide	20 ppm	< 1
Chlorine	10 ppm	< 1
n-Heptane	500 ppm	< 1
Toluene	200 ppm	< 1
Isopropyl Alcohol	200 ppm	1.3
Acetone	200 ppm	< 1

2.4.4. Nitrogen Dioxide Sensor

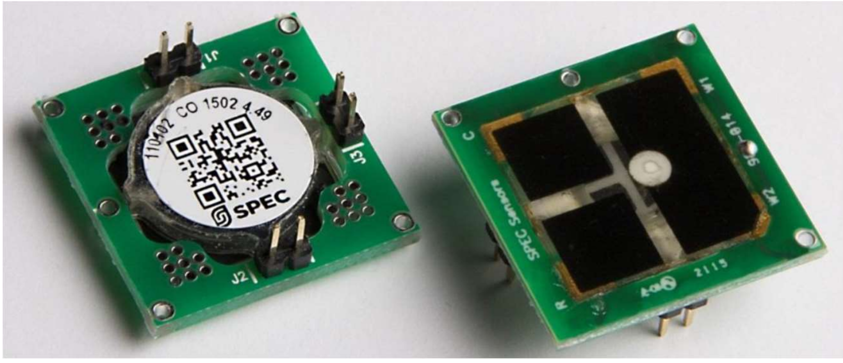


Figure 24 Assonometric view SPEC SENSOR 3SP_NO2_5FP Taken from https://www.mouser.it/

For the same reasons of the CO sensor choice, an electrochemical Spec sensor 3SP_NO2_5F P has been chosen in order to monito NO_2 concentration. All the interested parameters are collected in the following table (Tab.28):

Table 28 Sensor specification. Taken from https://www.mouser.it/

SPECIFICATIONS	
Measurement range	0 to 5 ppm
Lower Detection Limit	< 20 ppb
Resolution	< 20 ppb
Repeatability	< ± 5 % of reading or 10 ppb
Response time- t90	< 15 s
Sensitivity	-30 ± 10 nA/ppm
Expected Operating Life	> 5 years
Operating Temperature Range	-40 to 50°C (recommended -20 to 40 °C)
Operating Humidity Range	0 to 95 %
Power consumption	10 to 50 uW

The sensor signal is affected by temperature fluctuation, easy to compensate. The datasheet shows the Temperature dependency of the 3SP_NO2_5F P under constant humidity of 40-50%.

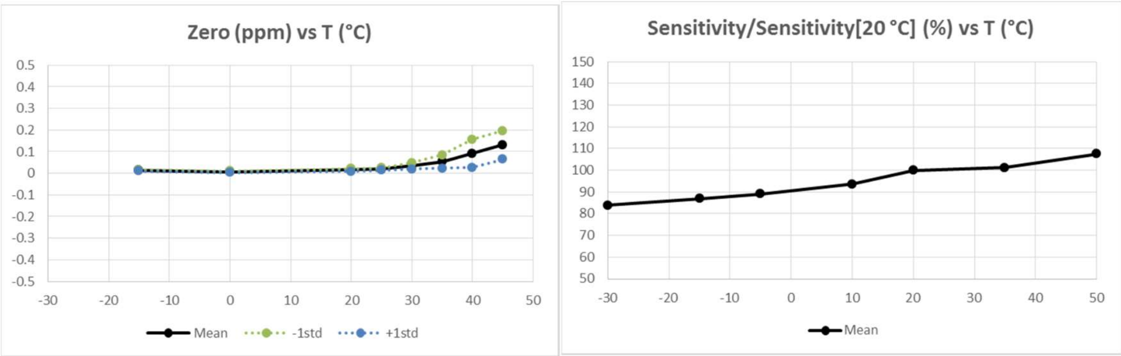


Figure 25 Sensor temperature dependency. Taken from https://www.mouser.it/

As previously mentioned, cross-sensitivity to other gases is common for most of electrochemical sensors. The following table lists the relative response of usual potential interfering gases, and the concentration at which the data was collected.

Table 29 Relative response of usual potential interfering gases. Taken from https://www.mouser.it/

Gas	ppm	Typical Response as ppm NO_2
Carbon Monoxide	100	**<0.02**
Chlorine	10	**<0.5**
Ethanol	100	**<1**
Hydrogen Sulfide	5	**<0.02**
Nitric Oxide (NO)	5	**<0.1**
Nitrogen Dioxide	**5**	**5**
Ozone	1	<0.1
Sulfur Dioxide	5	**<0.02**

2.4.5 Carbon Dioxide Sensor

Most of the sensors considered for CO_2 monitoring, had high current consumption and high response time. Although the cost and size of the Sensirion SCD30 were higher, this sensor was chosen because of its high accuracy.

Figure 26 Assonometric view SENSIRION- SCD30. Taken from https://www.mouser.it/

The datasheet shows the specifications, from which it is important to underline the CO_2 measurement range between 0-40000 ppm. Moreover the accuracy of ±30 ppm, in the calibrated range (400-10000 ppm) where more than 90% of the sensors shown this accuracy. The repeatability, equal to ±10 ppm, as the root mean square error of consecutive measurements at constant conditions. The temperature stability (between 0-50°C) has been tested at 400 ppm with a changing temperature, and it varies of ±2.5 ppm. The response time $t_{63\%}$ of 20 s, means that in 20 s 63% of a respective step function is achieved.

The table below resumes all those parameters:

Table 30 Sensor specifications. Taken from https://www.mouser.it/

Parameter	Conditions	Value
CO_2 measurement range	12C, UART	0-40000 PPM
Accuracy	400 ppm – 10000 ppm	± 30 ppm
Repeatability	400 ppm – 10000 ppm	± 10 ppm
Temperature stability	T=0…50°C	± 2.5 ppm/°C
Response time	$t_{63\%}$	20 s

The datasheet specifies also the operation conditions linked to a certain lifetime. The table below summarize these aspects:

Table 31 Sensor operation conditions. Taken from https://www.mouser.it/

Parameter	Value
Temperature operating conditions	0-50°C
Humidity operating conditions	0-95% RH
Sensor lifetime	15 years

2.4.6 PM2.5-PM10 Sensor

Figure 27 Assonometric view SENSIRION- SEN 54. Taken from https://www.mouser.it/

The sensor chosen for monitoring particulate matter concentration (PM2.5 and PM10) is Sensirion's SEN54. Negative aspects include its larger size and higher power consumption than other competitors. Nevertheless, such a sensor is lower cost and also allows monitoring of other quantities such as temperature, relative humidity, and TVOC. Although the latter is also monitored by its own ad hoc sensor, this property allowed further comparison in metrology.

The sensor has been fully calibrated by manufacturer and the specifications, under 25 ± 2°C, 50± 10% RH, 5 V supply voltage, are reported in the table below (Tab.32):

Table 32 Sensor specifications from datasheet. Personal elaboration taken from https://www.mouser.it/

Parameter	Conditions	Value	Units
Mass concentration specified range	-	0 to 1000	µg/m³
Mass concentration size range	PM 1.0	0.3 to 1.0	µm
	PM 2.5	0.3 to 2.5	µm
	PM 4	0.3 to 4.0	µm
	PM 10	0.3 to 10.0	µm
Mass concentration precision for PM 2.5	100 to 1000 µg/m³	± 10	% measured value
Mass concentration precision for PM 10	100 to 1000 µg/m³	± 25	% measured value/year
Typical start-up time	200-300 #/cm³	8	s
	100-200 #/cm³	16	s
	50-100 #/cm³	30	s

Where typical start-up time is defined as the “time after starting Measurement-Mode, until a stable measurement is obtained”.

In order to achieve the best results, the following operating conditions must be fulfilled (Tab.33):

Table 33 Operating conditions. Taken from https://www.mouser.it/

Condition	Parameter	Recommended		Absolute Max/Min		Unit
		Min.	Max.	Min.	Max.	
Operating conditions	Temperature	10	40	-10	50	°C
	Relative Humidity	20	80	0	90	%RH

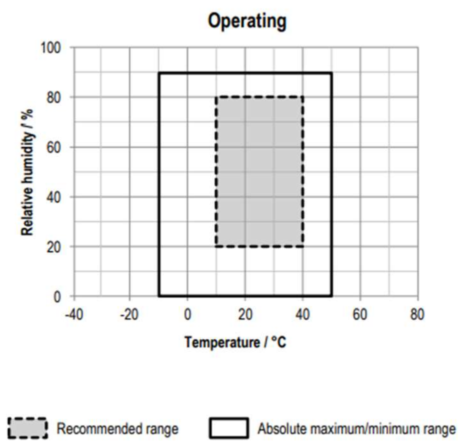


Figure 28 Graphical representation of operating conditions

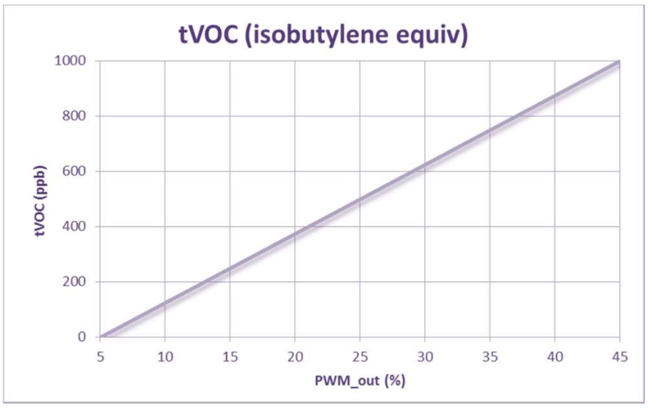
2.4.7. TVOC Sensor

Figure 29 Axonometric view SGX-SENSORTECH_MiCS-VZ-89TE. Taken from https://www.mouser.it/

The chosen sensor combines a typical MOS (metal oxide semiconductor) gas sensor with a detection algorithms to control TVOCS in indoor spaces. Briefly a MOS gas sensor operates according to the following principles:

In clear air, the electric current flow is arrested by oxygen, absorbed on the sensing material surface, that attracts donor electrons in tin dioxide. When reducing gases, like TVOC, are present in the air, oxygen reacts with these gases resulting in a reduction of its surface density. As electrons are free into the tin dioxide, current can flow through the sensor.

The following graph (Fig.33) shows the conversion scale to transform the PWM output signal (Pulse-width modulation, that is a method of controlling the average power delivered by an electrical signal) of MICS-VZ-89TE to equivalent TVOC concentration in ppb.



VOC (isobutylene) [ppb]	PWM Output (%)
0	5
200	13
500	25
1000	45

Figure 30 Conversion scale to transform the PWM output signal to equivalent TVOC concentration in ppb. Taken from https://www.mouser.it/

The monitoring range is between 0-1000 ppb isobutylene equivalent TVOCs, and the response time in lower than 5 seconds. Moreover this sensor should always operate in Temperature conditions between 0°C and 50°C, and in RH condition between 0% and 95%. The following table summarizes this specifications (Tab.35).

Table 34 Sensor specifications. Taken from https://www.mouser.it/

Detection Method	Semiconductor gas sensor
Monitoring Range	0-1000 ppb isobutylene equivalent TVOCs
Response Time	< 5 s
Warm-up Time	15 min
Operating Temperature	0°C to 50°C
Operating RH	0% to 95%

The technical datasheet suggest to avoid the exposure to high concentration of organic solvents, ammonia, silicone vapor and cigarette smoke. This prescription will be take into account during the calibration phase.

2.4.8 Formaldehyde (CH_2O) Sensor

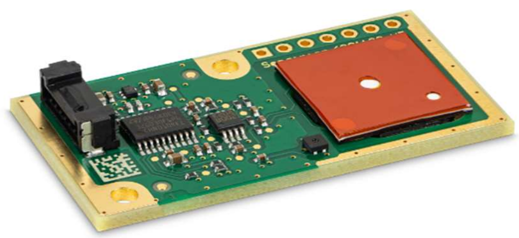


Figure 31 Axonometric view SENSIRION SFA30. Taken from https://www.mouser.it/

Among the selected sensors, Sensirion's SFA30 has a significantly higher cost (about 25 euros more) but its datasheet states its accuracy values and current consumption. In addition, the market availability of the other sensors considered is limited. These are the reason why it has been selected.

As NO_2 and CO sensors, also HCHO sensor is based on an electrochemical technology. The sensor is able also to read also temperature and relative humidity. Moreover its output is the value in ppb of the formaldehyde concentration fully temperature/humidity compensated and factory calibrated.

In addition to this SFA30 presents a low cross-sensitivity to ethanol (<25ppb).

The formaldehyde measurement range of the sensor is between 0-1000ppb, and its accuracy is ±20 ppb or ±20% of the measured value. For which concern its repeatability, it is equal to ±5 ppb or ±5% of the measured value. Sensor resolution is 1 ppb, while its response time is lower than 2 minutes. In order to last at least 6 years, the temperature operating condition should be between 0°C and 40°C, while the humidity one should be between 10% and 90%. Tab.35 shows all the technical specification provided by the producer.

Table 35 Formaldehyde Sensing Specifications. Taken from https://www.mouser.it/

Parameter	Conditions	Value	Units
Measurement range	-	0-1000	ppb
Resolution	-	1	ppb
Accuracy	(50±5)%RH, (25±3) °C; Formaldehyde concentration 0…200 ppb	±20 ppb or ±20% of the measured value	-
Repeatability		±5 ppb or ±5% of the measured value	-
Cross sensitivity to ehanol	Tested at 5.0 ppm ethanol	<0.5% (<25 ppb)	-
Operating temperature	-	0-40	°C
Operating humidity	Non-condensing	10-90	%
Response time	Response to concentration change	<2	min
Service life	At standard conditions	>6	years
Long-term drift	At standard conditions	<5 ppb or <5% of the measured value	per year

2.4.9 Sound Pressure Level Sensor

Figure 32 Axonometric view ST-IMP34DT05. Taken from https://www.mouser.it/

The IMP34DT05 is an ultra-compact, low-power, omnidirectional, digital MEMS microphone built with a capacitive sensing element. It has been chosen because of its digital output, in order to simplify the design phase.

Its measurement range is between 100 – 10000 Hz, but the accuracy is not declared by the manufacturer.

2.6 MULTISENSOR COMPONENTS: HARDWARE SYSTEM

The architecture of the multi-sensor has been developed at the hardware level to make the device capable of acquiring the physical quantities shown previously in Tab. 21 and communicating the respective data to the server. The hardware components that make up the electronic part of the sensor are given below:

- The low-cost sensors capable of acquiring the physical quantities listed in Table 21 .
- The conditioning circuits that allow the electrical signal output from the sensors to be adapted to the input of the analog-to-digital converter.
- The microcontroller, which acquires data from the sensors, processes it and handles high-level communication with the server.
- The Wi-Fi module, which allows the multi-sensor access to the local and dedicated Wi-Fi network, and handles data transfer and reception from the server.
- A power supply unit to power the remaining blocks.
- An external memory, for the microcontroller to store partial results related to data processing if its internal memory is insufficient.
- A removable SD card-type memory, which allows the installer a quick configuration of the multi-sensor.

The figure below schematizes in graphic form the block diagram of the multi-sensor under development.

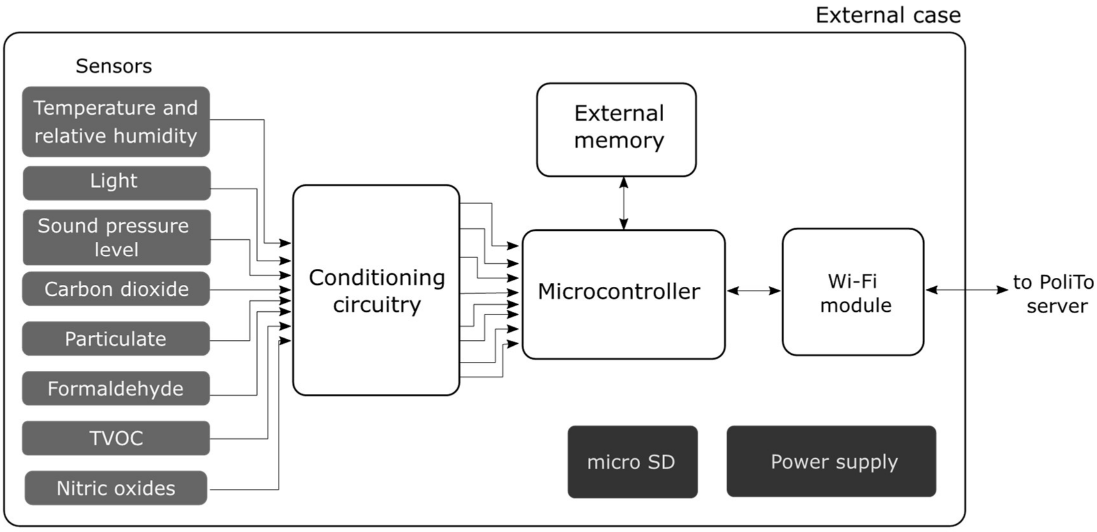


Figure 33 Schematization of the block diagram of the multi-sensor under development. Taken from (Bevilaqua D. ,2023)

- External Memory

The need to introduce additional external memory into the system, arises from the large amount of measurements sampled by the sensors. Before the results can be sent to the server, they must be stored within the system to perform the required processing. It has been estimated that audio occupies the largest amount of memory. Considering that all quantities partially occupy the memory board and that RAM memories in microcontrollers cannot store more than a hundred kB, it was necessary to introduce SDRAM (Synchronous Dynamic RAM) memory. The choice was dictated by the high capacity, low cost and high availability in the market. On the opposite side, microSD was discarded due to low market availability, as well as, SRAM (Static RAM) memories due to high cost.

- Wifi Module

The multisensor connects to a local Wi-Fi network present at the installation site. The WiFi module adopted is Adafruit's ESP8266, which is responsible for data transfer to and from the server. It supports the MQTT protocol, which is highly popular in the IoT domain given its ease of use and configuration, and to the reduced impact on hardware and network resources; the Network Time Protocol (NTP), which synchronizes the clocks of all the multisensors; and the WPA2-Enterprise security protocol.

- Power

DET team simulated the total power consumption by consulting the datasheets of the sensors to determine their power consumption, and assuming plausible values for the microcontroller and WiFi module. Below is the graph (Fig. 37) estimating the power dissipation when the frequency of acquisition of the quantities measured by the sensors changes, calculated through the following power consumption equation for the system:

$$P_{diss} = 5\,V * I_{particolato} + 3.3\,V * (I_{MCU} + I_{WiFi} + I_{sensori})$$

Where:

$I_{particolato}$: is the current drawn by the particulate sensor (powered at 5 V)

I_{MCU} : is the current drawn by the microcontroller (powered at 3.3 V)

I_{WiFi} : is the current drawn by the WiFi module (powered at 3.3 V)

$I_{sensori}$): is the current drawn by the sensors (powered at 3.3 V)

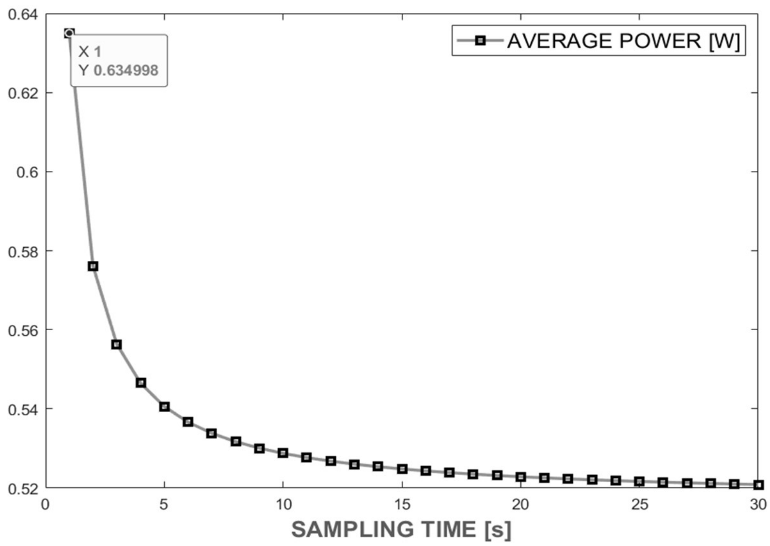


Figure 34 Estimation of the power dissipated by the system as the frequency of acquisition of the quantities measured by the sensors changes

Initially, it was planned to power the multisensor with battery power. After a market investigation of battery packs with dimensions of 10x10x4 cm, it was found that the device would last about 40 hours. This would have resulted in excessive maintenance. Therefore, a main power supply for the system was chosen.

- Microcontroller

Based on the aforementioned design choices, ST Microcontrollers, STM F7e H7 series, with at least 176 pins (i.e., the elements that protrude and allow communication with the eternal) were selected. In fact, the microcontroller must support the following functions:

  - Two I2C interfaces (one for the sensors and one for the WiFi module).
  - Two UART interfaces (one for the formaldehyde sensor and one for debugging)
  - Two ADCs for the analog sensors
  - SDRAM memory
  - Several free pins for connecting LEDs

- Printed Circuit Board (PCB)

After the evaluation and selection of various components and sensors, the Printed circuit board (PCB) was designed. It is an electronic assembly that uses copper conductors to create electrical connections between components. The PCB provides mechanical support for the electronic components so that the device can be mounted in an envelope. Initially, the estimated overall dimensions were around 10 cm in diameter, with a circular shape. During development, this diameter increased to 14 cm, with a thickness of 2 mm. In the end it became necessary to split the PCB in two. It assumed a rectangular shape. It has a V-shaped plate on which the sensors are installed, thus serving as the electronic part of the multisensor. The second part comprises the power and controller board. They are divided by a central vertical plate to avoid overheating of the parts, as well as the mutual influence of the components on the sensors.

From the shape and dimensions of the PCB, the multisensory case was molded.

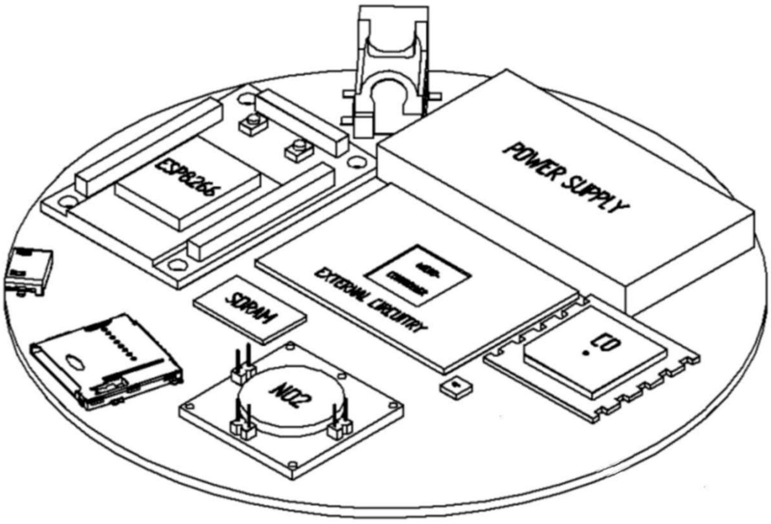


Figure 35 First PCB hypothesis: circular shape. Taken from (Bevilaqua D. ,2023)

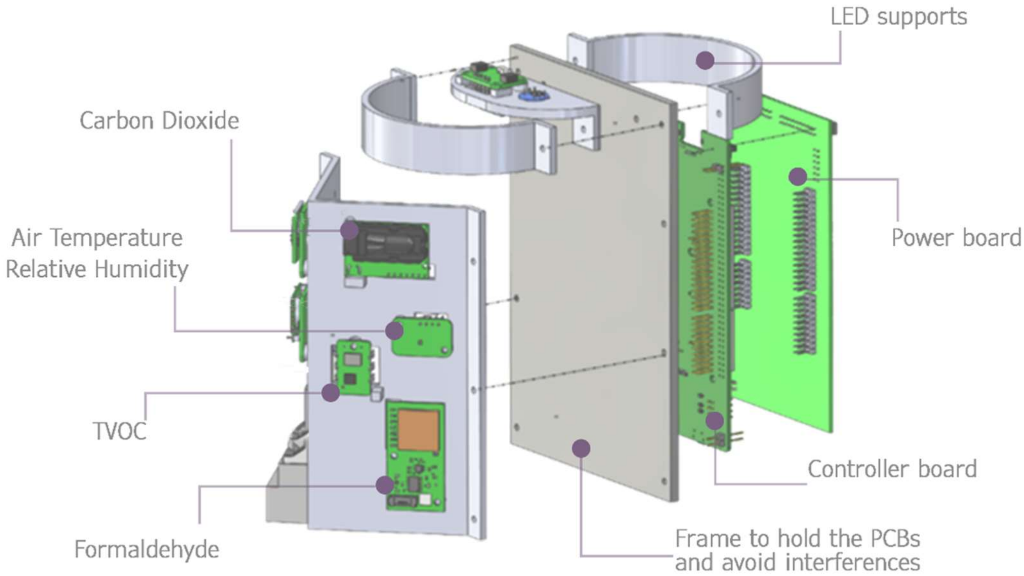


Figure 36 Last PCB project. Taken from (Bevilaqua D. ,2023)

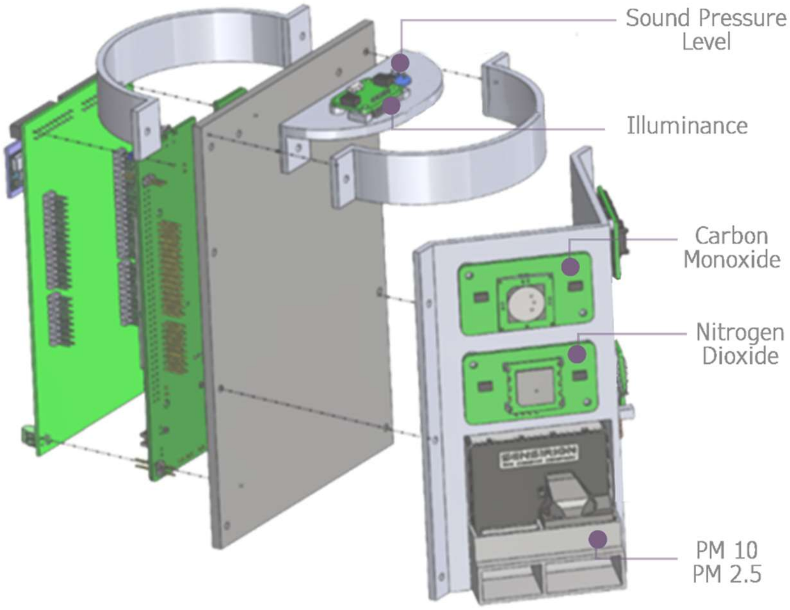


Figure 37 Last PCB project. Taken from (Bevilaqua D. ,2023)

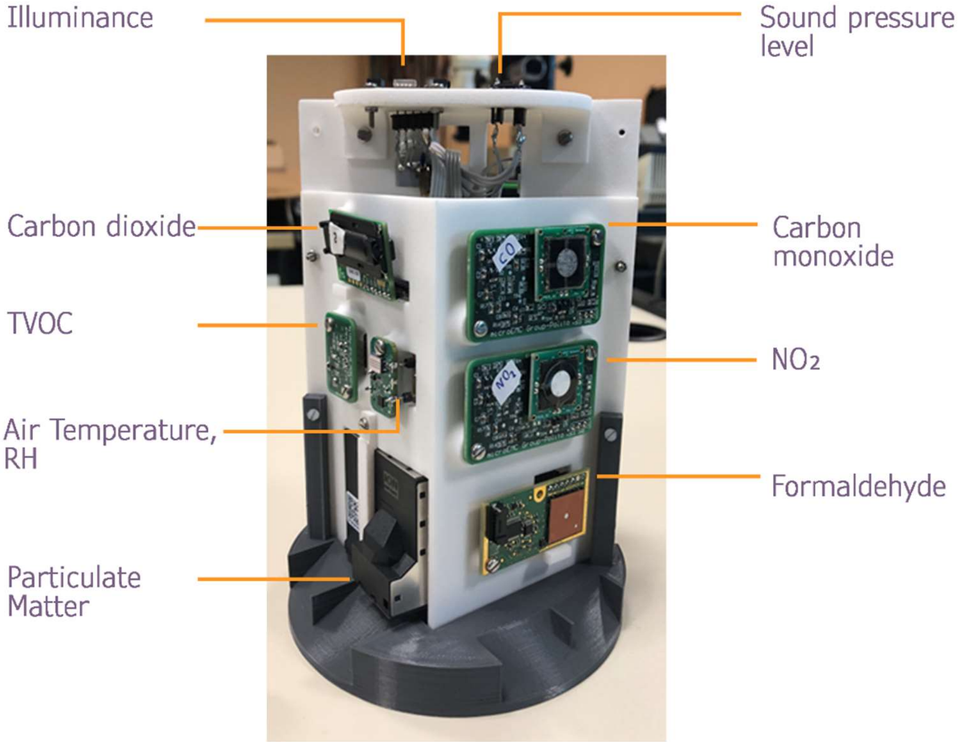


Figure 38 PCB printed prototype

2.7 CASE DESIGN

At the design stage, certain specifications were dictated to be met in the design of the case:

- Dimensions as small as possible;
- In order to ensure "omnidirectionality," i.e., good reception of sound waves from any direction, the microphone must be placed at an elevated point in the structure;
- The illuminance sensor must maximize the amount of incident light in order to obtain more accurate information. For this reason, it must be placed overhead of the structure;
- The temperature and relative humidity sensor must be in contact with the outside air so that the sensed parameters coincide as closely as possible with those perceived by the user;
- Placement of the air quality sensors (CO_2, PM, formaldehyde, TVOC, CO, and NO_2) so that they are exposed to the outside air as much as possible so as to reduce the response time;
- Versatile use of the multisensor, physically adaptable to any space and user needs;
- Making a side opening for the power cable;
- Giving the researcher the ability to access the micro USB and microSD connector without too much difficulty for possible reprogramming;
- Inserting several LEDs to show the user the environmental quality in real-time.

The shape and dimensions of the case evolved with those of the PCB, which, as previously exposed, initially presented a circular shape. At an early stage, the case presented a cylindrical shape (Fig.42, 43) with a diameter of 14.60 cm and a height of 6.80 cm. The illuminance and sound pressure level sensors were equally located at the top, while the side surface of the cylinder was perforated to circulate air inside and disperse heat.

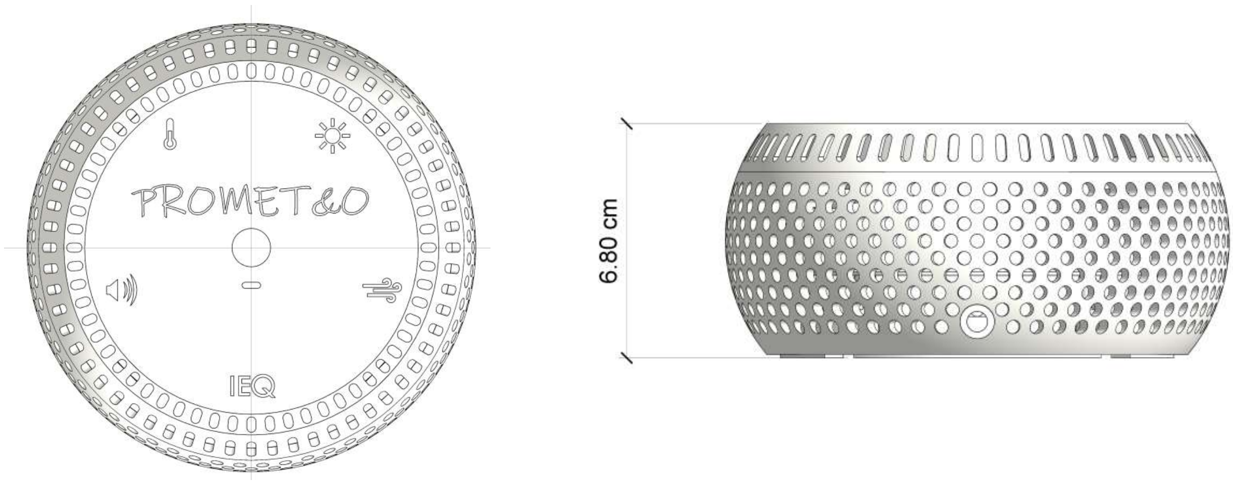


Figure 39 (a) First case hypothesis: top view. In (b) lateral view. Taken from (Bevilaqua D. ,2023)

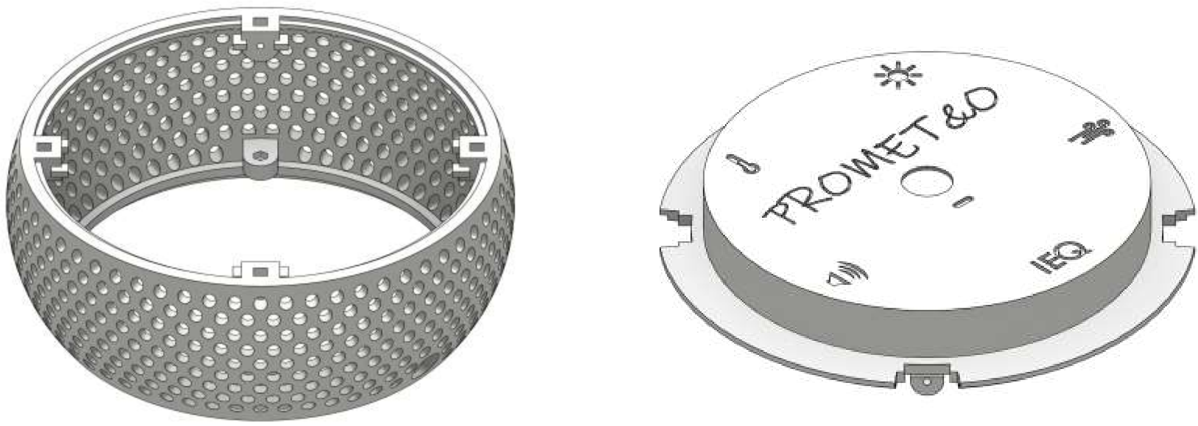


Figure 40 (a) First case hypothesis: axonometrical view. In (b) lid view, Taken from (Bevilaqua D. ,2023)

Currently the PROMET&O multisensor case is the PLA (Polylactic acid) structure that embeds all the electronic components. Taking into account the components it must contain within it, the case is characterized by a cylindric shape with a maximum size of 18 cm in height and 12 cm in diameter. As it has to be printed with a 3D filament printer, it consists of several pieces joint by screws. The case (Fig. 46) is the main component. The top surface shows the engraving of the PROMET&O logo, the four symbols of the environmental quality domains (acoustic, air quality, thermal, and visual), and the term IEQ. The perimeter of the cover surface is slightly smaller, leaving a useful space for the dissipation of heat generated by the operating sensors. Both the opening for the illuminance sensor and the opening for the MEMS microphone are also located on the cover. On the perimeter, the case has a series of symmetrical holes in both the front and back in order to provide additional ventilation and prevent components from overheating. Below the same holes are engraved PROMET&O lettering. Above, instead, there are ten openings on each side housing as many LEDs, the activation of which indicates the percentage of environmental quality, thus visible from all angles.

At the base level, the case has two significantly larger openings that allow the PM 2.5 and PM 10 sensors to draw in and expel air through its supplied fan (Fig.43). The base also features PCB support columns to connect the various components together (Fig.44).

Two jacks are provided to connect the external power supply to the power board, one on the side to be used in case the multisensor is installed on a desk, and one at the bottom in case the installation is either pole-mounted or wall-mounted. For wall-mounted installation, a special cylindrical holder has been designed with a lower hole for the charger (Fig. 43). The support can be attached to the vertical surface by means of a screw. For mounting on the pole, the base of the holder (Fig. 45) perfectly fits the shape of the rod, predisposing an inlet for the power cable. The multisensor is then inserted superiorly.

Renderings of possible multisensor arrangements are shown in Fig. 48 and the first 3D printer-printed prototype is shown in Fig. 46.

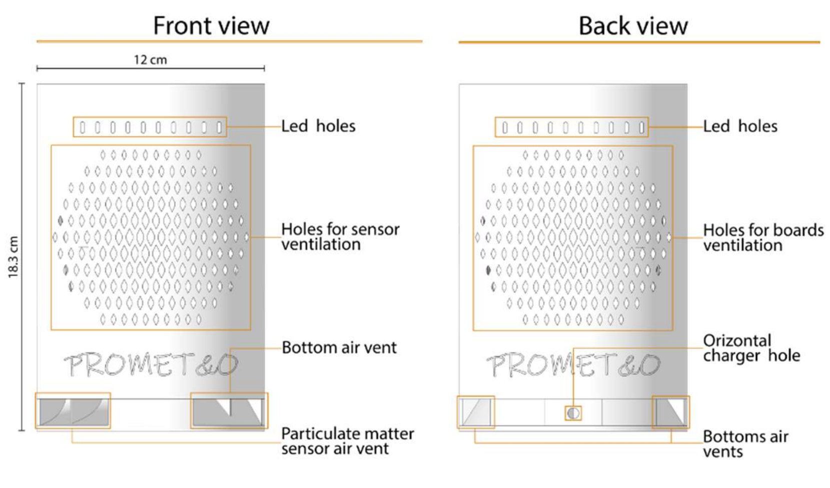


Figure 41 Front and back view of the multisensor case. Taken from (Bevilaqua D. ,2023)

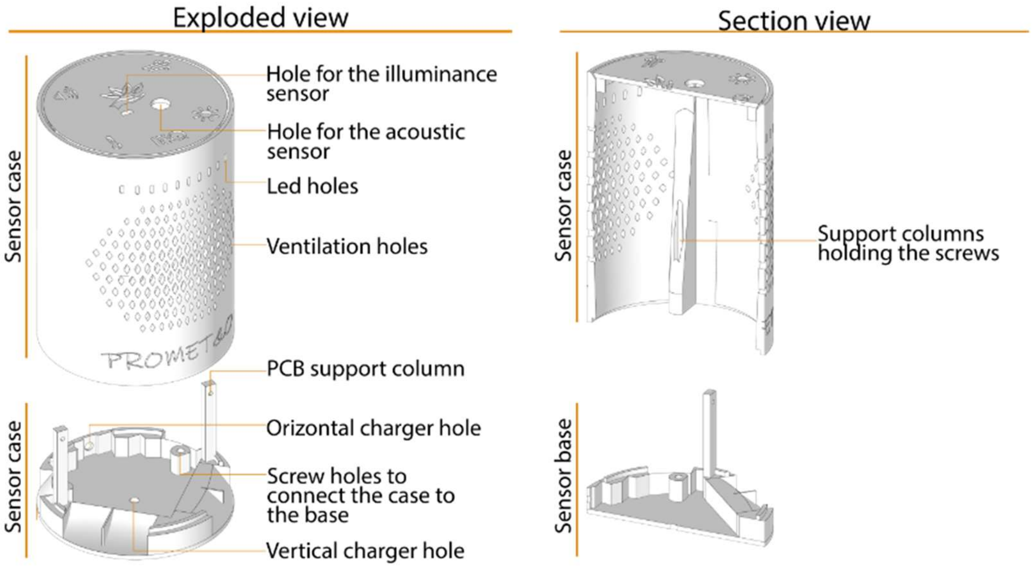


Figure 42 Exploded and section view of the multisensor case. Taken from (Bevilaqua D. ,2023)

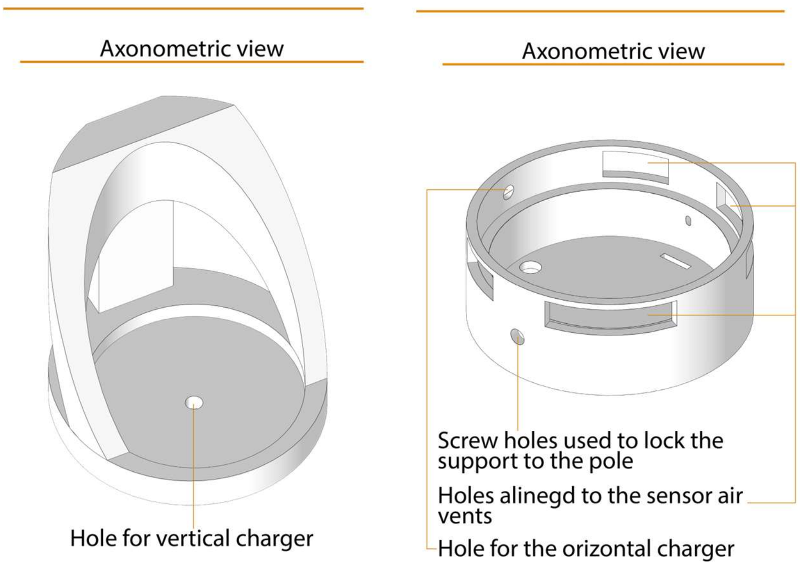


Figure 43 Axonometric view of the supports. Taken from (Bevilaqua D. ,2023)

Figure 44 3D printed PROMET&O prototype

2.8 PROMET&O DATA ACQUISITION

As anticipated in paragraph 2.1, the peculiarity and innovation of the PROMET&O multisensor is the dual focus of the objective and subjective aspects of environmental quality. Therefore, the data collected are on two levels:

- Objective data, acquired by the multisensor. They concern with the temporal trend of the physical quantities to be monitored.
- Subjective data acquired by personal questionnaire, which represents the responses provided by end users.

2.8.1 Objective Data Acquisition

The sensors acquire physical quantities periodically, with ad hoc sampling rates (f_s). The data acquired by the sensors are stored in memory by the microcontroller, which, after a period of time called T_{report}, calculates the following statistical values:

- Arithmetic mean
- Maximum
- Minimum
- Trend: defined as the most frequent value among those considered
- Median: reordering the data in an increasing manner.
- Standard deviation
- Tenth percentile: 10 % of the values are less than the 10th percentile

- Ninetieth percentile: 90 % of the values are less than the 90th percentile

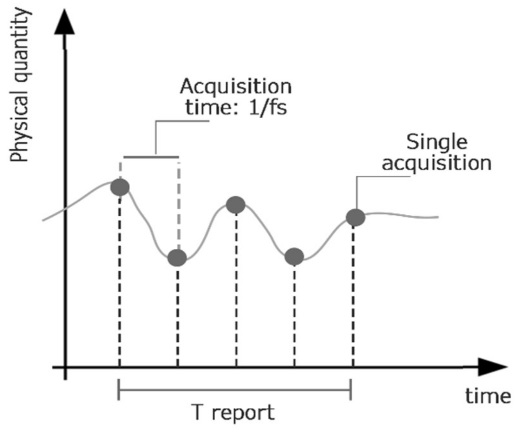


Figure 45 Graphical explanation of Treport

Table 37 shows fs and T_{report} for each physical quantity:Table 36 T_{report} for each physical quantity

Physical quantity	Sampling Time (Sensor Reading In Point Mode - Raw Data)			Report Time (Statistical Data Communicated To The Server)			Real Time
	Min	Default	Max	Min	Default	Max	
Temperature	0,1 s	1 s	-	30 s	30 s	15 min	5 min
Relative Humidity	0,1 s	1 s	-	30 s	30 s	15 min	5 min
Illuminance	1 s	1 s	-	30 s	30 s	15 min	1 min
Sound pressure level	22 kHz	22 kHz	44 kHz	1 s	1 s	15 min	5 s
Formaldehyde	0.5 s	3 s	60 s	30 s	1 min	15 min	1 min
Particulate	1 s	3 s	60 s	30 s	1 min	15 min	1 min
TVOC	3 s	3 s	60 s	30 s	1 min	15 min	1 min
NO_2	-	3 s	60 s	30 s	1 min	15 min	1 min
CO	-	3 s	60 s	30 s	1 min	15 min	1 min
CO_2	1 s	3 s	60 s	30 s	1 min	15 min	1 min
Thermal comfort	-	-	-	-	-	-	15 min
Visual comfort	-	-	-	-	30 s	-	1 min
Acoustic comfort	-	-	-	-	1 s	-	5 s
Indoor Air Quality (IAQ)	-	-	-	-	1 min	-	1 min
Indoor Environmental Quality (IEQ)	-	-	-	-	-	-	15 min

The minimum values of f_s are due to the internal operation of the sensors, while the maximum values were decided to avoid undersampling of physical quantities. The minimum values of T_{report} were selected in order to perform statistical calculations on a sufficient number of data. On the other hand, a maximum report time of 15 minutes was identified, as it was considered useful to remain in this range for proper observation and evaluation of the trend of the quantities over time.

Once the samples have been obtained and the calculations explained earlier have been performed, the data are transferred to the WiFi module and there they are properly packaged and then transferred to the server.

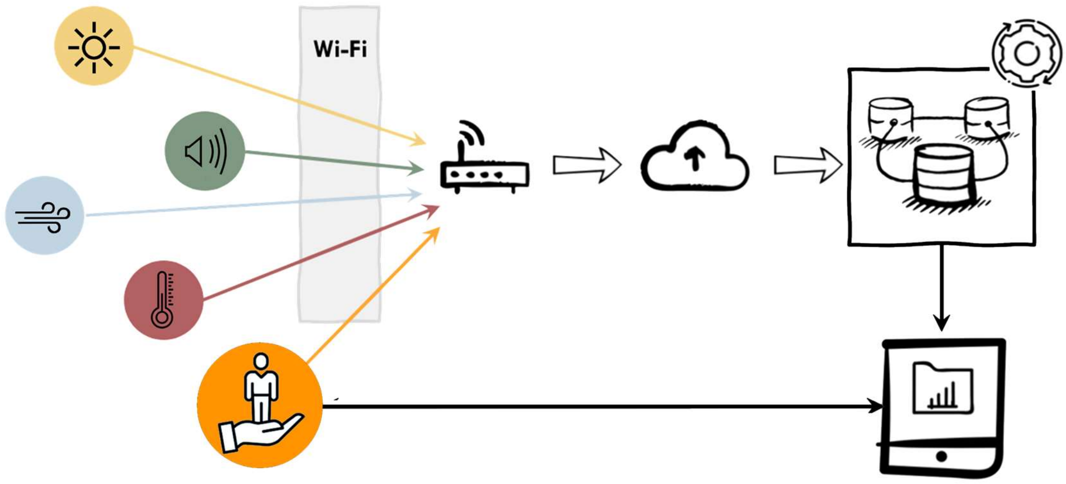


Figure 46 Objective data acquisition process. Taken from (Bevilaqua D. ,2023)

2.8.2 Key Performance Indicators

The quality of the internal environment will be returned through the key performance indicators, obtained thanks to specific algorithms that take into consideration the values of the quantities monitored in the environment. These algorithms have been developed on the basis of the analysis of standards, environmental sustainability protocols and specific scientific literature on this topic. Thanks to these algorithms it is possible to obtain a percentage value that describes the level of environmental quality relating to each individual domain (thermal, acoustic, visual and air quality) and globally.

Overall IEQ is calculated as follow:

$$IEQ\ [\%] = \frac{(TQ + AQ + IQA + VQ)}{4}$$

Where

TQ= Thermal Quality

AQ= Acoustic Quality

IAQ= Indoor Air Quality

VQ= Visual quality

As mentioned in chapter 2, an elevated IEQ does not means that the occupant is satisfied with the environment. Each quality domain has to fulfill its own requirements. The following table (Tab.38) schematizes the Key performance indicators

Table 37 Key performance indicators

KEY PERFORMANCE INDICATOR			RANGE	REFERENCE	DEFINITION
Thermal comfort	TC	%	0-100%	Parkinson et. al, Building and Environment, 2019	Thermal comfort is that condition of mind which expresses satisfaction with the thermal environment
Acoustic comfort	AC	%	0-100%	Parkinson et. al, Building and Environment, 2019	Acoustic comfort is that condition, in a specific environment, in which the user experiences a sense of well-being related to the hearing conditions.
Visual comfort	VC	%	0-100%	Parkinson et. al, Building and Environment, 2019	Visual comfort is that condition of satisfaction of visual requirements expressed by the user
Indoor Air Quality	IAQ	%	0-100%	Parkinson et. al, Building and Environment, 2019	Indoor air quality is considered acceptable when there are no specific pollutants in harmful concentrations and no conditions that are likely to be associated with occupant's health or comfort complaints.
Indoor Environmental Quality	IEQ	%	0-100%	Parkinson et. al, Building and Environment, 2019	Indoor Environmental Quality is the physical characterization of indoor environments in terms of thermal, acoustic, lighting and indoor air quality.

:

2.8.3 Subjective Data Collection

Subjective data is collected by the use of a questionnaire to users, who are asked to express their degree of satisfaction with the indoor environment through a special web application. This questionnaire will be discussed more in detail in the following paragraph 2.9.2. Operationally, the responses obtained are sent to the DynamoDB database, through its API (application programming interface), and stored according to the type of question. Specifically, responses indicating a rating scale are converted into numbers representing comfort level. Multiple-choice answers are stored as an array of all selected answers. Finally, comments are stored as strings. Numerical conversion of the comfort or discomfort feeling experienced by the user is done through previously established criteria shown in Tab.39. This makes it possible to obtain the percentage value of subjective environmental comfort both relative to individual areas and overall.

Table 38 Criteria to convert the answers into comfort percentage. Taken from (Bevilaqua D. ,2023)

THERMAL COMFORT TC [%] = (A1 + A2)/2				ACOUSTIC COMFORT		VISUAL COMFORT		INDOOR AIR QUALITY	
Please indicate on the following scale how YOU feel NOW (A1)		Please indicate on the following scale how YOU find the AIR VELOCITY in your environment NOW (A2)		Please indicate on the following scale how YOU find the NOISE in your environment NOW		Please indicate on the following scale how YOU find your VISUAL environment NOW		Please indicate on the following scale how YOU find the AIR QUALITY in your environment NOW	
+3 Hot	25%	Very draughty	25%	Very annoying	25%	Very uncomfortable	25%	Very smelly	25%
+2 Warm	50%	Draughty	50%	Annoying	50%	Uncomfortable	50%	Smelly	50%
+1 Slightly warm	75%	Slightly draughty	75%	Slightly annoying	75%	Slightly uncomfortable	75%	Slightly smelly	75%
0 Neutral	100%	Not draughty	100%	Not annoying	100%	Not uncomfortable	100%	Not smelly	100%
-1 Slightly cool	75%								
-2 Cool	50%								
-3 Cold	25%								

Finally, this information is sent to the server, which also stores the objective data via the MQTT protocol. The database thus makes it possible to compare subjective and objective data.

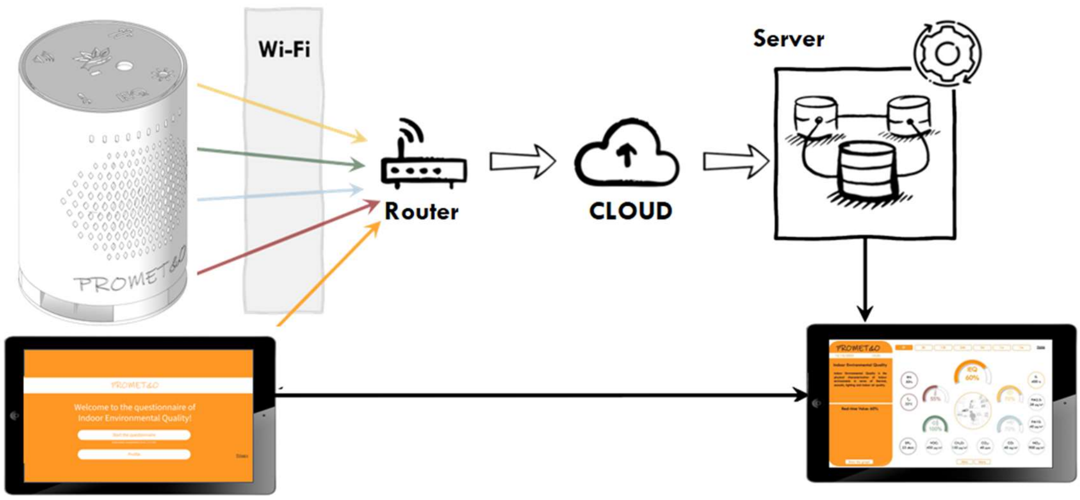


Figure 47 Subjective data acquisition process. Taken from (Bevilaqua D. ,2023)

2.9 PROMET&O INTERFACE: QUESTIONNAIRE AND DASHBOARD

From the merging of the various components described above, the final product provided to the user is a unicum that encompasses both the objective qualitative state of the indoor environment and the individual contribution provided by the user for its assessment. The leitmotif lies in the concept of gamification and user involvement, which lead to the dashboard, i.e. the graphic interface for displaying data, passing through the questionnaire on the feeling of comfort or discomfort with the surrounding environment.

2.9.1. Gamification and User Involvement

As previously mentioned, one of the main goal of PROMET&O project is to engage as many users as possible. This characteristic makes PROMET&O an uniqueness compared to its market competitors. In order to involve the user as much as possible, the concept of Gamification has been developed under several aspects. This strategy belongs to the wider concept of "Intervention".

According to Flury-Keubler and Gutscher (Psychological_Principles_of_Inducing_Beh, 2001), Intervention or stimuli "shape the individual's action possibilities or have an influence on the effects of any actions performed". This concept contains in itself so many possibility to reach its goal. A first division can be made among:

1. “direct” (real-time) vs “indirect” (delayed) feedback (Darby, 2006)
2. “Opt-in” (deciding to take part in a program) vs “opt-out” (not actively decide to take part) feedback programs. (Carroll et al. 2009)

It has been demonstrated (Kastner & Matthies, 2014; Langevin et al., 2013) that the most successful way to first engage and then change users’ behavior is to provide them:

1. Background information, for example the reason why they should change a behavior.
2. Info about possible actions to properly modify it (hints and tips).
3. Feedback information about how the changing process is going, and its results.

This phase is called “Attention stage”.

Moreover it is useful to pay attention to how a certain topic is presented. The higher is its appeal the higher are the possibilities to lead to a behavioural change.

Collecting some literature on the topic (D’Oca et al., 2014; Jacucci et al., 2009; Karlin et al., 2015; Maréchal & Holzemer, 2015), it is possible to list some highlights that should be considered:

1. Present information that can be ad hoc for the interest group. They should be easily understandable and colorful, and match the habits, skills and knowledge, intention and environmental constraints of the group. In fact, the next section will present the "Hints and more" engagement strategy, mainly focused on office environment and everyday behaviors that workers can easily adopt.
2. The intervention should relate to daily life and adapt the information to the chosen group.
3. The information should be specific and targeted for each behavior.
4. Need to make aware of the impact the current action has and what benefits a behavioral change might bring.
5. The actions described should be achievable without undue effort.

Among the intervention strategy PROMET&O project focus on the concept of "gamification". There is no a single definition of this word. "Gamification is the usage of game mechanics and game thinking in serious contexts. [...] Using prepared and predefined rules and goals, gamification approaches produce results within a game which are connected to a real world outcome." (The S3C Consortium 2012-2016, Guideline Gamification). In general, the term is used to describe those game elements and mechanics used in an interactive system to motivate and engage end-users (Hamari et al., 2014). This strategy is largely used in several fields. The most common is the educational one, followed by commerce, health and exercise, work, sustainable consumption and so on. Even if some researches have proved that gamification leads to short-term results (Farzan et al., 2008), as it is perceived as a novelty, some others have shown harmful effects on users still engaged, due to its removal (Hamari, 2011; Thom et al., 2012). In any case, the mix of several intervention types may help to achieve a long-term impact and promote a changing behaviour (Fischer, n.d.; Maréchal & Holzemer, 2015).
The interface of the PROMET&O project itself adopts a gamified graphic system. The survey administered through tablets makes use of eye-catching graphics and allows the user to provide his or her own final feedback. In addition, reading the objective data collected by the multisensor in graph form allows for enhanced user engagement and greater comprehensibility even for a layperson. Thus, the interface also lends itself to an educational purpose: to make the user aware of the meaning and limits set by legislation of the monitored parameters, as well as to place the user temporally and spatially within the environmental conditions of the office in different time ranges. PROMET&O also resorts to the use of hints and more, easily accessible with a click on the dashboard, created with the purpose of concretely suggesting to the user the right behavior to adopt.

2.9.2 PROMET&O Questionnaire to collect users' feedbacks

Frequently, post-occupancy evaluation (POE) assess occupant satisfaction with the indoor environment and their comfort through occupant surveys (P. Li et al., 2018). These can be split in two different categories:

1. general and comprehensive assessments,

2. “right-now” surveys (Shiffman, 2014).

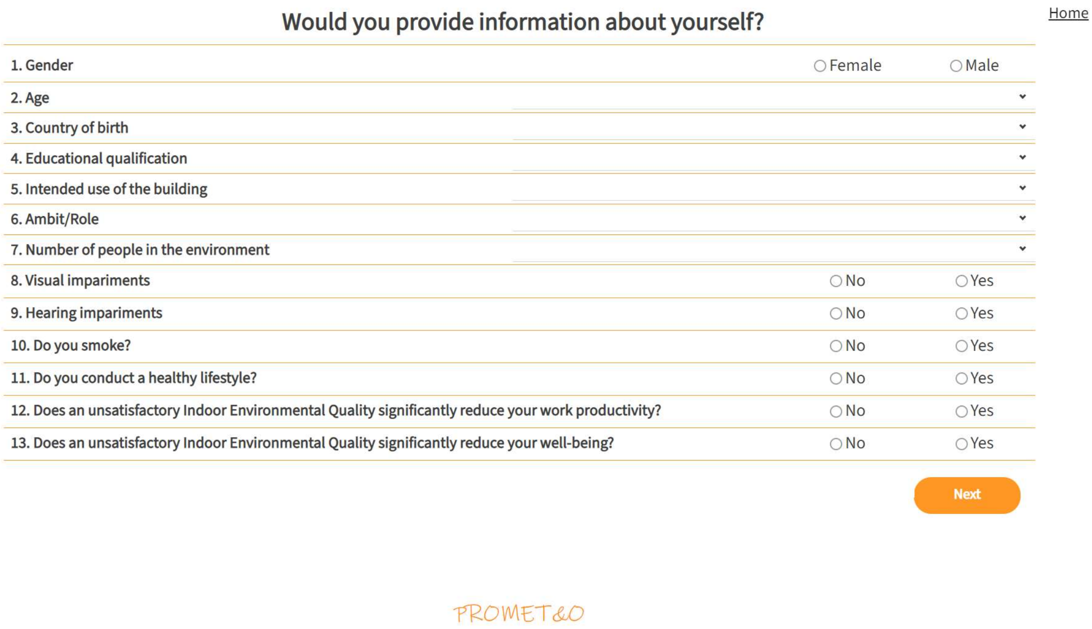
The former collect a general report of the building, evaluate users’ long-term satisfaction and comfort, and gather occupant characteristics (Frontczak et al., 2012; Schiller et al., 1988). The latter aim to outline the occupant perception of the indoor environment at the exact moment in which he’s filling the survey. A right-now survey is usually characterized by typical expressions, such as “Right now I fell/prefer (Benton et al., 1990)”. IEQ objective measurements, such as air temperature, air velocity, sound pressure level, illuminance, and CO_2 concentration level, and subjective feedbacks, provided by right-now surveys, are usually combined.

Traditionally occupant surveys have always been distributed with a paper-based format. Recently, with the development of new technologies, surveys may be shared out through computer software, mobile devices (Newsham et al., n.d.; Parkinson et al., 2013; Zagreus et al., 2004) or web-based tools, such as SurveyMonkey™, Qualtrics™, and Google Forms™. In this way technological obstacles to generate, share and examine digital surveys are overtaken.

Due to developments in measurement technologies, less expensive, more accurate and easy-to-use, smaller and portable sensors are available. For this reason continuous IEQ monitoring systems are a current research topic, aimed to be designed and permanently distributed through an indoor environment (Cheung et al., 2017; R. de Dear et al., 2018; Kim et al., 2019; Liu et al., 2019; Parkinson et al., 2019a).

Previously, a subjective questionnaire was formulated and implemented to be administered to users through dedicated tablets. The development process was preceded by a literature search, from which rules were extrapolated to develop an appealing and engaging questionnaire. The individual terms used were cautiously chosen in order to minimize possible misunderstandings, choosing, for example, those with as few meanings as possible, or those with fewer emotional overtones, such as to influence responses. The use of verb forms is equally important. For example, the use of active verbs is more persuasive than passive ones (Roopa et al., 2012; Brancato et al. 2006). The questionnaire, therefore, presents itself as simple and understandable (Hoffmeyer, 2006; Roopa & Rani, 2012; Schütze, 2011).

The administration of the questionnaire is designed to investigate the individual user's perception of comfort inherent in the four domains (thermal, visual, acoustic, air quality) and global, followed by two sections devoted to personal and behavioral questions. The questions follow a logical process starting with the general sense of satisfaction/unsatisfaction and then descending into the detail of the environmental domain, ending in the two additional sections collecting personal data in order to understand the influence of these variables on the user's perception. To reduce compilation time, users can create a personal account and save personal and behavioral variables (see Fig 51, 52) so that they do not have to re-enter them each time they complete the questionnaire.



Home

Would you provide information about yourself?

1. Gender	○ Female	○ Male
2. Age		
3. Country of birth		
4. Educational qualification		
5. Intended use of the building		
6. Ambit/Role		
7. Number of people in the environment		
8. Visual impariments	○ No	○ Yes
9. Hearing impariments	○ No	○ Yes
10. Do you smoke?	○ No	○ Yes
11. Do you conduct a healthy lifestyle?	○ No	○ Yes
12. Does an unsatisfactory Indoor Environmental Quality significantly reduce your work productivity?	○ No	○ Yes
13. Does an unsatisfactory Indoor Environmental Quality significantly reduce your well-being?	○ No	○ Yes

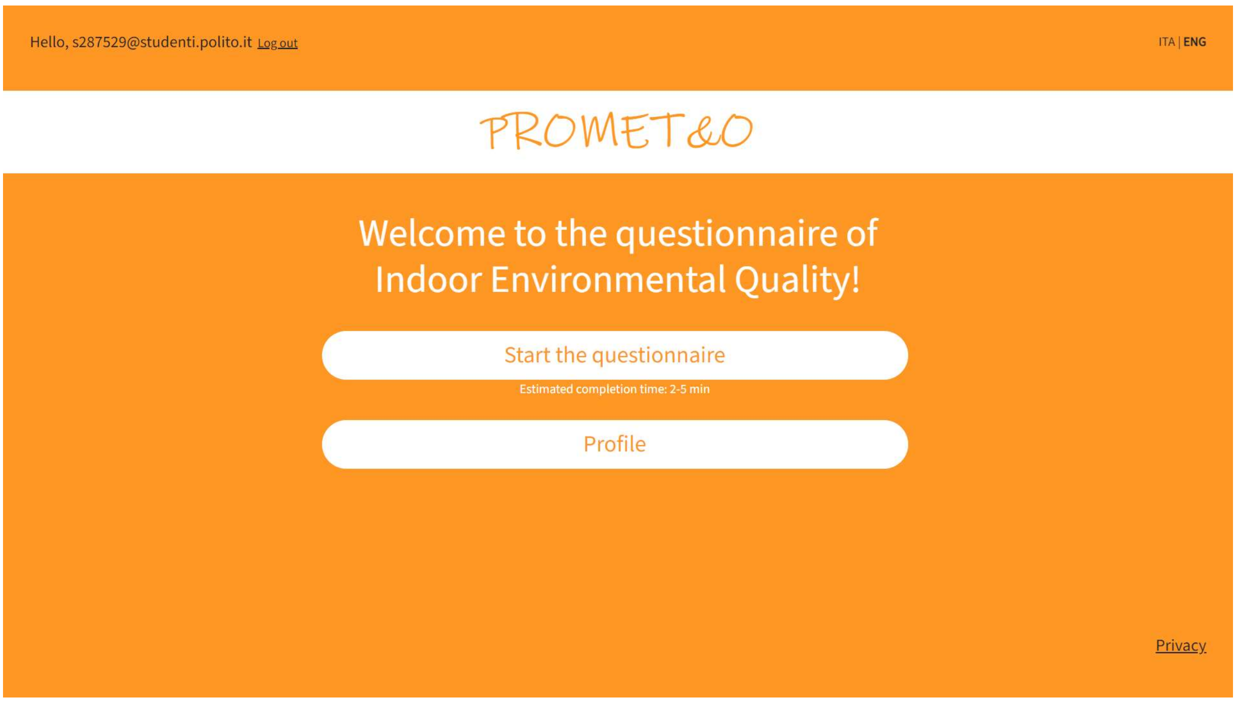
Next

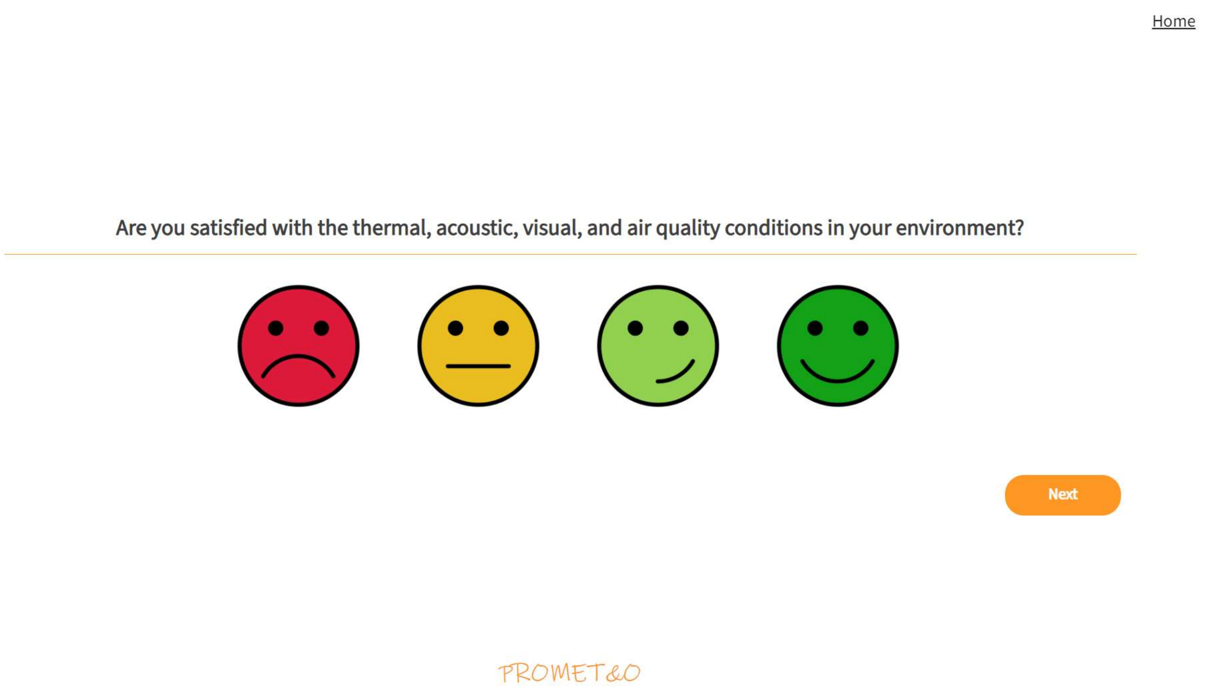
PROMET&O

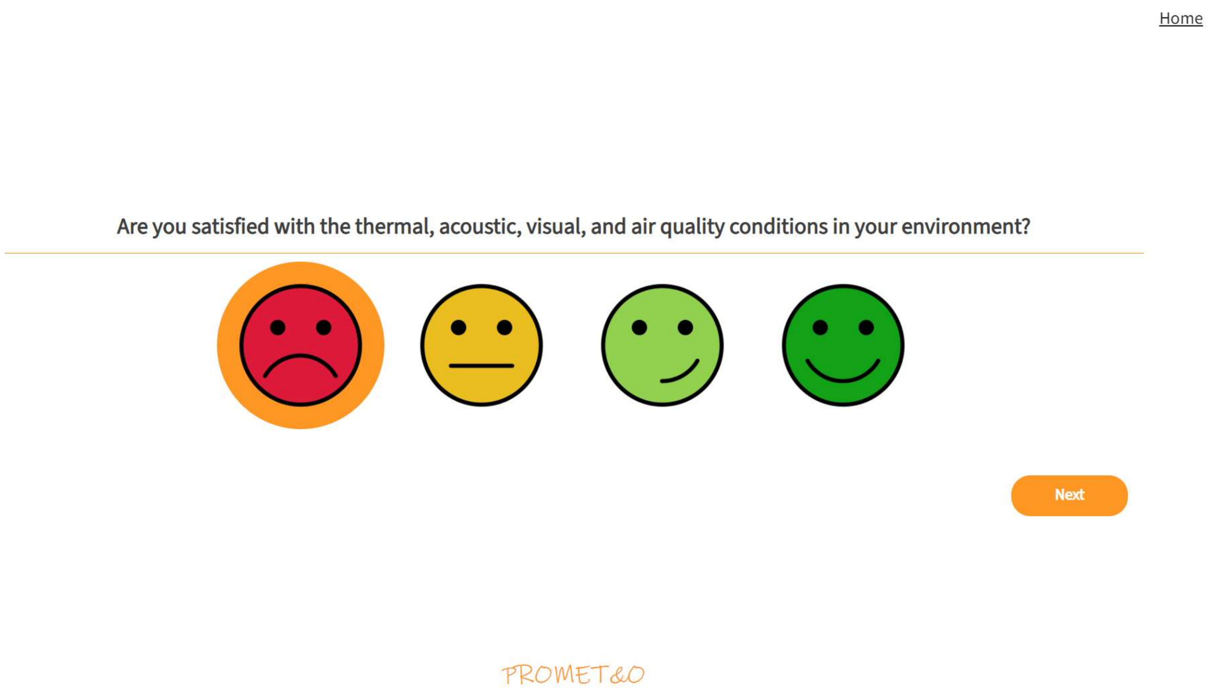
Figure 48 Personal and behavioral variables on the account. Taken from (Bevilaqua D. ,2023)

Figure 49 Personal and behavioral variables on the account. Taken from (Bevilaqua D. ,2023)

The following is an emulated possible pathway for filling out the questionnaire as an authenticated user.




Home
Are you satisfied with the thermal, acoustic, visual, and air quality conditions in your environment?
Next
PROMET&O


Home
Are you satisfied with the thermal, acoustic, visual, and air quality conditions in your environment?
Next
PROMET&O

Home

1. Your evaluation is negative, can you tell us which environmental quality aspects are you dissatisfied with?

You can choose one or more answers

THERMAL ACOUSTIC VISUAL INDOOR AIR QUALITY

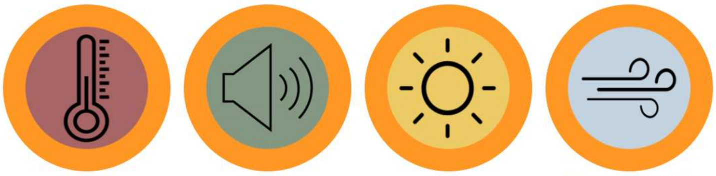
Next

PROMET&O

Home

1. Your evaluation is negative, can you tell us which environmental quality aspects are you dissatisfied with?

You can choose one or more answers



THERMAL ACOUSTIC VISUAL INDOOR AIR QUALITY

Next

PROMET&O

Home

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

2. Please indicate on the following scale how YOU feel NOW.

- ○ Hot
- ○ Warm
- ○ Slightly warm
- ○ Neutral
- ○ Slightly cool
- ○ Cool
- ○ Cold

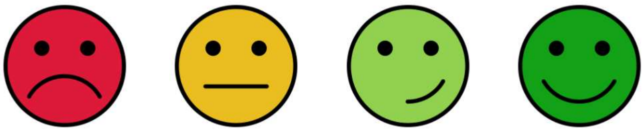
Next

PROMET&O

Home

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

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



Very draughty | Draughty | Slightly draughty | Not draughty

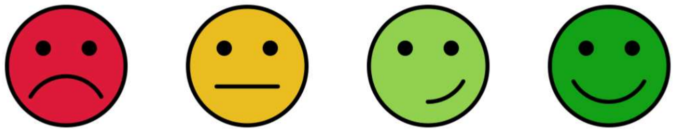
Next

PROMET&O

Home

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

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



Very annoying | Annoying | Slightly annoying | Not annoying

Next

PROMET&O

Home

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

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

You can choose one or more answers

- ☐ Building systems
- ☐ Computer, printer, other office equipments
- ☐ People chatting
- ☐ Road traffic
- ☐ Other noises from the outside
- ☐ Other
- ☐ None

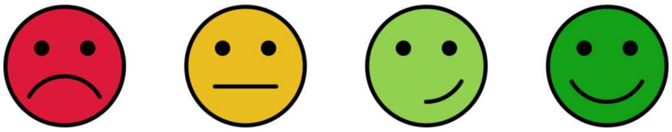
Next

PROMET&O

Home

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

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



Very uncomfortable | Uncomfortable | Slightly uncomfortable | Not uncomfortable

Next

PROMET&O

Home

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

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

You can choose one or more answers

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

Next

PROMET&O

Home

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

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

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

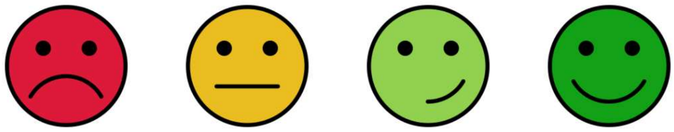
Next

PROMET&O

Home

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

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



Very smelly | Smelly | Slightly smelly | Not smelly

Next

PROMET&O

Home

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

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

You can choose one or more answers

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

Next

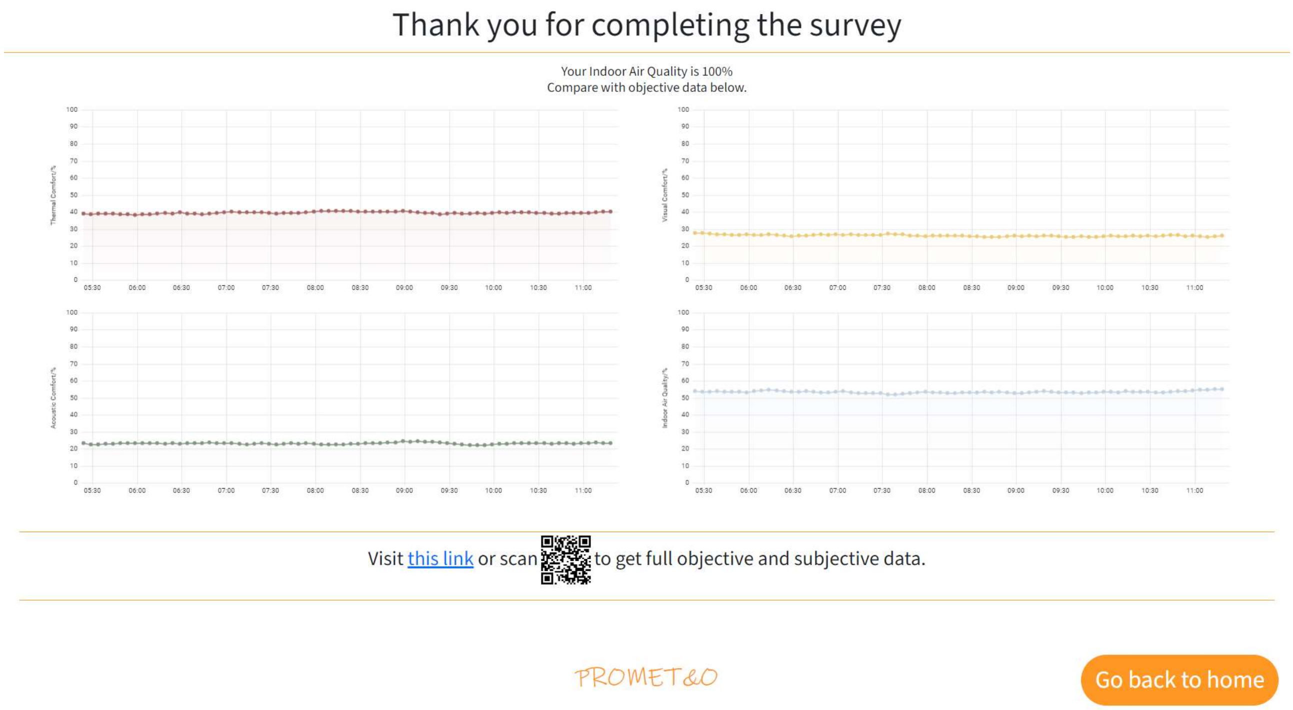
PROMET&O

Home

11. If you want, you can leave other comments

Complete

PROMET&O



2.9.3 PROMET&O Dashboard

At the end of the questionnaire, logged users can have access to the dashboard. Its graphic layout was developed through the use of power point, then implemented as a website by the DAUIN team. The interface presents a right-hand side with the comfort percentages for both the four individual domains of environmental comfort and global comfort. By clicking on each of them, it is possible to consult the values of the physical quantities and indices, expressed according to their unit of measurement. On the left, instead, there is a box showing parameter definitions, as well as statistical parameters such as mean value, standard deviation, 10th percentile and 90th percentile, for each time range, except Real Time (RT). The particularity of the dashboard also lies in the possibility of choosing one's own reference time range between Real Time, 3h, 12h, 24h, 3d, 1w, 1m, by clicking on the respective button at the top (Fig. 53). The user is also given the possibility of viewing the graph of the quantity, at the selected time (Fig. 54), as well as comparing the same quantity in several time ranges, or different quantities in the same time range (Fig.55).

In the lower part of the screen, two buttons "Hints" and "More" are shown, which will be discussed in detail in the next paragraph.

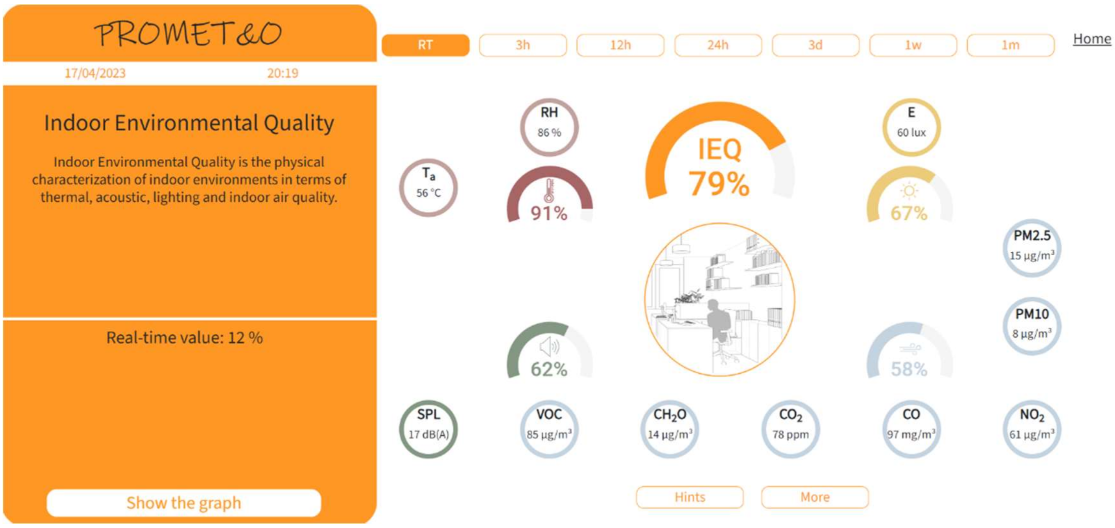


Figure 50 Dashboard and time range. Taken from (Bevilaqua D. ,2023)

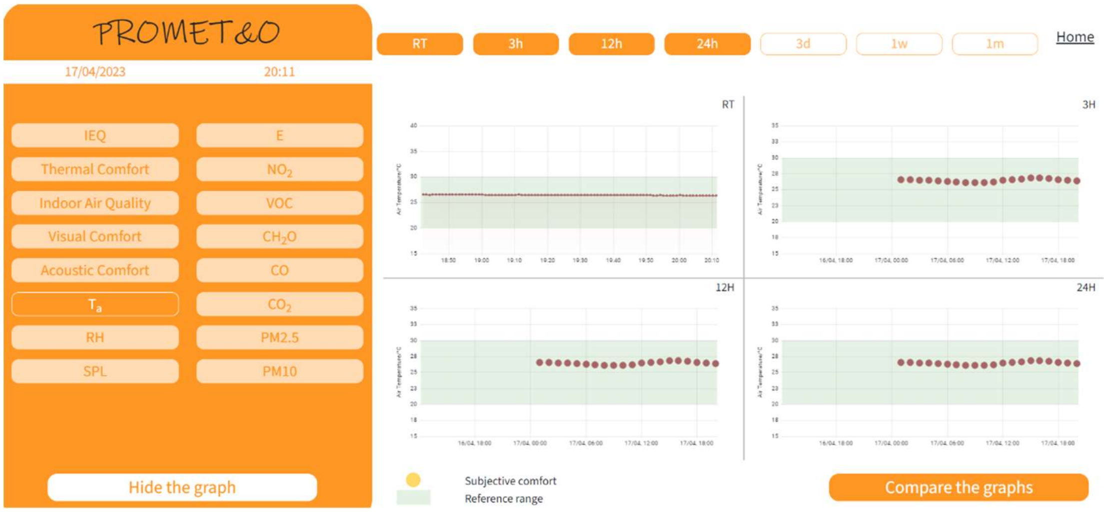


Figure 51 Dashboard: comparing graphs of the quantities in different times. Taken from (Bevilaqua D. ,2023)

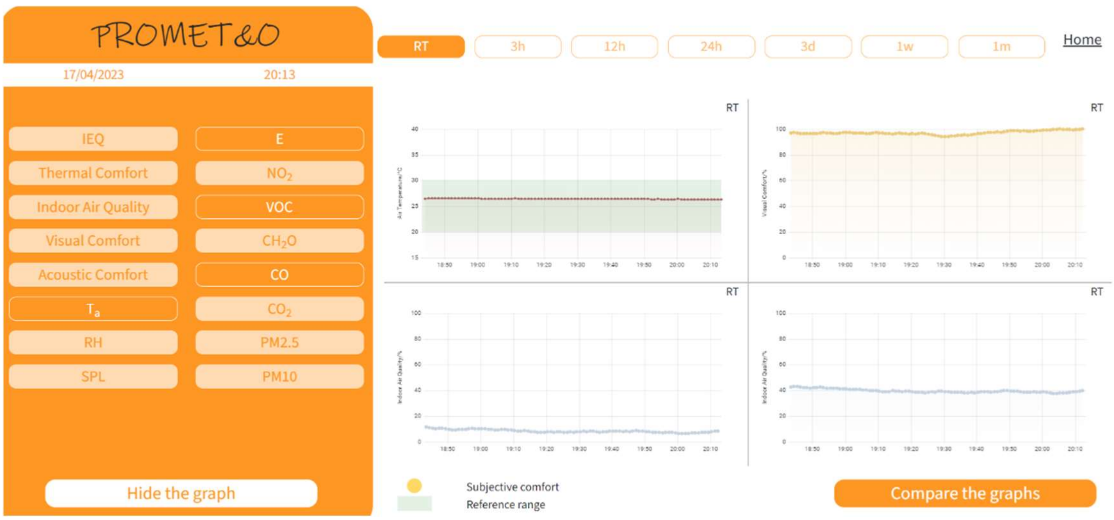
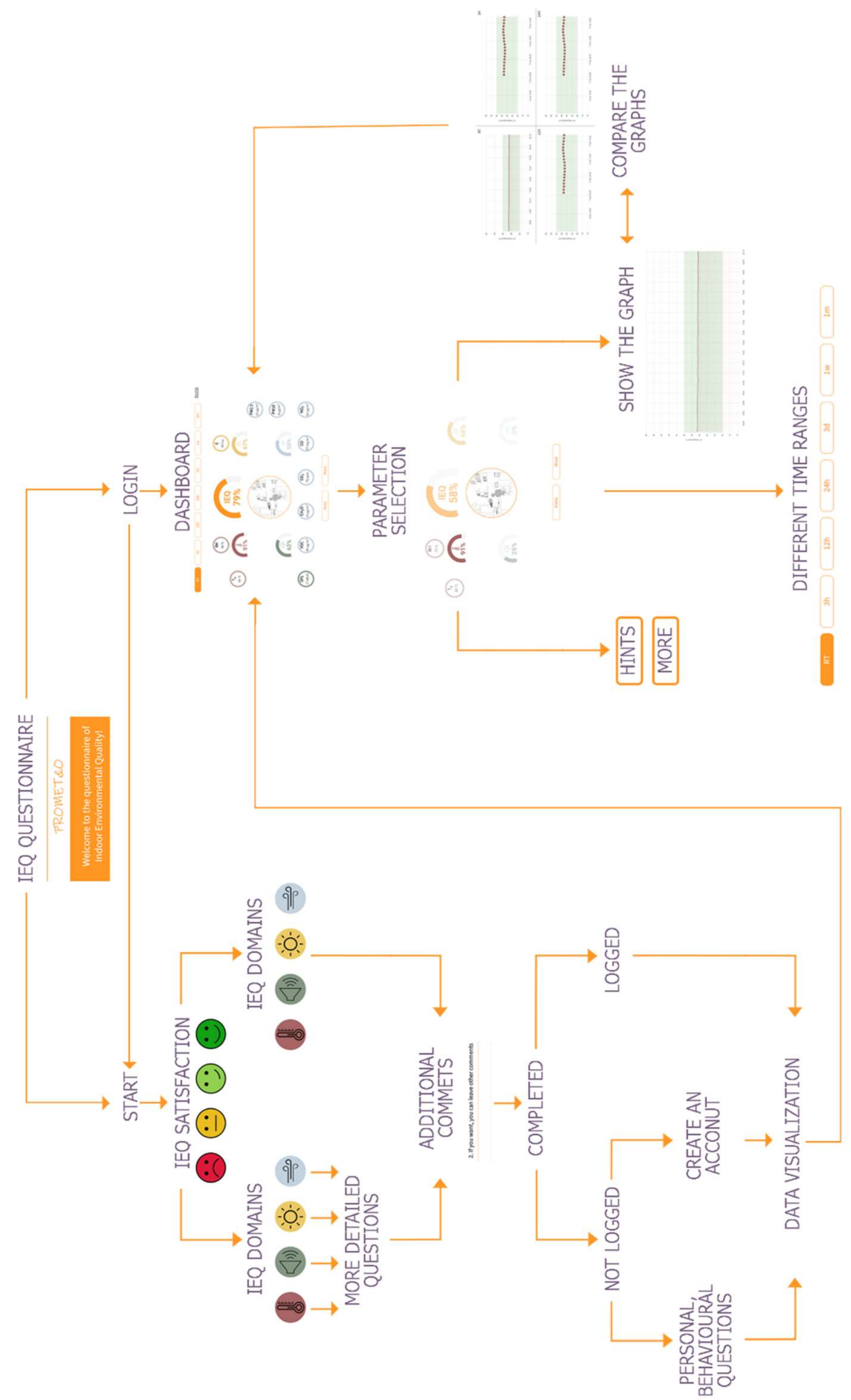


Figure 52 Dashboard: comparing graphs of different quantities. Taken from (Bevilaqua D. ,2023)

In figure 56 the path that the user has to follow to consult the graphs, starting from the questionnaire, is show

2.9.4. Hints and More: an Instrument to Involve



The user does not change behavior if he or she is just given environment-friendly information. The three-part process of information, knowledge, and consequent appropriate behavior can work only in a situation of warned danger **(Hanss et al., 2016; Hanss & Böhm, 2010)**. For this reason, in addition to the graphical feedback, shown on the dashboard display, the PROMET&O project adds an innovation: the "hints" and "more." Users need to know not only what behavior to change, but also how to do it and what alternatives they have. With this in mind, then, the "More" are buttons, as shown in Fig.57, that can satisfy the user's curiosity related to one of the monitored environmental parameters or domains. The "Hints", on the other hand, suggest the correct behavior to be adopted in order to keep the parameters within the thresholds and thus ensure a higher environmental quality for the entire office. In a future implementation, possible POP-UPs to act as reminders were also considered.

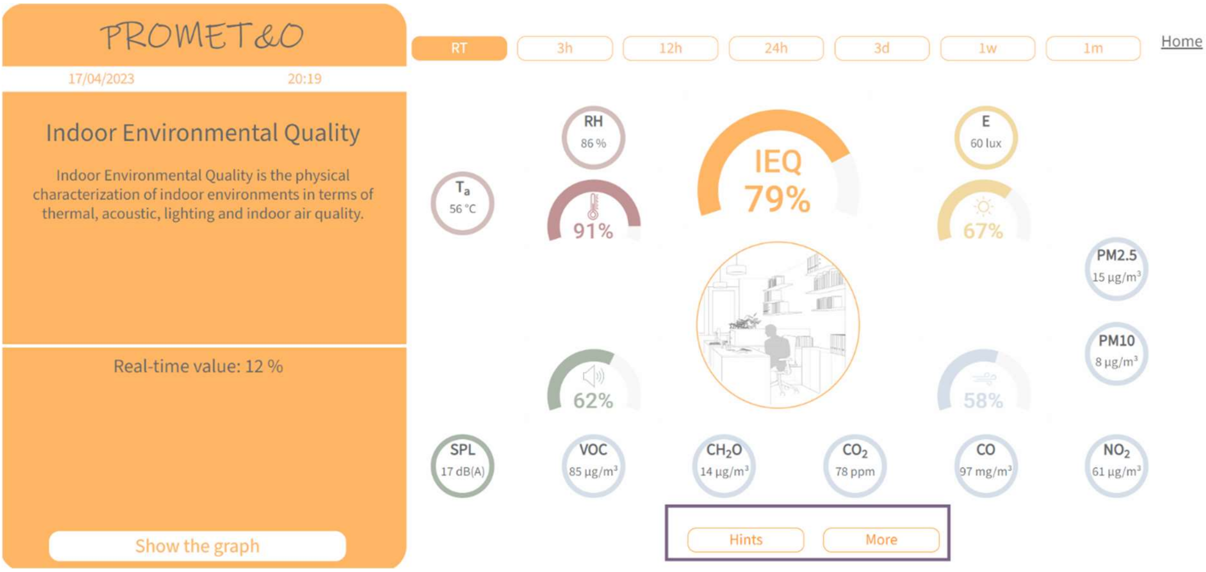


Figure 53 Hints and more buttons showed on the dashboard. Taken from (Bevilaqua D. ,2023)

The following table (Tab. 40) shows all the hints, more and pop-up that will be displayed on the web extention.

Table 39 Hints and more table

PARAMETER	HINTS	REFERENCE	MORE	REFERENCE	POP-UP	REFERENCE
Ta	Drink water in case of temperature higher than the acceptable range (about 1 glass every 15-20 minutes), and wear lightweight, breathable and comfortable cotton clothing	nr	To be at the peak of their productivity, workers have to operate in a thermally comfortable environment. It has shown that the best thermal setting for an office ranges between 20°C and 26°C. If the temperature exceeds the former limit, the productivity decreases of 2% for each 1°C more.	(de Dear et al., 2013; Seppänen & Fisk, 2006b)	It has been demonstrated that our working performance is 6% lower when our office is over-heated and 4% lower when it is cold.	WELL
RH	Try to ensure a relative humidity between 40-60%, through natural ventilation. According to the World Health Organization (WHO), this optimal range will reduce the spread of seasonal respiratory illnesses.	WHO	Low indoor air humidity (<30%) causes vulnerable airways and dry and tired eyes, affecting the overall work performance. Increasing the indoor air humidity may be a treatment of the risk of infection and transport of virus. In fact, at lower relative humidity, exhaled droplets stay longer in the air and, due to their progressive shrinkage, they tend to reach easier the lower airways.	Wolkoff et al. (2021)	It has been showed that office workers exposed to a relative humidity below 30% were more likely to experience 25% more stress than those exposed for the same amount of time to a relative humidity between 30 and 60%.	Razjouvan et al. (2020)
Thermal comfort	Thermal comfort is perceived differently by each individual and depends on, among other factors, the activity you are performing and what you are wearing. To ensure your thermal comfort without compromising the perception of others, adopt a flexible dress code.	WELL,WHO, ASHRAE55	Thermal comfort is related to occupants' health, well-being and productivity and is appraised as one of the highest contributing factors to overall human comfort in buildings. Thermal comfort is interconnected with integumentary, endocrine and respiratory body systems and it may impact multiple health outcomes. For example asthma in adults can be caused by exposure to cold air and sudden temperature change.	WELL	Participants thermally unsatisfied felt more dissatisfaction also with air quality, noise and lighting. The workers who perceived thermal environment as "neutral" or "slightly cool" were the most productive ones.	(Geng et al., 2017)
E	Particularly strong shadows can cause the visual apparatus to adapt too abruptly. For example, for paper-based tasks, avoid to put objects or your arms between light direction and you.	nr	An higher illuminance improves subjective alertness and vitality of the employees, who as a consequence feel less tired, more energic and have shorter reaction times on the psychomotor vigilance tasks.	Smolders et al., 2012	According to the guidelines, the light level in an office should be 300 lx for screen-based tasks, while 500 lx for paper-based tasks.	ISO 8995:2002(E)

Visual comfort	Use the shading system wisely to improve your visual comfort.	Kim et al. 2017	Visual comfort is defined as "a subjective condition of visual well-being induced by the visual environment". The physiology of human eye, the spectral emission of the light source, the amount of light and its distribution on surfaces are the main aspects that may affect visual comfort. Moreover, daylight should be preferred, as it is the main regulator system for the human body. It controls people circadian rhythm, providing physical and mental energy for the day. This is the reason why a well-designed illumination system can really improve people quality of life.	(Carlucci et al., 2015)	Office workers without windows reported poorer sleep quality and higher daytime dysfunction than their counterparts with access to natural light.	WELL
SPL	A strategy to reduce the sound level is to move the point source away from people. As sample, moving a copy machine in another room can reduce the noise level by more than 15 dB. If you need to talk, move away from other people or choose a separate conference room.	COLDEN CORPORATION	Human ear is limited to the perception of sound pressure levels from 0 dB to 120 dB, that is considered the threshold of pain. Nevertheless, these limits depend on individual's sensitivity. Human perception of sound frequency (known as "pitch"), ranges from approximately 20 to 20000 Hz, with augmented perception within the frequency range of human voice, that is between 1000 Hz and 6000 Hz.	WELL	In general, a tone whose sound level fluctuates is more annoying than one whose level is constant.	nr
Acoustic comfort	Remember to respect other people's comfort and perception. If you need to talk, move away from other people or choose a separate conference room.	nr	Acoustic comfort is a satisfactory status with acoustical condition in an environment. A lack in acoustic comfort has evident psychological consequences on humans, including stress and de-concentration. Some studies have shown how higher blood pressure, higher production of stress hormones and anxiety, reduction of the ability to remember and to focus on, are linked to elevated levels of noise	(Evans et al., 1998)	Office occupants are more disturbed by a lack of acoustical privacy than by the level of noise or echo. "Noise due to conversation" is the one that dissatisfies occupants the most, even more than footsteps, office equipment or ventilation.	Artan Ilter et al. (2019)
CO	Overconcentration of CO can be avoided by ensuring fresh air flow into your indoor space and using	WHO	Carbon monoxide is an odorless, colorless, and tasteless gas caused by incomplete combustion.	IQAir	Different researches have demonstrated a strong interrelation	(Fisk , 2009; Dimitroulopoulou and Bartzis, 2013)

TVOC	In order to reduce the concentration of TVOCs in your indoor environment, often refresh the air and choose products with less or no TVOCs.	EPA	TVOCs are totally volatile organic compounds, with potential health effects depending on the level and the time of exposure. Short term effects could be headache, eyes, skin and respiratory tract irritation, bronchitis, central nervous system symptoms, cardiovascular and respiratory diseases, impacts on livers and cancer. TVOCs can be found in everyday products, such as paints, varnishes, detergents, cleaning products, but also photocopiers and printers.	Shrubsole et al. (2019)	Don't let your nose guide you! Also a good smell, like the one of sprays or detergent products, may hide a release of TVOCs.	nr
Formaldehyde	In order to reduce the concentration of formaldehyde in your indoor environment, choose products that meet the standards on formaldehyde emissions, increase the rate of ventilation and ensure a relative humidity between 40-60%.		Formaldehyde is a colorless, flammable gas with a strong smell, highly reactive at room temperature. This compound can be found in building materials and insulating, most composite wood products, glues, paints and coatings, detergent, soaps and electronic equipment. Materials and products emit formaldehyde for several months, mainly in indoor environment with high relative humidity and high indoor temperature. Formaldehyde represents a risk to human health, causing irritation of the skin, eyes, nose throat, and with high levels of exposure may cause some types of cancers.	WHO	On average, 10% productivity loss could be attributable to health issues related to poor indoor air quality in office buildings.	WELL
IAQ	EPA guidelines to improve the indoor air quality of your office suggest to: • Do not block air vents or grilles. • Comply with the office and building smoking policy. • Water and maintain office plants properly. • Dispose of garbage promptly and properly. • Store food properly. • Avoid bringing products into the		We spend most of our time in closed spaces (homes, offices, schools, or other building environments) in which we are exposed to innumerable air contaminants, including biological agents and chemical pollutants that easily enter our body through inhalation. In the recent global burden of disease study, indoor air pollution was rated as the third most		It has experimentally confirmed a strong link between IAQ and productivity on common tasks as math calculation, text typing or proofreading.	(Fanger , 2000; Wargocki et al., 2000; Langer and Beko,2013).

	in a proper way all devices running on fossil fuels.		It is poisonous and potentially letal.		between Sick Building Syndrome (SBS) and insufficient air exchange, less than 10 l/s.	
CO_2	Very large increases in ventilation rates, sufficient to reduce indoor CO2 concentrations to approximately outdoor levels, would be expected to decrease prevalence of sick building syndrome (SBS) symptoms by 85%.	REHVA	Indoor CO2 concentration depends on many factors such as number of people in the space, activity carried out, time spent by the users in the indoor space, air exchange and outer air volume flow. Indoor concentration of CO2 greater than 1000 ppm, together with other air contaminant factors, could be associated to sick building syndrome (SBS) symptoms. These terms refer to an acute discomfort that can lead to headaches, irritation of nose, eyes and throat, coughing, nausea, difficulty concentrating, fatigue.	REHVA	According to a study by Harvard, SUNY and Syracuse University in 2017, workers exposed to higher levels of CO2 (1200 ppm) were 50% less productive than the ones exposed to lighter CO2 levels (550 ppm).	Allen J.G. et al. (2015)
NO_2	Indoor concentration of NO2 strictly depends on outdoor sources, such as local traffic or other combustion sources. If you work close to a busy road, avoid to open too often the window and prefer mechanical ventilation with an efficient filtration system. You can do also more, first for your office, than for the planet: encourage public transport, biking and walking to reduce NO2 emissions.	WHO / (Salonen et al. 2019)	Most nitrogen dioxide in the environment comes from burning fuel in vehicles and power plants, but also by natural activity such as lightning strikes, volcanoes, oceans, biological decay. Reacting with water, it turns into nitric acid, contributing to lake acidification and acid rain. Exposure to indoor NO2 can lead to allergic deseases like asthma.	IQAir	Children, people with asthma, and adults with heart and respiratory disorders are most affected by nitrogen dioxide levels.	IQAir
PM	Remember to never smoke indoor, run a room purifier and don't forget to monitor your air quality indoor and outdoor.		Particulate matter are suspended particles, found in dust, sort, dirt and smoke. The major sources of PM are anthropical (power plant combustion, vehicle combustion, wildfires). PM2.5 particles measure 2.5 microns or less in diameter. They causes 7 million preventable deaths every year, as they can be suspended in the air for longer and be absorbed into the bloodstream through inhalation. PM 10, instead measure 10 micrometers in diameter or less, and can cause tissues damage and asthma, in the long term.		If the world met the new WHO guidelines, 80% of PM 2.5-related deaths could be avoided.	WHO

	building that could release harmful or bothersome odors or contaminants. • Notify your building or facility manager immediately if you suspect an indoor air quality problem.		important source of ill health for the world’s population. Health effects due to exposure to indoor air pollutants can be short and long term and of different severity. Furthermore has been found out a relationship between indoor air quality and occupants' productivity in buildings: on average, 10% productivity loss is recorded in office buildings in the USA. About 35% of total absenteeism can be attributed to insufficient provision of fresh air in buildings. On the other hand, productivity can be improved up to 29% providing adequate ventilation in buildings.			

2.10 OBJECTIVE AND SUBJECTIVE VALIDATION

In order to understand the user feedback of both the environmental comfort questionnaire and the data visualization dashboard, a validation phase was performed. Both anonymous questionnaires and interviews were used to collect subjective feedback, which was useful for the modification and implementation of certain functions as well as graphic components. In the following paragraphs, first the validation procedure for the objective interface will be described in detail, then the one for the subjective interface.

2.10.1 Objective Interface validation

The methodology dedicated to the evaluation of the graphical display of Indoor Environmental Quality (IEQ) and Indoor Environmental Comfort (IEC) data was validated by allowing users to freely navigate within the PROMET&O web page. After logging in with a specially generated 'personal token', they were asked to access their profile and then the 'dashboard' section. It shows the different quantities monitored by the multi-sensor (at present, the values are fictitious as the multi-sensors are not yet active in the field), both in real time and in other time frames (3 hours, 12 hours, 24 hours, 3 days, 1 week, 1 month). In order to involve and inform the user about the IEQ, it is possible to read the definitions of the monitored quantities, as well as to access the 'Hints' and 'More', which will be discussed in more detail in the following chapter. Briefly, by clicking on these two buttons, the user receives hints on how to implement his or her comfort level and further information about the selected quantity, respectively.

In addition, the user can decide to consult the graph inherent to the physical quantity or the environmental comfort domain, and compare either the same quantity over different time frames, or different quantities, up to a maximum of 4.

In April 2023, a verification and acquisition of feedback useful for improving the interface was conducted. Specifically, a questionnaire was administered anonymously, online, and 10 additional users were interviewed. The survey methods as well as the results obtained are shown below.

For the validation of the objective interface, a questionnaire of 30 questions, including open-ended and multiple-choice questions, was drawn up using Microsoft Forms. It was distributed by e-mail. It is provided in full below:

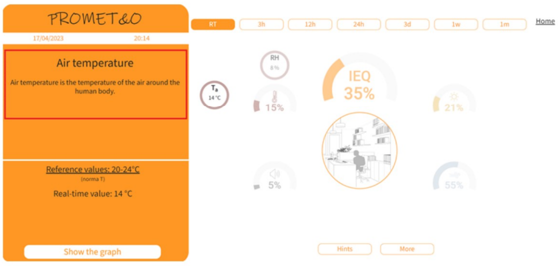
Feedback raccolta e visualizzazione dei dati oggettivi

Dashboard

Benvenuto!
Adesso puoi navigare nella dashboard sulla qualità ambientale interna, cliccando sul link seguente:
https://paris.prometeo.click/dashboard
Le tue credenziali sono:
Personal token: validazione
Entra nella sezione "profilo", poi "dashboard". Dopo averla utilizzata, rispondi al test di valutazione.

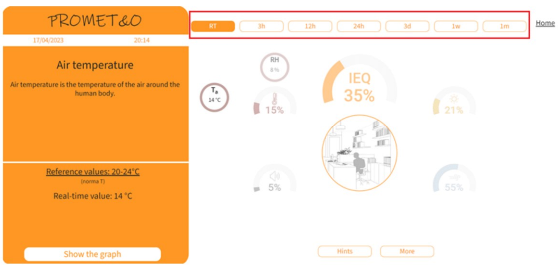
1

Ritieni che sia utile la descrizione della grandezza\indice?



- SI
- NO

Ritieni che sia utile la possibilità di scegliere un arco temporale?



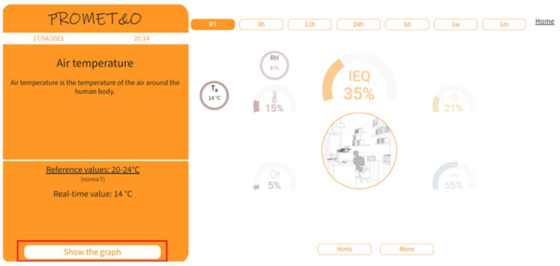
- SI
- NO

3

Ne aggiungeresti \ rimuoveresti qualcuno?

4

Ritieni interessante la possibilità di vedere il grafico della grandezza monitorata?



SI

NO

5

Trovi sia intuitivo ed immediato il comando di visualizzazione del grafico?

SI

NO

6

Se no, come lo modificheresti?

Ritieni gli "HINTS"

- [ ] UTILI
- [ ] NECESSARI
- [ ] INTERESSANTI
- [ ] Altro

Ritieni i "MORE"

- [ ] UTILI
- [ ] NECESSARI
- [ ] INTERESSANTI
- [ ] Altro

Apporteresti modifiche? Quali?

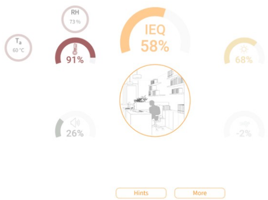
Come valuteresti il resoconto grafico complessivo?

☆ ☆ ☆ ☆ ☆

Apporteresti modifiche? Quali?

12

Trovi sia immediata la comprensione della grandezza selezionata con il sistema colore saturo/trasparente?

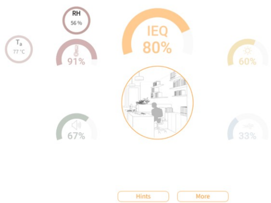


◯ SI

◯ NO

13

Ritieni che il colore risalti sufficientemente?



◯ SI

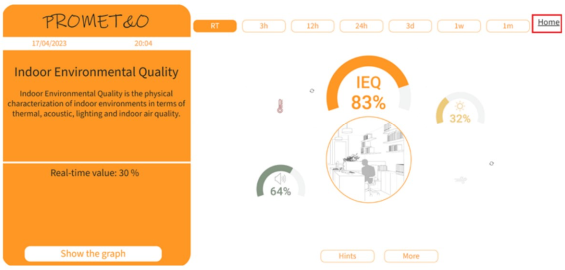
◯ NO

14

Apporteresti modifiche? Quali?

15

A quale schermata credi debba condurre il tasto "Home"?



- INIZA IL QUESTIONARIO
- SCHERMATA IEQ INIZIALE
- Altro

16

Come lo modificheresti?

17

Complessivamente, valuta la facilità di navigazione e comprensione della dashboard

☆ ☆ ☆ ☆ ☆

18

Ritieni che il grafico real time (RT) sia complessivamente comprensibile?

- SI
- NO

19

Ritieni che l'inserimento del comfort soggettivo nel suddetto grafico sia

- [ ] UTILE
- [ ] NECESSARIO
- [ ] INTERESSANTE
- [ ] Altro

20

Ritieni adeguato il modo grafico di comunicazione di conformità alla normativa?

- ○ SI
- ○ NO

21

Adotteresti un sistema differente? Quale?

22

Implementeresti la legenda?

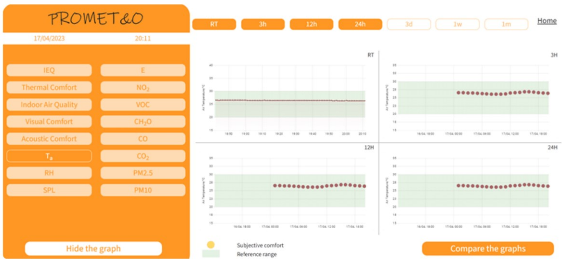
- ○ SI
- ○ NO

23

Se sì, come?

24

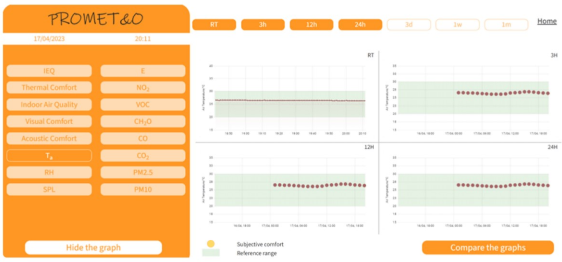
Ritieni che la possibilità di confrontare in parallelo la stessa grandezza durante diversi archi temporali sia:



- [ ] UTILE
- [ ] NECESSARIO
- [ ] INTERESSANTE
- [ ] Altro

25

E verificarne la conformità con le soglie secondo normativa (rettangolo verde) in parallelo?



- [ ] UTILE
- [ ] NECESSARIO
- [ ] INTERESSANTE
- [ ] Altro

26

Ritieni che il confronto grafico tra più grandezze diverse sia:

- [ ] UTILE
- [ ] NECESSARIO
- [ ] INTERESSANTE
- [ ] Altro

27

Complessivamente apporteresti modifiche\ integrazioni a questa sezione?

[ ]

28

Complessivamente, come valuteresti l'intera interfaccia oggettiva?

☆ ☆ ☆ ☆ ☆

29

Quanto ritieni che questo stile di visualizzazione ti coinvolga e renda partecipe sulle tematiche della IEQ (Indoor Environmental Quality)?

☆ ☆ ☆ ☆ ☆

30

Complessivamente, hai ulteriori suggerimenti?

[ ]

The interview was conducted as follows: after browsing the PROMET&O dashboard, the interviewee was asked to fill in the 30-question form. In addition, they were asked to answer some further questions:

1. Do you find the dashboard graphically impactful?

    a. Which elements stand out the most?

2. Do you think the dashboard is able to make the user more aware of the quality of the internal environment?

    a. If yes, thanks to which elements?

    b. Do you find the language too technical or understandable by any user?

3. Do you think the dashboard engages the user and entices him/her to fill in the questionnaire?

    a. If yes, thanks to which elements?

4. Name at least two elements that impressed you positively and that you would like to see adopted in other graphical interfaces of this type:

5. Overall, do you have any other suggestions/criticisms?

Feedback from the questionnaire

From the answers to the questionnaire, the following results emerged, broken down according to the specific topic:

Basic functionality

a. Description of the parameter monitored

96% of the respondents found the description of the monitored physical quantity useful.

b. Choice of time frame

Only 4% of the respondents considered the possibility of choosing the display time frame as not useful. In fact, one respondent considers the display of data from 12 hours and the previous 3 days to be superfluous. The modification of real time, specified as RT, or, at least, the addition of an icon is also suggested.

c. Graph Display

Next, it was asked whether the possibility of displaying the graph was interesting, with 93% positive responses. The command to display the graph seemed intuitive to 79% of the respondents. A suggestion was also made to add a graphic symbol to the top right or left. Some considered it necessary to move the button to a more visible position, such as at the bottom centre of the page.

"Hints" and "More" commands

36% of the respondents thought the 'Hints' command was interesting, 42% useful, 6% necessary, and 17% other, i.e. 'useful but needs to be detailed', 'potentially interesting but not very engaging', 'sometimes they can be very obvious'.

19% of the respondents found the 'More' command interesting, 52% useful, 6% necessary, 23% other, i.e. to be detailed because with very general descriptions similar to those of the 'Hints'. One suggestion is to change the term "More" to "Info" and to add a button for switching directly from "Hints" to "More".

Graphic Appearance Evaluation

The overall graphic report received an average rating of 3.85 out of 5 stars, suggesting the use of more contrasting colours. 86 per cent of the respondents found the saturated/transparent colour system for selecting the monitored size understandable, although as many as 68 per cent felt that the colour did not stand out sufficiently.

Ease of navigation and understanding

The ease of navigation and understanding of the dashboard was rated 3.54 out of 5 stars on average.

Graphs

86% of the respondents felt that the real time (RT) graph was understandable. The inclusion of subjective comfort in the graph was rated useful by 56% of the respondents, necessary by 19%, interesting by 22%. The graphic way of communicating compliance with the regulations in force for the size monitored was considered adequate by 96% of the sample, although very 'didactic', the lettering being too small in size.

Legend

48% of the respondents would implement the legend of the graphs by explaining what is meant by "subjective comfort", citing the reference standard, standardising the colour of the dot in the legend and in the graph, and inserting the reference of the data obtained through monitoring ("objective data").

Comparison of graphs

a. Same size, different time span

The possibility of parallel comparison of the different size during different time periods was considered useful by 52% of the respondents, necessary by 19%, interesting by 26% and other by 3%, i.e. "not very understandable as a function".

b. Compliance with thresholds according to regulations

The parallel comparison of compliance with thresholds according to regulations was considered useful by 48% of the users, necessary by 26% and interesting by 26%.

Different quantities

The graphical comparison of different quantities, on the other hand, appeared useful to 55% of the respondents, necessary to 13%, interesting to 29%, other to 3%, i.e. 'weakly interesting'.

Overall assessment

In conclusion, the overall assessment of the entire objective interface was rated with an average of 3.74 out of 5 stars, with the visualization style also making the user feel involved in the IEQ topic with an average of 3.54 out of 5 stars.

2.10.2 Subjective Interface Validation

Once the user interface was designed, it was validated. This interface is dedicated to the return of monitored data and calculated indices, as well as to the process of acquiring feedback from users on perceived comfort in offices, collected continuously and non-intrusively.

In October 2022, a survey was conducted in which 9 tablets were delivered to 9 offices located in Turin. Specifically: a C2R Energy Consulting office, five shared research offices, an open-space research office, a single research office, and an administrative office of the Polytechnic University of Turin.

Users of the offices were asked to fill out the questionnaire at least 2 times a day, not for the purpose of data collection, but to evaluate the ease of execution, comprehensibility, and effectiveness of the questionnaire.

At the end of the two weeks, a 40-questions questionnaire (Fig.59) was submitted to them via Microsoft Form links, and 4 of them provided additional feedback directly to the designers.

In order to validate the applied methodology, therefore, feedback inherent only to user's own satisfaction with the operation and understanding of the questionnaire was acquired in two different forms:

1. Feedback acquired anonymously via Microsoft Form
2. Feedback acquired via interview

Analyzing the results, it was possible to make some changes that would make the questionnaire itself more understandable and effective, distinguishable in:

- Modification to the flow of the questionnaire: i) a section was added to determine the "satisfactory domain" after a positive response to the first question; ii) the possibility was given to create the personal account in the login section.

- Modifications to the content of the questions: i) the homepage was changed to make the objective of the questionnaire clearer; ii) questions deemed insufficiently clear by users were modified; iii) explanation pop-ups were added on how to answer the questions (Fig.58).

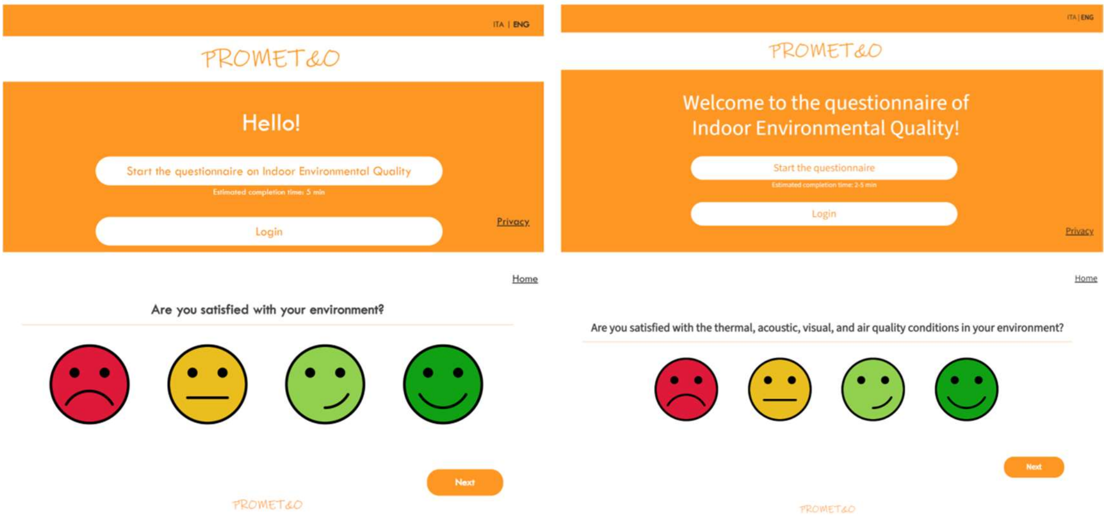


Figure 54 Homepage modification (a) before, (b) after the feedback

1. Feedback acquired anonymously

Analysis of the feedback acquired via a questionnaire on Microsoft Form revealed that 83% of the participants thought the graphics of the questionnaire were pleasant; 100% thought the use of smilies as a liking scale was appropriate; 83% thought the icons of the four domains were easily recognizable; 100% considered the number of questions adequate for expressing their comfort and the personal questions relevant; only 33% created an account, (a result that highlighted the need to better explain its benefits); only 33% considered the graphics shown at the end of filling out the questionnaire to be clear enough, making it necessary to make further adjustments to clarify their content.

2. Feedback acquired through an interview

To further confirm the data collected, 4 participants provided some feedback directly to the designers, which was discussed and helped in the process of optimizing the questionnaire.

These comments to the questionnaire are divided into 4 areas:

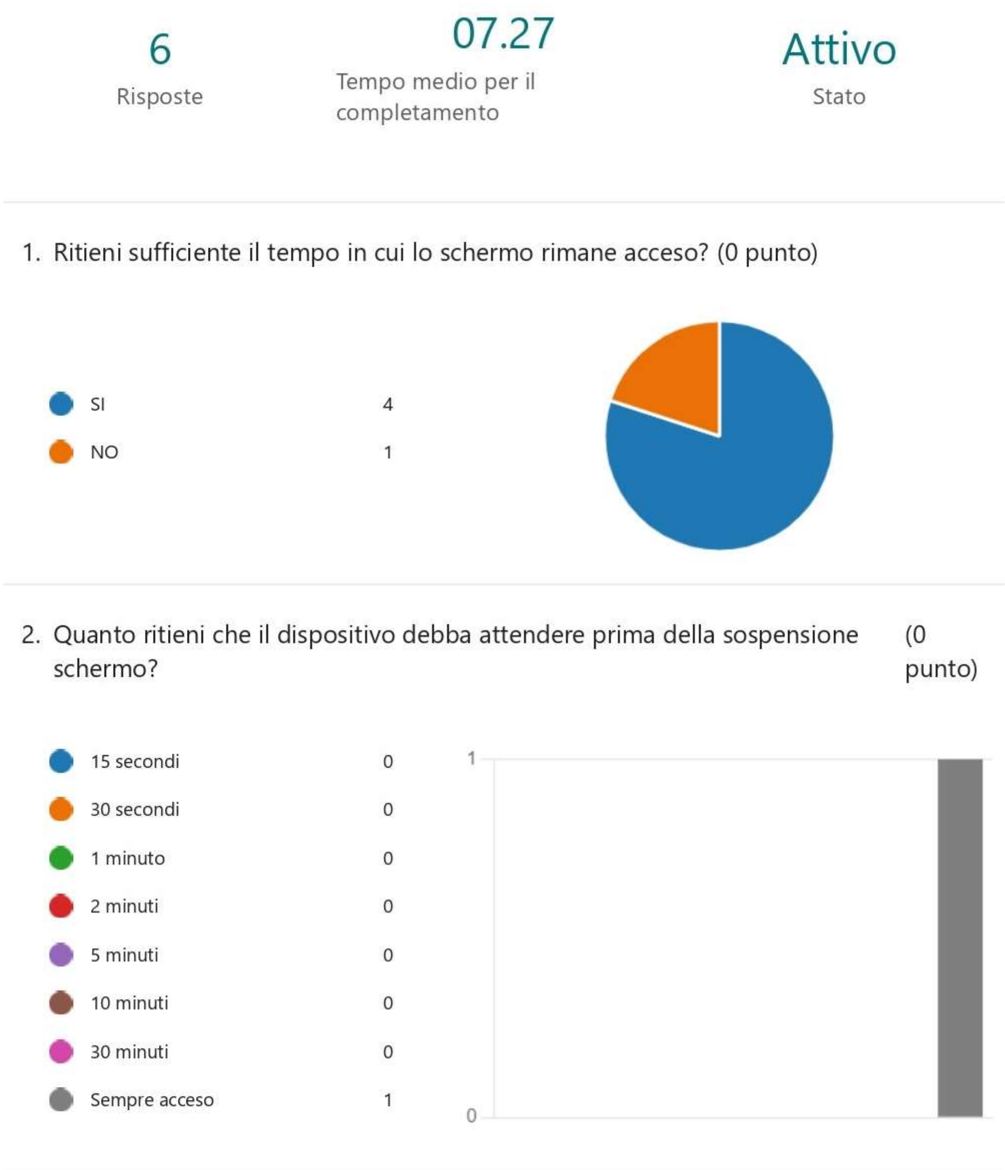
(a) Structure of the experience: overall, the questionnaire was found to be streamlined and quick to complete, with a positive note about the average time for completion. Users interviewed highlighted the usefulness of not stopping the questionnaire following a slightly positive or positive evaluation, adding a request to identify with respect to which domains a feeling of well-being is perceived. For this reason, the path of the questionnaire was modified.

(b) Rating scale: one user stated that he preferred a rating system on a 5-value scale, as it provides a neutral value in between. In fact, the developers purposely provided a 4-value scale to direct the user toward a more negative or more positive condition regarding the first question. The domain-specific questions, on the other hand, were taken from ISO 28802:2012.

(c) Mode of communication: it is considered necessary for information and questions to be as accurate as possible. One user pointed out that the first question "Are you satisfied with your environment" can be understood as satisfaction at the visual, olfactory, acoustic, or thermal level, but also at the ergonomic, furniture, and color levels. For this reason, the first question was changed to "Are you satisfied with the thermal, acoustic, visual, and air quality conditions in your environment?" One user pointed out the need to better specify the purpose of the questionnaire on the homepage. Finally, it was stated how it is not immediate to understand that more than one answer can be selected in some, so the explanation was supplemented.

(d) Final feedback: All users reported difficulty in interpreting the content of the graphs shown at the end of completing the questionnaire. Therefore, it was modified by adding more explicit captions and labels. In addition, one user expressed a desire to display personalized data based on the answers provided. Initially, the choice was directed toward showing the comfort indices of all users over time, however, this choice could have generated privacy complications: if users in the office see who completes the questionnaire they can easily trace their comfort data. So, the choice was made to show only the personal comfort data of the respondent user.

The following questions are taken from the “Subjective interface validation questionnaire”, made by the use of Microsoft Forms.



7. Perché? (0 punto)

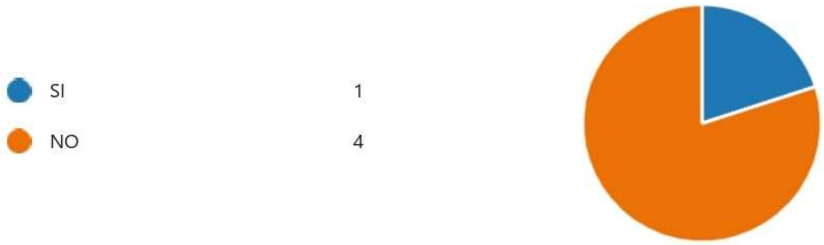
0

Risposte

Risposte più recenti

8. Trovi che il cavo del caricabatterie sia sufficientemente lungo? (0 punto)

9. Trovi forviante la possibilità di tornare indietro tramite il simbolo in basso a sinistra? (0 punto)



10. Sei soddisfatto della grafica della schermata iniziale? (0 punto)

3. Trovi che il collegamento al questionario sulla schermata home sia facilmente riconoscibile? (0 punto)

SI	4
NO	1

4. Preferiresti (0 punto)

modalità alternativa	0
logo alternativo	1
nome alternativo	1
altro	0

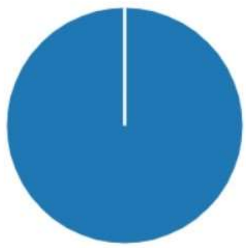
5. altro (0 punto)

0
Risposte

Risposte più recenti

6. Trovi che il questionario sia facilmente accessibile? (0 punto)

SI	5
NO	0



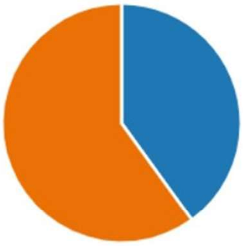
11. Cosa cambieresti? (0 punto)

1 Risposte

Risposte
Il Pulsante "Start the questionnaire ..." ha la scritta troppo lunga. Si potrebbe mettere la coda (IEQ) nel corpo della schermata iniziale e non nel tasto. Sarebbe interessante inserire un pulsante per il sign in

12. Generalmente, effettui il questionario con login? (0 punto)

SI	2
NO	3



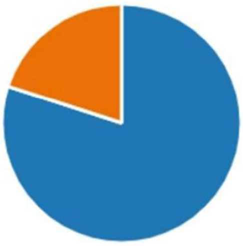
13. Perché? (0 punto)

2 Risposte

Risposte
Perchè non obbligatorio, anche se potrei decidere di farlo per evitare di dover rispondere sempre alle domande alla fine del questionario
non ne vedo il motivo, cosa cambia lato mio?

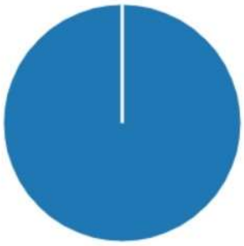
14. Preferiresti creare il tuo account prima della compilazione del primo questionario? (0 punto)

SI	4
NO	1



15. Sei soddisfatto del metodo di valutazione attraverso emoticon? (0 punto)

SI	5
NO	0



16. Quale metodo alternativo sceglieresti? (0 punto)

0
Risposte

Risposte più recenti

17. Ritieni che i colori scelti condizionino in qualche modo le tue risposte? (0 punto)

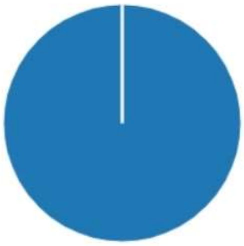
SI	2
NO	3

18. Ritieni che le icone scelte per i 4 parametri IEQ siano facilmente riconoscibili? (0 punto)

SI	4
NO	1

19. Ritieni che le possibilità di risposta siano sufficienti ad esprimere il tuo livello di comfort? (0 punto)

SI	5
NO	0



20. In quale dei 4 parametri di IEQ? (0 punto)

Thermal	0
Visual	0
Acoustic	0
Air quality	0

21. Quali ulteriori risposte inseriresti? (0 punto)

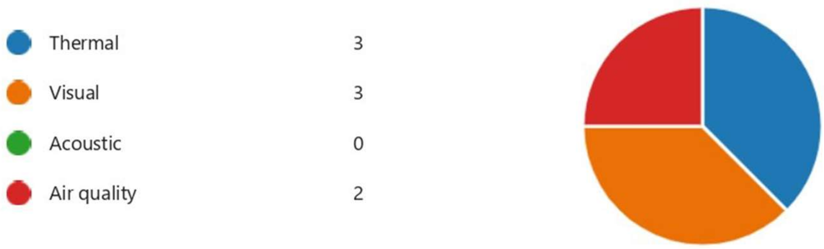
0
Risposte

Risposte più recenti

22. Selezionando "OTHER", preferiresti inserire una risposta aperta? (0 punto)

SI	2
NO	3

23. Quale parametro influenza maggiormente il tuo livello di comfort? (0 punto)



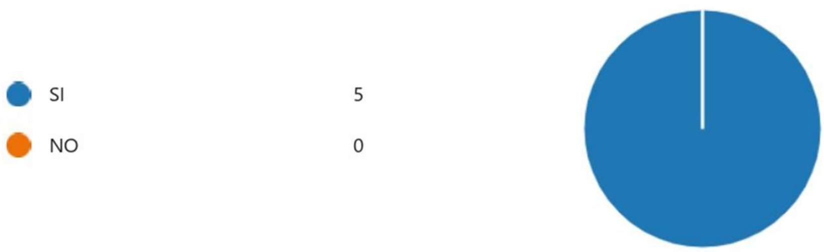
24. Ritieni che ciascun parametro influenzi allo stesso modo il tuo livello di comfort? (0 punto)

25. In che percentuali ripartiresti l'influenza dei 4 parametri? (0 punto)

1
Risposte

Risposte
Non è facile rispondere. I comfort lo si nota quando è assente, al momento nel luogo del sondaggio non ho particolari discomfort acustici o visivi, pertanto al momento mi sembrano meno rilevanti. Se però avessi forti fenomeni di abbagliamento o forti rumori diventerebbero di predominante importanza.

26. Dopo la compilazione del questionario, ritieni che le domande personali siano sufficienti? (0 punto)

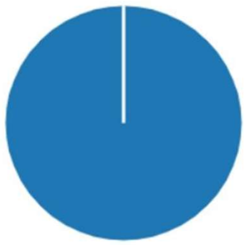


27. Mediamente, a quante domande personali hai risposto? (0 punto)

Tutte	3
Meno della metà	1
Più della metà	0
Nessuna	1

28. Ritieni che le domande personali siano (0 punto)

Attinenti	4
Necessarie	0
Nessuna delle precedenti	0



29. Quali domande aggiungeresti? (0 punto)

1 Risposte

Risposte
Potrebbe essere interessante sapere da quanto tempo l'utente è nel luogo del sondaggio. Immagino che la percezione del discomfort possa anche essere influenzata dal tempo di esposizione al "problema"

30. Quali domande rimuoveresti? (0 punto)

1 Risposte

Risposte
Il paese di nascita non mi sembra particolarmente rilevante ai fini del sondaggio

31. Ritieni che le opzioni "YES"/"NO" siano sufficienti? (0 punto)

32. Hai avuto difficoltà nel selezionare il paese? (0 punto)

33. Perché? (0 punto)

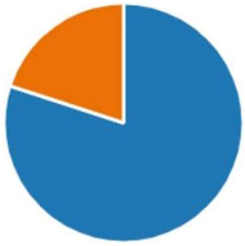
1
Risposte

Risposte
Non è difficile ma eccessivamente lungo. Forse inserendo dei "preferiti" in alto (ad esempio la nazione dove viene erogato il sondaggio) oppure dando la possibilità di scrivere in modo da accelerare la selezione

34. In fase di compilazione delle risposte personali, ritieni sia utile essere avvisato del fatto che "accedendo tramite login non sarà più necessario rispondere a tali domande"? (0 punto)

35. Ritieni utile la possibilità di concludere il questionario già nella prima fase (emoticon)? (0 punto)

- SI 4
- NO 1



36. Trovi leggibili e comprensibili i grafici che appaiono alla fine del questionario? (0 punto)

- SI 2
- NO 3

37. Perché? (0 punto)

2
Risposte

Risposte
L'asse orizzontale non ha un'etichetta molto chiara, l'unità di misura andrebbe messa tra parentesi quadre. Il grafico in alto a sinistra non si vede bene
Non essendo contestualizzati non so a cosa si riferiscano nè se ci debbano essere, idem per il link e qrcode

38. Inseriresti un titolo/ descrizione? (0 punto)

2
Risposte

Risposte più recenti
"si"

39. Complessivamente, noti altre criticità? (0 punto)

2
Risposte

Risposte
Non altre rispetto a quelle già segnalate
Il fatto di non poter evidenziare più di un fattore ambientale di cui lamentarmi

40. Complessivamente, quali ritieni siano i punti di forza? (0 punto)

2
Risposte

Risposte
Buona comprensibilità, facile da compilare
L'accessibilità e la velocità di completamento del questionario

Figure 55 40-questions questionnaire for subjective interface validation

3 METROLOGY IN PROMET&O PROJECT: AN OBJECTIVE PHASE

The concept of measurement permeates people's everyday lives, mainly in commercial, industrial and scientific contexts. The concept of measurement belongs to the wider concept of metrology, i.e. the science that deals with measurement and its applications.

The measurement of a physical quantity can have multiple goals:

- The comparison of the measurement from the instrument with that obtained by different subjects, with other equipment, in different environments.
- The comparison of the measurements obtained with compliance to normative reference values.

In any case, two conditions must be met for the measurement to be valid in a wide geographical context:

- The measurement must be obtained through an unbroken chain of comparisons with devices linked to primary national or international standards, in which the measurement uncertainty is stated explicitly;
- The instrumentation used must be calibrated against samples that themselves provide traceable measurements, resulting in a “chain of traceability”.

It should be pointed out that an instrument subjected to a calibration process does not strictly provide referable measurements. In fact, it is necessary for the measurement process to take place in a controlled process, ensuring that:

- The measurement requirements, previously explained, are met by the metrological characteristics of the instrument;
- The measuring equipment is calibrated or adjusted periodically;
- The conditions under which the calibration process takes place are established and monitored;
- Any systematic effects that may alter measurements are identified and corrected;
- The uncertainty of the process is realistically estimated, taking into account all significant contributions of uncertainty.

It should be reminded that, in the early 2000s, monitoring concerning Indoor Environmental Quality was solely performed by resorting to extremely expensive instruments, in the order of tens thousands of dollars and often not mobile. The past decade has seen not only a growing interest in this field, but also an evolution on how monitoring could be done, as well as who might be able to carry out campaigns, thanks to the advent of low-cost sensors. The data are easily accessible, but the low accuracy of the data obtained makes it necessary to carefully analyze and interpret the data, especially if comparisons of the output of the low-cost sensor to that of the reference instrument are to be made (Giordano et al., 2021).

Qualitative analysis of the indoor microenvironment, especially for what concern the Air Quality domain, is sufficient precise when monitored by low-cost sensors. Of course, despite the encouragement in using these cheap devices, the relevance of high quality instruments is not matchable. Thus, once the low-cost sensor have been purchased, a standardized protocol for its evaluation and calibration needs to be defined (Sá et al., 2022).

The difficulty in calibrating a low-cost sensor is not the process itself. It generally involves measuring the actual condition through a reference instrument, which works as a comparison for the data measured by the sensor. The complexity is mainly methodological and precedes the operational phase. It is necessary to establish a proper protocol that answers certain questions (Giordano et al., 2021):

Which measurement range should be applied for calibration?

Which reference instruments are most suitable? And is one sufficient?

For the calibration of gas sensors, what types of aerosols should be used and in which concentrations?

Under which temperature and relative humidity conditions should calibration be carried out?

One of the key steps, which precedes the calibration phase and serves to ensure its maximum performance, is the design and choice of the low-cost sensor (see

Paragraph 2.4). This is required by the fact that sensor behavior can be affected by various external parameters, such as indoor space, setting and environmental conditions (Sá et al., 2022).

In fact, it is one of the biggest challenge in the low-cost sensor calibration (Liang, 2021). According to some of the relevant paper consulted to further the knowledge on low cost sensors, gas sensors are very sensitive to their interfering environment. The most influential parameters are relative humidity (RH), temperature, pollution level and sensor age (Liang, 2021; Wei et al., 2018; Williams et al., 2013).

This is the reason why a cautions reading of the low-cost sensor data is required. For example, it has been demonstrated higher inaccuracies for PM sensors, able to convert particle light scattering signals into PM mass concentration. To avoid an overestimation of PM mass concentration in high humidity environments, it is useful to associate a device to dry incoming particles (Tryner et al., 2021a).

Even if low-cost sensors are more inaccurate and are affected by cross-sensitivity with other pollutants, they are even more studied and chosen for research projects. The main causes are reduced dimensions, continuous and real-time monitoring, and easiness of use (Justo Alonso et al., 2022).

It is precisely the variability of the results and uncertainties of the low-cost sensors that prompted the PROMET&O team to experimentally investigate the behavior of the sensors used, and consequently the success of the entire project. The objective phase in the metrology of the four environmental comfort domains is therefore fundamental and required a detailed knowledge of the metrology system, as well as the reference standards both general and for the different domains, also using scientific literature.

3.1 ORGANIZATION OF METROLOGY

In order for the results of a measurement to be globally valid and comprehensible, it is necessary for the metrological context to be regulated nationally and internationally, and for the units of measurement to be globally recognized. The following is an overview of the international and national Italian metrological frameworks and bodies.

3.1.1 International field

At the international level, the Metre Convention is recognized as the international treaty that established the adoption of a globally recognized system of measurement, and therefore, units of measurement. At the time of its signature, in Paris in 1875, there were 17 member states. Today, there are 64 member states and 36 associate states.

The convention gave rise to three bodies working jointly:

1. BIPM (The International Bureau of Weights and Measures), the international metrology center in Sevres.

2. CGPM (Conference Generale des Poids et Mesures), i.e. the meeting of delegates from all member states that meets in Paris every four years. The topics addressed are:

   a. Any arrangements required to ensure the propagation and improvement of the International System of Units (SI);
   b. New scientific discoveries in metrological determination;
   c. Development and organization of the BIPM for the next four years.

3. CIPM (Comité International des Poids et Mesures), the administrative committee that meets annually at the BIPM.

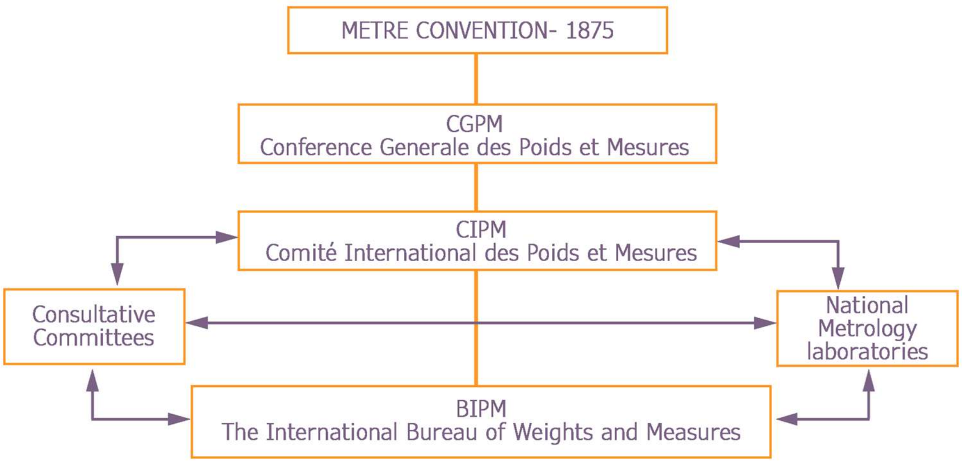


Figure 56 International organization of metrology. Personal elaboration from (Carullo A., 2022)

The main CGPM decisions that, from 1954 to 2018, defined the System of measurement units have been:

1. 10th CGPM (1954): introduction of a globally recognized system of units, including:
    a. Length (metre)
    b. Mass (kilogram)
    c. Time (second)
    d. Electric current (ampere)
    e. Temperature (degree Kelvin)
    f. Luminous intensity (candela)
2. 11th CGPM (1960): the system previously set has been named International System of Units (SI).
3. 14th CGPM (1971): the measure unit of the amount of substance became the mole.
4. 26th CGPM (2018): The International System of Units has been revised.

The measurement units determined by the National Meteorological Institutes (NMIs) are connected to the measuring instruments, through an indirect dissemination. The process that allows dissemination to take place is the metrological chain, i.e. a series of calibrations following a well-defined pattern:

national sample - first-line sample of calibration centers - measuring instrument.

So that, it is fundamental to ensure the equivalence among the primary standard realized by different NMIs. With this aim the Mutual Recognition Arrangement (MRA) have been signed in 1999. This agreement established that NMIs have to participate to international experimental comparison (Key Comparisons), whose results states the Calibration and Measurement Capabilities (CMCs) of each NMI.

Moreover, each NMIs has to operate in compliance with EN ISO/IEC 17025.

The dissemination process is carried out by accredited secondary laboratories. Verification of system quality, metrological capabilities, as well as what kind of calibrations the laboratory is able to conduct, in which measurement range and with which uncertainty, is conducted by calibration bodies, such as ACCREDIA, United Kingdom Accreditation Service (UKAS) and Deutscher Akkreditierungs Rat (DAR). Furthermore they created international associations such as the European cooperation for Accreditation (EA), or the International Laboratory Accreditation Cooperation (ILAC).

3.1.2 National field

In Italy there are two metrological institutes:

- I.N.RI.M (Istituto Nazionale per la Ricerca Metrologica), It creates, maintains and develops national reference standards for the basic units of the International System (SI) (metre, kilogram, second, ampere, kelvin, mole and candela) and their derived units. This ensures the reliability of measurements at national level and their comparability at international level.
- I.N.M.R.I.: Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti, with a focus on ionizing radiation and standards for its measurement units.

Also these Italian institutes signed the MRA in 1999.

The secondary laboratories, accredited by the Italian Accreditation Body (ACCREDIA), and called LAT centers, calibrates their reference standards using the NMI primary standards. Intesad, the dissemination of the measurement units happens towards the users of measuring instrument and standards.

3.2 MEASUREMENT UNCERTAINTY

One of the main factors to take into account when performing measurements is that they always possess a certain degree of uncertainty, namely the measurement uncertainty. This component is never null, as:

1. In reality, one operates not in an ideal case, but in a real one, so the instruments and samples are not ideal.
2. There are interactions between the equipment and the sample that alter their state.
3. Environmental conditions contribute to uncertainty.

3.2.1 Classification Of Measurement Methods: direct and indirect

Measurement methods can be classified according to the number of readings taken in order to assign a value to the quantity under measurement (single-reading measurement methods, repeated-reading measurement methods), or according to the mode of operation by which the value is assigned (direct measurement methods, indirect measurement methods).

Single-reading measurement methods: a single instrument reading is taken.

Repeated-reading measurement methods: the measurement is the result of a statistical analysis of several readings of the quantity under the same conditions.

Direct measurement methods: the reading, or series of readings, allows the measurement to be assigned to the parameter, without knowing any other parameters, except, for example, the influence quantities.

Indirect measurement methods: some other parameter measured in a direct method serves as a starting point for assigning the measurement to a parameter.

Direct measurement methods:

These methods involve the comparison between the quantity being measured and the quantity generated by a sample.

In the case of direct reading, for each instrument indication (I), subject to the application of the measurand to its input, a measurement m is assigned, following the relation:

$$m = f_t(I)$$

Where f_t= calibration diagram

This method includes uncertainty contributions:

- Instrumental uncertainty, expressed by the manufacturer;
- Reading uncertainty;
- Instrumental load, generated by the alteration of the system due to instrument-system interaction;
- Intrinsic uncertainty of the measurand;

- Uncertainty due to influence quantities.

Comparison by opposition between the quantity being measured and another of the same type, involves the use of an auxiliary instrument that calculates the equivalence condition between the measurand m and a quantity c_x of the sample:

$$m = c_x$$

Uncertainty is determined by various contributions:

- Uncertainty and sample resolution;
- Uncertainty of equivalence between measurand and magnitude;
- Instrumental load;
- Intrinsic uncertainty of the measurand;
- Measurement uncertainty of the influence quantity.

Among the comparison methods, there is also the zero method. It is mainly used in electrical circuits, as an auxiliary device detects the zeroing of a current or voltage in the circuit, corresponding to the equilibrium condition:

$$m = f(c1, c2, \dots cn)$$

Uncertainty is determined by various contributions:

- uncertainty and sample resolution;
- uncertainty of the zero condition;
- instrumental load;
- intrinsic uncertainty of the measurand;
- measurement uncertainty of the influence quantities.

There is a variant of the previously described method, which is called the substitution method. After achieving the equilibrium condition for which:

$$m = f(c1, c2, \dots cn)$$

A sample of homogeneous size C_R is substituted in place of the measurand m:

$$C_R = f(c1, c2, \dots cn)$$

Thus

$$m = C_R$$

Indirect Measurement Methods

This method requires that the measurand and the other parameters involved, estimated through direct measurement methods, are linked by a mathematical model of the type:

$$m_I = f(m_{D1}, m_{D2}, \dots m_{DN})$$

Where

m_I is the measurand obtained indirectly;

m_{Di} is the directly measured quantity.

The uncertainty contributions in this case are given by:

- The uncertainties of the directly obtained quantities;
- The uncertainty of the mathematical model.

3.2.2 Estimation Of Measurement Uncertainty: deterministic and probabilistic model

The Deterministic Model

In past decades, the model adopted for uncertainty estimation was the deterministic model. It involved assigning the parameter a value band, i.e. a limited interval, symmetrical to the assigned value m0. This interval has certain characteristics:

1. the measurand has a high probability of being included in the range;

2. each element of the interval is equally valid for the purpose of representing the measurand, as the probability distribution of the assigned values is not carried out.

The relation expressing the measure m of the parameter is expressed as:

$$m = (m_0 \pm I)\, U$$

Where

I = absolute uncertainty of measurement

U = unit of measurement of m_0.

Taking the above into account, the value band assigned as a measure of the parameter will be *2I*, symmetrical to m_0.

If the value bands determined with different methods, equipment, or times have at least one element in common, then they are said to be compatible.

In order to make communication and perception of uncertainty easier, it is sometimes preferred to adopt a relative value of uncertainty I_r , defined as:

$$I_r = \frac{I}{m_0}$$

Or the relative percentage value $I_{r\%}$:

$$I_{r\%} = \frac{I}{m_0} \cdot 100$$

The Propagation Of Uncertainty

As specified above, uncertainty is determined by combining the various uncertainty contributions.

If measurements were obtained by direct measurement methods, then the various uncertainty contributions (e.g. instrumental uncertainty and measurement uncertainty) are simply added together.

In the case of indirect method measurements, the combination of uncertainties is performed in several steps.

The measurement parameter Y is linked to the other parameters X_i following the model:

$$Y = f(X_1, X_2, \dots, X_N)$$

The value band assigned as a measure of Y, has a central value y_0, determined from the central values x_{i0} of the other parameters:

$$y_0 = f(x_{10}, x_{20}, \dots, x_{N0})$$

The semi-amplitude of the y-value range, I_y, is obtained from the absolute maximum uncertainties of the other quantities I_{xi}, such as:

$$I_y = \left|\frac{\partial f}{\partial x_1}\right|_{(x_{10},\dots x_{N0})} \cdot I_{x1} + \dots + \left|\frac{\partial f}{\partial x_N}\right|_{(x_{10},\dots x_{N0})} \cdot I_{xN}$$

Solved through Taylor series development, approximated to first-order terms.

Since the deterministic model for uncertainty propagation considers the maximum value of the uncertainties I_{xi}, and sums the various uncertainty contributions in absolute value, it is clear that the main failing of this model is the overestimation of the uncertainty of the quantity y.

Applying the deterministic model for calculating uncertainty, the essential information to be provided is expressed below:

- The estimated value of the measurand and its unit of measurement;
- The value range, or interval, assigned to the measurand, in the form of absolute, relative or reduced uncertainty;
- The value, as well as the uncertainty, of the quantities determining the state of the system and their influence quantities;
- In the case of a repeated reading method, the number of readings.

Note that it is important to express the measurement uncertainty correctly, making explicit the correct number of decimal places. Generally, for uncertainties greater than 5 %, it is expressed to one decimal place, whereas for uncertainties less than 5 %, at most the number of decimals becomes two. During calculation, however, the significant numbers are all retained so as not to add further errors.

The Probabilistic Model

The European standard ISO/IEC 98-3:2008 "Uncertainty of measurement - Part 3: Guide to the expression of uncertainty in measurement", which is the current reissue of GUM:1995 within ISO/IEC, describes the model that should be used today for the calculation of measurement uncertainty, according to a more realistic estimation than the one obtained following the deterministic model.

The model described is of the probabilistic type. The quantity being measured is considered as a random variable (r.m.), to which a probability density function (p.d.f.) is associated. The estimate of the expected value of this function is the value assigned to the measurand.

Two concepts are introduced, namely:

- type uncertainty, i.e. the type deviation of the probability function from the magnitude expressing the deviations of the individual observations of the measurand from its mean value;
- systematic effect, i.e. a constant value that always influences the result in the same way. An example of this is the non-zeroing of the system.

These must be properly identified and corrected.

A significant difference with the deterministic model can be found in the assigned value range. In the probabilistic model, this is an interval whose probability of the value of the measurand lying within it is assigned. Thus the value band is called the confidence interval, while the probability is the confidence level. The confidence interval of the quantity in measure x is equal to the expanded uncertainty:

$$U(x) = k \cdot u(x)$$

Where

k = coverage factor

$u(x)$= type uncertainty

If x_0 is the estimate of the measurand, we deduce that the confidence interval will be between the following extremes:

$$x_0 - k \cdot u(x) \div x_0 + \ k \cdot u(x)$$

The regulations also establish two procedures (A and B) for assessing uncertainty contributions:

- Category A assessment of uncertainty, following an a posteriori statistical approach;
- Category B assessment of uncertainty, following a probabilistic model from a priori information, often provided by third parties. An example is the calibration certificates provided by the manufacturer.

3.2.3 Category A and Category B Uncertainty Assessment

In this case, a generic quantity X is generated from the repeated-measurement method, whose N observations (x1, x2,...xN) constitute the sample. The estimation follows several steps, described below:

1. Calculation of the mean value (or expected value) μ through the empirical mean $\bar{x}$ of the sample:

$$\bar{x} = \frac{1}{N}\sum_{k=1}^{N} x_k$$

According to the central limit theorem, the sum n of independent variables with identical distributions is a normally distributed variable. The mean can also be assumed as the sum of n identically distributed variables divided by N. By repeating this sampling, several normally distributed averages are obtained. Their probability density will be Gaussian.

2. Calculation of the empirical adjusted variance $s^2(x)$ of the sample:

$$s^2(x) = \frac{1}{N-1}\sum_{k=1}^{N}(x_k - \bar{x})^2$$

3. Calculation of the experimental standard deviation $s(x)$, i.e. the positive square root of the corrected empirical variance. It also indicates the degree of dispersion of the individual observations around the empirical mean $\bar{x}$:

$$s(x) = \sqrt{s^2(x)} = \sqrt{\frac{1}{N-1}\sum_{k=1}^{N}(x_k - \bar{x})^2}$$

4. Calculation of the variance of the mean $s^2(\bar{x})$, i.e.:

$$s^2(\bar{x}) = \frac{s^2(x)}{N}$$

5. Calculation of the experimental standard deviation of the mean $s(\bar{x})$, which expresses the degree of dispersion of different estimates of the empirical mean $(\bar{x})$ from the estimated value :

$$s(\bar{x}) = \frac{s(x)}{\sqrt{N}}$$

At the end of the process, the measurement of the quantity X, as the desired value of X is obtained, i.e. $\bar{x}$, and the (absolute) type uncertainty u(x), equal to the experimental type deviation of the mean $s(\bar{x})$.

Category B Uncertainty Assessment

Following this assessment procedure, uncertainty is obtained from information provided by third parties, such as calibration diagrams and technical specifications of instruments provided by manufacturers. It is necessary to make this uncertainty explicit as a type uncertainty. However, there is no unique procedure to achieve this, such as the statistical procedure adopted by the Category A evaluation. Below are possible scenarios and the operations to be performed:

- The expanded uncertainty U(x) and coverage factor (k) are known. Therefore, using the inverse formula, it will be sufficient to divide the expanded uncertainty by the coverage factor to obtain the typical uncertainty u(x).
- The expanded uncertainty U(x) and the confidence level are known. Assuming a Gaussian dispersion probability, for each confidence level, expressed as a percentage, the uncertainty is obtained by dividing the

expanded uncertainty by the coverage factor corresponding to that level. Typically, the confidence levels and corresponding coverage factors considered are:

68,3% → k=1

95,4% → k=2

99,7% → k=3

If the value range of amplitude 2I is known and the dispersion is uniform, the uncertainty is obtained as:

$$u(x) = \frac{I}{\sqrt{3}}$$

3.2.4 Combined Uncertainty and Expanded Uncertainty

This leads to the formulation and calculation of the combined uncertainty $u_c(x)$ and the expanded uncertainty $U(x)$.

The typical combined uncertainty is obtained from the contribution of the previously calculated uncertainties and is expressed as follows:

$$u_c(x) = \sqrt{u_A^2(x) + u_B^2(x) + u_{BN}^2(x)}$$

Where

$u_A^2(x)$= uncertainty evaluated according to procedure type A, typically the experimental mean deviation $s(\bar{x})$;

$u_B^2(x)$= uncertainty evaluated according to procedure type B, usually the accuracy stated by the manufacturer;

$u_{BN}^2(x)$= additional contributions of uncertainty evaluated according to the Type B procedure, such as environmental conditions that may affect the system.

The last step consisting in multiply the combined uncertainty $u_c(x)$ for the coverage factor (k). So far, the Expanded Uncertainty U(x) is obtained.

At the end of the process, the uncertainty will be equal to:

$$y_0 = \bar{x} \pm U(x)$$

3.3 CALIBRATION PROCESS

Calibration is a widely used term in the field of metrology. It is defined as a process of characterizing a measuring instrument with the aim of defining its metrological characteristics. This term is often mistakenly confused with the term “adjustment”, which, on the other hand, indicates the operation aimed at making the measuring instrument more accurate. It is in fact performed every time the user uses the instrument, while calibration is usually carried out once a year by a certified institution, in accordance with ISO/IEC 17025. Adjustment, therefore, adjusts the instrumental full scale, i.e. the maximum value that can be measured by a given measuring instrument.

Calibration Purposes

The purposes of a calibration process can be classified as follows:

- Definition of instrument characteristics

  In other words, the use of calibration to define the metrological characteristics of the instrument (accuracy, repeatability, reproducibility, linearity). In this way, it is possible to define the functionality of the instrument, verify its correspondence to certain requirements, and obtain information on the variation of the value of the quantity.

- Determining the accuracy of the instrument

  From the analysis of the metrological characteristics, it is possible to obtain the value of the measurement uncertainty. It is mainly applied when the calibrator, i.e. the object of calibration, is a reference instrument and, therefore, the accuracy of the instrument with respect to its nominal value is to be defined.

- Determining the trans-characteristics of the instrument

  This is applied when the measuring instrument is a transducer, i.e. a device that transforms the quantity read into a signal, generically of an electrical nature, which is easier to read and process by special indicators. Knowledge of the quantity/signal ratio determines the correct reading of the measured quantity.

Calibration methodologies

The calibration process may be carried out through three methods:

1. Calibration by comparison

The accuracy of the calibrator is calculated by analyzing the difference between the measurement of the same quantity made by the calibrator and the one obtained by the reference instrument.

2. Calibration by substitution

The accuracy of the calibrator is obtained from the difference between the reading of the sample, which is or generates the quantity being measured by the calibrator, and the measurement results of the calibrator.

3. Direct calibration

This is usually used for the calibration of reference instruments. In this case, the sample measures the quantity directly generated by the calibrator. The accuracy of the calibrator, therefore, results from the comparison between its nominal value and the measurement of the sample.

3.3.1 Calibration Relation

Calibration relation is the estimation of the unknown measurand M through the instrument indication I. There are various forms for expressing the calibration relation:

- Calibration diagram, i.e. the graphical form; it takes uncertainty contributions into account;
- Calibration function, i.e. the analytical form;
- Calibration table, i.e. the tabular form.

This relationship may be estimated resorting to a calibration process.

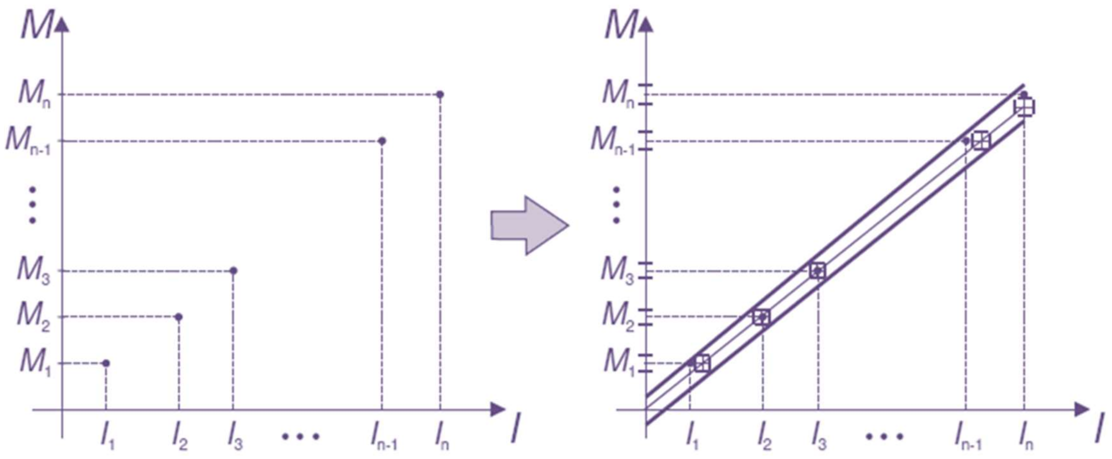


Figure 57 Calibration relation of a measuring instrument. Personal elaboration from (Carullo A., 2022)

The interpolation of the values and indications generates a series of points, used to plot a calibration curve, that best matches this series.

Calibration Function Diagram

It is possible to obtain the calibration function diagram, i.e. the relationship that assigns for each value of the output quantity supplied by a reference instrument (L0), placed on the x-axis, a reasonable range of values attributable to the measurand (ΔM).

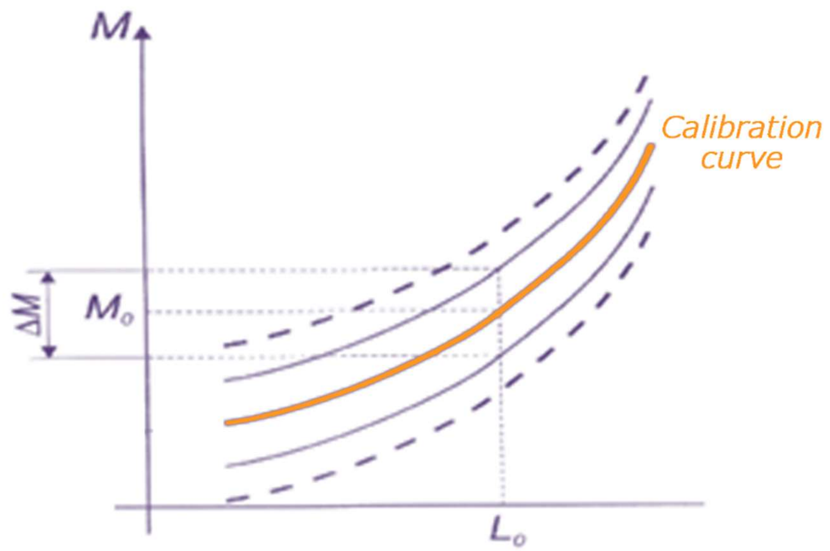


Figure 58 Calibration Function Diagram. Personal elaboration from Carullo A. (2022).

Looking at the graph, it is possible to obtain two types of information:

- **Calibration curve**, i.e. the unique relationship between each value of the output variable and the midpoint of the measurand value range. If there is a proportionality relationship between output and measurand, the curve takes the form of a straight line. In this case, the proportionality is expressed by a coefficient called calibration constant.
- **Calibration uncertainty**, or, graphically, the width of the value band. It can be expressed in different ways
    - in absolute value with the same unit of measurement as the measurand (absolute uncertainty)
    - in relative value by relating it to the value of the midpoint of the band with which it is associated (relative uncertainty)
    - in reduced value by relating it to a certain value of the measuring range, usually the upper limit (reduced uncertainty)

Certain characteristics can be derived from the calibration function, i.e. the analytical form to express the calibration relation:

- Sensitivity: this is given as the inverse of the slope of the calibration curve, or the reciprocal of the angular coefficient of the tangent to the calibration curve at the point under consideration, and may refer to any point on the curve. Where the curve is a straight line, the sensitivity is expressed as the inverse of the calibration constant. The unit of measurement is expressed as the ratio of that of the measurand to that of the output variable.
- Linearity: Indicates the deviation of the calibration curve from the straight line. It is calculated by analyzing the maximum value of the deviation of the individual points of the curve from a specifically defined reference line.
- Resolution: indicates the minimum change in the measurand that causes a noticeable change in the indication of a measuring instrument.
- Discrimination Threshold: means the maximum change in the value of the measurand that does not cause an appreciable change in the indication of a measuring instrument.

- Repeatability: indicates the ability of a measuring instrument to obtain similar indications in the case of repeated readings of the same quantity, carried out under the same conditions.
- Stability: indicates the ability of the device to maintain its metrological characteristics unchanged over a period of time.
- Drift: indicates the variation in the indication of a measuring device, not caused by changes in the measured quantity.
- Hysteresis: when the values of the measurand are varied in an increasing or decreasing manner, the instrument may tend to give different readings corresponding to the same measurand. Hysteresis is defined as the maximum variation of these values.

3.3.2 Calibration in ideal case and real case

If one were in an ideal case, the process defining a calibration relation could be described as one-input/one-output. That is, for each application of an unknown measurand M, the measuring instrument corresponds to an indication I. A calibration relation is thereby defined, which enables the evaluation of the measurand $\hat{M}$.

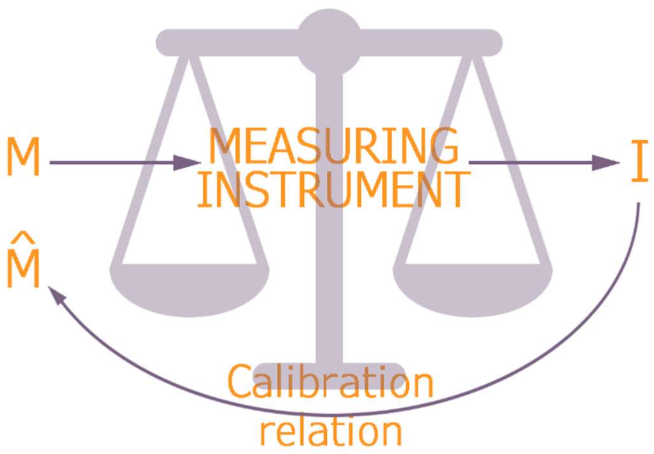


Figure 59 Calibration relation in the ideal case. Personal elaboration from (Carullo A., 2022)

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In the real case, however, there is no single input, but various quantities of influence, resulting in a many-inputs/one-output type of calibration relation.

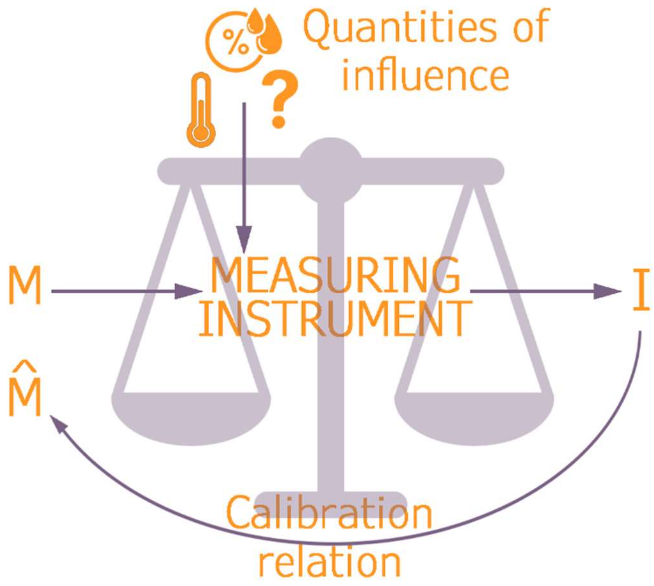


Figure 60 Calibration relation in the real case. Personal elaboration from (Carullo A., 2022)

Previously, uncertainties have been neglected. It must be considered in the real case that the indications I depend both on the measured value M, but also on influences that affect the calibration relationship. Examples are temperature and humidity.

To simplify the difficulty of taking these influences into account, the calibration process is streamlined by assigning different calibration relations to different fields of use, i.e. ranges of influence in which this relation is valid (see Fig. 63). Usually, the calibration function, in this case, is expressed as:

$M_0=I_0$

$\delta M=\pm(A*\text{Reading} + B*\text{Range})$

In which A and B are parameters that assume different values depending on the field of use.

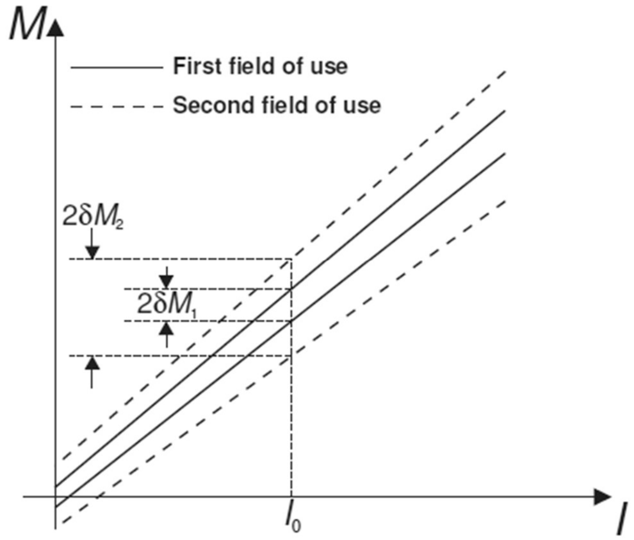


Figure 61 Calibration diagram of a measuring instrument and fields of use. Taken from (Carullo A., 2022)

3.3.3 Verification of Calibration

It should be remembered that one of the most influential quantities is time (time drift). In fact, manufacturers tend to specify the calibration interval, i.e. the period of validity of the calibration performed. After this interval, the calibration relationship may no longer be valid (e.i. 90 days, 1 year and 2 years).

To verify the validity of the calibration outside this interval, it is necessary to perform a verification of calibration. This is also done if a particular event has changed the calibration relationship. The process is performed:

1. Applying a series of known values to the input of the instrument to be verified;
2. Verifying that the indications recorded by the instrument respect the calibration relation;
3. By analysing the two possible situations of input values:
    a. PASS: $S_i=|M_i-I_i| < \delta I_i$, the calibration relation is confirmed;
    b. FAIL: $S_i> \delta I_i$, calibration relation is not valid.

Where

M_i= applied value (input)

I_i= Indication of the instrument (output)

δI_i = max admitted error

S_i = measurement error

In the case of a fail situation, it is necessary to carry out some operations on the instrument for |Mi-Ii| < dIi, called adjustment.

Considering that an uncertainty $u(M_i)$ is associated with the reference value M_i in the real case, two intermediate conditions can occur in the pass and fail verification, analyzed above, namely:

FALS FAIL: $S_i > \delta I_i$, even if the instrument is conform to its calibration relation;

FALS PASS: $S_i < \delta I_i$ even if calibration relation is no more valid.

By following a probabilistic approach, which differs from the old deterministic approach, in which one took the worst-case scenario and thus risked overestimating the error, one can estimate the probability of a false event.

The Test Uncertainty Ratio (TUR) is often used to assess the probability of a false event, as well as the adequacy of a reference instrument:

$$TUR_i = \frac{u(I_i)}{u(M_i)}$$

Where

$u(I_i)$ is the standard uncertainty in the instrument at the generic test-point M_i

It follows from the relationship that the higher the Test Uncertainty Ratio, thus if $u(M_i) \ll u(I_i)$, the lower the probability of a false event.

Some laboratories impose a minimum value of TUR=4.

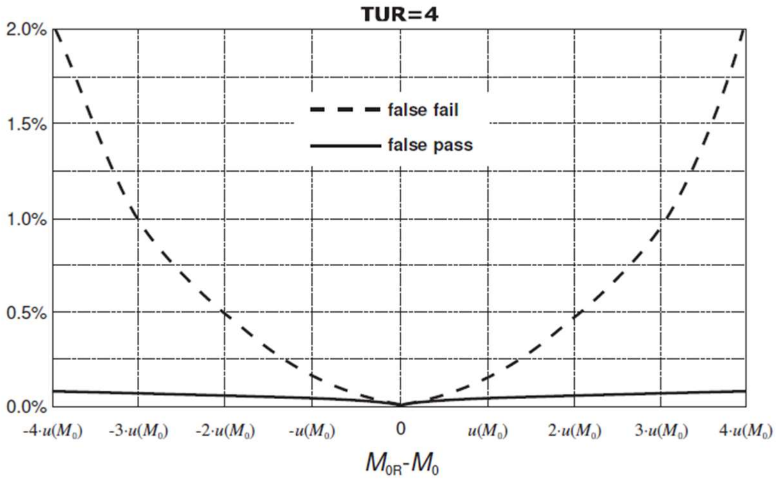


Figure 62 Probability of fals fail/pass with TUR=4. Taken from (Carullo A., 2022)

Generally when the possibility of a false result is high, e.g. when TUR>3, the instrument must follow an adjustment procedure, i.e. the set of actions performed on the instrument so that the prescribed indications correspond to the known quantities applied. The values are applied differently in the case of an analogue rather than a digital device. In the former case, variable components are regulated, in the latter the calibration constant is changed using software procedures.

3.3.4 Statement of Conformity

In order to assess the conformity of a parameter to certain conditions, the x_0 measurement data must be compared with a tolerance interval, delimited by an Upper Limit (UL) and a Lower Limit (LL). If these are exceeded, one may find oneself in a Fail situation, while if the measurement is within the LL-UL range, one may find oneself in a Pass situation.

Since, however, the measurement is always characterized by its own uncertainty u(x), a process must be followed to take this into account.

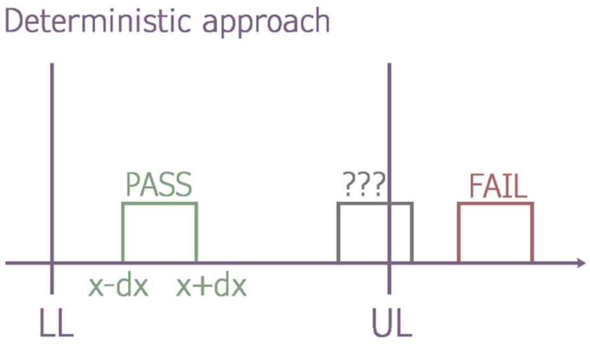


Figure 63 Statement of conformity in the deterministic approach. Personal elaboration from (Carullo A., 2022)

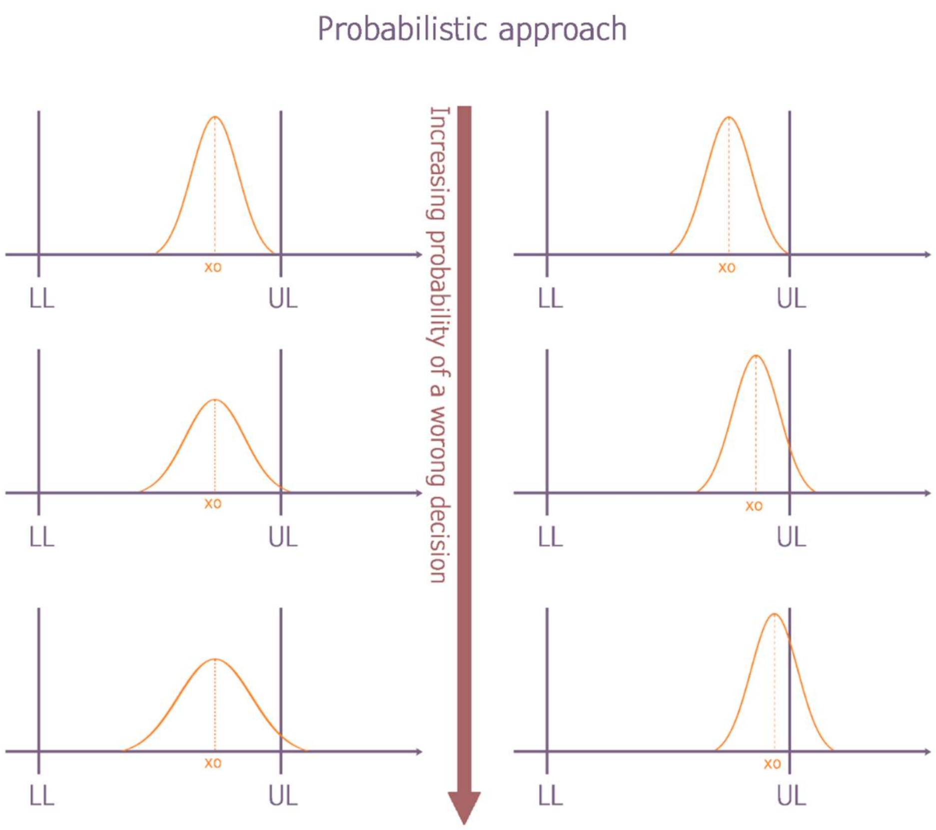


Figure 64 Statement of conformity in the probabilistic approach. Personal elaboration from (Carullo A., 2022)

There are two methods:

1. Indirect, where the measurement uncertainty is already assigned, U(x) < U_{max} (x);

2. Direct, in which the concept of 'guard band' and 'acceptance limit' is introduced.

It must first be specified that the 'tolerance limit' (TL) refers to the permissible values of a certain parameter, while the 'acceptance limit' (AL) refers to the permissible measured values. The risk of not accepting a non-compliant value is limited by imposing that AL < TL. The difference between the two limits TL and AL is called the guard band.

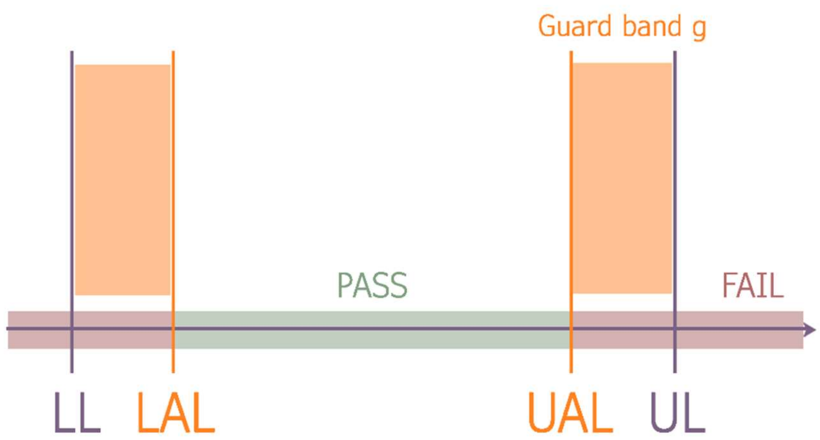


Figure 65 Guard band and acceptance limits. Personal elaboration from (Carullo A., 2022)

A minimum probability of false acceptance (PFA_{min}) can be estimated for each value of the ratio Cm:

$$Cm = \frac{UL - LL}{2\,U(x)}$$

Where

UL is the upper limit

LL is the lower limit

$U(x)$ is the expanded uncertainty, or the guard band $g = kw * u(x)$

The guard-band factor kw, depends on the chosen confidence interval. It can be calculated by applying the inverse of the cumulative standard normal distribution of 1-PFA.

For a 95% confidence interval, the coefficient is assumed to be 1.96, while for a 99% confidence interval, it rises to 2.576.

It is possible to calculate the upper acceptance limit UAL by subtracting the expanded uncertainty from the upper limit UL, while the lower acceptance limit LAL results from adding the expanded uncertainty to the lower limit LL:

$$UAL = UL - k_w * u(x)$$

$$LAL = LL + k_w * u(x)$$

3.4 CALIBRATION NORMATIVE REFERENCE

In order to carry out the calibration process correctly, it was necessary to research current standards.

In the legislative field, reference is mainly made to three standards relating to calibration and testing laboratories:

- ISO 10012 – Measurement management systems – Requirements for measurement processes and measuring equipment. It provides guidance for the management of the measurement process as well as for the metrological confirmation of measuring instruments.

- ISO/IEC 17025 – General requirements for the competence of testing and calibration laboratories. It defines the technical and management requirements to be met by the calibration laboratory, as well as the structure of the required documentation.

- ISO/IEC Guide 98-3:2008-Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995). It sets out the basic rules for evaluating and expressing measurement uncertainties.

Specifically, for each of the four domains constituting the indoor environment, its own regulations were found and analysed. These define the criteria and conditions to be met for the calibration procedure to be properly carried out.

Tab. Shows schematically each monitored parameter and the standard to which it refers.

Thermal	Visual	Acoustic	Air Quality
Standard Test Method For Calibration Of Thermocouples By Comparison Techniques- E220-19.	BS 667:2005- Illuminance meters- Requirements and test methods. BS ISO/CIE 19476:2014- Characterization of the Performance of Illuminance Meters and Luminance Meters.	BS EN 61094-8:2012 Measurement Microphones – Part 8: Methods for determining the free-field sensitivity of working standard microphones by comparison.	BS EN ISO 14956: 2002 Air quality. Evaluation of the suitability of a measurement procedure by comparison with a required measurement uncertainty. BS EN ISO 9169:2006 Air quality — Definition and determination of performance characteristics of an automatic measuring system.

3.4.1 Sensors for thermal parameters

The purpose of the "Standard Test Method For Calibration Of Thermocouples By Comparison Techniques (E220 – 19)" is to describe the principles, equipment and procedures for calibrating unused thermocouples by comparison with a reference thermometer. These can be either a reference instrument or a batch of purchased and assembled thermocouples, as in the case of this project. Although each type of thermocouple has its own temperature range, the overall maximum permissible range for this procedure is from -195°C to 1700°C.

The standard explains that calibra"Ion'by comparison is performed by measuring the electromotive force of the thermocouple in an isothermal environment or medium, while simultaneously measuring the temperature of the latter with a sufficiently accurate reference thermometer.

The choice of medium and the conditions under which the calibration by comparison is performed is crucial, as its success depends heavily on keeping the instruments at the same temperature.

After defining the temperature range to be covered and the desired calibration uncertainty, one can proceed with the choice of apparatus. The standard suggests various possibilities:

- Comparison Baths and Furnaces: the thermocouple and the reference thermometer are brought to the same temperature, within a temperature-controlled comparison medium.
- Liquid Baths: This procedure is carried out in a temperature range between -150°C and 630°C. It involves immersing the instrument to be calibrated in a liquid bath (water or oils) that keeps the temperature constant and uniform.
- Fluidized Powder Baths: This procedure is carried out in a temperature range between -70°C and 980°C. In this case, the comparison is made with a gas-fluidized bath of aluminum oxide or similar powder. A second reference thermometer is also used.
- Tube Furnaces: An electrically heated tube furnace is used, with temperatures up to 620°C.
- Isothermal Blocks: The temperature difference between the thermocouples and the reference thermometer is assessed using a block of material with high thermal conductivity, which reduces temperature variations.

The standard also specifies the types of reference thermometers that can be used, remembering that their choice depends on the temperature range to be covered:

- Platinum Resistance Thermometers (highest accuracy; -196 °C to 962 °C; calibration uncertainties as low as 0.001 °C);
- Thermistors (range -40 °C to 150 °C; uncertainty of 0.001 to 0.01 °C.);
- Liquid-in-Glass Thermometers (-80 °C to 400 °C);
- Types R and S Thermocouples (from 960 °C to 1200 °C);
- Type B Thermocouples (above 1200 °C);
- Type T Thermocouples (range of -195 °C to 370 °C;
- Gold versus Platinum Thermocouples (0 °C to 1000 °C; uncertainties of approximately 0.01 °C to 0.02 °C).

The calibration procedure is also described:

After determining the calibration points, the electromotive force of the thermocouple at each point is measured and the temperature at each is measured with the reference thermometer. A minimum of 3 consecutive readings is required. It is essential that steady-state conditions are reached before acquiring the data.

The calibration process ends with interpolation between the calibration points. Taking a reference table from the standard, the difference DE=Er-E must be calculated, where Er is the reference value from the table and E is that of the thermocouple at the calibration point. A least squares fit of the resulting data is often chosen as the methodology. Once the DE function is obtained, as a function of temperature, each value of E is corrected by adding an amount DE obtained from the curve. Alternatively, the DE function can be subtracted from the thermocouple reference function to create a single function. Finally, the standard points out that these functions are only valid within the calibration interval.

3.4.2 Sensors for visual parameters

In Visual calibration field two main standards have been taken into account.

The first one is “BS 667:2005-Illuminance meters-Requirements and test methods”.

The purpose of the standard is to define the performance requirements for illuminance meters, when they are used for the measurement of photopic illuminance, in applications other than luminaire measurement. It distinguishes two types of instruments:

- Type L (laboratory instruments), from which the most accurate results can be obtained. However, they are not suitable for field measurements.
- Type F (field instruments), they are easier and more versatile to use, in fact they are suitable for use in the field or in working environments. They present a disadvantage, i.e. lower accuracy.

Defining the quantities, specifically in Section 7 and Annex B, deals with calibration. The ideal ambient temperature is 20°C ± 2°C unless specifically stated by the manufacturer. When measuring high illuminance levels, care must be taken to minimize the effects of overheating and the resulting temperature rise. Calibration can be performed by using a reference lamp or a reference meter. The basic principle is to calibrate the instrument by comparison with a second meter when they are exposed to the same level of illuminance generated by the same light source.

The procedure consists of:

- Position the head of the photometer perfectly so that the illuminance strikes its geometric center normally.
- Vary the distance of the lamp filament to achieve adequate illuminance values; at least one value per measurement interval.
- Record the illuminance value given by the meter.
- After replacing the head of the reference photometer with that of the instrument to be calibrated, repeat the procedure.

The standard suggests covering the photometer head between measurements and exposing it for a sufficiently long time so that the measurement obtained is stable.

In paragraph C9, however, the standard indicates how to determine the spectral correction factor. Correction of the meter reading may be necessary. It depends on the difference between the spectral power distribution of the reference instrument ($S_r(\lambda)$) and the light source ($S_t(\lambda)$), and the relative spectral responsivity of the photometer head ($s(\lambda)$).

The corrected illumination factor (E) is obtained as:

$E = F x E_t$

Where

E_t is the value of the test source illuminance measured.

F is the spectral correction factor.

The standard explicit how to calculate F:

$$F = \frac{\sum_{380}^{780} S_t\,(\lambda) V(\lambda) \times \sum_{380}^{780} S_r\,(\lambda) s(\lambda)}{\sum_{380}^{780} S_t\,(\lambda) s(\lambda) \times \sum_{380}^{780} S_r\,(\lambda) V(\lambda)}$$

Where

s(λ) is the relative spectral responsivity of the illuminance meter;

S_r(λ) is the spectral power distribution of the reference source used to calibrate the illuminance meter;

S_t(λ) is the spectral power distribution of the source to be measured;

V(λ) is the CIE spectral luminous efficiency function of the meter.

The second standard is "BS ISO/CIE 19476:2014- Characterization of the Performance of Illuminance Meters and Luminance Meters".

The purpose of the standard is to define quantity indices and their measurement procedures as well as standard calibration conditions for luminance and illuminance meters.

Section 4, specifically, analyses the calibration conditions. The photometer must be calibrated using as a reference an instrument whose calibration is traceable to the International System of Units (SI). Ideal calibration conditions include

- an ambient temperature of 25°C, with a non-polarized incandescent lamp with a color temperature of 856K.
- Thermal stabilization of the photometer in the room, for at least one hour before the start of calibration.

- The receptor of the photometer must be uniformly and fully illuminated.

The standard requires a recalibration of the instrument:

- After the validity interval stated by the manufacturer, or
- At the latest after 2 years, or
- If it is considered that certain performances have changed.

During calibration, the illuminance meter must receive incident light normal to the reference plane where it is positioned. Please note that the reference instrument used for comparison must be placed in exactly the same location and with the same orientation.

The standard defines that the photometric calibration uncertainty is due not only to uncertainties generated during the process but also to certified values of the reference standard. The latter are derived from the calibration certificate of the standard. The former, on the other hand, can result from multiple factors:

- uncertainty related to the value of the standard of work;
- the aging of the standard;
- the spectral mismatch with respect to the V(λ) function for the measured source
- uncertainties related to the electrical measured values of both the standard and the device being tested
- uncertainties related to geometric arrangements (the position of the actual reference planes in relation to each other and angular alignments).
- stray light;
- ambient temperature variation;
- photometer temperature variation from heating due to radiance of the source; and
- finite resolution of the display.

The standard states a way to correct the reading in order to decrease the uncertainty. It is necessary to be able to quantify measurement parameters or other contributions of uncertainty, as well as whether the photometric signal change resulting from the parameter change is known (e.g. through a sensitivity coefficient).

3.4.3 Sensors for air quality parameters

The standard BS EN ISO 14956: 2002 Air quality. Evaluation of the suitability of a measurement procedure by comparison with a required measurement uncertainty, focuses on procedures to be adopted in the air quality field. Its purpose is to:

- Estimate the measurement uncertainty from actual or stated values and evaluate its compliance with the metrological characteristics required by the user at a given temperature.
- Assess whether the chosen measurement method is applicable.
- Define requirements for the dynamic behavior of instruments.

To do so, the standard briefly and pointedly explains the procedure to be followed in calculating the uncertainty, referring to the GUM:1995 standard. It then summarizes the steps through a table (Fig.70) whose ultimate goal is to determine whether or not the procedure is applicable.

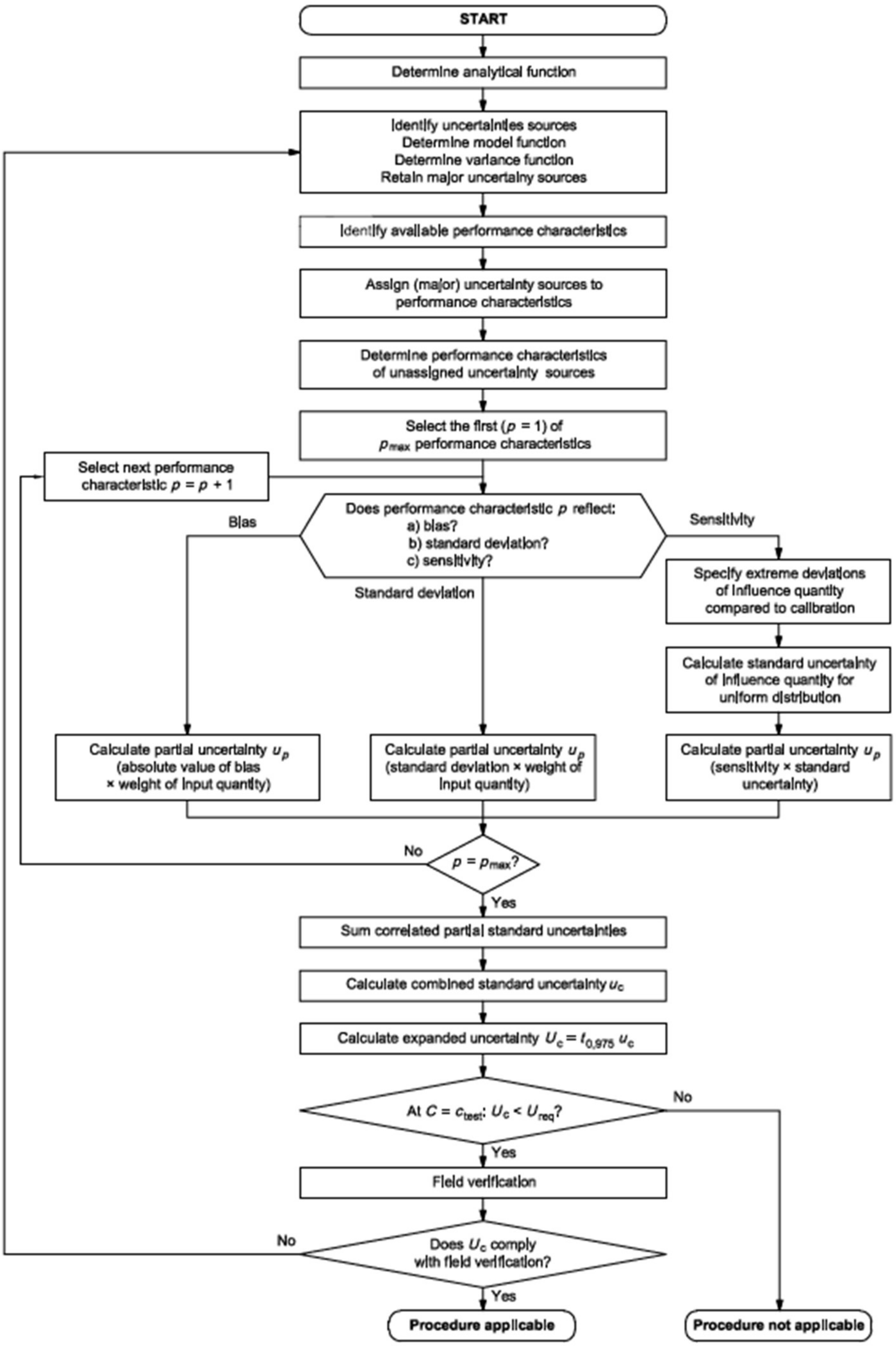


Figure 66 Flowchart for assessing fitness for use of the measurement procedure (taken from BN ES ISO 14956:2002)

BS EN ISO 9169:2006 Air quality — Definition and determination of performance characteristics of an automatic measuring system is the second standard in air quality field, more focused on the calibration process. After defining the main specific terms, the requirements and respective test conditions to be possessed are specified, namely:

- the performance to be determined;

- the measurement range in which the tested system operates;
- the expected field operating time;
- the number of systems to be tested and their signal.

Next, the standard specifies minimum requirements for measuring instruments and measurements:

- at least 4 reference measurements, and as many as 4 equally measured values in the measurement interval;
- a time equal to at least 4 times the response time must be waited before starting measurements;
- the average response must be calculated on a sample of at least 30 data, for continuous systems.
- The reference data must have an expanded uncertainty, in the 95 % confidence interval, less than 10 % of the gas concentration.
- To test the repeatability of the instrument, at least 10 consecutive measurements must be taken, during which the gas concentration may vary by no more than 25 %.

3.4.4 Sensors for acoustic parameters

After defining the specific nomenclature, the standard "BN EN 61094-8:2012. Measurement Microphones – Part 8: Methods for determining the free-field sensitivity of working standard microphones by comparison" dictates the reference environmental conditions under which the calibration should be performed. They include:

- Air temperature 23°C
- Atmospheric pressure 101.325 kPa
- Relative humidity 50%

Next, the standard describes the general principle behind free-field comparison calibration.

The calibrated reference microphone and the microphone to be calibrated are exposed to the same sound pressure, either simultaneously or sequentially, and under the same environmental conditions as above. In this case, the ratio of their open-circuit output voltages corresponds to the ratio of their free-field sensitivities. It can therefore be deduced from the free-field sensitivity of the reference microphone, which is known, that both the modulus and phase of the tested microphon''s free-field sensitivity can be derived.

If the two microphones are to be exposed to the same sound power sequentially, its signal as well as the ambient conditions must remain the same. For example, an additional microphone can be introduced to monitor.

If, on the other hand, the microphones are exposed simultaneously, no care is taken to ensure that the conditions remain unchanged, but rather the identification of several points in the sound field characterized by the same sound pressure is required. For example, one can configure the test space and the sound source in such a way that the sound field is symmetrical. It is essential that the two microphones do not disturb each other.

Among the general requirements imposed by the standard, the space where the test is performed must limit as far as possible the influences caused by changing weather conditions, air currents, temperature gradients, and electromagnetic interference, as well as background noise.

Free-field measurements can generally be carried out using two approaches:

1. Operating in an environment that prevents the reflection of sound from the source, and thus recreating a free field. Usually the space can be an anechoic chamber, whose walls are covered with sound-absorbing material, or a hemianechoic chamber, when one of its walls is made of reflecting material.
2. remove the signal content corresponding to the sound received indirectly, using signal processing methods, and thus simulate a free-field environment.

In the case of complex measurements, the methods can be combined.

The reference microphone used should be a standard laboratory microphone (LS) or a standard working microphone (WS) with a known free-field sensitivity and uncertainty corresponding to the desired calibration frequency range.

3.5 CALIBRATION OF LOW COST SENSORS IN LITERATURE

In the preliminary stage of research, it was necessary to consult relevant material in the literature in order to:

- Trace the reference standards used by other researchers regarding the calibration of various sensors;
- Define the protocols and conditions under which to perform the various sensor calibrations for PROMET&O, as well as for theultisensoryr itself;
- Compare the results obtained with those found in the literature.

Parallel searches were then conducted, for each parameter monitored, through the Scopus database. The keywords adopted included the fixed use of“"low-cost senso”" &“"calibration”" differentiating each search by the use of“"environmental parameter nam”" &“"environmental comfort domain”" In addition, a search was also conducted covering any multi-sensor calibration.

- Air temperature“"low-cost senso”" & “"calibratio”" & “"temperatur”" & “"thermal comfor”"
- Relative humidity“"low-cost senso”" & “"calibratio”" & “"relative humidit”" & “"thermal comfor”"
- Illuminance“"low-cost senso”" & “"calibratio”" & “"illuminanc”" & “"visual comfor”"
- Sound pressure level“"low-cost senso”" & “"calibratio”" & “"MEM”" & “"microphone”"
- CO_2“"low-cost senso”" & “"calibratio”" & “"carbon dioxid”" & “"indoor air qualit”"
- CO 4“"low-cost senso”" & “"calibratio”" & “"carbon monoxid”" & “"indoor air qualit”"
- PM“"low-cost senso”" & “"calibratio”" & “"particulate matte”" & “"indoor air qualit”"

- NO_2“"low-cost senso”" & “"calibratio”" & “"nitrogen dioxid”" & “"indoor air qualit”"
- TVOC“"low-cost senso”" & “"calibratio”" & “"TVO”" & “"indoor air qualit”"
- Multisensor“"devic”" & “"calibratio”" & “"indoor environmental qualit”"

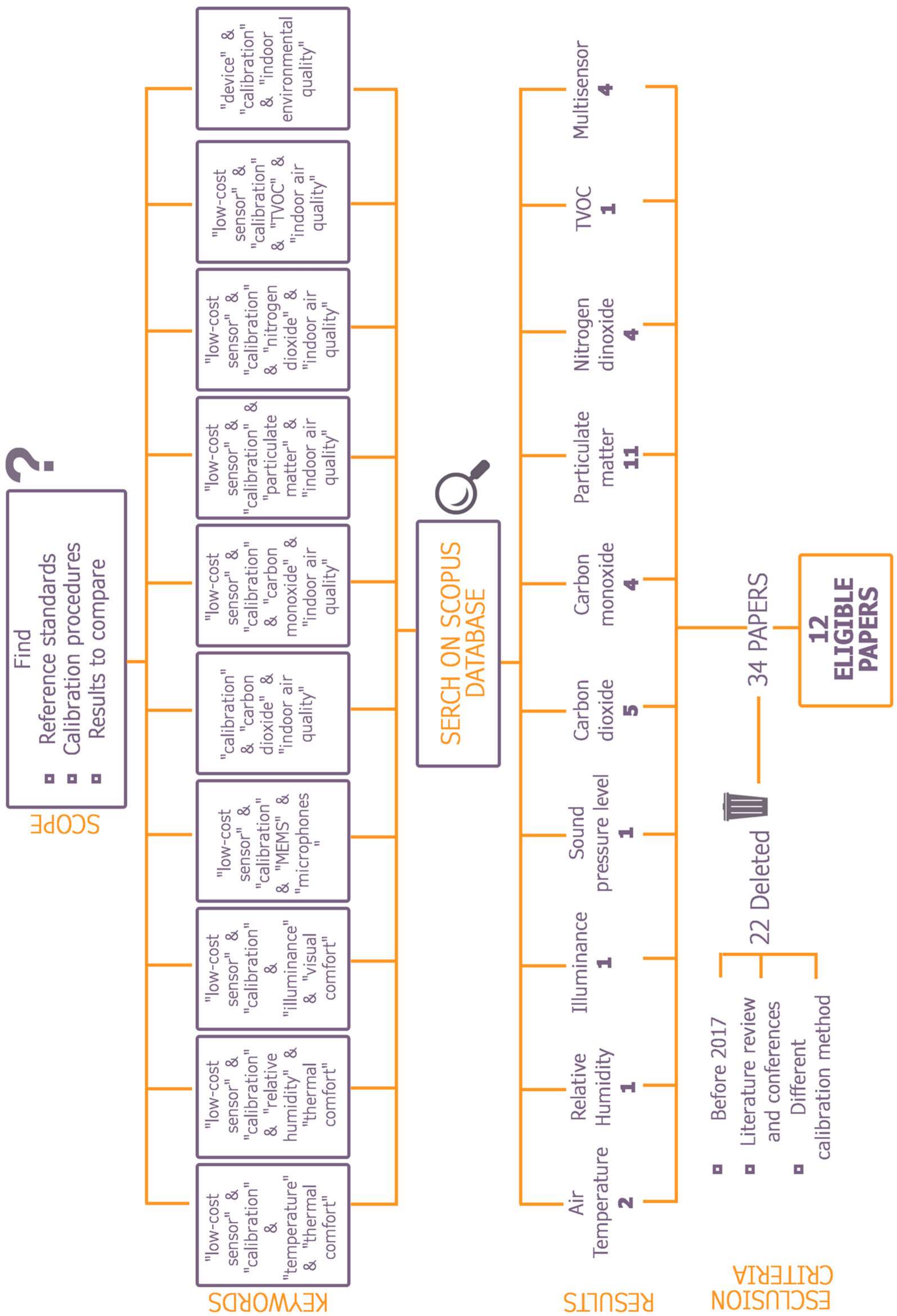
The inclusion criteria were:

- Papers published in scientific journals within the last 5 years;
- The calibration process described must be by comparison.

The search yielded a total of 34 results, broken down into:

- Air temperature 2 results
- Relative humidity 1 result
- Illuminance 1 result
- Sound pressure level 1 result
- CO_2 5 results
- CO 4 results
- PM 11 results
- NO_2 4 results
- TVOC 1 result
- Multisensor 4 results
- Table 41 below shows the keywords associated with the searches for each parameter, as well as the number of results obtained.
- In the next step, results other than scientific articles, such as conference papers or literature reviews, were first excluded, then the amount of homologous papers in the various results, and finally the results prior to 2017. Thus, from the initial 34 results, there were 14 results.
- Subsequently, through the reading of the abstract, papers in which the calibration was done by different methodologies than the comparison method were excluded.
- From the article readings, some bibliographic sources were consulted, reaching a total of eligible papers of 12. The overall results are show in Tab 42.

Table 40 Literature review: scope, keywords, exclusion criteria, eligible papers



Comparing the chosen papers, some peculiarities emerged:

- Research topic mainly focused on the area of indoor air quality. In 100% of the papers, the parameters monitored by the sensors in calibration, concern IAQ. Specifically, in 9 out of 12 papers the sensor monitors the indoor concentration of carbon dioxide, and as many as 6 papers monitor particulate matter. Volatile organic compounds (TVOCs) are monitored in 5 papers, formaldehyde in 2 papers, and nitrogen dioxide (NO_2) as well as nitrogen (O_3) in only one.

  Thermal aspects, i.e., temperature and relative humidity, are also covered in 75% of the papers. Acoustic and light parameters are covered in only one out of 12 papers.
- Calibration procedure in a controlled environment.

  7 out of 12 papers perform a procedure, first of verification then calibration of the sensors, under controlled conditions and meeting their own reference standards. They, in addition, differ according to their country. For example, Parkinson et al.(Parkinson et al., 2019b) determined the calibration range, according to field measurements stored in the NABERS (National Australian Built Environment Rating System) Indoor Environment databases.

  Tending to recreate controlled environmental conditions, the researchers used the climate chamber as an instrument, varying its parameters according to calibration steps. For example, those imposed by Entradas Silva et al. included: 4 calibration points for the temperature sensor, in the range from 5 to 35 °C, with a step of 10°C; 6 calibration points for the relative humidity sensor, in the range from 30 to 90%, with a step of 10%. The research conducted by Pereira et al. Provides for 4 thermal calibration points (10-15-25-35 °C), 6 hygrometric calibration points (50-60-70-80-90-95%), for CO_2 concentration, on the other hand, 6 calibration points (400 700 1000 1500 2000 2500 ppm) and for each of them the values were compared by varying the temperature value in the range between 15 °C and 25 °C and the relative humidity value in the range 50%-90%.

As an alternative to using the climatic chamber, with regard to the relative humidity sensor, Martín-Garín et al.(Martín-Garín et al., 2018) proposed the use of the saturated aqueous solutions method, according to the standard“"ASTM, 104-85, Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions”" This procedure is based on the use of air-tight vessels in which the aqueous solution is introduced to achieve a hygrothermal equilibrium within the enclosure. The different degrees of humidity are obtained by different aqueous solutions of saturated salts at a constant temperature (23 °C ± 0.5 °C). The relative humidity balance is performed at the following points: LiCl 11.30%, MgCl 2 32.89, Mg (NO_3) 2 53.30%, KCl 84.64%.

3 papers, on the other hand, monitor the sensors only under uncontrolled conditions, i.e., real-world scenarios. Jiang et al. (Jiang et al., 2021) They propose displaying particulate matter sensors on a 6x5x3m table inside the Shanghai Environmental Monitoring Center. Tryner et al. (Tryner et al., 2021b), on the other hand, test, first the individual PM, CO_2, CO, NO_2, O_3 and TVOC sensors, then all together inside the Home Health Boxes (Fig.71), inside a kitchen (4.3 x 5.1m) normally occupied in Fort Collins, Colorado.

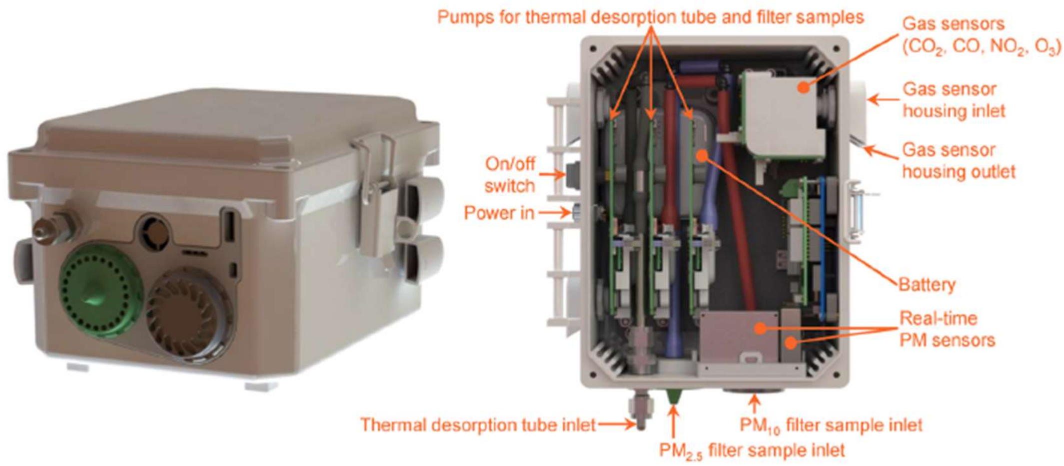


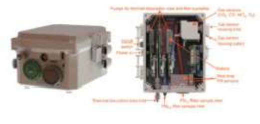
Figure 67 Home Health Box. Taken from (Tryner et al., 2021)

Chojer et al. (Chojer et al., 2022) finally test the school scenario by monitoring sensors in 4 rooms of a nursery and primary school.

- The sensor readings differ considerably from those of the reference instruments, before calibration. For Zheng et al. (Zheng et al., 2022), for example, the mean square deviation of temperature sensor readings reaches 1.7°C, against a manufacturer-guaranteed uncertainty of ±1°C, while that of the RH sensor reaches 11%, against a manufacturer-guaranteed uncertainty of ±5%. The research conducted by Pereira et al. examines the average variation between the sensor readings and those of the reference instrument. A minimum variation of -45.2% and a maximum of 44.4% was demonstrated for relative humidity measurements. For the temperature sensor it varied between -10.9% and 7.7%, while for the CO_2 sensor it ranged between -5.5% and 17%. The results of the research conducted by Tryner et al. (Tryner et al., 2021b) also show a high mean absolute error (measured value - reference value). Specifically, it holds:
  46% for CO_2, 57% for CO, 63% for NO_2, 175% for O_3.
- The most widely adopted calibration method is linear regression.
- The CO_2 sensor appears to be affected by temperature and relative humidity (Mylonas et al., 2019; Pereira & Ramos, 2022).
- Loss of accuracy due to time. In the work of Pereira et al. (Pereira & Ramos, 2022) the test lasted 24 months, after which, an increase in uncertainty was evidenced.

Table 41 Presentation of the results

#	TITLE	AUTHOR	YEAR	PROTOTYPE	SENSORS SPECIFICATIONS	PARAMETERS	CALIBRATION RANGE	REFERENCE INSTRUMENT	TYPE OF ERROR		THERMAL	LIGHTING	IAQ	ACOUSTIC	SETTING	LOCATION OF THE CALIBRATION	MORE
1	Continuous IEQ monitoring system: Performance specifications and thermal comfort classification	Parkinson et al.	2019	low-cost monitoring system SAMBA	nr	Air temperature	18–27 °C	VelociCalc 9565-A, TSI	STANDARD ERROR OF ESTIMATE (SEE)	0.26°C (± 0,05)	X	X	X	X	small-scale wind tunnel	controlled environmental chamber of the IEQ Lab (University of Sydney)	Comparing SAMBA measurements to measurements made with laboratory-grade counterpart sensors indicate linearity of calibrated responses, with the exception of sound pressure level and illuminance. The underestimation of SPL between 45 and 55 dBA is likely due to the response characteristics of the electret microphone to different frequencies. Further calibration is required to improve linearity over the full range of interest. The overestimation of illuminance measurements above 750 lux suggests the sensor response over the tested range may be better described by polynomial rather than linearregression.
						Relative humidity	20–70%			1.04% (± 0.12)							
						Globe temperature	18–27 °C			0.16°C (± 0,03)							
						Air speed	0.00–0.40 m/s	54T21 Dantec Dynamics		0.015 m/s (± 0.000)							
						Carbon Dioxide	0–2000 ppm	TSI Q-Trank 7575 (±3% of reading or ±50ppm)		9ppm (± 2)					sealed chamber (79x19x19)		
						Carbon Monoxide	0–15 ppm	Fieldpiece SCM 4 (± 5% of reading or ± 1ppm)		1,2ppm (± 0,4)							
						Particulate Matter	0.00–0.10 mg/m^3	TSI DustTrak II 8532		0.024 mg/m^3 (±0.010)							
						Formaldehyde	0.0–0.4 ppm	HalTech HFX205		0.02 ppm (±0.01)							
						Sound pressure level	40–75 dBA	SPL meter (Type 1: NL-52, Rion)		2.4 dBA (±0.4)							
						Iluminance	0–1600 lux	T10A, Konica Minolta (± 2% linearity)		8.9% (±1.5%)							
2	Capabilities and limitations of wireless CO2, temperature and relativehumidity sensors	Mylonas et. al	2019	six types of commercially available wireless IEQ sensors	±0,3;±0,5 K	Air temperaure	16°-30°	high precision thermometer with an accuracy of ±0.03 K	1) Xnorm = (X - Xmin) / (Xmax - Xmin) 2) Xnorm * coefficient	MAX: -1,9 K/+1,5K	X		X		climate chamber 3,5m x 2,5 m x 2,5 m	International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark.	The deviations of temperature, relative humidity and CO2 concentration measurement have been calculated by comparison between the actual conditions in the climate chamber and the measurement from the reference instruments. Error of each sensor= measured value-measured value by reference instrument.Linear regression analysis was applied to investigate how the CO2 measurement error of an indoor environment sensor varied as a functionof the other measured factors.The results shown that CO2 accuracy depends on several factors, according to the sensor tested. Some of them were more affected by CO2 concentration, other by an increasing humidity level or temperature.
					±2;±10 %	Relative humidity	5-88%	humidity sensor had an accuracy of±1.5%		MAX: −38.9%/+9.2%							
					±30;±50 ppm	Carbon Dioxide	400 ppm-1930ppm	photoacoustic multi-gas analyser with an accuracy of±3%		MAX: -413ppm/+798ppm							
3	Climate monitoring in World Heritage List buildings with low-cost data loggers: The case of the Jerónimos Monastery in Lisbon (Portugal)	Entradas Silva et al.	2020	a prototypes based on the Arduino technology, that includes 7 data loggers, 9 temperature and RH sensors, 1 CO2 device and 13 thermistors	nr	Air temperature	5-35 °C (step 10°C)	a 10k PT1C3J2 thermistor	MAX DIVERGENCE	± 0,1°	X		X		climatic chamber (FITOC IMA 300 EDT I)	the Jerónimos Monastery in Lisbon (Portugal)	Sensors exposed for 3 hours to 4 different stationary climatic conditions, collecting data every minute. RESULTS: ± 0,1% between reference sensors and tested sensors
						Relative humidity	30-90%	capacitive sensor SHT31-DIS from the Sensirion		± 0,1%					controlled environment with satured salt solution		
						Carbon Dioxide	NR	SenseAir CO2 Engine® K30 STA		±50 ppm							
4	Environmental monitoring system based on an Open Source Platform and the Internet of Things for a building energy retrofit	Martín-Garín et al.	2018	data-acquisition system made by: -Electronic board (ESP-8266 WiFi microcontroller) -MicroSD shield -Environment sensors (for RH and T) -Magnetic switch sensor -CO2 sensor -OLED display	nr	Air temperature	5-35 °C	datalogger AHLBORN 2549 with the FHAD 46 2 sensor(accuracy of± 0.3 °C).	VALIDATION REFERENCE ACCURACY	± 0.6 °C	X		X		climatic chamber	Spain	Sampling time: 1 minute. Duration: 90 min for each step
						Relative humidity	11,30%; 32,89%; 53,30%; 84,64%	salt solutions		± 3 %					using the saturated aqueous solutions method		This procedure is based on the use of air-tight vessels in which the aqueous solution is introduced to achieve a hygrothermal equilibrium within the enclosure.The different degrees of humidity are obtained by different aqueous solutions of saturated salts at a constant temperature(23 °C ± 0.5 °C) . The relative humidity balance is performed at the following points: LiCl 11.30%, MgCl 2 32.89, Mg (NO3) 2 53.30%, KCl 84.64%. Sampling time: 1 minute. Duration: 24 h for each dessicator
						Carbon Dioxide	nr	nr		± 50 ppm					nr		
5	Evaluation of low-cost formaldehyde sensors calibration	Alonso et al.	2022	eight identical pre-calibrated LCS Sensirion Arduino Shield	SGF30_SHTC1a (accuracy 1 ppb; ± 0,3 °C; ± 3 % RH)	TVOC	nr	nr	nr	similar results	X		X		a 1.5 m3 plexiglas mini environmental chamber with dedicated ventilation, heating, and humidification systems run as the tests required	Trondheim, Norway	The LCS over-and under-estimated the values obtained by the reference sensor, but they presented very similar dynamic responses, indicating that LCS could be used to detect concentration changes after calibration calibrated using measurements in a laboratory's small chamber. The sensors were exposed to the same formaldehyde sources as laboratorygrade equipment. Some of the experiments were repeated after one year. The data obtained by low-cost and professional-grade sensors were then estimate the residuals, i.e., the error in the model-based predictions.
						Air Temperature		Pegasor AQTM Indoor (accuracy ± 0,2°C; ± 1,5%)		overestimate							
						Relative humidity				over and underpredict							
				eight identical pre-calibrated formaldehyde	LCS Dart Sensors WZ-S (accuracy < 0,001 ppm)	Formaldehyde		Graywolf FM-801 (accuracy ± 10 %)		overestimate							
6	Laboratory evaluation of low-cost air quality monitors and single sensors for monitoring typical indoor emission events in Dutch daycare centers	Zheng et al.	2022	five types of LCMs (low cost air quality monitor) and five LCSs	CUBIC PM2012SE (PM1 & PM2.5 ±10 μg/m3, ±10% reading; PM10: ±25 $\mu g/m^3$)	Particulate Matter	0.8 - 1054,5 $\mu g/m^3$	Grimm Aerosol Spectrometers (Model 11-D, GRIMM AerosolTechnik Ainring GmbH & Co. KG, Germany) ACCURACY: ±3% or 1 μg/m3 for PM2.5	R^2	MIN: 0 MAX: 1	X		X		climatic chamber (52.5 m3 (W*L*H = 3.6 × 5.4× 2.7 m), 2 scenario: 1)cool and dry [20 ± 1 °C & 40 ± 10%], 2)warm and humid [26 ± 1 °C & 70 ± 5%]	Eindhoven, Netherlands	Results showed that tested LCMs had the ability to capture DCCs activities by simultaneously monitoring multiple IAQ parameters, and LCMs/LCSs revealed a strong correlation with RGIs in most events (R2 values from 0.7 to 1), but, for some events, the magnitude of responses varied widely.
					CUBIC CM1106SL-N (± 50 ppm or 5% of reading)	Carbon Dioxide	500-2300 ppm	a Photoacoustic Gas Monitor (INNOVA 1512, LumaSense Technologies)+ Multipoint Sampler and Doser (INNOVA 1403, LumaSense Technologies. ACCURACY: ± 1.5%		MIN: 1 MAX: 1							
					Renesas ZMOD4410 (±25%)	TVOC	100-455 ppb	Aeroqual Photoionization Detectors (accuracy ±10%)		MIN: 0,8 MAX: 1							
					Sensirion SHT30 (±1 °C)	Air temperature	20-27°C	EE08 series transmitters each with a data logge. accuracy of ± 0.05 °C and ± 2%	MEAN RMS	0.3°C-1.7°C							
					Sensirion SHT30 (±5% in the range of 15–45 °C)	Relative humidity	38% to 72 %			1% TO 11%							
7	Low-cost Arduino-based temperature, relative humidity and CO2 sensors - An assessment of their suitability for indoor built environments	Pereira et al.	2022	low-cost Arduino-compatible sensors	SHT31 (accuracy ± 0,3 °C; ± 2%) SHT85 (accuracy ± 0,1 °C; ± 1,5%)	Air temperature	10°C-35°C	two identical units of each sensor were used in two similar data loggers	AVARAGE DEVIATION	MIN: −10.9% (−1.0 °C) MAX: 7.7% (1.3 °C)	X		X		climatic chamber (Vötsch VC 4034)	Portugal	1)excellent behaviour and general compliance with applicable standards. 2)One of the CO2 sensors showed some correlation with relative humidity values in short-term exposure. 3)Long-term tests, carried out over 24 months, showed that some of the sensors lost accuracy.
					SHT75 (accuracy ± 0,3 °C; ± 1,8%) DHT11 (accuracy ± 2 °C; ± 4%)	Relative humidity	50%-95%			MIN:−45.2%(-14.7%) MAX: 44.4%(40.3%)							
					T6713-5K (accuracy ±25 or ±3% (400–2000) ±30 or ±3% (2000–5000) K30 (accuracy ±30 ppm or ±3%) SEN0159 (accuracy ±100 ppm)	Carbon Dioxide	400-2500 ppm	sensor CM-0001 pulled by a micro-pump. ACCURACY: ±30 ppm		MIN: −5.5%(-24.3 ppm) MAX:17.0%(162.3 ppm)					inside an acrylic box (Fig. 3) in a climatic chamber (ARALAB Fitoclima 3600EDTU).		

8	On-field test and data calibration of a low-cost sensor for fine particles exposure assessment	Jiang et al.	2021	light-scattering based sensor (Plantower PMS 7003)	Plantower PMS 7003 (accuracy ± 15%)	PM 1, 2,5, 10	nr	tapered element oscillating microbalances (TEOM) monitor	R^2	> 0,82 (strong)			X		on a table at the center of the lab (6 m × 5 m × 3 m).	Shanghai Environmental Monitoring Center	Posthoc data calibration methods for sensors were based on a multiple linear regression model (MLRM) and a random forest model (RFM).
									RSE relative standard deviations	(16–21%) between sensors							
9	Performance assessment of low-cost environmental monitors and single sensors under variable indoor air quality and thermal conditions	Demanega et al.	2022	performance evaluation of eight consumer grade multi-parameter monitors and eight single parameter sensors	Sensirion SCD40 (±0.5 °C; ±2% RH) Littelfuse 11492 (±0.2 °C)	Air temperature		A thermal anemometer (Model 425, Testo) with an air velocity probe and a data logger (Model 435(accuracy ±0.2 ◦C)	MAX DIVERGENCE	± 0,6◦C	X		X		In the controlled chamber(63.3 m³), we generated eight air pollution sources, each at two thermodynamic conditions a) cool and dry (20 ± 1 ◦C, 30 ± 5%), b) warm and humid (26 ± 1 ◦C, 70 ± 5%).	Fribourg, Switzerland.	A correlation coefficient close to 1 indicates a strong correlation, while a unitary regression coefficient suggests a good accuracy of the measurement data. In practice, a good correlation means that a tested device responds proportionally to concentration changes, while a good accuracy indicates a quantitative agreement with a reference instrument.
					Sensirion SHT31-D (±2%)	Relative humidity		LI-COR 850 Biosciences gas analyzer (LI-COR) (accuracy ± 1.5% mv)		± 5%							
					Sensirion SPS30 (max of ±10% and ±10 µg/m3) Alphasense OPC-N3 (±15%) Alphasense OPC-R1 (±15%) NovaFitness SDS018 (max of ±15% and ±10 µg/m3)	PM	0-2500 µg/m³	Grimm Model 1371, Aerosol Technik (miniWRAS) error below 10%.	MEAN RELATIVE ERROR (MRE)	MIN: 43% MAX: 128%							
					nr	TVOC	0-4000 ppb	TVOC monitors: a) GrayWolf AdvancedSense Pro b) Aeroqual Photoionization Detector (accuracy:< ±0.2 ppm +10%.)		MIN: 43% MAX: 153%							
					CO2meter K30 (±30 ppm ± 3%)	Carbon Dioxide	0-1500 ppm	LI-COR 850 Biosciences gas analyzer (LI-COR) (accuracy 1,5% reading)		MIN: 3% MAX: 48%							
10	Design and testing of a low-cost sensor and sampling platform for indoor air quality	Tryner et al.	2021	9 "Home Health Box" (HHB) (220 × 170 × 130 mm)—that used time-integrated pollutant samplers and low-cost sensors	PMS5003, Plantower	PM 2,5	nr	LI-820 CO2 Gas Analyzer	NORMALIZAED MEAN ABSOLUTE ERROR (NMAE)	PM 2,5 16%			X		an occupied kitchen (4,3*5,1 m) closed on three sides	Fort Collins, Colorado, USA	
					SPS30, Sensirion	PM 10		two Q-Trak Indoor Air Quality Monitors (7575-X with model 982 probe, TSI Incorporated,		nr							
					SCD30, Sensirion	Carbon Dioxide				CO2 46%							
					CO-B4,	CO				CO 57%							
						NO2		Trace Level Chemiluminescence NO–NO2-NOx Analyzer, Model 42C		NO2 63%							
						O3		UV Photometric O3 Analyzer, Model 49C		O3 175%							
					nr	TVOC		nr		nr							
11	Design, fabrication, and calibration of the Building EnVironment and Occupancy (BEVO) Beacon: A rapidly-deployable and affordable indoor environmental quality monitor	Fritz et al.	2022	Building EnVironment and Occupancy (BEVO) Beacon	Sensirion SDC30 ±(30 + 3% of MV) ppm	Carbon Dioxide	< 1500 ppm	LI-COR Model 6252	R^2	0.62-0.99	X		X		UTest House at UT's Pickle Research Center, steel chamber 8 m3; retrofitted incubator equipped with an electric heater (Tair)	Austin, Texas	2 calibration approaches: device-specific and environment-averaged Calibrated sensors performed well when compared to reference monitors or calibrated gas standards.
					SPEC DGS CO (±15% of MV)	CO	0, 1, 2, 4 ppm (calibration steps) using 10 ppm CO gas standard	Background, Gas Standard		0.98-0.99							For each senso univariate linear models of the form y=b+mx where y is the corrected CGS (CONSUMER-GRADE SENSOR) reading, x is the raw CGS measurement, and b and m are intercept and slope parameters.
					Sensirion SVM30 (± 15% of MV)	TVOC	nr	None		nr							
					Sensirion SDC30 ± (0,4+0,023 x (MV-25)°C	Air temperature	21÷ 32 °C (RH constant)	Michell Instruments S8000		0.89-0.99							
					Sensirion SPS30 (± 10 ÷ ± 25)µ/m³	PM (1 2,5 4 10)	< 50 µg/m3	TSI Aerodynamic Particle Sizer Model 3321		PM2.5 (-0.13-0.91).							
12	Can data reliability of low-cost sensor devices for indoor air particulate matter monitoring be improved? – An approach using machine learning	Chojer et al.	2022	three commercially available low-cost IoT devices for indoor air quality monitoring in real-world.	AirVisual Pro	PM1	no range as in on-field	TSI DUSTTRAK DRX Aerosol Monitor	MEAN RELATIVE ERROR (MRE)	min -5,604 ; max 1,357			X		4 rooms of a nursery and primary school	Porto city, Portugal	
					PurpleAir PAII SD,	PM2,5				min -0,528; max 3,225							
					uRAD Monitor Model A3	PM 10				min -1,506; max=2,709							

3.6 CALIBRATION ITER FOR PROMET&O PROJECT

Within the framework of the PROMET&O project, mainly for logistical reasons, it was decided to carry out, in the first instance, a metrological confirmation. As each sensor has been manufacturer calibrated, its metrological characteristics are defined yet. If the verification determines that the sensor does not match these characteristics, a proper calibration process will also be carried out.

The standard ISO 10012 - Measurement management systems - Requirements for measurement processes and measuring equipment, defines the concept of 'metrological confirmation' as 'the set of operations required to ensure that a measuring device conforms to the requirements for its intended use'. This standard also states that for metrological confirmation of instrumentation to be correct, it requires:

- Define the requirements to be met by the device;
- Define the actions to verify the suitability of the device to the requirements.

The metrological requirements to be met are defined by the user and vary from scope to scope, the CMR (Customer Metrological Requirements), while the device's own metrological characteristics are defined as MEMC (Measuring Equipment Metrological Characteristics).

Schematizing the metrological confirmation process (Fig. 72) of measuring equipment, if the MEMCs meet the CMRs, the metrological confirmation is validated.

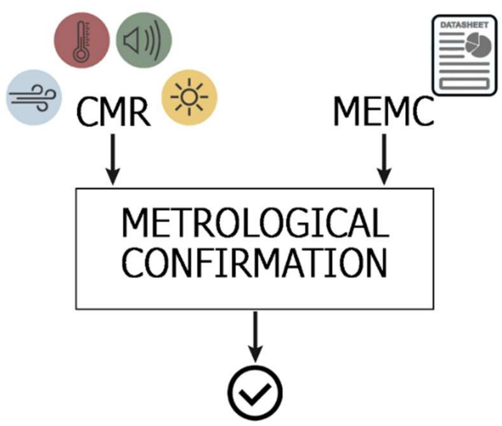


Figure 68 Metrological confirmation process. Elaboration from (Carullo A., 2022)

Since the very definition of MEMCs and CMRs plays a key role in the effectiveness of the metrological confirmation process, special care must be taken in this first step.

For this reason, the definition of CMRs within the PROMET&O project, and thus of indoor environmental quality, was carried out with reference to the thresholds dictated by current regulations, as explained in Tab 21. Basically, the threshold value of each monitored parameter was translated in terms of CMR.

The CMRs adopted were the characteristics of each sensor, provided by the manufacturer's datasheet. Remember, however, that these characteristics do not relate to the specific sensor under analysis, but rather to the entire batch of nominally identical devices. Although it is assumed that the device possesses MEMCs equal to or superior to those declared by the manufacturer, the presence of inferior performance cannot be excluded. It is therefore necessary to separate the nominal characteristics ($MEMC_{nom}$), i.e. those from the datasheet, from the actual characteristics of the specific sensor, obtained following an experimental calibration check ($MEMC_{eff}$).

Having explained the specific nomenclature, the measurement process can be summarized as follows:

1. Establish CMRs according to the scope and use of the sensor.

2. Selection of sensors whose $MEMC_{nom}$, specified by the manufacturer, meet the previously established requirements.

3. After the sensor has been purchased, the $MEMC_{eff}$ are established by means of experimental tests, which will be discussed in more detail in the next paragraphs.

4. If the $MEMC_{eff}$ meet the CMRs, the sensor complies with the requirements for the intended use, so no actual metrological characterization is required. Otherwise, the calibration and correction phase will follow.

Even if at time 0, i.e. the time when the calibration check takes place, the sensor is in compliance, its metrological performance decreases over time, making periodic verification of the $MEMC_{eff}$ necessary. Typically, the calibration function of an instrument is valid for a period of between a few months and a few years and is explicitly stated by the manufacturer. After the first check, which is carried out on the basis of the explicit validity period, one can autonomously choose, on the basis of the results obtained, to narrow or extend the confirmation interval.

Since sensors are influenced by other quantities such as primarily, temperature, humidity, or pollutants that may increase cross-sensitivity (see paragraph 2.4.3), it is necessary to carry out the verification process under conditions as close as possible to those of actual use.

In fact, in the CMRs it is necessary to specify the monitoring conditions, including:

- The range of expected environmental quantities (T, RH, atmospheric pressure);
- The expected range of other quantities, e.g. the concentration of pollutants;
- The presence of critical working conditions, such as strong vibrations or high dust concentrations.

Note that the choice of device is dictated not only by the quantity being monitored but also by the resolution and uncertainty with which to estimate it. These must be lower than the CMR.

Within the framework of the PROMET&O Project, it was established that the measurement chain for each monitored quantity included a calibration procedure. Two different conditions can occur which are followed by different operations:

1. If the metrological requirement defined by the team (CMR) is met by the uncertainty of the sensor, as reported by the manufacturer in the data sheet ($MEMC_{nom}$), a metrological verification step is carried out. This is conducted by comparison with a reference instrument, which is more accurate than the sensor, and aims to estimate whether the error of the reference chain is below the maximum permissible error.

2. In the event that the metrological requirements (CMR) are not met a priori by the sensor uncertainty stated on the datasheet ($MEMC_{nom}$), the correction of the measurement chain calibration function is carried out. Also for this case, the

characterization procedure is carried out by comparison with a reference instrument.

Tab 43 shows the specifications of the sensor, as well as the $MEMC_{nom}$ according to the datasheet, and the CMR. If the first condition occurs, i.e. that the established uncertainty requirement is met by the nominal value of the sensor, the background is colored white. Otherwise, i.e. if the second condition occurs, the background is colored purple.

Table 42 Measuring Equipment Metrological Characteristics and Customer Metrological Requirements for the range of interest of each sensor

Parameter	Sensor measurement range	$MEMC_{nom}$	Range	CMR
T	-40 °C to 125 °C	± 0.2 °C	(0-60) °C	±0.5°C (BS EN ISO 7726:2001)
Rh	(0-100) %	± 1.8 %	(30-70) %	±5% (ANSI/ASHRAE 55:2017)
E_v	(0-120) klx	15 % measured value	-	±5% (WELL)
CO	(0-1000) ppm	± 2.75 nA/ppm (sensitivity)	-	1 ppm at values between 0 and 10 ppm (WELL)
CO_2	(0-40000) ppm	± (30 ppm +3% mv)	(400-10000) ppm	10% at 750 ppm (WELL)
NO_2	(0-5) ppm	±30 % mv	(0-5) ppm	20% (WELL)
PM2.5	(0-1000) µg/m^3	± (5 µg/m^3 + 5% mv)	(0-100) g/m^3	≤ 15% (WELL)
PM10	(0-1000) µg/m^3	± (25 g/m^3)	(0-100) g/m^3	-
CH_2O	(0-1) ppm	±20 % mv	(0-200) ppb	20 ppb (0-100 ppb) (WELL)
SPL	122.5 dB (SPL) AOP	Not declared	< 45 dB (A)	±0.5 dB (1 kHz) (WELL)

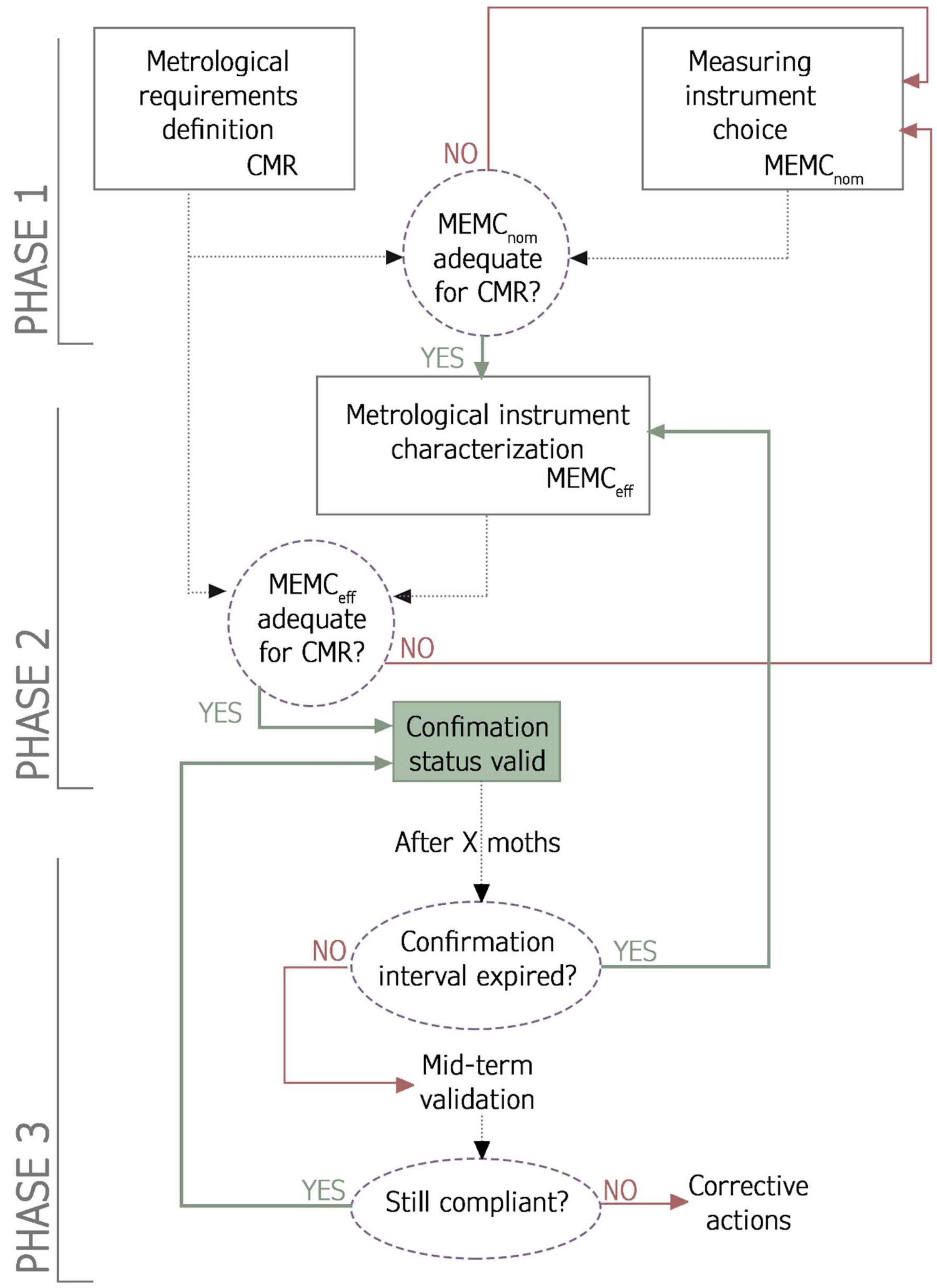


Figure 69 Lifecycle of a measuring instrument. Elaboration from (Carullo A., 2022)

3.6.1 Calibration Verification of the sensors

Before the calibration phase, the standards to be followed were defined, as in paragraph 3.4. The procedure of calibration verification, as described above, has been performed on the sensors. They were tested in several configurations:

1. The sensor, single and uncovered, to verify that the nominal metrological characteristics, declared by the manufacturer were similar to the actual ones, as well as still within the acceptable range of the set requirements. The procedure was carried out for sensors of: Temperature, Relative Humidity, CO_2, Sound Pressure Level, Illuminance,...

2. The sensor inside a simplified case, emulating the final case, to estimate its influence on the sensor's uncertainty. The test was carried out for both the Illuminance and Sound Pressure Level sensors.

3. Finally, the sensors assembled on the PCB and housed inside the final case were calibrated simultaneously.

3.6.2 Thermal: Air Temperature and Relative Humidity Sensor

Air Temperature Sensor

Setting and procedure

The calibration verification for the temperature sensor, Sensirion SHT 41, was carried out in the Mykratos climate chamber. The sensor being measured, a platinum resistance thermometer, Pt100, with an uncertainty in the reference range of ± 0.05°C, and a thermo-hygrometer, Testo 175, with an uncertainty of ± 0.5°C,used as reference instruments, have been placed inside the chamber (Fig. 74).

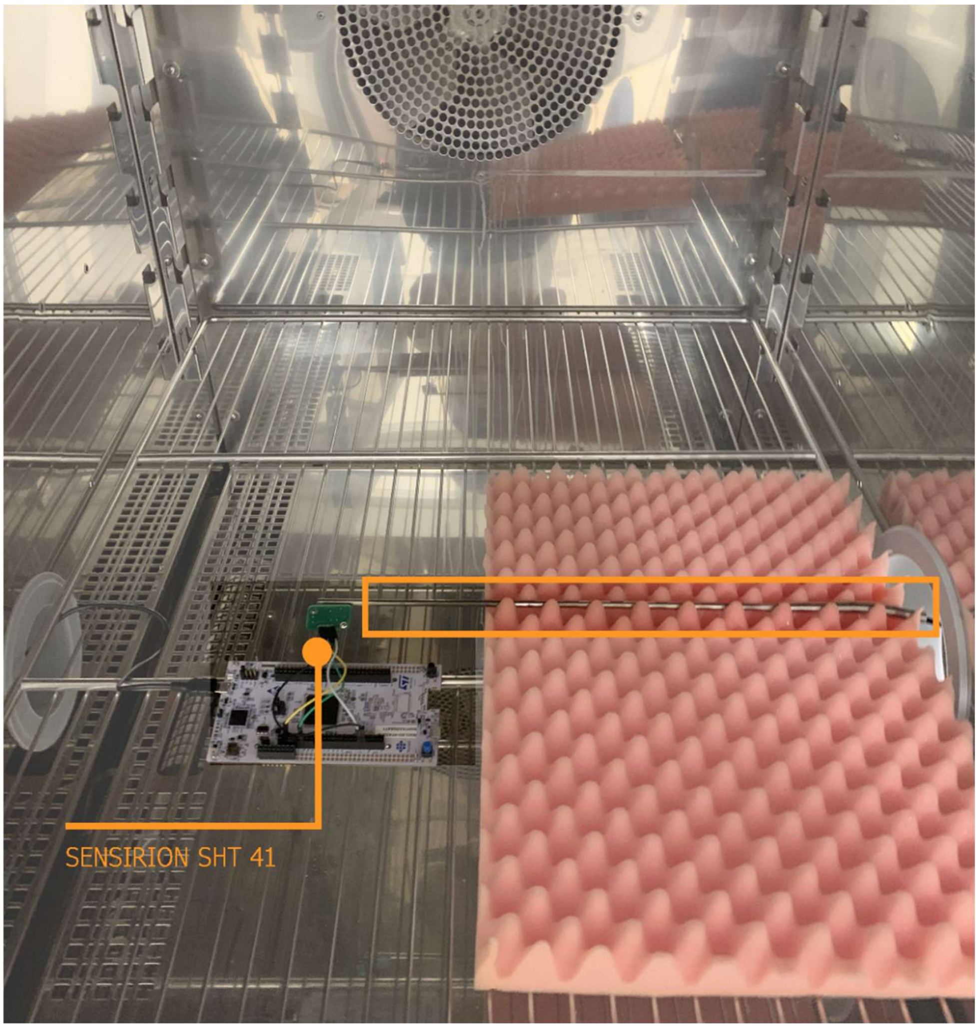


Figure 70 Disposition inside the climatic chamber of the sensor and Pt100

Three different set points were configured, i.e. 10°C, 20°C, 30°C, as they represented the conditions most suitable for the sensor's field of use.

The sensor was connected to the core board, and thus to the computer by means of a USB cable, allowing the data to be displayed and collected via the Putty software. One datum per second was sampled, then averaged over 30 s, for a total of approximately 12 minutes for each temperature setting.

The Pt100 sensing element inside the chamber operates by changing its electrical resistance as the temperature changes and providing a resistance datum expressed in Ohms (Ω) on an external display (Fig. 75).

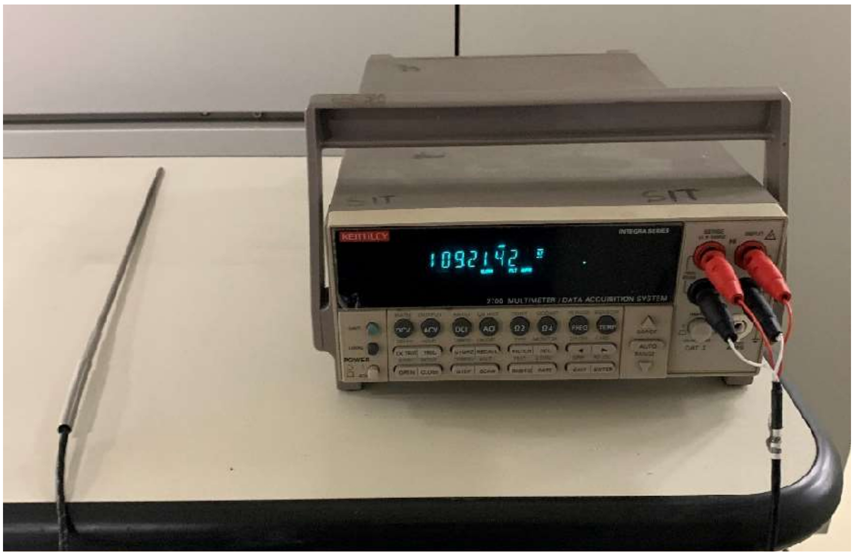


Figure 71 Pt 100

A resistance datum was sampled every 30 seconds. Subsequently, through a linear interpolation procedure, the respective temperature was derived for each datum. Specifically, the calibration center, in this case the Politecnico di Torino itself, provided a table showing the temperature expressed in °C and the corresponding resistance in Ω. Once having identified between which two extremes of temperature and respective resistance is the datum expressed in ohms, it is sufficient to apply the following formula:

$$T_{act} = T_1 + \frac{(T_2 - T_1)}{(R_2 - R_1)} \cdot (R_{act} - R_1)$$

Where

T_{act}= actual temperature

T_1= the lower temperature in which T_{act} lies

T_2=the higher temperature in which T_{act} lies

R_1= the lower resistance in which T_{act} lies

R_2= the higher resistance in which T_{act} lies

R_{act}= actual resistance, sampled by Pt100.

The settings were changed manually through the Mykratos software, and the data recorded in the same way when switching from one temperature to another, to monitor the behaviour of the sensor in a dynamic state.

Results

Temperature 30°C

The test at 30°C ran for 11 minutes, from 10:32 to 10:43. A total of 22 data were collected. They were calculated in order:

1. La media empirica ($\bar{x}$);
2. Sample variance ($s^2(x)$);
3. Standard deviation ($s(x)$);
4. Mean standard uncertainty ($u_a(\bar{x})$);
5. Combined uncertainty ($u_c(x)$), taking into account the reference instrument uncertainty as well as the sensor resolution;
6. Expanded uncertainty ($U(x)$), using as coverage factor in order to assure a coverage interval of 95,4%;
7. Upper limit (UL) and Lower limit (LL);
8. Upper acceptance limit (UAL) and lower acceptance limit (LAL).

As shown in Table 44 and Fig.76 the readings of the two devices diverged by values between -0.03÷0.00 °C, highlighting that the sensor tends to underestimate the actual value.

Table 43 Calculation of error, statistic indexes, uncertainties and acceptance limits for temperature 30° C

Starting time	End time	Temperature		Measurement Error	E-U(X)	E+U(X)	Number of measurements	$(x_k-\bar{x})^2$	Sample Variance	UPPER LIMIT
10:32	10:43	Sensiron SHT-41	PT100	E			n		$s^2(x)$	UL
		29,63	29,65	-0,03	-0,12891	0,07766	22	0,0019	0,00147	0,5
		29,62	29,65	-0,02	-0,12545	0,08112	Empirical mean	0,0016	Standard Deviation	LOWER LIMIT
		29,64	29,65	-0,01	-0,11402	0,09255	X	0,0029	s(x)	LL
		29,64	29,65	-0,01	-0,11424	0,09233	29,58	0,0034	0,03839	-0,5
		29,62	29,63	-0,01	-0,11547	0,09110		0,0012	Mean standard uncertainty	guard-band factor
		29,61	29,62	-0,02	-0,12119	0,08538		0,0005	$u_a(\bar{x})$	kw
		29,61	29,63	-0,01	-0,11743	0,08914		0,0008	0,00818	2
		29,62	29,63	-0,01	-0,11174	0,09483		0,0013	PT100 Uncertainty	guard-band
		29,62	29,62	-0,01	-0,10996	0,09661		0,0012	u_{b1} [°C]	g
		29,59	29,59	-0,01	-0,11016	0,09641		0,0000	0,05	0,016369178
		29,55	29,56	-0,02	-0,12024	0,08633		0,0015	Sensor Resolution	UPPER ACCEPTANCE LIMIT
		29,53	29,55	-0,02	-0,12491	0,08166		0,0027	u_{b2} [°C]	UAL=UL-g
		29,54	29,56	-0,03	-0,13063	0,07594		0,0022	0,01	0,4836
		29,56	29,58	-0,02	-0,12217	0,08440		0,0004	Combined Uncertainty	LOWER ACCEPTANCE LIMIT
		29,59	29,61	-0,01	-0,11735	0,08922		0,0001	$u_c(x)$	LAL=LL+g
		29,60	29,60	0,00	-0,10816	0,09841		0,0002	0,05164	-0,4836
		29,56	29,57	-0,01	-0,10830	0,09827		0,0005	Expanded Uncertainty	
		29,53	29,55	-0,02	-0,12635	0,08022		0,0028	U(x)	
		29,53	29,56	-0,03	-0,13512	0,07146		0,0027	0,10329	
		29,56	29,58	-0,03	-0,12893	0,07764		0,0008	Coverage factor	
		29,56	29,57	-0,01	-0,11299	0,09358		0,0004	k	
		29,54	29,54	0,00	-0,10501	0,10156		0,0019	2	
Sampling time		1 data/s averaged on 30s	1 data/30s				$\Sigma\,(x_k-\bar{x})^2$	0,0309		

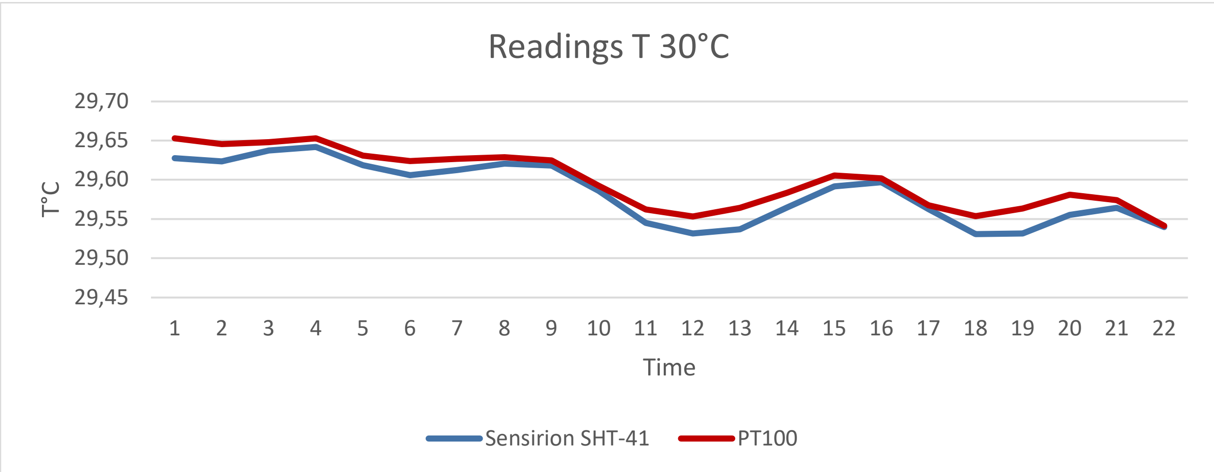


Figure 72 Sensor and reference instrument readings 30° C

Fig.77 shows the graph containing both the measurement error (E, lilac line), given by the difference of the sensor reading and that of the reference instrument, as well as the measurement error stripped of the expanded uncertainty component (E-U(x) orange line), and the measurement error to which the expanded uncertainty is added (E+U(x), gray line). These lines are related to the upper limit (UL, yellow line), lower limit (LL, light blue line), upper acceptance limit (UAL, green line) and lower acceptance limit (LAL, pink line). As can be seen, the values fall within the range dictated by the previously imposed CMRs (see Tab.43), which is ±0.5 °C, as well as within the confidence interval. Therefore, the SHT-41 sensor, at a temperature of 30°C, is verified and suitable for use with a probability of 95.4%.

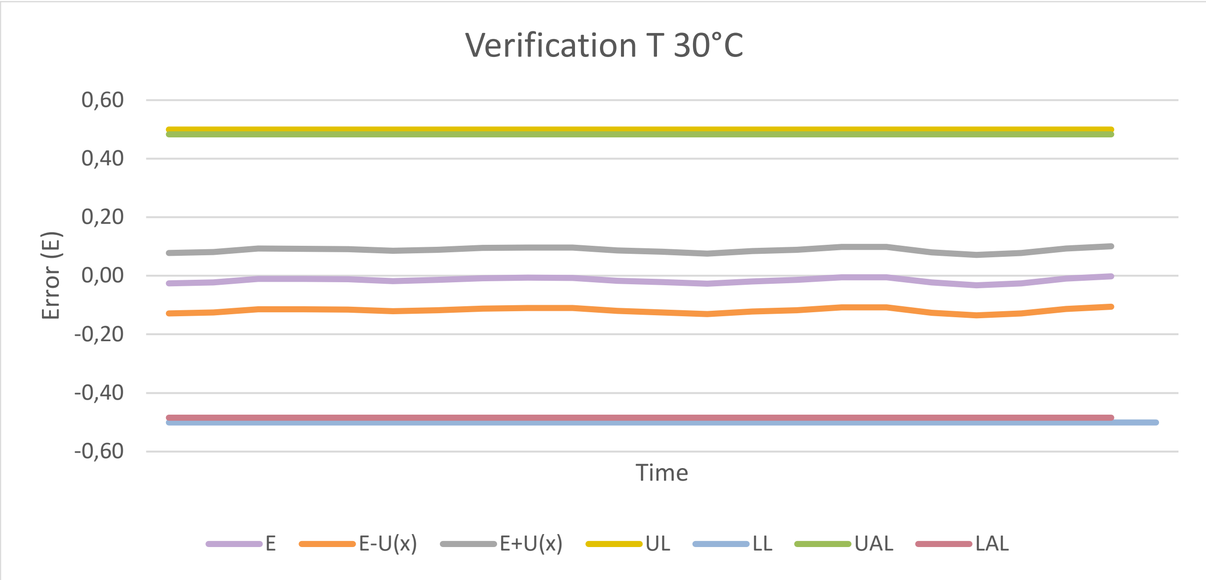


Figure 73 Calibration verification with a confidence level of 95,4% at 30°C

The confidence interval was then further changed to 99.7%, thus using the coverage coefficient of 3. As shown by the graph in Fig.78, the data are still within the limits.

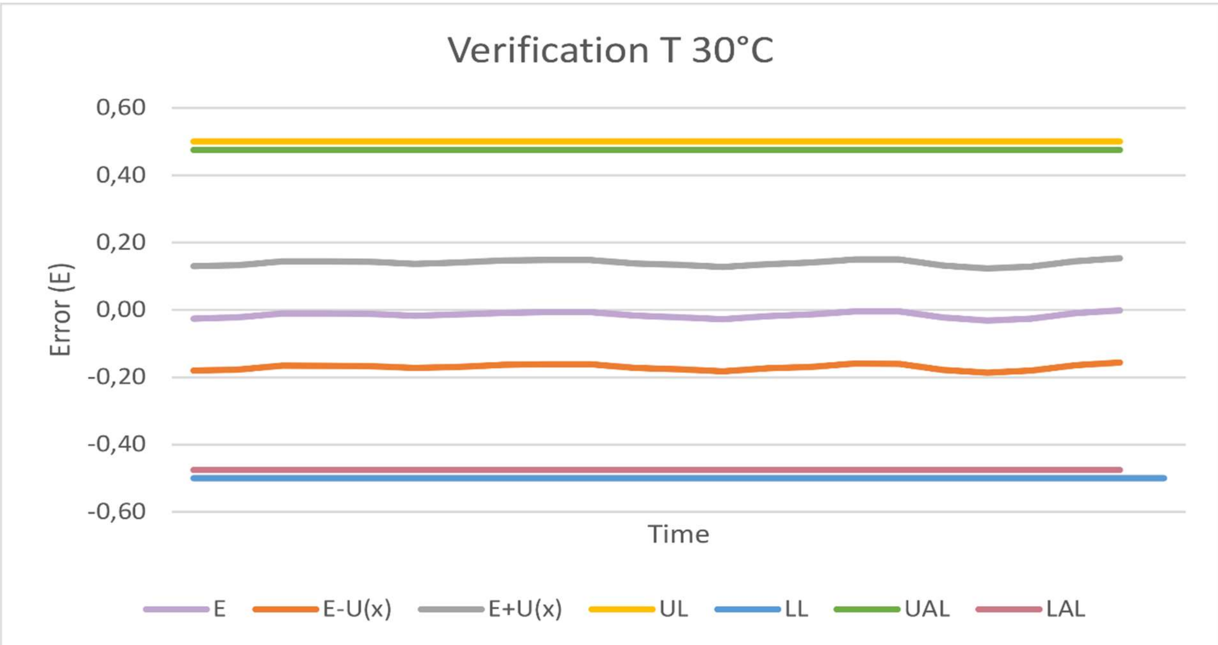


Figure 74 Calibration verification with a confidence level of 99,7% at 30°C

Temperature 20°C

The test at 20°C was scheduled to last 12 minutes, from 11:04 to 11:16. A total of 21 data were collected. It can be seen from Tab.44 that even at a temperature of 20°C, the SHT-41 sensor still underestimates the true value with an error range of -0.11÷ -0.05 °C.

Using the same procedure previously described, the different statistical variables were calculated. In the end, the extended uncertainty is ± 0.103 °C.

Table 44 Calculation of error, statistic indexes, uncertainties and acceptance limits for temperature 20° C

Starting time	End time	Temperature		Measurement Error	E-U(X)	E+U(X)	Number of measurements	$(x_k-\bar{x})^2$	Sample Variance	UPPER LIMIT
11:04	11:16	Sensiron SHT-41	PT100	E			n		$s^2(x)$	UL
		19,48	19,60	-0,11	-0,11314	-0,11314	21	0,0042	0,00147	0,5
		19,49	19,60	-0,11	-0,10878	-0,10878	Empirical mean	0,0038	Standard Deviation	LOWER LIMIT
		19,50	19,61	-0,11	-0,11010	-0,11010	X	0,0023	s(x)	LL
		19,50	19,61	-0,12	-0,11529	-0,11529	19,55	0,0025	0,03833	-0,5
		19,49	19,60	-0,11	-0,10945	-0,10945		0,0028	Mean standard uncertainty	guard-band factor
		19,55	19,64	-0,09	-0,09372	-0,09372		0,0000	$u_a(\bar{x})$	kw
		19,57	19,66	-0,09	-0,08601	-0,08601		0,0004	0,00836	2
		19,55	19,64	-0,09	-0,08908	-0,08908		0,0000	PT100 Uncertainty	guard-band
		19,57	19,66	-0,09	-0,09181	-0,09181		0,0003	u_{b1} [°C]	g
		19,58	19,67	-0,08	-0,08489	-0,08489		0,0011	0,05	0,01673
		19,55	19,64	-0,09	-0,09107	-0,09107		0,0000	Sensor Resolution	UPPER ACCEPTANCE LIMIT
		19,52	19,61	-0,09	-0,09224	-0,09224		0,0006	u_{b2} [°C]	UAL=UL-g
		19,54	19,65	-0,12	-0,11742	-0,11742		0,0001	0,01	0,4833
		19,60	19,69	-0,09	-0,08956	-0,08956		0,0024	Combined Uncertainty	LOWER ACCEPTANCE LIMIT
		19,61	19,68	-0,07	-0,07123	-0,07123		0,0038	$u_c(x)$	LAL=LL+g
		19,58	19,64	-0,06	-0,06405	-0,06405		0,0009	0,05167	-0,4833
		19,53	19,63	-0,10	-0,09950	-0,09950		0,0002	Expanded Uncertainty	
		19,56	19,67	-0,11	-0,10710	-0,10710		0,0001	U(x)	
		19,59	19,67	-0,08	-0,07725	-0,07725		0,0017	0,10334	
		19,59	19,65	-0,06	-0,05835	-0,05835		0,0016	Coverage factor	
		19,57	19,62	-0,05	-0,05272	-0,05272		0,0004	k	
									2	
Sampling time		1 data/s averaged on 30s	1 data/30s				$\Sigma (xk-\bar{x})^2$	0,0294		

The growth in uncertainty can also be seen by comparing the readings taken by the two devices and shown in Fig.79.

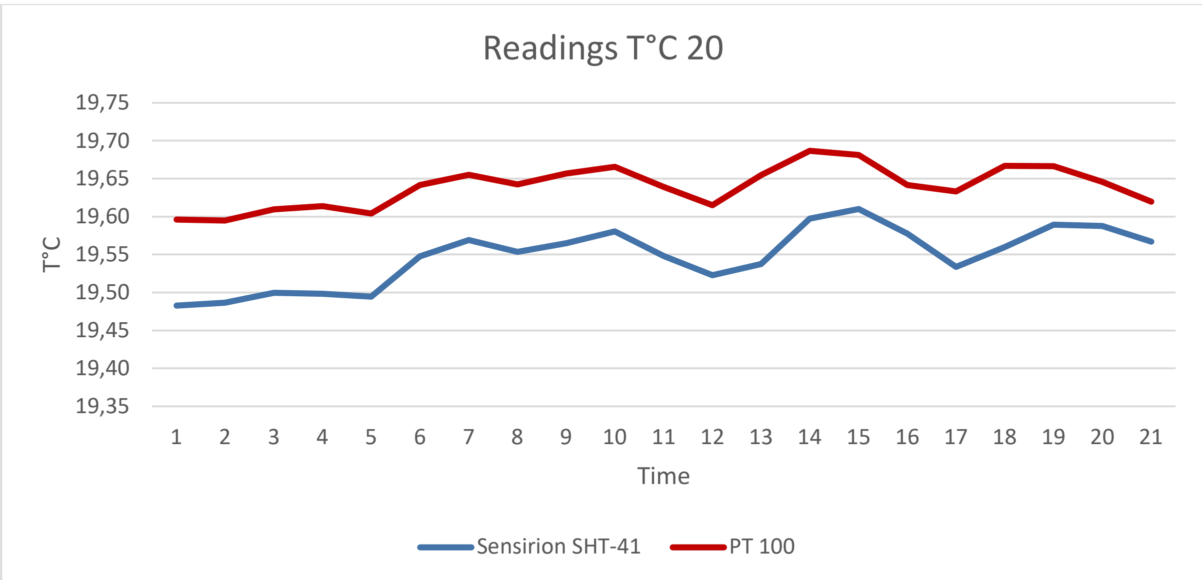


Figure 75 Sensor and reference instrument readings 20°C

Finally, the data in the 20°C conditions were graphed, reporting:

E error, error with extended uncertainty E-U(x), E+U(x), lower and upper limits, and acceptance limits.

As in the previous case, the sensor is verified under these conditions and for its range of use, with a 95.4 percent confidence level.

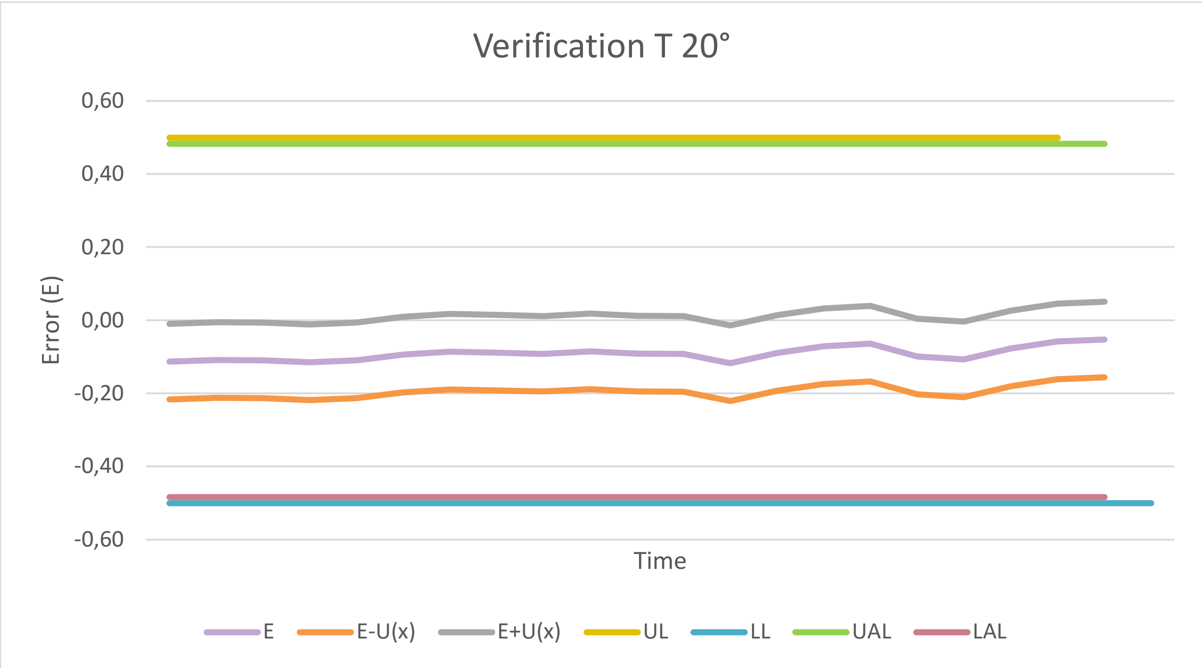


Figure 76 Calibration verification with a confidence level of 95,4% at 20°C

It was also found that even choosing a confidence interval of 99.7%, with a coverage factor of k=3, the sensor still passes the verification procedure.

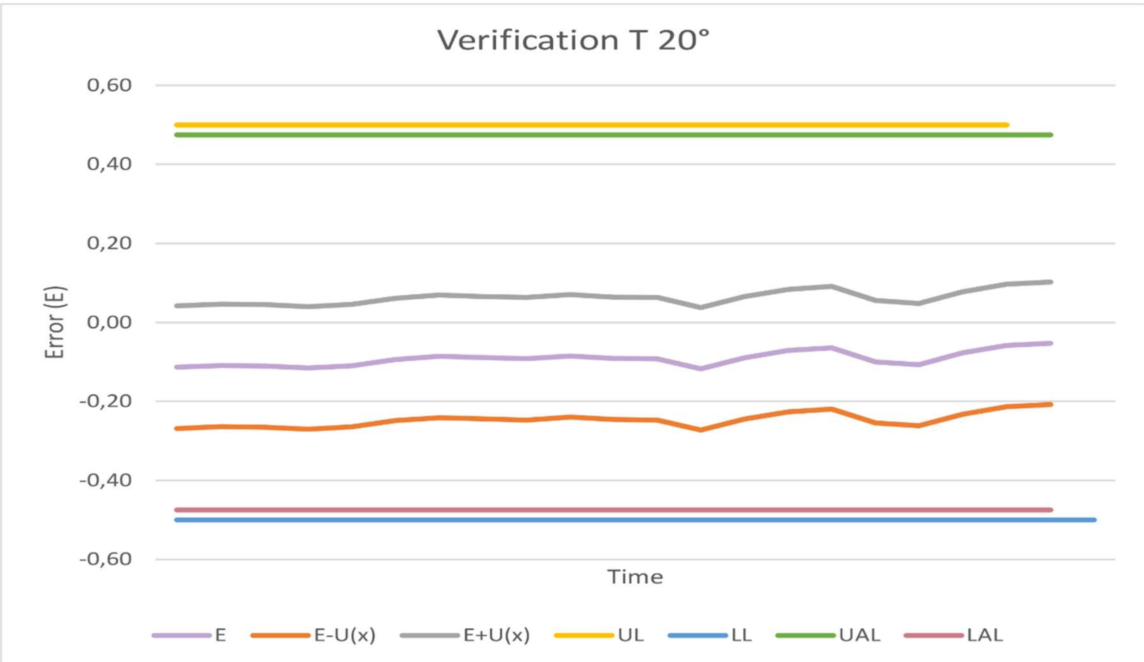


Figure 77 Calibration verification with a confidence level of 99,7% at 20°C

Temperature 10°C

The test at 10°C was scheduled to last 12 minutes, from 11:43 to 11:55. A total of 20 data were collected. From Tab.46 it can be seen that, at a temperature of 10°C, the SHT-41 sensor still underestimates the true value with an error range of -0.17÷-0.08 °C. Using the same procedure as previously described, the different statistical variables were calculated. In the end, the extended uncertainty is ± 0.1027 °C.

Table 45 Calculation of error, statistic indexes, uncertainties and acceptance limits for temperature 10°

Starting time	End time	Temperature		Measurement Error	E-U(X)	E+U(X)	Number of measurements	$(x_k - \bar{x})^2$	Sample Variance	UPPER LIMIT
11:43	11:55	Sensiron SHT-41	PT100	E			n		$s^2(x)$	UL
		9,40	9,54	-0,14	-0,246	-0,040	20	0,0001	0,00083	0,5
		9,38	9,52	-0,14	-0,239	-0,034	Empirical mean	0,0000	Standard Deviation	LOWER LIMIT
		9,41	9,54	-0,13	-0,233	-0,027	X	0,0005	s(x)	LL
		9,43	9,55	-0,12	-0,225	-0,019	9,39	0,0016	0,0289	-0,5
		9,45	9,57	-0,12	-0,227	-0,021		0,0036	Mean standard uncertainty	guard-band factor
		9,38	9,51	-0,13	-0,237	-0,031		0,0001	$u_a(\bar{x})$	kw
		9,36	9,50	-0,14	-0,242	-0,037		0,0007	0,0065	2
		9,41	9,54	-0,13	-0,233	-0,028		0,0004	PT100 Uncertainty	guard-band
		9,37	9,50	-0,12	-0,228	-0,022		0,0002	u_{b1} [°C]	g
		9,35	9,48	-0,14	-0,240	-0,035		0,0019	0,05	0,013
		9,37	9,51	-0,13	-0,235	-0,030		0,0003	Sensor Resolution	UPPER ACCEPTANCE LIMIT
		9,41	9,51	-0,10	-0,205	0,000		0,0004	u_{b2} [°C]	UAL=UL-g
		9,37	9,48	-0,11	-0,212	-0,006		0,0005	0,01	0,4871
		9,35	9,50	-0,15	-0,249	-0,044		0,0016	Combined Uncertainty	LOWER ACCEPTANCE LIMIT
		9,39	9,53	-0,14	-0,245	-0,040		0,0000	$u_c(x)$	LAL=LL+g
		9,42	9,50	-0,08	-0,186	0,019		0,0009	0,0514	-0,4871
		9,36	9,48	-0,12	-0,225	-0,019		0,0010	Expanded Uncertainty	
		9,36	9,53	-0,17	-0,273	-0,067		0,0010	U(x)	
		9,42	9,52	-0,10	-0,204	0,002		0,0011	0,10279	
		9,40	9,48	-0,08	-0,185	0,021		0,0001	Coverage factor	
									k	
									2	
Sampling time		1 data/s averaged on 30s	1 data/30s				$\Sigma (x_k - \bar{x})^2$	0,0158		

The trend of readings is similar to that of devices under conditions at 10°C (Fig.82).

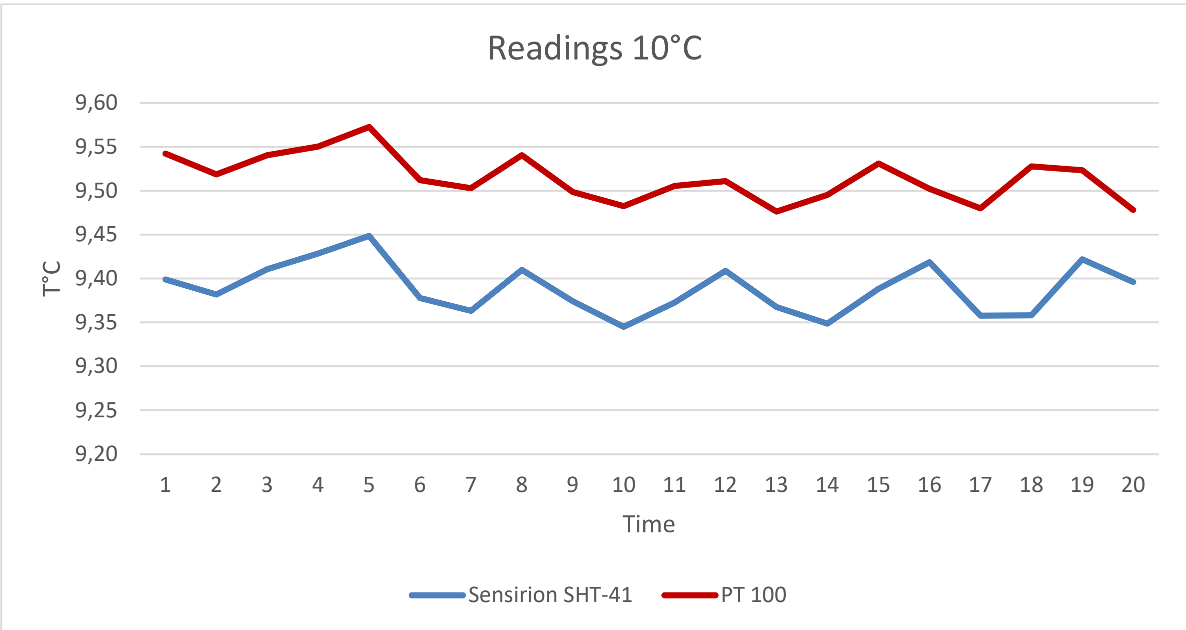


Figure 78 Sensor and reference instrument readings 10°C

Finally, the data in the 10°C conditions were graphed, reporting:

E error, error with extended uncertainty E-U(x), E+U(x), lower and upper limits, and acceptance limits.

As in the previous case, the sensor is verified under these conditions and for its range of use, with a 95.4 percent confidence level.

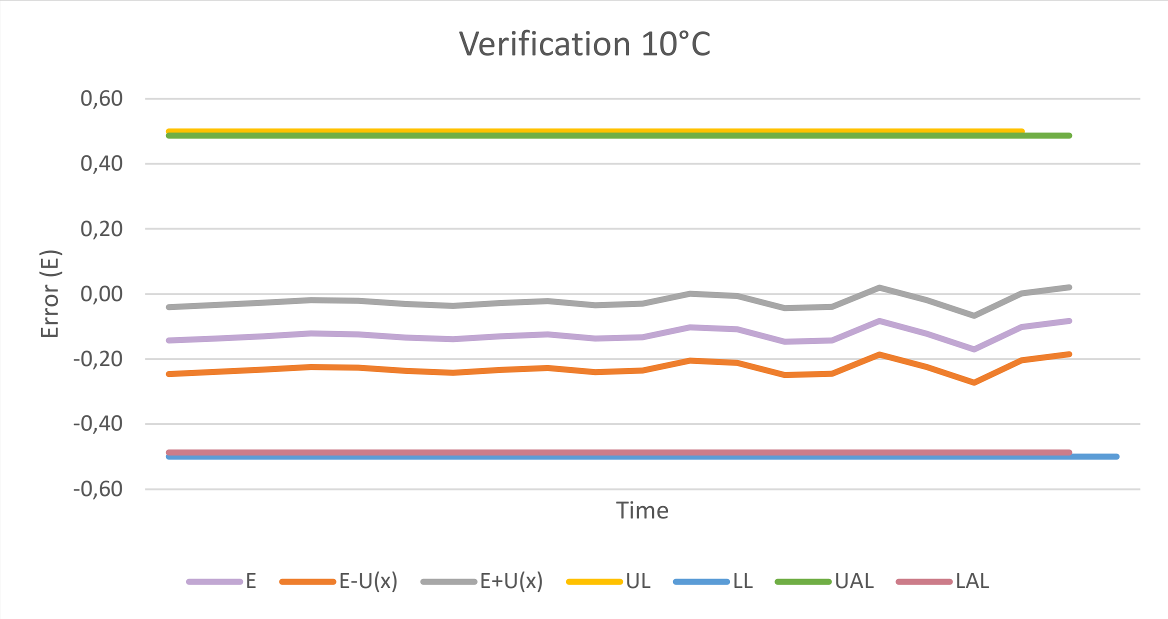


Figure 79 Calibration verification with a confidence level of 95,4% at 10°C

The sensor again complies for 99.7% of the sample with the defined limits, as shown in Fig.84, where the coverage coefficient k used is 3.

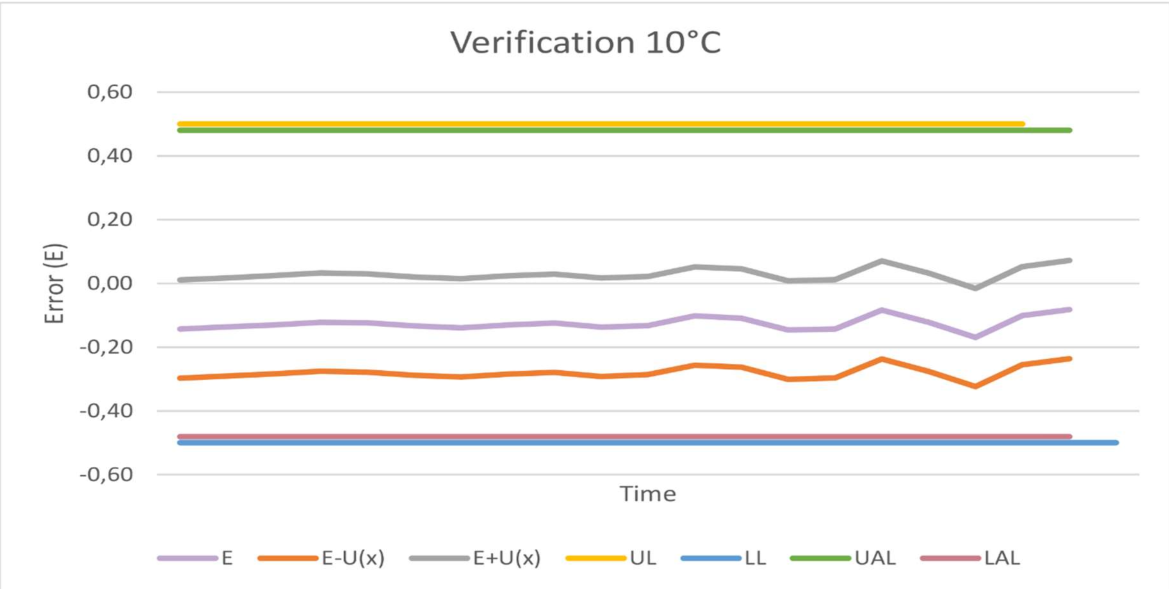


Figure 80 Calibration verification with a confidence level of 99,7% at 10°C

Relative humidity sensor

Setting and procedure

The calibration verification procedure of the relative humidity sensor, SHT41, which it should be remembered is also the temperature sensor, was also carried out in the same Mykratos climatic chamber. The reference instruments used for comparison with the data acquired by the sensor under analysis were both the Testo 175 data logger (uncertainty ± 3%RH) and the climatic chamber itself (uncertainty ±1%RH ÷ ± 3%RH). The instruments were placed simultaneously in the climatic chamber, the sensor was connected to the core board, which in turn was connected to the PC via a USB cable (Fig. 85). The relative humidity conditions set were: 22%, 39%, 75%, 94%, with a constant temperature of 23°C.

Figure 81 Disposition inside the climatic chamber of the sensor and TESTO 175

Once the desired conditions were reached, the sensor sampled one datum per second, then averaged the values over 30 s, resulting in 1 datum every 30 seconds.

The climatic chamber sensor, on the other hand, sampled one datum every 30 seconds.

Each setup lasted approximately 30 minutes.

Again, in order to monitor the dynamic state behaviour of the sensor, the data obtained when switching from one relative humidity to another were also collected.

Results

RH 22%

The SHT-41 sensor was tested at the constant temperature of 23°C exposed to a relative humidity of 22% for a total of 32 minutes. Data were collected from the sensor every second, then averaged over 30 seconds. The climatic chamber collected one data item per second. The total number of data turns out to be 61. By resorting to the previously described calculations, statistical parameters were calculated. As shown in Tab.47 and Fig.86, the relative humidity values measured by the two devices differ in the range of ≈ -3÷-1 %. So, as in the case of temperature, also for humidity the sensor tends to underestimate the actual value. Taking into account the sensitivity of the sensor as well as the uncertainty of the reference instrument, the combined uncertainty of 1.002 % was calculated. Multiplying the figure by the 95.4 percent coverage factor, k=2, the expanded uncertainty was 2.004 %.

Table 46 Calculation of error, statistic indexes, uncertainties and acceptance limits for relative humidity 22%

Starting time	End time	Relative Humidity		Measurement Error	E-U(X)	E+U(X)	Number of measurements	$(x_k-\bar{x})^2$	Sample Variance
15:24	15:56	Sensiron SHT-41	Mykratos climatic chamber	E			n		$s^2(x)$
		18,99	21,79	-2,79	-4,797	-0,78801	61	0,0040	0,26137
		18,37	22,12	-3,75	-5,757	-1,74786	Empirical mean	0,3205	Standard Deviation
		18,58	22,13	-3,55	-5,559	-1,55030	X	0,1256	s(x)
		19,40	21,76	-2,36	-4,365	-0,35617	18,93	0,2167	0,51124
		19,90	21,20	-1,30	-3,305	0,70396		0,9388	Mean standard uncertainty
		19,36	21,08	-1,72	-3,728	0,28069		0,1803	$u_a(\bar{x})$
		18,77	21,42	-2,65	-4,653	-0,64411		0,0252	0,06546
		18,54	21,75	-3,22	-5,223	-1,21470		0,1569	Mykratos Uncertainty
		18,73	21,75	-3,02	-5,028	-1,01931		0,0404	u_{b1} [%]
		19,28	21,53	-2,25	-4,254	-0,24536		0,1199	1
		18,95	21,25	-2,30	-4,302	-0,29334		0,0004	Sensor Resolution
		18,42	21,17	-2,75	-4,757	-0,74781		0,2629	u_{b2} [%]
		18,30	21,42	-3,12	-5,122	-1,11275		0,3966	0,01
		18,49	21,47	-2,98	-4,986	-0,97702		0,1966	Combined Uncertainty
		19,20	21,24	-2,04	-4,040	-0,03094		0,0730	$u_c(x)$
		19,23	20,97	-1,75	-3,749	0,25935		0,0891	1,00219
		18,64	20,97	-2,33	-4,333	-0,32384		0,0838	Expanded Uncertainty
		18,24	21,27	-3,04	-5,041	-1,03194		0,4818	U(x)
		18,22	21,48	-3,27	-5,274	-1,26487		0,5128	2,00438
		18,79	21,37	-2,58	-4,587	-0,57779		0,0205	Coverage factor
		19,25	21,04	-1,79	-3,795	0,21330		0,1013	k
		18,76	20,83	-2,07	-4,076	-0,06699		0,0295	2
		18,27	20,99	-2,72	-4,728	-0,71920		0,4433	UPPER LIMIT
		18,05	21,29	-3,24	-5,243	-1,23465		0,7687	UL
		18,44	21,34	-2,91	-4,911	-0,90226		0,2451	10
		19,21	21,15	-1,94	-3,944	0,06508		0,0772	LOWER LIMIT
		19,18	20,81	-1,63	-3,636	0,37312		0,0628	LL
		18,95	20,79	-1,84	-3,846	0,16275		0,0003	-10
		18,97	21,11	-2,14	-4,148	-0,13930		0,0016	guard-band factor
		18,83	21,37	-2,54	-4,547	-0,53809		0,0105	kw
		19,15	21,55	-2,40	-4,406	-0,39771		0,0478	2
		19,17	21,55	-2,38	-4,382	-0,37278		0,0571	guard-band
		18,71	21,51	-2,80	-4,805	-0,79616		0,0507	g
		18,34	21,61	-3,26	-5,268	-1,25958		0,3478	0,13092
		18,57	21,73	-3,16	-5,168	-1,15918		0,1331	UPPER ACCEPTANCE LIMIT
		19,32	21,61	-2,30	-4,301	-0,29176		0,1494	UAL=UL-g
		19,71	21,33	-1,62	-3,626	0,38306		0,6062	9,8691
		19,10	21,14	-2,04	-4,041	-0,03190		0,0297	LOWER ACCEPTANCE LIMIT
		18,50	21,37	-2,86	-4,868	-0,85916		0,1833	LAL=LL+g
		18,09	21,74	-3,65	-5,658	-1,64954		0,7069	-9,8691
		18,01	21,88	-3,87	-5,872	-1,86361		0,8441	
		18,83	21,73	-2,90	-4,901	-0,89217		0,0097	
		19,75	21,26	-1,51	-3,514	0,49471		0,6783	
		19,67	20,83	-1,16	-3,164	0,84515		0,5435	
		19,14	20,81	-1,67	-3,675	0,33343		0,0420	
		18,79	21,26	-2,47	-4,478	-0,46891		0,0198	
		18,74	21,74	-2,99	-4,998	-0,98888		0,0348	
		19,25	21,94	-2,69	-4,697	-0,68839		0,0996	
		19,24	21,81	-2,56	-4,569	-0,55980		0,0983	
		18,62	21,64	-3,02	-5,025	-1,01666		0,0966	
		18,27	21,67	-3,40	-5,402	-1,39301		0,4331	
		18,18	21,84	-3,65	-5,658	-1,64948		0,5612	
		18,72	21,71	-2,98	-4,988	-0,97902		0,0437	
		19,56	21,39	-1,83	-3,836	0,17321		0,3934	
		19,60	21,01	-1,41	-3,418	0,59123		0,4408	
		19,37	20,84	-1,47	-3,473	0,53561		0,1956	
		19,51	21,15	-1,64	-3,644	0,36429		0,3343	
		19,78	21,53	-1,76	-3,762	0,24631		0,7127	
		20,05	21,79	-1,75	-3,751	0,25814		1,2415	
		19,66	21,87	-2,21	-4,214	-0,20534		0,5250	
		19,12	21,99	-2,87	-4,875	-0,86593		0,0362	
Sampling time		1 data/s averaged on 30s	1 data/30s				$\Sigma (x_k-\bar{x})^2$	15,6822	

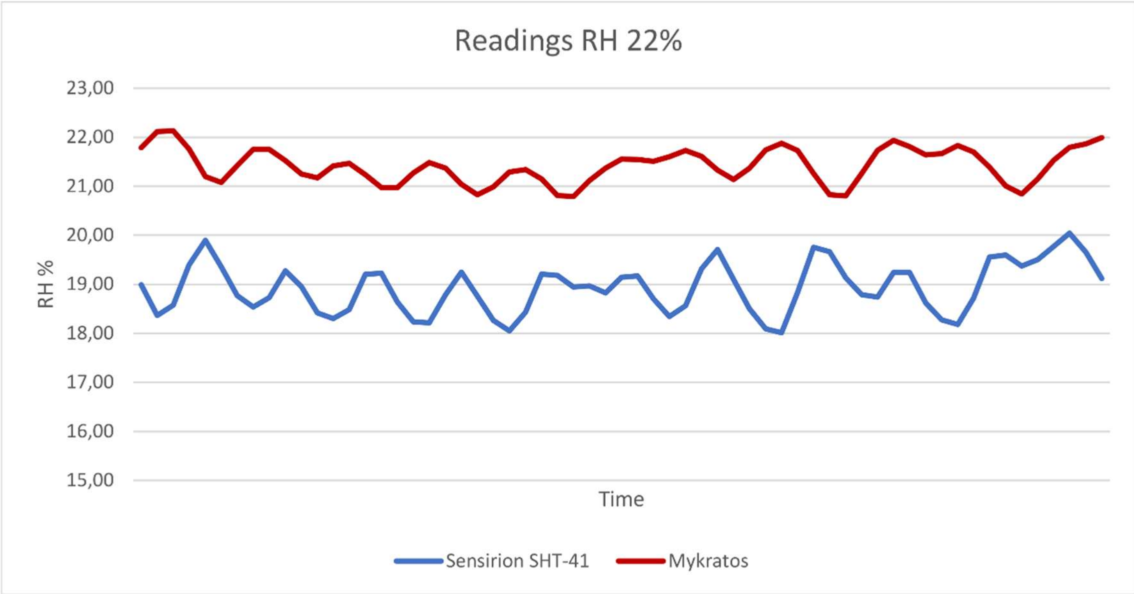


Figure 82 Sensor and reference instrument readings RH 22%

The graph in Fig.87, shows the curves representing the measurement error with its uncertainty component, in relation to the limits allowed by the established CMRs (± 5%). While the upper limit, as well as the upper acceptance limit, are not exceeded, the values do not fall within the lower limit. Therefore, the sensor is not verified and requires a true calibration operation.

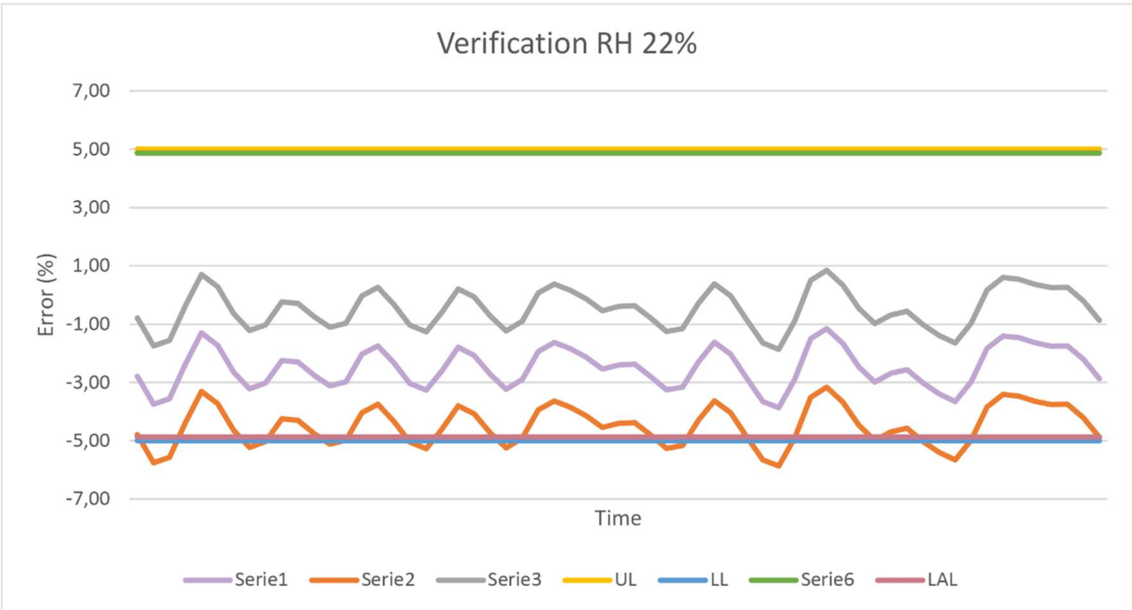


Figure 83 Calibration verification with a confidence level of 95% at RH 22%

RH 39%

The SHT-41 sensor was tested at the constant temperature of 23°C exposed to a relative humidity of 39% for a total of 28 minutes. Data were collected from the sensor every second, then averaged over 30 seconds. The climatic chamber collected one data item per second. The total number of data turns out to be 59. By resorting to the previously described calculations, statistical parameters were calculated. As shown in Tab.48 and Fig.88, the relative humidity values measured by the two devices differ in the range of ≈ -4,11÷-3 %. So, as in the case of temperature, also for humidity the sensor tends to underestimate the actual value, even more than the previous setting. Taking into account the sensitivity of the sensor as well as the uncertainty of the reference instrument, the combined uncertainty of 1 % was calculated. Multiplying the figure by the 95.4 percent coverage factor, k=2, the expanded uncertainty was 2 %.

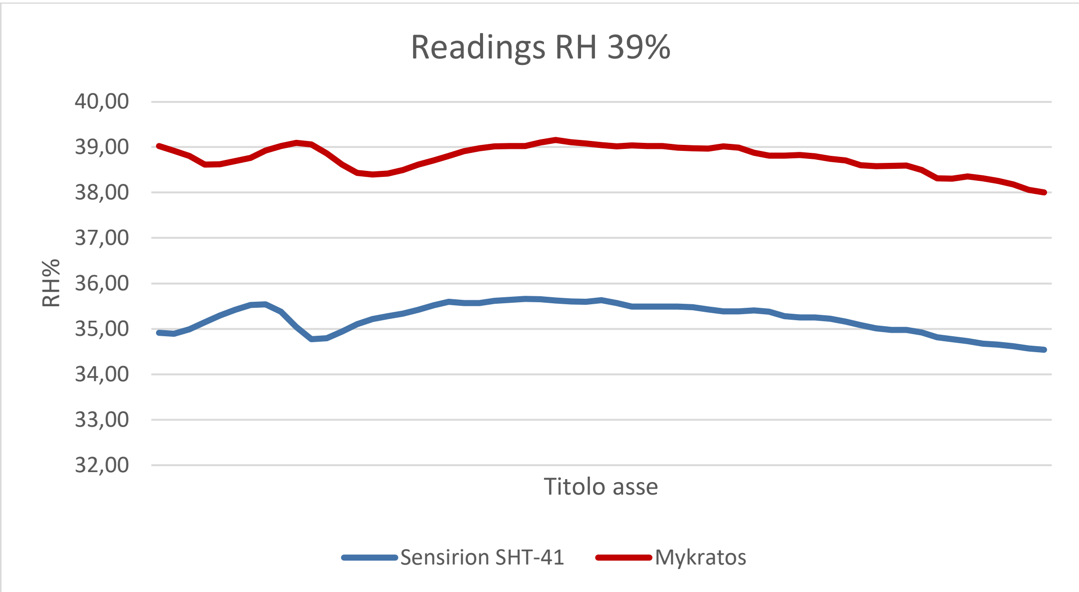


Figure 84 Sensor and reference instrument readings RH 39%

Table 47 Calculation of error, statistic indexes, uncertainties and acceptance limits for relative humidity 39%

Starting time	End time	Relative Humidity		Measurement Error	E-U(X)	E+U(X)	Number of measurements	$(x_k-\bar{x})^2$	Sample Variance
16:30	16:58	Sensiron SHT-41	Mykratos climatic chamber	E			n		$s^2(x)$
		34,91	39,02	-4,11	-6,114	-2,111	59	0,1039	0,10798
		34,89	38,92	-4,03	-6,028	-2,024	Empirical mean	0,1172	Standard Deviation
		34,99	38,80	-3,81	-5,815	-1,811	X	0,0597	s(x)
		35,15	38,61	-3,47	-5,471	-1,467	35,23	0,0076	0,32860
		35,29	38,62	-3,33	-5,334	-1,330		0,0034	Mean standard uncertainty
		35,42	38,69	-3,27	-5,276	-1,273		0,0341	$u_a(\bar{x})$
		35,52	38,76	-3,24	-5,240	-1,236		0,0850	0,04278
		35,54	38,92	-3,39	-5,389	-1,386		0,0924	Mykratos Uncertainty
		35,38	39,02	-3,64	-5,644	-1,640		0,0212	u_{b1} [%]
		35,04	39,09	-4,05	-6,050	-2,046		0,0366	1
		34,77	39,06	-4,28	-6,287	-2,283		0,2098	Sensor Resolution
		34,79	38,86	-4,07	-6,071	-2,068		0,1931	u_{b2} [%]
		34,94	38,61	-3,67	-5,672	-1,668		0,0830	0,01
		35,10	38,43	-3,33	-5,334	-1,330		0,0173	Combined Uncertainty
		35,21	38,40	-3,18	-5,183	-1,179		0,0003	$u_c(x)$
		35,28	38,42	-3,14	-5,140	-1,136		0,0023	1,00096
		35,34	38,49	-3,15	-5,156	-1,152		0,0109	Expanded Uncertainty
		35,42	38,62	-3,20	-5,201	-1,197		0,0341	U(x)
		35,52	38,71	-3,19	-5,195	-1,191		0,0802	2,00193
		35,59	38,80	-3,21	-5,213	-1,209		0,1293	Coverage factor
		35,57	38,91	-3,35	-5,350	-1,346		0,1106	k
		35,56	38,97	-3,41	-5,409	-1,405		0,1102	2
		35,62	39,02	-3,40	-5,402	-1,399		0,1469	UPPER LIMIT
		35,64	39,02	-3,38	-5,384	-1,380		0,1640	UL
		35,66	39,02	-3,36	-5,362	-1,358		0,1820	5
		35,65	39,10	-3,45	-5,454	-1,450		0,1741	LOWER LIMIT
		35,63	39,16	-3,53	-5,531	-1,528		0,1557	LL
		35,60	39,11	-3,50	-5,506	-1,502		0,1386	-5
		35,60	39,08	-3,48	-5,485	-1,481		0,1332	guard-band factor
		35,63	39,04	-3,41	-5,415	-1,411		0,1591	kw
		35,57	39,01	-3,44	-5,447	-1,443		0,1128	2
		35,49	39,03	-3,54	-5,547	-1,543		0,0657	guard-band
		35,49	39,02	-3,53	-5,534	-1,530		0,0672	g
		35,49	39,02	-3,53	-5,532	-1,528		0,0681	0,08556
		35,49	38,99	-3,50	-5,505	-1,501		0,0648	UPPER ACCEPTANCE LIMIT
		35,48	38,98	-3,50	-5,501	-1,497		0,0600	UAL=UL-g
		35,43	38,97	-3,54	-5,540	-1,537		0,0379	4,9144
		35,39	39,01	-3,63	-5,628	-1,624		0,0238	LOWER ACCEPTANCE LIMIT
		35,39	38,99	-3,60	-5,603	-1,599		0,0239	LAL=LL+g
		35,41	38,87	-3,47	-5,471	-1,467		0,0298	-4,9144
		35,38	38,81	-3,44	-5,441	-1,437		0,0203	
		35,28	38,81	-3,54	-5,539	-1,535		0,0019	
		35,25	38,83	-3,58	-5,580	-1,576		0,0003	
		35,25	38,79	-3,55	-5,548	-1,544		0,0003	
		35,22	38,74	-3,52	-5,523	-1,519		0,0002	
		35,16	38,71	-3,55	-5,551	-1,547		0,0056	
		35,08	38,60	-3,52	-5,519	-1,516		0,0230	
		35,01	38,58	-3,57	-5,569	-1,565		0,0480	
		34,98	38,58	-3,61	-5,610	-1,606		0,0659	
		34,97	38,59	-3,62	-5,618	-1,614		0,0669	
		34,92	38,49	-3,57	-5,576	-1,572		0,0982	
		34,81	38,31	-3,50	-5,498	-1,494		0,1753	
		34,77	38,30	-3,53	-5,534	-1,530		0,2141	
		34,73	38,35	-3,62	-5,621	-1,617		0,2514	
		34,67	38,31	-3,64	-5,639	-1,635		0,3126	
		34,66	38,26	-3,60	-5,605	-1,601		0,3334	
		34,62	38,18	-3,56	-5,563	-1,559		0,3763	
		34,57	38,06	-3,49	-5,489	-1,485		0,4397	
		34,54	38,00	-3,46	-5,466	-1,462		0,4794	
Sampling time		1 data/s averaged on 30s	1 data/30s				$\Sigma (x_k-\bar{x})^2$	6,2628	

The graph in Fig.89, shows the curves representing the measurement error with its uncertainty component, in relation to the limits allowed by the established CMRs (± 5%). While the upper limit, as well as the upper acceptance limit, are not exceeded, the values do not fall within the lower limit. Therefore, also in this case, the sensor is not verified and requires a true calibration operation.

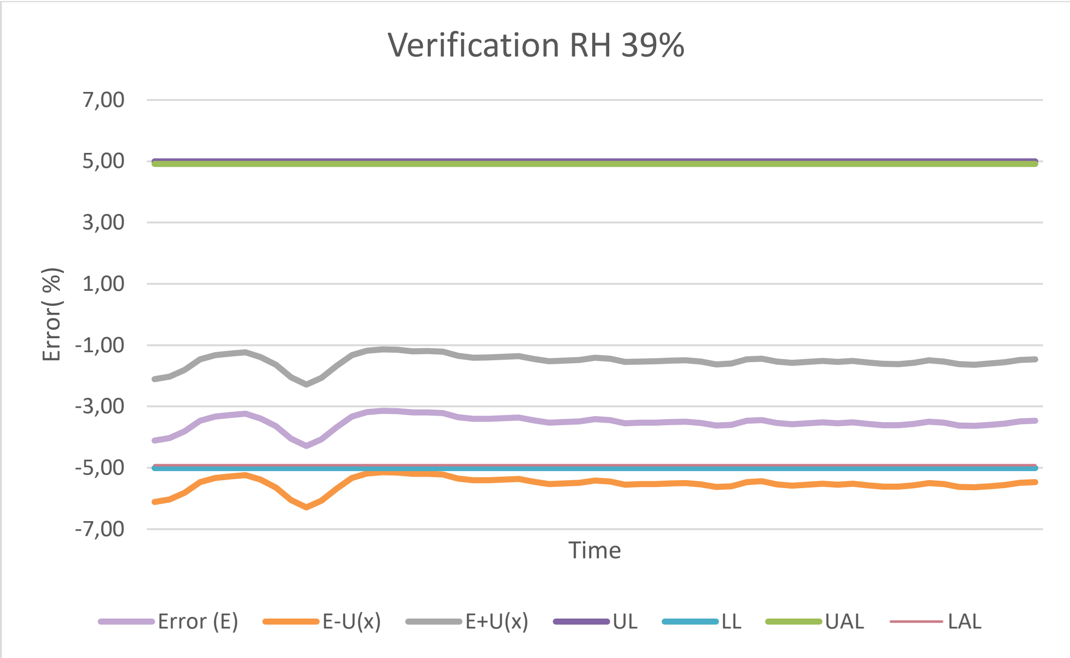


Figure 85 Calibration verification with a confidence level of 95% at RH 39%

RH 75%

The test under conditions of 75 percent relative humidity lasted 26 minutes, collecting a total of 51 data. Their analysis shows that the sensor underestimates the actual value more than previous cases in the range of -4.82÷-5.80 %, as shown in Tab 49. The deviation of the data measured by the two devices is also evidenced by the readings graphically shown in Fig.90.

The combined uncertainty is 1.002 %, while the expanded uncertainty is 2.005 %.

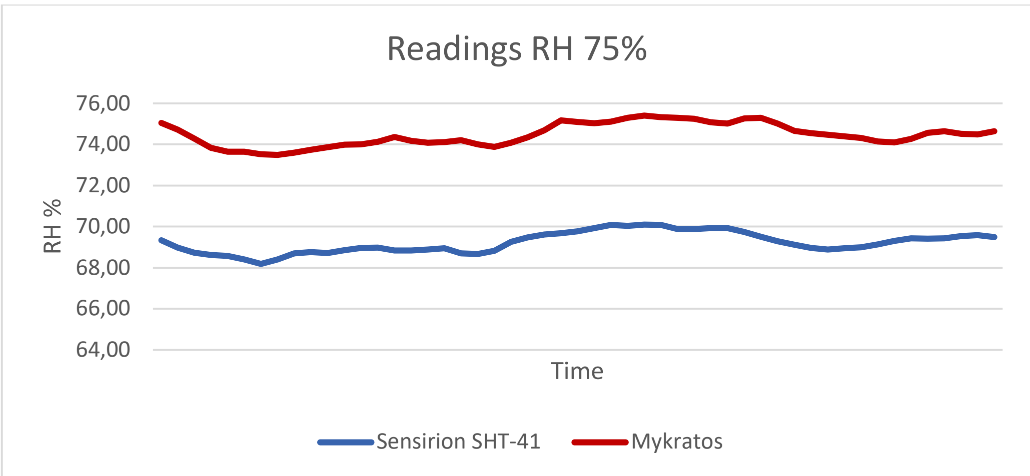


Figure 86 Sensor and reference instrument readings RH 75%

Table 48 Calculation of error, statistic indexes, uncertainties and acceptance limits for relative humidity 75%

Starting time	End time	Relative Humidity		Measurement Error	E-U(X)	E+U(X)	Number of measurements	$(x_k - \bar{x})^2$	Sample Variance
17.34	18:00	Sensiron SHT-41	Mykratos climatic chamber	E			n		$s^2(x)$
		69,33	75,05	-5,72	-7,723	-3,713	51	0,0128	0,25780
		68,98	74,72	-5,75	-7,751	-3,740	Empirical mean	0,0578	Standard Deviation
		68,72	74,29	-5,57	-7,574	-3,563	X	0,2500	s(x)
		68,62	73,83	-5,21	-7,217	-3,207	69,22	0,3584	0,50774
		68,58	73,65	-5,07	-7,077	-3,067		0,4130	Mean standard uncertainty
		68,40	73,65	-5,25	-7,253	-3,243		0,6751	$u_a(\bar{x})$
		68,19	73,52	-5,33	-7,340	-3,329		1,0664	0,07110
		68,41	73,50	-5,09	-7,100	-3,090		0,6615	Mykratos Uncertainty
		68,69	73,60	-4,91	-6,917	-2,906		0,2791	u_{b1} [%]
		68,76	73,74	-4,98	-6,984	-2,973		0,2079	1
		68,72	73,87	-5,15	-7,159	-3,149		0,2520	Sensor Resolution
		68,85	73,99	-5,15	-7,152	-3,141		0,1399	u_{b2} [%]
		68,96	74,01	-5,05	-7,055	-3,045		0,0693	0,01
		68,97	74,12	-5,16	-7,163	-3,152		0,0633	Combined Uncertainty
		68,84	74,36	-5,52	-7,523	-3,513		0,1452	$u_c(x)$
		68,83	74,17	-5,34	-7,346	-3,335		0,1487	1,00257
		68,88	74,08	-5,21	-7,212	-3,201		0,1183	Expanded Uncertainty
		68,95	74,12	-5,17	-7,172	-3,162		0,0722	U(x)
		68,69	74,21	-5,52	-7,523	-3,513		0,2820	2,00515
		68,66	74,00	-5,34	-7,344	-3,334		0,3095	Coverage factor
		68,82	73,88	-5,07	-7,074	-3,064		0,1629	k
		69,26	74,08	-4,82	-6,822	-2,812		0,0017	2
		69,48	74,34	-4,86	-6,869	-2,859		0,0679	UPPER LIMIT
		69,61	74,69	-5,08	-7,085	-3,075		0,1529	UL
		69,67	75,16	-5,49	-7,498	-3,488		0,2049	5
		69,77	75,09	-5,32	-7,326	-3,316		0,3051	LOWER LIMIT
		69,93	75,03	-5,10	-7,102	-3,092		0,5055	LL
		70,08	75,11	-5,03	-7,037	-3,027		0,7362	-5
		70,03	75,30	-5,27	-7,272	-3,261		0,6653	guard-band factor
		70,11	75,41	-5,30	-7,309	-3,298		0,7921	kw
		70,08	75,33	-5,25	-7,256	-3,246		0,7362	2
		69,88	75,29	-5,42	-7,423	-3,412		0,4317	guard-band
		69,88	75,25	-5,37	-7,378	-3,367		0,4378	g
		69,92	75,08	-5,16	-7,163	-3,153		0,4961	0,14219
		69,92	75,02	-5,10	-7,107	-3,097		0,4881	UPPER ACCEPTANCE LIMIT
		69,74	75,26	-5,52	-7,523	-3,513		0,2749	UAL=UL-g
		69,50	75,30	-5,80	-7,807	-3,797		0,0799	4,8578
		69,28	75,02	-5,74	-7,745	-3,735		0,0042	LOWER ACCEPTANCE LIMIT
		69,11	74,66	-5,54	-7,549	-3,538		0,0110	LAL=LL+g
		68,96	74,55	-5,59	-7,598	-3,587		0,0666	-4,8578
		68,89	74,47	-5,58	-7,585	-3,575		0,1107	
		68,95	74,39	-5,45	-7,451	-3,441		0,0734	
		68,99	74,32	-5,33	-7,337	-3,327		0,0534	
		69,12	74,14	-5,02	-7,020	-3,010		0,0090	
		69,30	74,10	-4,80	-6,800	-2,790		0,0071	
		69,43	74,27	-4,84	-6,846	-2,836		0,0461	
		69,41	74,56	-5,15	-7,156	-3,146		0,0364	
		69,42	74,64	-5,22	-7,225	-3,215		0,0412	
		69,54	74,51	-4,98	-6,980	-2,970		0,1026	
		69,58	74,49	-4,91	-6,914	-2,903		0,1298	
		69,50	74,65	-5,15	-7,155	-3,144		0,0765	
Sampling time		1 data/s averaged on 30s	1 data/30s				$\Sigma (x_k - \bar{x})^2$	12,8899	

The graph in Fig.91 shows a more critical situation than the previous ones, as even the measurement error, which neglects the uncertainty component, crosses the lower limit. Therefore, the sensor is not verified in this range and needs a calibration process.

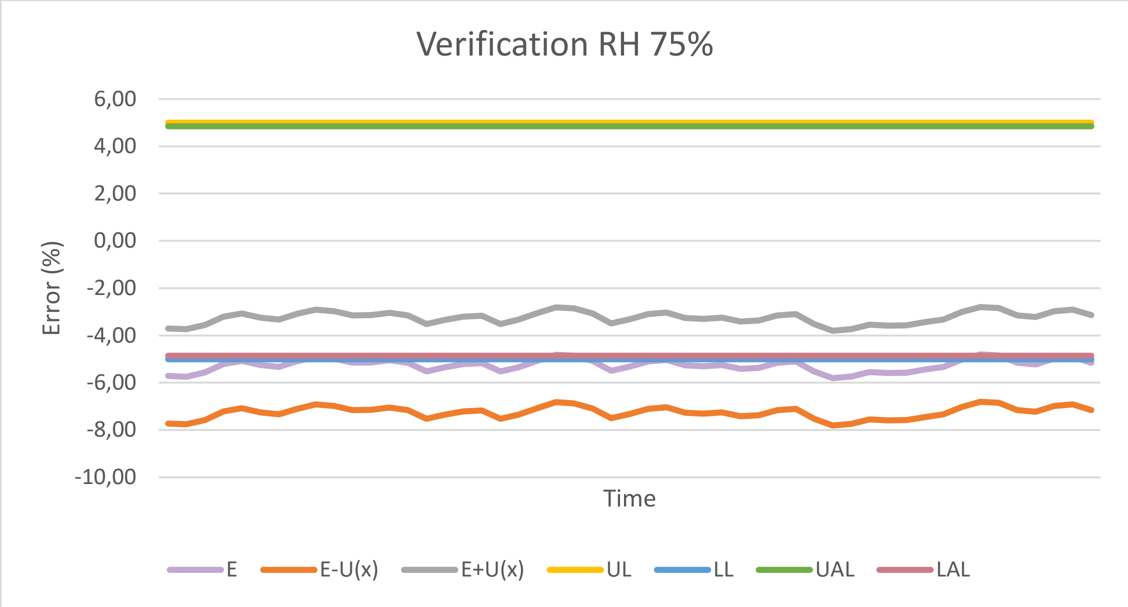


Figure 87 Calibration verification with a confidence level of 95% at RH 75%

RH 94%

The test under conditions of 94 percent relative humidity lasted 28 minutes, collecting a total of 47 data. Their analysis shows an underestimate in the range of -5,55÷-6,70%, as shown in Tab 50. The deviation of the data measured by the two devices is also evidenced by the readings graphically shown in Fig.92. It is therefore possible to say that the effective uncertainty of the sensor increases with increasing relative humidity conditions.

The combined uncertainty is 1 %, while the expanded uncertainty is 2 %.

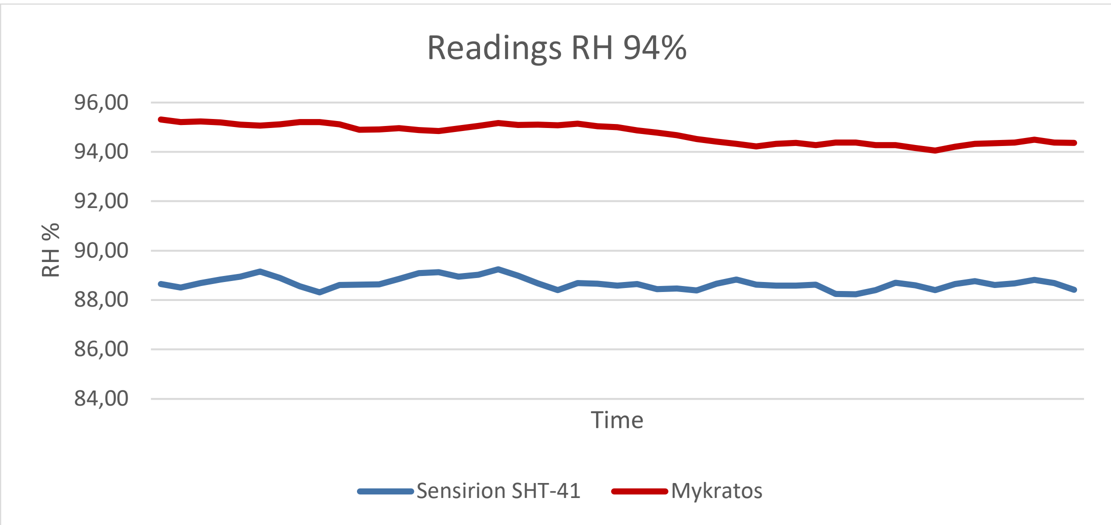


Figure 88 Sensor and reference instrument readings RH 94%

Table 49 Calculation of error, statistic indexes, uncertainties and acceptance limits for relative humidity 94%

Starting time	End time	Relative Humidity		Measurement Error	E-U(X)	E+U(X)	Number of measurements	$(x_k - \bar{x})^2$	Sample Variance
12:28	12:52	Sensiron SHT-41	Mykratos climatic chamber	E			n		$s^2(x)$
		88,64	95,31	-6,67	-8,670	-4,668	47	0,0010	0,05470
		88,51	95,21	-6,70	-8,701	-4,698	Empirical mean	0,0268	Standard Deviation
		88,68	95,23	-6,55	-8,554	-4,551	X	0,0000	s(x)
		88,83	95,19	-6,35	-8,354	-4,351	88,68	0,0249	0,23387
		88,94	95,10	-6,16	-8,161	-4,159		0,0718	Mean standard uncertainty
		89,15	95,07	-5,91	-7,914	-3,911		0,2294	$u_a(\bar{x})$
		88,89	95,11	-6,22	-8,223	-4,220		0,0468	0,03411
		88,56	95,21	-6,64	-8,645	-4,643		0,0128	Mykratos Uncertainty
		88,31	95,20	-6,89	-8,891	-4,888		0,1315	u_{b1} [%]
		88,61	95,12	-6,50	-8,504	-4,501		0,0036	1
		88,62	94,90	-6,28	-8,279	-4,276		0,0031	Sensor Resolution
		88,64	94,90	-6,26	-8,263	-4,261		0,0013	u_{b2} [%]
		88,86	94,96	-6,10	-8,098	-4,096		0,0345	0,01
		89,09	94,89	-5,80	-7,799	-3,796		0,1717	Combined Uncertainty
		89,12	94,85	-5,72	-7,722	-3,720		0,2019	$u_c(x)$
		88,94	94,95	-6,01	-8,007	-4,004		0,0720	1,00063
		89,03	95,05	-6,02	-8,023	-4,020		0,1248	Expanded Uncertainty
		89,25	95,17	-5,92	-7,921	-3,918		0,3272	U(x)
		88,98	95,09	-6,11	-8,114	-4,112		0,0928	2,00126
		88,68	95,10	-6,42	-8,417	-4,414		0,0000	Coverage factor
		88,40	95,07	-6,67	-8,676	-4,673		0,0773	k
		88,69	95,14	-6,45	-8,446	-4,444		0,0003	2
		88,65	95,04	-6,39	-8,388	-4,385		0,0004	UPPER LIMIT
		88,58	95,00	-6,43	-8,427	-4,424		0,0096	UL
		88,65	94,86	-6,21	-8,216	-4,213		0,0007	5
		88,44	94,77	-6,33	-8,329	-4,327		0,0534	LOWER LIMIT
		88,46	94,67	-6,21	-8,210	-4,207		0,0445	LL
		88,39	94,51	-6,12	-8,119	-4,117		0,0786	-5
		88,66	94,41	-5,75	-7,751	-3,749		0,0002	guard-band factor
		88,83	94,32	-5,49	-7,492	-3,489		0,0236	kw
		88,62	94,22	-5,60	-7,605	-3,603		0,0034	2
		88,58	94,33	-5,75	-7,749	-3,746		0,0089	guard-band
		88,59	94,36	-5,77	-7,775	-3,773		0,0073	g
		88,62	94,28	-5,66	-7,662	-3,659		0,0035	0,06823
		88,25	94,38	-6,13	-8,127	-4,125		0,1795	UPPER ACCEPTANCE LIMIT
		88,24	94,37	-6,13	-8,131	-4,128		0,1886	UAL=UL-g
		88,41	94,27	-5,86	-7,866	-3,863		0,0727	4,9318
		88,69	94,27	-5,58	-7,577	-3,574		0,0004	LOWER ACCEPTANCE LIMIT
		88,60	94,16	-5,56	-7,559	-3,557		0,0056	LAL=LL+g
		88,40	94,06	-5,66	-7,664	-3,662		0,0764	-4,9318
		88,65	94,20	-5,55	-7,549	-3,547		0,0005	
		88,76	94,32	-5,56	-7,563	-3,560		0,0074	
		88,60	94,35	-5,74	-7,744	-3,742		0,0049	
		88,68	94,38	-5,70	-7,701	-3,699		0,0000	
		88,82	94,49	-5,68	-7,678	-3,676		0,0202	
		88,69	94,37	-5,69	-7,688	-3,685		0,0002	
		88,41	94,36	-5,95	-7,949	-3,946		0,0701	
Sampling time		1 data/s averaged on 30s	1 data/30s				$\Sigma (x_k - \bar{x})^2$	2,5161	

As expected, the test at 94% relative humidity shows the sensor behavior that most differs from what is certified by the manufacturer. It is therefore not suitable for use and needs to be calibrated before utilization.

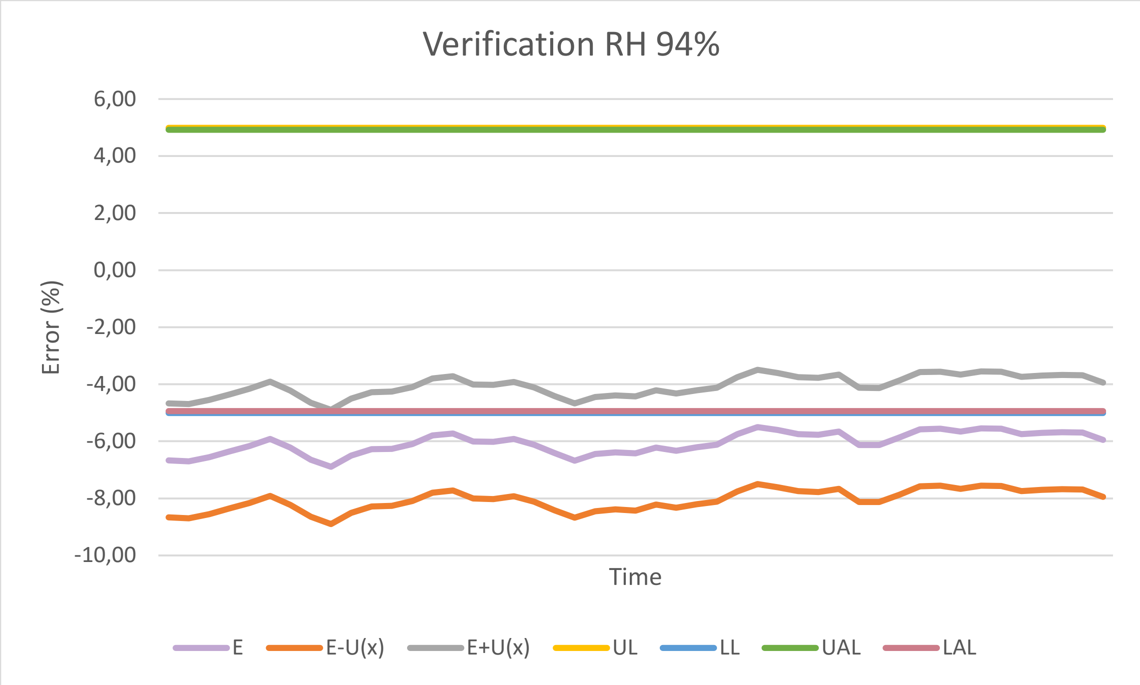


Figure 89 Calibration verification with a confidence level of 95% at RH 94%

CALIBRATION RESULTS

Through Matlab software, an appropriate code was generated to find the calibration function that could characterize the SHT41 relative humidity sensor. Since, as shown in Fig.93, the most unfavorable situation occurred under relative humidity conditions of 94%, the calibration function of the measurement chain was based on 3 data collected at RH 94%, 2 data at RH 75%, 2 data at RH 39% and 2 data at RH 22% Specifically, the data used are as follows:

Table 50 RH data used for calibration

RH		22%		39%		75%		94%		
Device	Reference	21.79	22.12	39.02	38.92	75.05	74.72	95.31	95.21	95.23
	Sensor	18.99	18.37	34.91	34.89	69.33	69.98	88.64	88.51	88.68

Fig.94 shows on the y-axis the value of the measurement with the sensor in calibration, and on the x-axis the reference value given by the instrument. The blue dots indicate the experimental values, i.e., the measured value in relation to the actual value, while the magenta line represents the linear calibration function, obtained by minimizing the sum of the square root of the difference between the function and the experimental values.

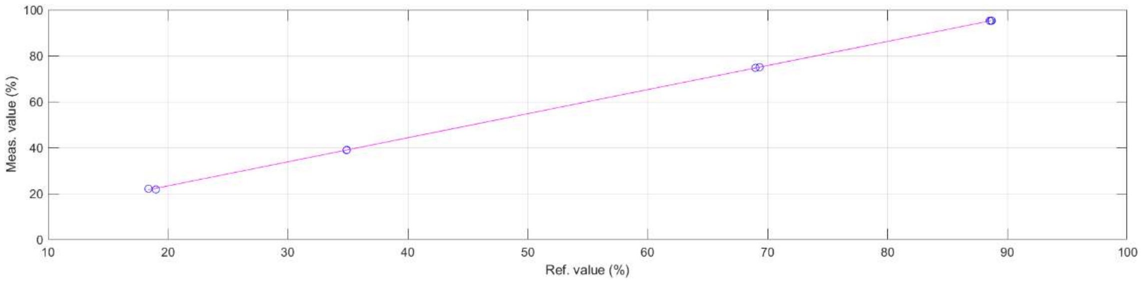


Figure 90 Calibration relation plotted through Matlab

Through the polyfit function, the polynomial that fits the data set previously shown in Tab.51 was found. The angular coefficient (m), that is, the slope of the calibration line, results in 1.048, while the intercept (q) equals 2.387. So the calibration function results:

$$y = 1{,}048 \cdot x + 2{,}387$$

The residual fitting error of about 0.5% is shown in Fig.95. This uncertainty value is added to the uncertainty of the reference instrument, which is 1%. This results in an expanded uncertainty (U_{adj}(RH)) of 0.5+1% m.v.

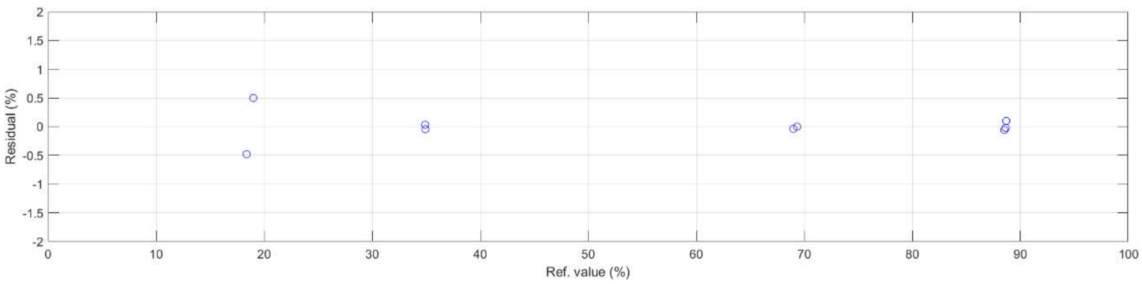


Figure 91 Residuals over reference value plotted through Matlab

Next, the relative humidity measurement chain was verified by comparing 9 additional data:

Table 51 RH data for calibration verification

RH		22%		39%		75%		94%		
Device	Reference	21.71	21.99	38.06	38.00	74.49	74.65	95.20	95.21	95.11
	Sensor	18.72	19.12	34.57	34.54	69.58	69.50	88.31	88.56	88.89

The following results are shown in Fig.96:

Axis y= Error (%)

Axis x= reference value (%)

Blue continuous line= extended measurement uncertainty of the characterized chain

Red symbols= are the data obtained before characterization

Green symbols= data obtained after characterization

The results show that the procedure was successful as all green symbols fall within the uncertainty range required by the previously imposed CMRs.

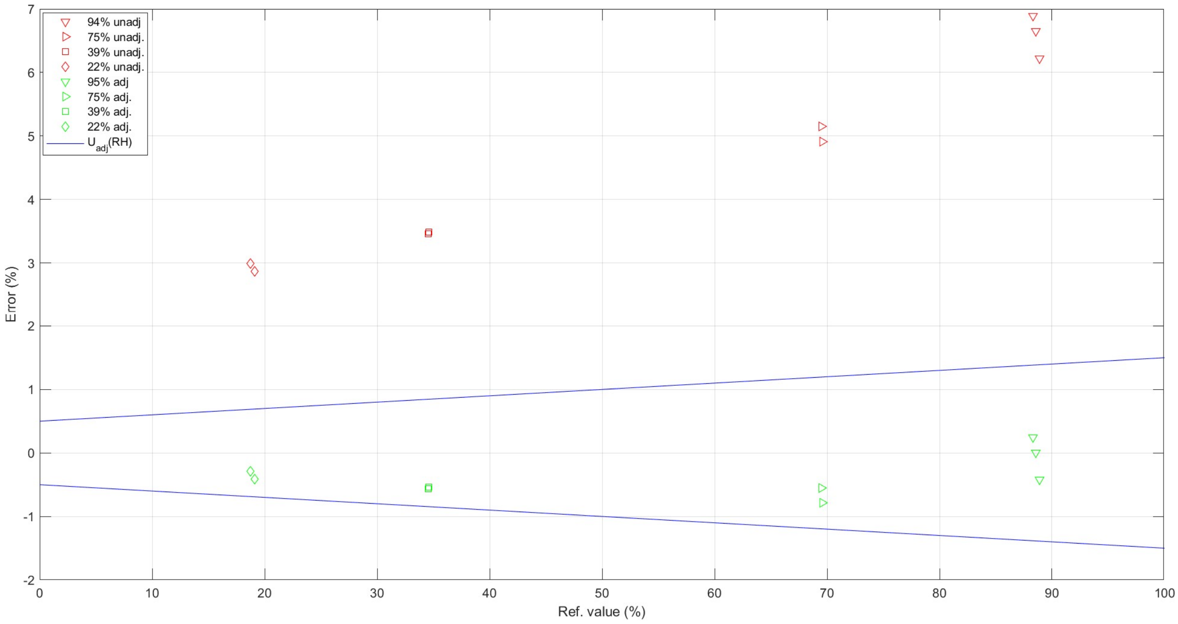


Figure 92 Adjusted error U_{adj}(RH) plotted though Matlab

The newly characterized data (green asterisk) are shown in the graph in Fig.97, where they are related to the pre-characterization data (red asterisk).

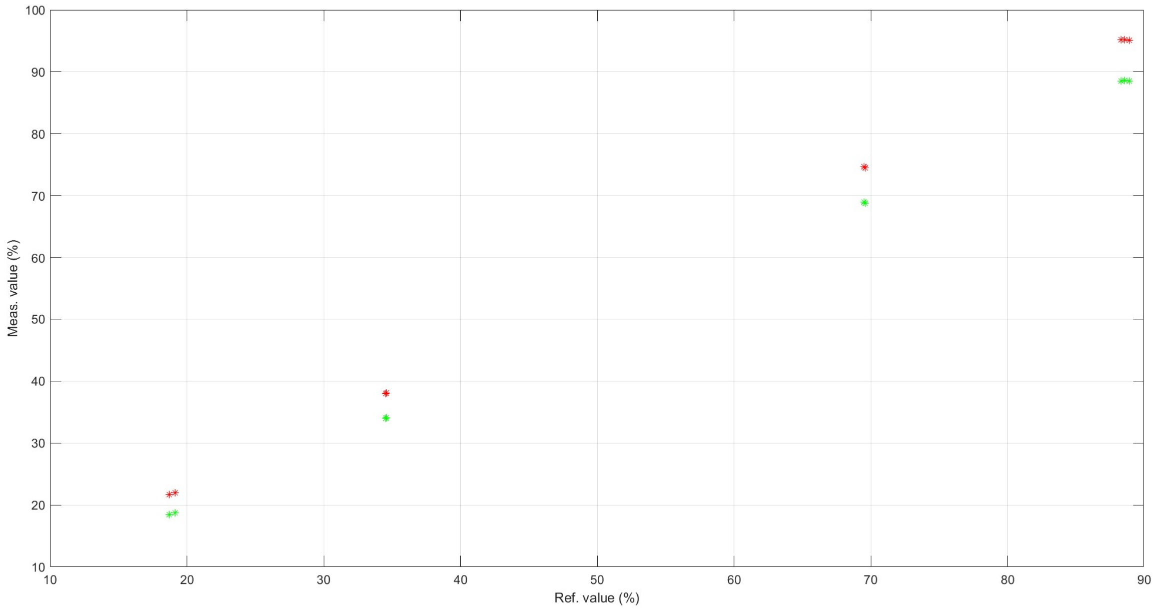


Figure 93 Data before and after metrological characterization

3.6.2 Visual: Illuminance Sensor

Setting and procedure

Calibration of the illuminance sensors is carried out at LAMSA in Turin, Italy (Laboratory for Analysis and Modelling of Environmental Systems). The testing is performed inside a completely dark room with closed doors and shutters. Field experiments are conducted over several days to test as many setups as possible. Basically, the goal is to understand the influence on sensor accuracy as it varied by:

1. LED light sources with different colour temperatures (2700K, 4000K, 5700K).

2. Upper covers with openings of different geometry.

Methodologically, calibration is performed by comparison between a reference sensor, namely RadioLux 111 luximeter (uncertainty ± 6,48%), and two low cost sensors, Vishay VEML7700 (uncertainty ± 15% m.v.).

Operationally, some instrumentation is necessary:

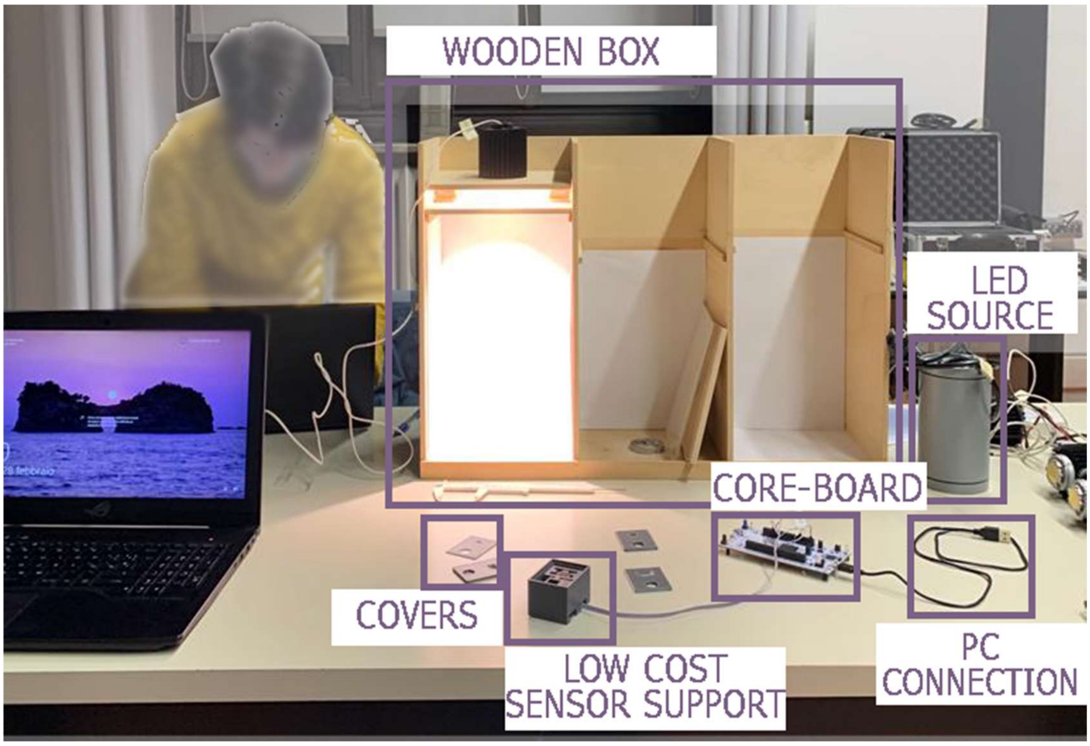


Figure 94 Instrumentation required for the test

1. WOODEN BOX: The experiment is simulated inside a plywood box (Fig.99), which is drilled on the top. The upper cover board is drilled to insert the LED

Figure 95 Wooden box

light source, while a second lower drilled board is needed for the application or non-application of the neutral density filter (nd). Internally, the structure is covered with white paper sheets in order to increase reflectivity, which would otherwise be reduced by the color and roughness of the wooden material. 2. LUXMETER SUPPORT: The photometer that acquires the data transmitted to the luxmeter is housed on a stand with a cylindrical base with a diameter of 55 mm and a total height, including the sensor, of 37.5 mm (Fig.101 a).

3. LOW COST SENSOR SUPPORT: The sensor is placed inside a rectangular PLB container with dimensions 58x40x37.5mm, 3D printed at the Polytechnic University of Turin, and configured to contain both the illuminance (E) sensor and the sound pressure level detection sensor (Fig. 100).

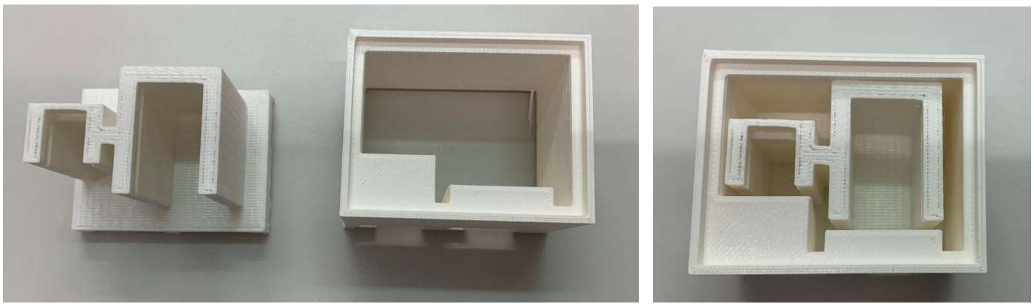


Figure 96 Low cost sensor support, 3D printed

In order not to affect the acquired data and respect the calibration protocol, the sensor must receive the light beam produced by the source, perfectly on the photoreceptor. To position the sensor perfectly in the box, two operations are conducted:

1. Take the measurements of the photoreceptor from the edges of the low cost sensor support (15.5mm from the right edge, 21mm from the bottom edge and 22.5mm from the top edge).
2. The outline of the container is traced in pencil on the white sheet covering the base of the wooden box.
3. The box containing the sensor is placed perfectly in the traced edges, taking care to always position it by pointing the connecting cables toward the open part of the structure.

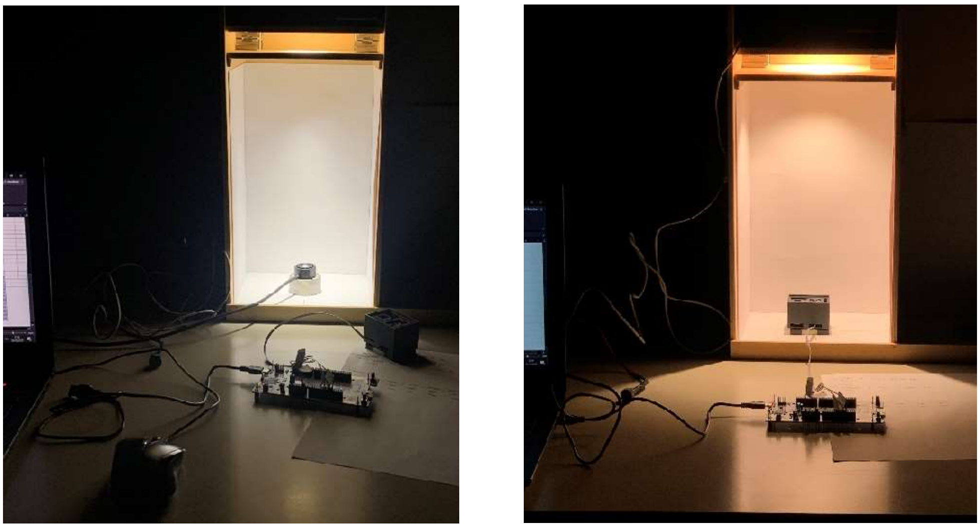


Figure 97 (a) luximeter support, tested at 4000K; (b) LCS support, tested under 2700K

4. INCLINED SUPPORTS: The purpose of the experiment is to evaluate the behavior of the sensor not only in the case of light incident perpendicular to the sensor but also in the case of grazing light. For this reason, two inclined supports of 30° and 60° are modeled and 3D printed, in Politecnico di Torino (Fig.102). The measurements (30°, 60°) are also chosen to optimize the subsequent comparison between the field calibration and that made by the manufacturer, which is reported on the datasheet. On the graph Relative Radiant Sensitivity versus Angular Displacement is associated, in fact, for each angle of incidence of the light source, the light sensitivity of the associated photoreceptor diode (see paragraph 2.4.2). For example, it is shown that for a VISHAY VELM 7700 sensor, an incidence angle of 30° corresponds to a sensitivity of about 85%, as well as for an angle of 60°, a sensitivity of 40%.

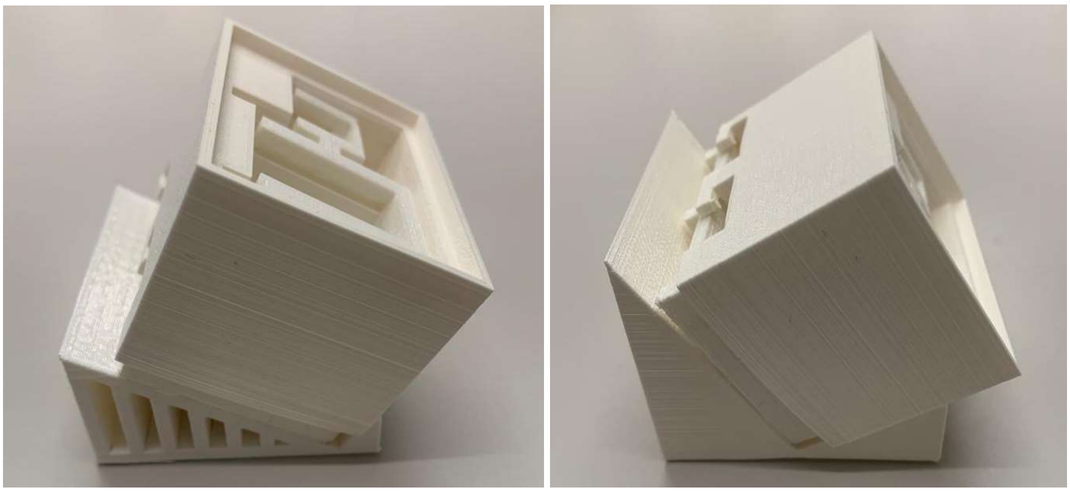


Figure 98 Inclined supports (a) 30°, (b) 60°.

5. CONNECTIONS: For data acquisition of the Visahy VELM 7700 low-cost sensor, the connections adopted are:

- Sensor-coreboard connection, via 20-cm-long cables outside the wooden box;
- Core board-PC connection, via USB cable to be connected to the computer input.

Moreover, the following connection system is required to acquire data for the RadioLux 111 reference instrument:

- Photoreceptor-luxmeter connection through a jack cable;
- Luxmeter-PC connection through a USB cable.

6. LED LIGHT SOURCES: The response of the sensor to 3 types of LED sources is tested:

SOURCE 1:

- 2700 K (yellow, warm light)
- DIMMERABLE (possibility to adjust the light intensity from time to time).

Additional notes: the spectrum of this source is very close to that of a halogen lamp, so the manufacturer of the vishay VELM 7700 claims lower sensor accuracy.

SOURCE 2:

- 4000 K (WARM WHITE LIGHT)
- NON-DIMMABLE

SOURCE 3:

- 5700 K (COOL WHITE LIGHT)
- NOT DIMMABLE
- Luminous efficiency: 59 lm/W
- CRI (color rendering index): 80
- IP: 65

7. OPTICAL FILTERS: A neutral density filter is used, specifically an optical filter from a camera. Its purpose is to reduce the light intensity of the source, but without altering its spectrum.

8. COVERS: The purpose of the calibration process involves the behavioural analysis of the Vishay sensor, by comparison with the reference instrument, either bare or when embedded and closed by specially made covers. Four

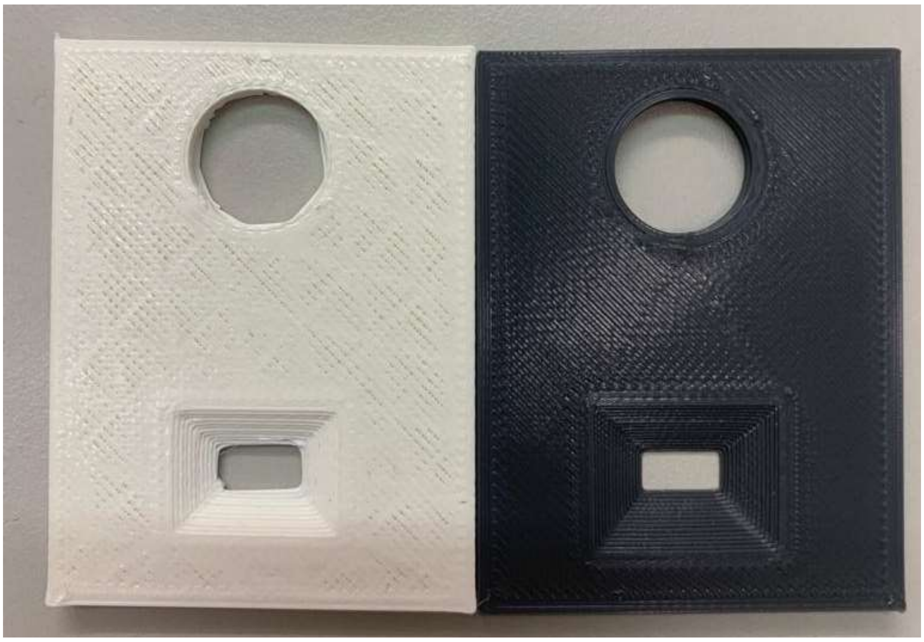


Figure 99 Cover 2 (45°), Cover 3 (60°)

covers were printed that had the opening above the sensor of different sizes and characteristics.

COVER 1:

Dimensions: 52.86 x 40 x 3 mm

The rectangular hole of size 9.17 x 5.31, 3 mm deep, is expected to generate marked shadows on the sensor, impairing its data acquisition, whose illuminance value would be far lower. The risk is greater in the case of grazing light, so the shape of the hole has been declined into two additional variants.

COVER 2:

Dimensions: 52.86 x 40 x 3 mm

The rectangular hole possesses walls that are inclined 45°, thus generating upper dimensions of 15.17 x 11.31 mm, and lower dimensions of 9.17 x 5.31 mm.

This configuration is expected to provide benefits in both normal incident and especially grazing light.

COVER 3:

Dimensions: 52.86 x 40 x 3 mm

The rectangular hole possesses walls that are inclined by 60°, thus generating higher dimensions of 21.46 x 15.91 mm, and lower dimensions of 9.17 x 5.31 mm.

This configuration is expected to provide benefits in both normal incident and especially grazing light, with superior performance to those with cover 2.

COVER 4:

Dimensions: 52.86 x 40 x 1 mm

The lid is totally analogous to n. 1, except for the thickness reduced to 1 mm. This choice was made to test how much this size can change the incidence of light and consequently the accuracy of the acquired data.

The process of the test is explained below:

The reference luxmeter acquires data through the photoreceptor, which are then made visible on the instrument display. The data are then collected on an Excel spreadsheet, previously programmed with a spreadsheet extension such that 1 data item per second is reported on each cell, for a total of 30 data items. Then they were averaged (V_{meanl}).

The low-cost Vishay VELM 7700 sensor, on the other hand, acquires 30 readings every two seconds, per setup. The first 30 values from the generated text file, are copied and pasted onto an excel sheet and their average value is calculated (V_{meanlc}).

Finally, the relative deviation (SR%) is calculated, i.e., by what percentage the low-cost sensor underestimates or overestimates the Illuminance (E) value compared to the reference instrument, hence, by how much it deviates from the same. The average value of the luxmeter data (V_{meanl}) is first subtracted from the average value calculated by the low cost sensor (V_{meanlc}), then divided by the same average value of the luxmeter. The result was obtained as a percentage.

$$SR\% = \frac{\mathrm{Vmeanl} - \mathrm{Vmeanlc}}{\mathrm{Vmeanl}}$$

This first calculation, which neglects the uncertainty component, was used primarily to understand which geometric configurations would allow the sensor to perform best.

RESULTS

The first comparison of results was made between those for sensor 1 exposed to LED sources with different color temperatures. The data are shown in Tab.53. It shows the average of the data acquired by the sensor, the average of the data acquired by the luxmeter, and the percentage error, calculated as described above. The two settings are: with and without cover, with and without filter, and with dimmer at maximum.

Table 52 Sensor 1 exposed to light sources with different coulour temperatures

SENSOR 1

28/02/2023		
2700 K dimmerabile	4000 K non dimmerabile	5700 K non dimmerabile
no cover		
no filter		
dimmer max		
MEAN (lx)	MEAN (lx)	MEAN (lx)
3537,80	3486,62	6063,65
LUXMETRO (lx)	LUXMETRO (lx)	LUXMETRO (lx)
4344	4049	8043
PERCENTAGE ERROR (%)	PERCENTAGE ERROR (%)	PERCENTAGE ERROR (%)
18,56	13,89	24,61

2700 K dimmerabile	4000 K non dimmerabile	5700 K non dimmerabile
no cover		
with filter		
dimmer max		
MEAN (lx)	MEAN (lx)	MEAN (lx)
36,76	32,45	62,18
LUXMETRO (lx)	LUXMETRO (lx)	LUXMETRO (lx)
36,48	30,86	65,05
PERCENTAGE ERROR (%)	PERCENTAGE ERROR (%)	PERCENTAGE ERROR (%)
-0,76	-5,16	4,41

As can be seen, overall Sensor 1 tends to behave better when exposed to an LED source with color temperature 2700 K, as well as the one that can best emulate the visible spectrum. Therefore, subsequent tests were conducted exclusively using that light source.

The second comparison was carried out under conditions involving:

- 2700K LED source
- Absence of cover to close the holder
- Absence of optical filter
- Dimmer at maximum and minimum

It is evident that the data acquired from sensor 2 tended to deviate less from the actual data, compared to those acquired from sensor 1. The cause probably falls on both wear and tear, as sensor one was used for a longer time, as well as exposed to higher temperatures for technical reasons. Also, as previously stated, the expected operation stated by the manufacturer is not the same among all sensors.

The second obvious result is that when the the dimmer is idling, and therefore the illuminance values are lower, the sensors tend to behave more like the luxmeter.

A third evidence lies in the fact that the dark gray colored holder always collects lower illuminance data than those collected by the sensor inside the new white colored holder. It is hypothesized that the cause lies in the color of the enclosure itself. White, in fact tends to reflect the light incident on the sensor, thus generating higher illuminance values.

Table 53 Sensor 1 and 2 inside new and old support (no filter)

28/02/2023	24/03/2023	24/03/2023	03/04/2023	03/04/2023
sensore 1	sensore 1	sensore 1	sensore 2	sensore 2
2700 K dimmerabile				
no coperchio				
senza filtro				
dimmer al massimo				
supporto grigio	supporto nuovo	supporto nuovo	supporto nuovo	supporto nuovo
prima misura	prima misura	seconda misura	prima misura	seconda misura
MEDIA:	MEDIA:	MEDIA:	MEDIA:	MEDIA:
3537,80	3671,07	3658,54	4044,81	4030,74
VALORE LUXMETRO	VALORE LUXMETRO	VALORE LUXMETRO	VALORE LUXMETRO:	VALORE LUXMETRO:
4344	4398,2	4395,2	4532,07	4516,53
ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE
18,56	16,53	16,76	10,75	10,76
sensore 1	sensore 1	sensore 1	sensore 2	sensore 2
2700 K dimmerabile				
no coperchio				
senza filtro				
dimmer al minimo				
supporto grigio	supporto nuovo	supporto nuovo	supporto nuovo	supporto nuovo
prima misura	prima misura	seconda misura	prima misura	seconda misura
MEDIA:			MEDIA:	MEDIA:
268,59	275,65	277,92	326,16	319,06
VALORE LUXMETRO			VALORE LUXMETRO:	VALORE LUXMETRO:
296,28	292,88	293,69	305,18	312,16
ERRORE PERCENTUALE			ERRORE PERCENTUALE	ERRORE PERCENTUALE
9,35	5,88	5,37	-6,87	-2,21

The results that emerged from the previous setting, were confirmed by the results shown in Tab.55. The present setting includes:

- 2700K LED source
- Absence of cover to close the stand
- Presence of optical filter
- Dimmer at maximum and minimum

Again, lower illuminance values correspond to results that are closer to the actual value. Note, however, that sensor 2 tends to greatly overestimate the true value, compared to sensor 1.

Table 54 Sensor 1 and 2 inside new and old support (with filter)

sensore 1	sensore 1	sensore 1	sensore 2	sensore 2
2700 K dimmerabile				
no coperchio				
con filtro				
dimmer al massimo				
supporto grigio	supporto nuovo	supporto nuovo	supporto nuovo	supporto nuovo
prima misura	prima misura	seconda misura	prima misura	seconda misura
MEDIA:			MEDIA:	MEDIA:
36,76	36,65	37,48	42,85	43,75
VALORE LUXMETRO			VALORE LUXMETRO:	VALORE LUXMETRO:
36,48	34,09	35,13	36,44	36,88
			ERRORE PERCENTUALE	ERRORE PERCENTUALE
-0,76	-7,50	-6,68	-17,59	-18,63
sensore 1	sensore 1	sensore 1	sensore 2	sensore 2
2700 K dimmerabile				
no coperchio				
con filtro				
dimmer al minimo				
supporto grigio	supporto nuovo	supporto nuovo	supporto nuovo	supporto nuovo
prima misura	prima misura	seconda misura	prima misura	seconda misura
MEDIA:			MEDIA:	MEDIA:
2,30	2,3	2,3	2,76	2,76
VALORE LUXMETRO			VALORE LUXMETRO:	VALORE LUXMETRO:
2,47	2,38	2,38	2,52	2,51
			ERRORE PERCENTUALE	ERRORE PERCENTUALE
6,96	3,36	3,36	-9,52	-9,96

The influence of the cover on sensor operation, is highlighted in Tab.56. As expected, the naked sensor performs better than in configurations with both a 90°-opening cover and a 60°-opening cover. However, the presence of a cover is necessary to protect the internal components of the multisensor. Therefore, it was decided to act on the shape of the opening near the illuminance sensor. As the results show, a normal 90° aperture generates shadows, resulting in an excessive underestimation of the true value by the sensor, by 33.08%. By flaring the aperture 60° from the vertical, the sensor is still found to underestimate the reference value, but by a smaller percentage than the previously tested cover. Therefore, subsequent tests were carried out on cover 1 (60°).

Table 55 Results with different covers openings

sensore 1	sensore 1	sensore 1
2700 K dimmerabile		
supporto grigio		
senza filtro		
dimmer al massimo		
senza coperchio	coperchio 90°	coperchio 60°
MEDIA:	MEDIA:	MEDIA:
3671,07	2930,99	3272,97
VALORE LUXMETRO	VALORE LUXMETRO	VALORE LUXMETRO
4398,2	4379,67	4370,07
16,53	33,08	25,10

Subsequently, the following configuration was tested:

- LED source with T 2700 K
- The sensor covered by the 60° cover
- Presence of the filter
- Dimmer at maximum and then at minimum

Contrary to expectations, when the dimmer is at maximum, the covered sensor performs better than the uncovered sensor. Note, however, that this happens only when the sensor is embedded in the new white-colored holder. This therefore could be explained by the high reflectivity of the holder, which alters and increases the illuminance reading. Therefore, the new multisensor case will have to take on a darker coloring, even if only internally. Under low illuminance conditions, and thus when the dimmer is at minimum, the covered sensor 1 tends to overestimate the reference value by almost 60%, while uncovered tended to underestimate it by about 3%. Sensor 2 tended to underestimate the actual value by 26.69%, while in the uncovered configuration it overestimated it by about 9%.

Table 56 Results with filter and 60° cover

sensore 1	sensore 1	sensore 1	sensore 2	sensore 2
2700 K dimmerabile				
coperchio 60°				
con filtro				
dimmer al massimo				
supporto grigio	supporto nuovo	supporto nuovo	supporto nuovo	supporto nuovo
prima misura	prima misura	seconda misura	prima misura	seconda misura
MEDIA:			MEDIA:	MEDIA:
30,60	34,47	35,14	37,97	38,43
VALORE LUXMETRO			VALORE LUXMETRO:	VALORE LUXMETRO:
36,75	35,63	35,78	36,54	36,85
			ERRORE PERCENTUALE	ERRORE PERCENTUALE
16,73	3,26	1,78	-3,92	-4,30
sensore 1	sensore 1	sensore 1	sensore 2	sensore 2
2700 K dimmerabile				
coperchio 60°				
con filtro				
dimmer al minimo				
supporto grigio	supporto nuovo	supporto nuovo	supporto nuovo	supporto nuovo
prima misura	prima misura	seconda misura	prima misura	seconda misura
MEDIA:			MEDIA:	MEDIA:
1,84	3,69	3,69	1,84	1,84
VALORE LUXMETRO			VALORE LUXMETRO:	VALORE LUXMETRO:
2,51	2,3	2,31	2,51	2,51
			ERRORE PERCENTUALE	ERRORE PERCENTUALE
26,63	-60,43	-59,74	26,69	26,69

Even in the configuration that differs from the previous one in the absence of the filter (see Tab.58), the data collected by the sensor tends to be less accurate as illuminance increases. In addition, the behavior of the covered sensor is worse than the uncovered one, as it tends to underestimate the readings almost twice as much.

Table 57 Results with 60° cove, without filter

sensore 1	sensore 1	sensore 1	sensore 2	sensore 2
2700 K dimmerabile	2700 K dimmerabile	2700 K dimmerabile	2700 K dimmerabile	2700 K dimmerabile
coperchio 60°				
senza filtro				
dimmer al minimo				
supporto grigio	supporto nuovo	supporto nuovo	supporto nuovo	supporto nuovo
prima misura	prima misura	seconda misura	prima misura	seconda misura
MEDIA:			MEDIA:	MEDIA:
221,81	242,84	246,35	261,86	264,65
VALORE LUXMETRO			VALORE LUXMETRO:	VALORE LUXMETRO:
303,30	293,53	291,99	292,27	296,77
			ERRORE PERCENTUALE	ERRORE PERCENTUALE
26,87	17,27	15,63	10,41	10,82
sensore 1	sensore 1	sensore 1	sensore 2	sensore 2
2700 K dimmerabile				
coperchio 60°				
senza filtro				
dimmer al massimo				
supporto grigio	supporto nuovo	supporto nuovo	supporto nuovo	supporto nuovo
prima misura	prima misura	seconda misura	prima misura	seconda misura
MEDIA:			MEDIA:	MEDIA:
2922,05	3272,97	3267,87	3490,74	3470,25
VALORE LUXMETRO			VALORE LUXMETRO:	VALORE LUXMETRO:
4458	4370,07	4369,07	4455	4436,8
			ERRORE PERCENTUALE	ERRORE PERCENTUALE
34,45	25,10	25,20	21,64	21,78

Then both sensor 1 and sensor 2 were tested on the supports inclined at 30° and 60° from the horizontal (see Fig.98), in order to evaluate the behavior of the sensor in the case of grazing light, such as that which may affect the desk from a side window. Tab.59 shows the results of the test conducted under the following conditions:

- LED source with T 2700K
- With and without filter
- Dimmer at maximum and minimum
- 30° and 60° support.

It is evident that with both supports, sensor 2 acquires data more similar to the reference data than sensor 1.

Again, the behavior of the sensor tends to worsen as the illuminance value increases. In addition, the percentage error is greater as the angle of the sensor increases from the horizontal, and thus on the 60° support. This is due both to the fact that the light does not normally affect the photoreceptor and to the shadows that the stand and cover generate. In addition, the presence of the lid leads to a higher underestimation of the actual value by the sensors.

Table 58 Results with inclined supports (30° and 60°)

03/04/2023	INCLINAZIONE 30°(DA ORIZZONTALE)						
sensore 1	sensore 1	sensore 1	sensore 1	sensore 1	sensore 1	sensore 1	sensore 1
supporto 30	supporto 30	supporto 30	supporto 30	supporto 30	supporto 30	supporto 30	supporto 30
no coperchio	no coperchio	no coperchio	no coperchio	coperchio 60 gradi	coperchio 60 gradi	coperchio 60 gradi	coperchio 60 gradi
2700 k	2700 k	2700 k	2700 k	2700 k	2700 k	2700 k	2700 k
senza filtro	senza filtro	con filtro	con filtro	con filtro	con filtro	senza filtro	senza filtro
dimmer al min	dimmer al max	dimmer al max	dimmer al min	dimmer al min	dimmer al max	dimmer al max	dimmer al min
MEDIA:	MEDIA:	MEDIA:	MEDIA:	MEDIA:	MEDIA:	MEDIA:	MEDIA:
264,78	3409,28	33,85	1,84	3,69	32,84	3041,25	235,07
VALORE LUXMETRO:	VALORE LUXMETRO:	VALORE LUXMETRO:	VALORE LUXMETRO:	VALORE LUXMETRO:	VALORE LUXMETRO:	VALORE LUXMETRO:	VALORE LUXMETRO:
292,19	4245	34,18	2,33	2,33	34,84	4219,87	287,65
ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE
9,38	19,69	0,95	21,03	-58,37	5,73	27,93	18,28
25/05/2023	INCLINAZIONE 30° (DA ORIZZONTALE)						
sensore 2	sensore 2	sensore 2	sensore 2	sensore 2	sensore 2	sensore 2	sensore 2
supporto 30	supporto 30	supporto 30	supporto 30	supporto 30	supporto 30	supporto 30	supporto 30
no coperchio	no coperchio	no coperchio	no coperchio	coperchio 60	coperchio 60	coperchio 60	coperchio 60
2700 k	2700 k	2700 k	2700 k	2700 k	2700 k	2700 k	2700 k
senza filtro	senza filtro	con filtro	con filtro	con filtro	con filtro	senza filtro	senza filtro
dimmer al min	dimmer al max	dimmer al max	dimmer al min	dimmer al min	dimmer al max	dimmer al max	dimmer al min
MEDIA:	MEDIA:	MEDIA:	MEDIA:	MEDIA:	MEDIA:	MEDIA:	MEDIA:
276,63	3681,58	41,29	2,30	1,84	36,71	3378,37	254,21
VALORE LUXMETRO:	VALORE LUXMETRO:	VALORE LUXMETRO:	VALORE LUXMETRO:	VALORE LUXMETRO:	VALORE LUXMETRO:	VALORE LUXMETRO:	VALORE LUXMETRO:
283,85	4261,07	35,00	2,25	2,29	35,19	4222,40	282,43
ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE
2,54	13,60	-17,98	-2,35	19,79	-4,33	19,99	9,99

03/04/2023	INCLINAZIONE 60° (DA ORIZZONTALE)						
sensore 1	sensore 1	sensore 1	sensore 1	sensore 1	sensore 1	sensore 1	sensore 1
supporto 60	supporto 60	supporto 60	supporto 60	supporto 60	supporto 60	supporto 60	supporto 60
no coperchio	no coperchio	no coperchio	no coperchio	coperchio 60	coperchio 60	coperchio 60	coperchio 60
2700 k	2700 k	2700 k	2700 k	2700 k	2700 k	2700 k	2700 k
senza filtro	senza filtro	con filtro	con filtro	con filtro	con filtro	senza filtro	senza filtro
dimmer al min	dimmer al max	dimmer al max	dimmer al min	dimmer al min	dimmer al max	dimmer al max	dimmer al min
MEDIA:	MEDIA:	MEDIA:	MEDIA:	MEDIA:	MEDIA:	MEDIA:	MEDIA:
202,84	2647,45	26,14	1,38	2,76	15,21	1486,32	106,97
VALORE LUXMETRO:	VALORE LUXMETRO:	VALORE LUXMETRO:	VALORE LUXMETRO:	VALORE LUXMETRO:	VALORE LUXMETRO:	VALORE LUXMETRO:	VALORE LUXMETRO:
232,87	3338,8	25,73	1,88	2,88	26,69	3320,47	222,5
ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE
12,89	20,71	-1,61	26,60	4,17	43,01	55,24	51,92
25/05/2023	INCLINAZIONE 60° (DA ORIZZONTALE)						
sensore 2	sensore 2	sensore 2	sensore 2	sensore 2	sensore 2	sensore 2	sensore 2
supporto 60	supporto 60	supporto 60	supporto 60	supporto 60	supporto 60	supporto 60	supporto 60
no coperchio	no coperchio	no coperchio	no coperchio	coperchio 60	coperchio 60	coperchio 60	coperchio 60
2700 k	2700 k	2700 k	2700 k	2700 k	2700 k	2700 k	2700 k
senza filtro	senza filtro	con filtro	con filtro	con filtro	con filtro	senza filtro	senza filtro
dimmer al min	dimmer al max	dimmer al max	dimmer al min	dimmer al min	dimmer al max	dimmer al max	dimmer al min
MEDIA:	MEDIA:	MEDIA:	MEDIA:	MEDIA:	MEDIA:	MEDIA:	MEDIA:
207,05	2726,49	28,26	1,38	0,92	20,99	2152,09	148,38
VALORE LUXMETRO:	VALORE LUXMETRO:	VALORE LUXMETRO:	VALORE LUXMETRO:	VALORE LUXMETRO:	VALORE LUXMETRO:	VALORE LUXMETRO:	VALORE LUXMETRO:
220,69	3377,87	26,14	1,73	1,84	28,00	3379,53	226,84
ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE	ERRORE PERCENTUALE
6,18	19,28	-8,12	20,10	50,03	25,03	36,32	34,59

CALIBRATION RESULTS

Through Matlab software, an appropriate code was generated to find the calibration function that could characterize the VISHAY VELM 7700 sensor. The calibration function of the measurement chain was based on 6 data collected using the 2700 K LED, as its spectral response is the nearest to the photopic human sensitivity. Specifically, the data used are as follows:

Table 59 E (lx) data for calibration verification

		E (lx)					
Device	Reference	4344	296.28	955.85	2788.11	36.48	2.47
	Sensor	3537.8	268.59	869.66	2927.51	36.76	2.30

Fig.104 shows on the y-axis the value of the measurement with the sensor in calibration, and on the x-axis the reference value given by the instrument. The blue dots indicate the experimental values, i.e., the measured value in relation to the actual value, while the magenta line represents the linear calibration function, obtained by minimizing the sum of the square root of the difference between the function and the experimental values.

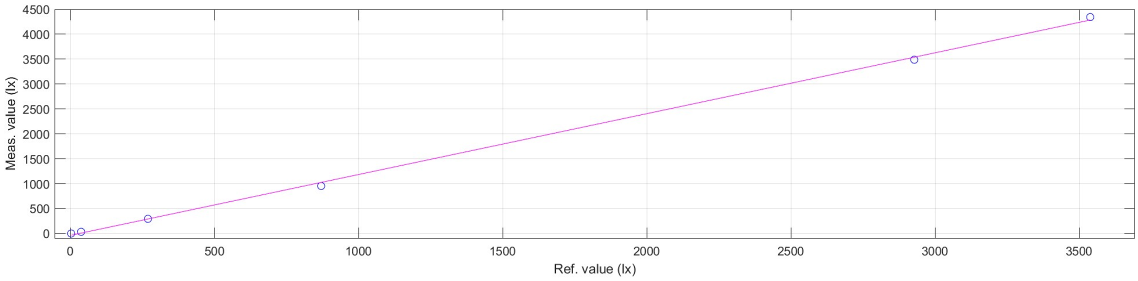


Figure 100 Calibration relation plotted through Matlab

Through the polyfit function, the polynomial that fits the data set previously shown in Tab.60 was found. The angular coefficient (m), that is, the slope of the calibration line, results in 1,2208, while the intercept (q) equals -34,508. So the calibration function results:

$$y = 1{,}2208 \cdot x - 34{,}508$$

The residual fitting error of about 60 lx is shown in Fig.105. This uncertainty value is added to the uncertainty of the reference instrument, which is 4%. This results in an expanded uncertainty ($U_{adj}(E)$) of 60+4% (m.v.) lx.

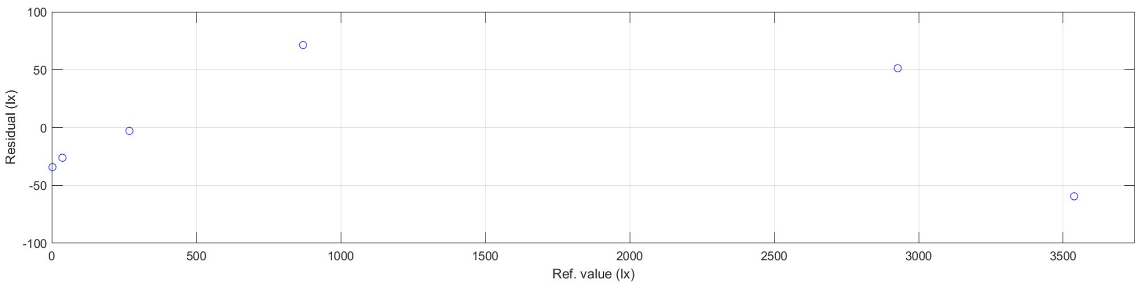


Figure 101 Residuals over reference value plotted through Matlab

Next, the relative illuminance chain was verified by adopting 9 additional data:

Table 60 E (lx) data for calibration verification

		E (lx)								
Device	Reference	36.65	37.48	2.30	3671.07	3658.54	275.65	3486.62	32.45	62.18
	Sensor	34.09	35.13	2.38	4398.20	4395.20	292.88	4049	30.86	65.05

The following results are shown in Fig.106:

Axis y= Error (%)

Axis x= reference value (%)

Blue continuous line= extended measurement uncertainty of the characterized chain

Red symbols= are the data obtained before characterization

Green symbols= data obtained after characterization

The results show that the procedure was successful as all green symbols fall within the uncertainty range required by the previously imposed CMRs.

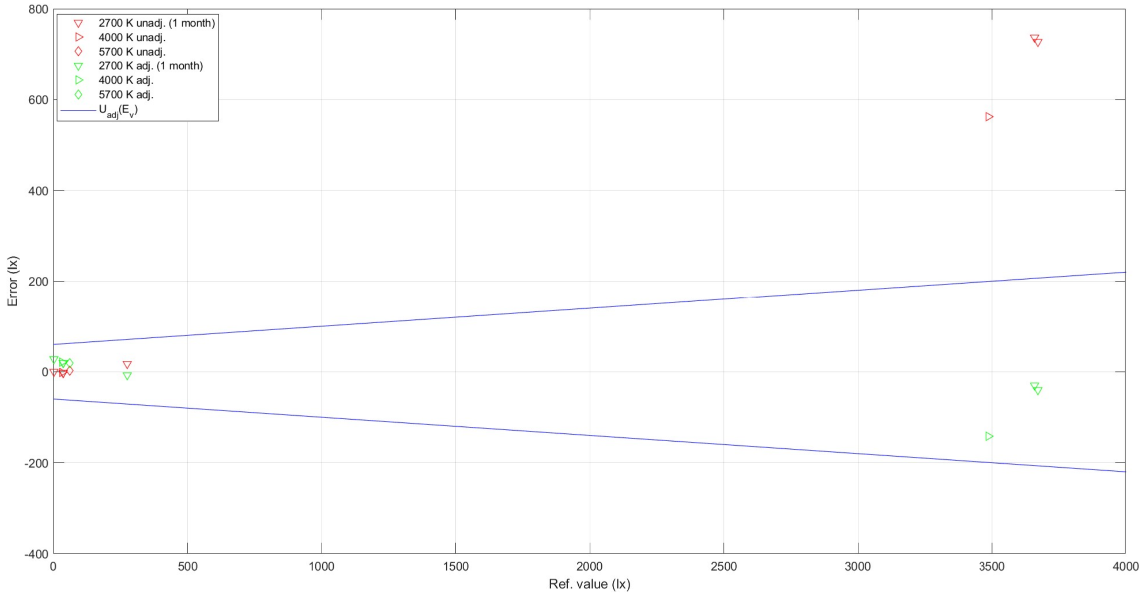


Figure 102 Adjusted error Uadj(RH) plotted though Matlab

The newly characterized data (green asterisk) are shown in the graph in Fig.107, where they are related to the pre-characterization data (red asterisk).

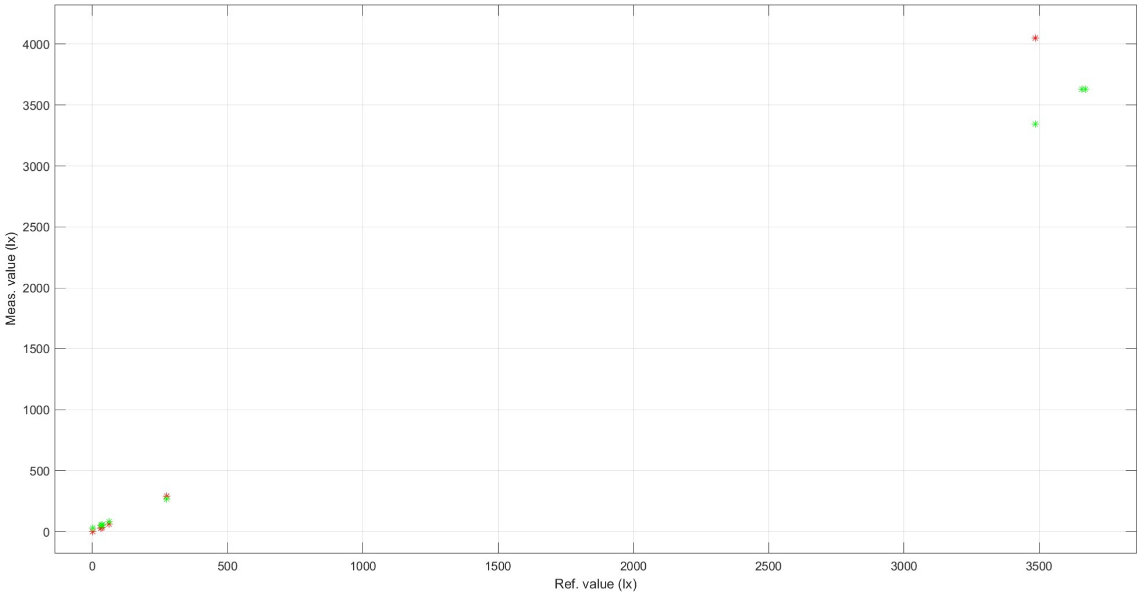


Figure 103 Illuminance data before and after metrological characterization

3.6.4 Air Quality: CO_2 Sensor

In terms of air quality, it is important to detect indoor CO_2 concentrations. The low-cost sensor chosen, mainly because of its stated accuracy, is the Sensirion-SCD30, as mentioned in Chapter 2.4.5. It is calibrated by comparison with the following reference instruments:

1. The Photoacoustic Gas Monitor - Innova 1512 (uncertainty ±0.25 m.v.)
2. Universal instrument for measuring environmental parameters Testo 400, associated with the Bluetooth humidity meter probe 605i.

Fig.108 shows the operation of the reference instrument:

1. The air sample is sucked in and hermetically sealed in the analysis cell.

2. The selected optical filter, placed inside the filter wheel, passes infrared light from a source.

3. The light transmitted by the filter is selectively absorbed by the gas to be monitored, undergoing an alternating rise and fall in temperature and consequently in gas pressure (acoustic signal).

4. Two microphones are mounted in the cell containing the gas to measure the acoustic signal, which is directly proportional to the measured gas concentration.

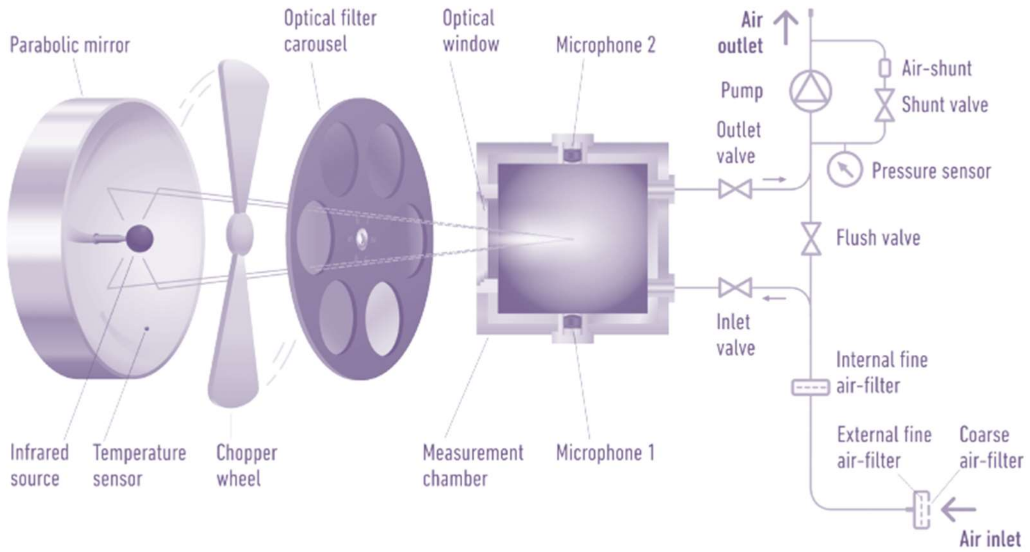


Figure 104 Graphical explanation of Innova 1512 operation taken from en-gs-innova1512-data-sheet.pdf

The test is carried out inside an office at the Polytechnic University of Turin. Fig.109 shows the test setting:

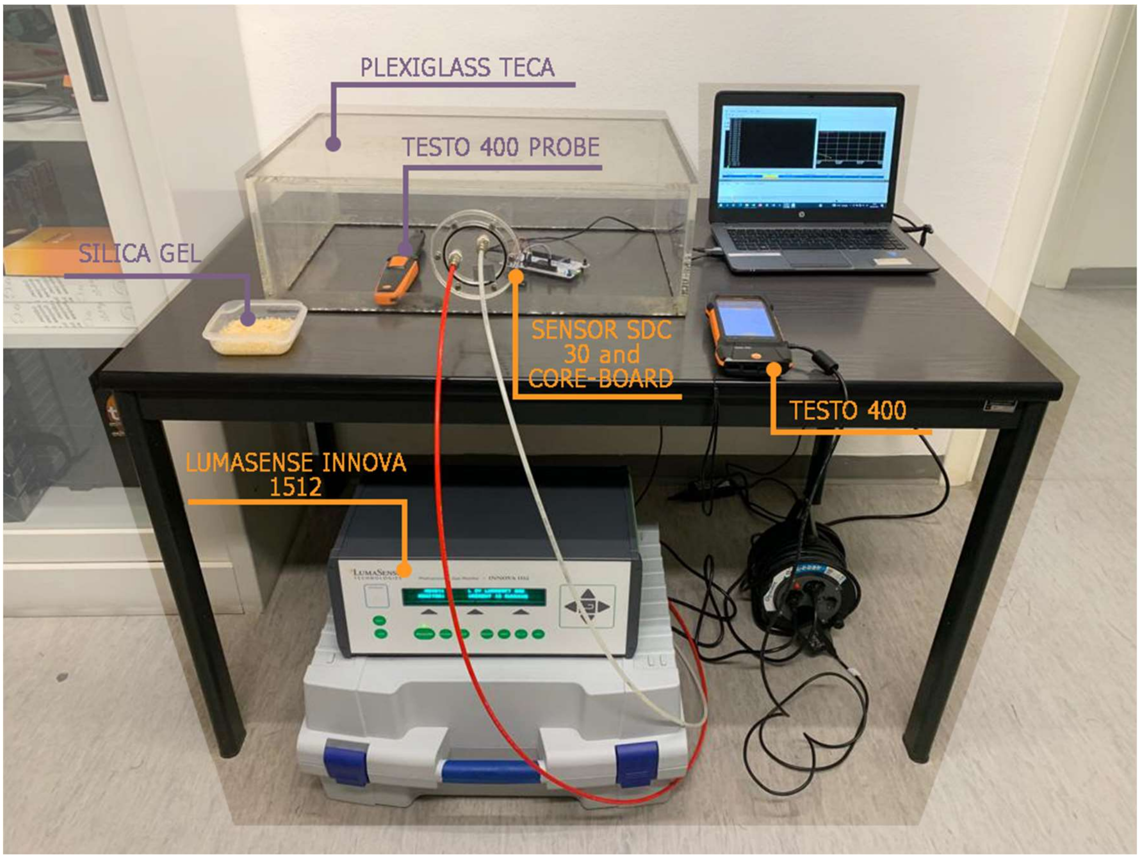


Figure 105 *Instrumentation required for the test*

Above the desk are placed a PC for data visualization and acquisition, the Testo 400 and a plexiglass theca (Fig.109) inside which are placed both the probe and the sensor connected to its core board. Below the workstation is placed the Photoacoustic Gas Monitor - Innova 1512. The core board is connected to the PC via USB cable coming out of a hole at the corner of the theca. The Photoacoustic Gas Monitor - Innova 1512 is instead connected to the theca via two rubber hoses (Fig.110). The first (red hose) injects air with known CO_2 concentration into the theca, the second (white hose) extracts air from the theca and leads it to the gastracer (INNOVA 1512) for analysis, as previously described. The instrument is set through its specific software with a sample integration time of 5 seconds.

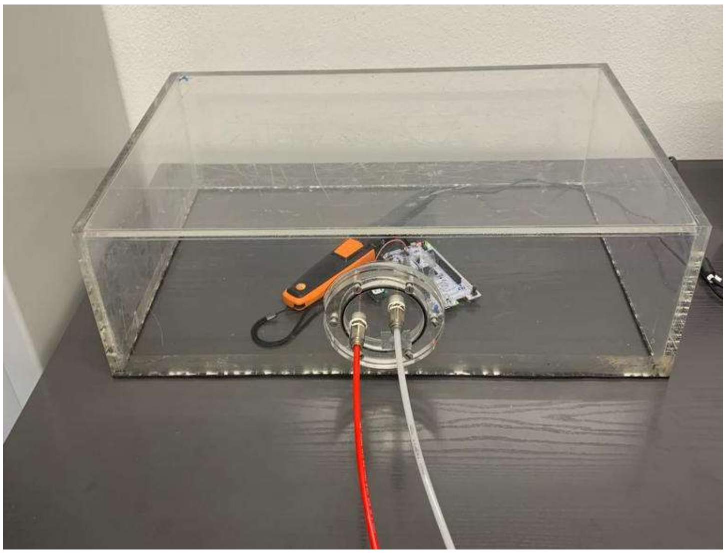


Figure 106 Teca, sensor, probe and hoses

The first test sets out baseline condition (about 500 ppm), that will be achieved by opening the windows for a few minutes and limiting the concentration of people inside the office. The test has a duration of 1h and 11 minutes (Tab.62)

Table 61 First test duration

Measurement 1_baseline	
Date	02/03/2023
Starting time	15:07
Ending time	16:15

The second setting involves a concentration of 1500 ppm, that will be achieved by insufflating CO_2 into the theca by steps through an air-inflated balloon (Fig.111).

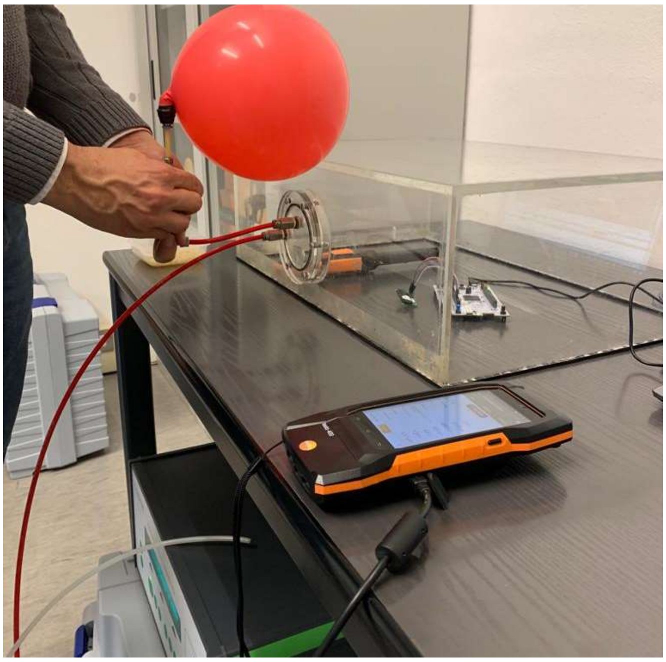


Figure 107 Air insufflation procedure

Some silica gel inside the balloon is used to reduce humidity. This time the test duration is of 22 h and 13 minutes (Tab.63)

Table 62 Second test duration

Measurement 2_1500 ppm	
Date	02/03/2023 - 03/03/2023
Starting time	16:47
Ending time	14:20

The third set with a concentration of 2500 ppm is achieved similarly to the previous one. The duration is of 1 day and 10 minutes (Tab.64).

Table 63 Third test duration

Measurement 3_2500 ppm	
Date	07/03/2023 - 08/03/2023
Starting time	12:14
Ending time	12:24

The duration of the test is chosen in order to acquire data until the CO_2 decays below the set analysis thresholds.

RESULTS

500 ppm

The SHT-41 sensor was tested under a CO_2 concentration of about 500ppm for a total of 68 minutes. Data were collected both from the sensor and the photoacoustic gas monitor every 60 second. The total number of data turns out to be 69. By resorting to the previously described calculations, statistical parameters were calculated. As shown in Tab.65 and Fig.112, the CO_2 values measured by the two devices differ in the range of ≈ -12.4÷ 8.03 ppm. So, for this setting, the sensor tends to underestimate the actual value for most of the time. Taking into account the sensitivity of the sensor as well as the uncertainty of the reference instrument, the combined uncertainty of 11.19 % was calculated. Multiplying the figure by the 95.4 percent coverage factor, k=2, the expanded uncertainty was 22.38 %.

Table 64 Calculation of error, statistic indexes, uncertainties and acceptance limits for CO_2 500 ppm

Starting time	End time	CO_2 (ppm)		Measurement Error	E-U(X)	E+U(X)	$(x_k - \bar{x})^2$	Number of measurements
15:07	16:15	Sensiron SSC 30	Lumasense 1512	E				n
		426,60	439	-12,40	-34,782	9,982	416,7160	69
		438,72	440	-1,28	-23,662	21,102	68,7842	Empirical mean
		445,72	444	1,72	-20,662	24,102	1,6735	X
		449,04	445	4,04	-18,342	26,422	4,1062	447,01
		447,22	443	4,22	-18,162	26,602	0,0426	Sample Variance
		447,42	447	0,42	-21,962	22,802	0,1651	$s^2(x)$
		446,64	440	6,64	-15,742	29,022	0,1396	16,43629
		445,89	446	-0,11	-22,492	22,272	1,2625	Standard Deviation
		447,03	443	4,03	-18,352	26,412	0,0003	s(x)
		449,13	446	3,13	-19,252	25,512	4,4791	4,05417
		449,17	445	4,17	-18,212	26,552	4,6500	Mean standard uncertainty
		449,50	449	0,50	-21,882	22,882	6,1821	$u_a(\bar{x})$
		449,43	446	3,43	-18,952	25,812	5,8389	0,48806
		449,64	446	3,64	-18,742	26,022	6,8979	Lumasense Uncertainty
		450,96	446	4,96	-17,422	27,342	15,5739	u_{b1} (1%mv) [ppm]
		451,89	446	5,89	-16,492	28,272	23,7791	5
		451,97	447	4,97	-17,412	27,352	24,5657	Sensor Resolution
		453,22	450	3,22	-19,162	25,602	38,5191	u_{b2} [%]
		454,10	450	4,10	-18,282	26,482	50,2167	10
		453,03	445	8,03	-14,352	30,412	36,1968	Combined Uncertainty
		451,71	448	3,71	-18,672	26,092	22,0560	$u_c(x)$
		451,29	449	2,29	-20,092	24,672	18,2874	11,19099
		449,05	448	1,05	-21,332	23,432	4,1468	Expanded Uncertainty
		448,26	449	-0,74	-23,122	21,642	1,5535	U(x)
		448,72	448	0,72	-21,662	23,102	2,9117	22,38198
		448,50	445	3,50	-18,882	25,882	2,2093	Coverage factor
		447,47	450	-2,53	-24,912	19,852	0,2083	k
		449,53	448	1,53	-20,852	23,912	6,3322	2
		451,72	451	0,72	-21,662	23,102	22,1500	UPPER LIMIT
		451,07	445	6,07	-16,312	28,452	16,4542	UL
		449,50	452	-2,50	-24,882	19,882	6,1821	45
		448,76	447	1,76	-20,622	24,142	3,0498	LOWER LIMIT
		449,74	449	0,74	-21,642	23,122	7,4331	LL
		449,63	447	2,63	-19,752	25,012	6,8454	-45
		448,86	445	3,86	-18,522	26,242	3,4091	guard-band factor
		444,95	448	-3,05	-25,432	19,332	4,2585	kw
		445,21	448	-2,79	-25,172	19,592	3,2531	2
		448,44	447	1,44	-20,942	23,822	2,0346	guard-band
		449,60	442	7,60	-14,782	29,982	6,6893	g
		446,63	447	-0,37	-22,752	22,012	0,1472	0,97613
		448,05	448	0,05	-22,332	22,432	1,0741	UPPER ACCEPTANCE LIMIT
		448,16	448	0,16	-22,222	22,542	1,3142	UAL=UL-g
		450,84	447	3,84	-18,542	26,222	14,6412	44,0239
		448,78	444	4,78	-17,602	27,162	3,1201	LOWER ACCEPTANCE LIMIT
		447,64	448	-0,36	-22,742	22,022	0,3923	LAL=LL+g
		447,46	447	0,46	-21,922	22,842	0,1993	-44,0239
		447,74	451	-3,26	-25,642	19,122	0,5276	
		445,45	447	-1,55	-23,932	20,832	2,4449	
		443,75	449	-5,25	-27,632	17,132	10,6512	
		442,66	446	-3,34	-25,722	19,042	18,9540	
		444,34	444	0,34	-22,042	22,722	7,1483	
		446,41	442	4,41	-17,972	26,792	0,3644	
		444,73	450	-5,27	-27,652	17,112	5,2149	
		443,91	448	-4,09	-26,472	18,292	9,6325	
		444,81	448	-3,19	-25,572	19,192	4,8560	
		442,59	447	-4,41	-26,792	17,972	19,5684	
		441,81	448	-6,19	-28,572	16,192	27,0777	
		441,65	445	-3,35	-25,732	19,032	28,7685	
		441,94	447	-5,06	-27,442	17,322	25,7417	
		443,90	447	-3,10	-25,482	19,282	9,6946	
		442,82	448	-5,18	-27,562	17,202	17,5865	
		443,74	447	-3,26	-25,642	19,122	10,7166	
		446,18	445	1,18	-21,202	23,562	0,6949	
		447,62	445	2,62	-19,762	25,002	0,3677	
		446,77	446	0,77	-21,612	23,152	0,0594	
		445,41	443	2,41	-19,972	24,792	2,5716	
		444,55	444	0,55	-21,832	22,932	6,0694	
		443,12	446	-2,88	-25,262	19,502	15,1603	
		442,15	447	-4,85	-27,232	17,532	23,6548	
Sampling time		1 data/min	1 data/min			$\Sigma (x_k - \bar{x})^2$	1117,6676	

Fig.112 shows the trend of readings from the two devices. They do not maintain a stable trend; in fact, the sensor alternates between data that underestimate the actual value and data that overestimate it.

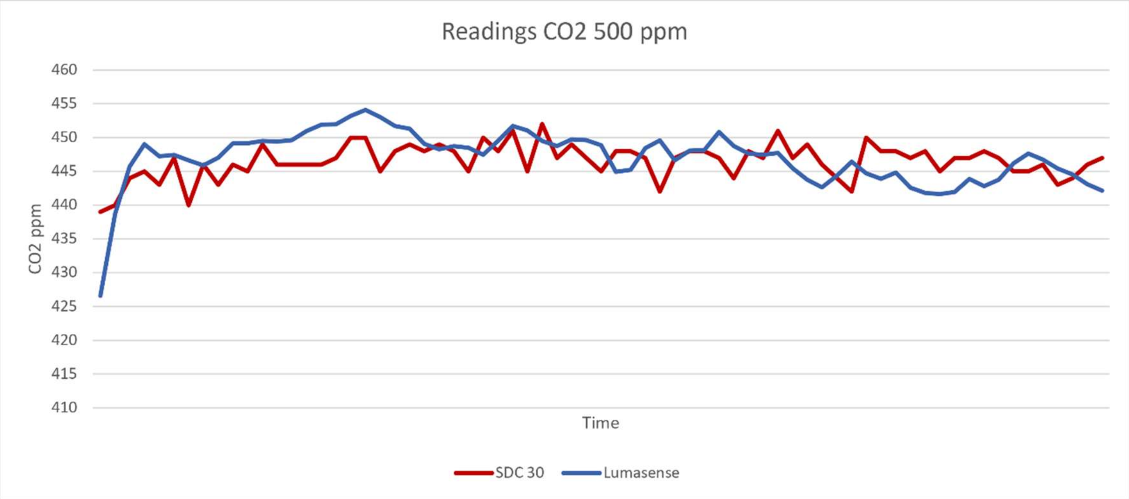


Figure 108 Sensor and reference instrument readings CO_2 500 ppm

Fig.113 shows the graph containing both the measurement error (E, lilac line), given by the difference of the sensor reading and that of the reference instrument, as well as the measurement error stripped of the expanded uncertainty component (E-U(x) orange line), and the measurement error to which the expanded uncertainty is added (E+U(x), gray line). These lines are related to the upper limit (UL, yellow line), lower limit (LL, light blue line), upper acceptance limit (UAL, blue line) and lower acceptance limit (LAL, pink line). As can be seen, the values fall within the range dictated by the previously imposed CMRs (see Tab.43), which is ±10% mv, as well as within the confidence interval. Therefore, the SDC 30, under 500 ppm conditions, is verified and suitable for use with a probability of 95.4%.

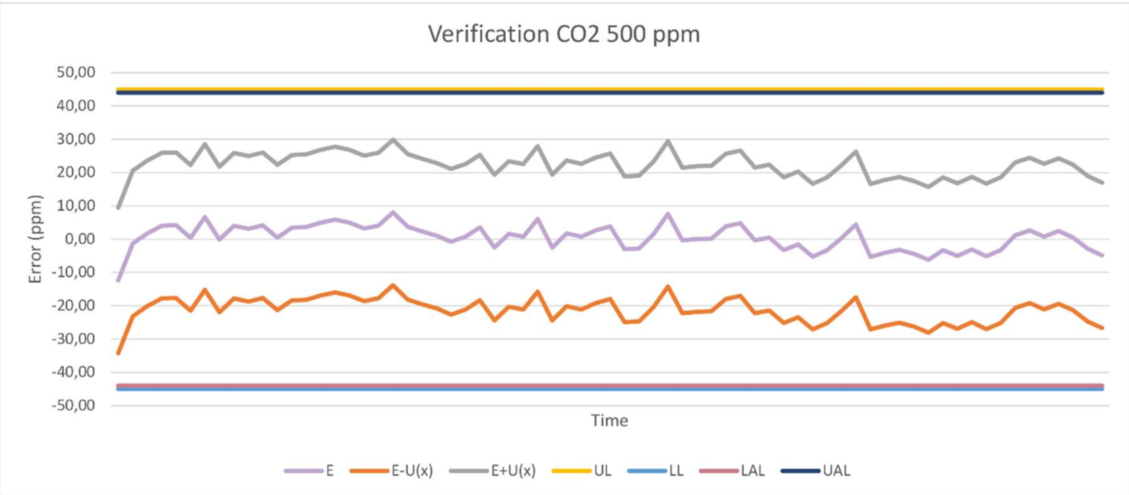


Figure 109 Calibration verification with a confidence level of 95% at CO_2 500 ppm

1500 ppm

SDC 30 was tested under CO_2 concentration conditions of about 1500 ppm. The test lasted 21 hours and 24 minutes, totaling a data sample of 1283. Adopting the same methods as before and taking into account the previously listed influence parameters, the combined uncertainty of 18.21 ppm was first calculated, and consequently the extended uncertainty in the confidence interval of 95.4 percent was calculated to be ± 36.42 ppm. As shown in both Tab.66 and Fig.110, the sensor tends by far to underestimate the actual values read by the reference instrument. This results in an increasing uncertainty compared with the previous CO_2 concentration condition.

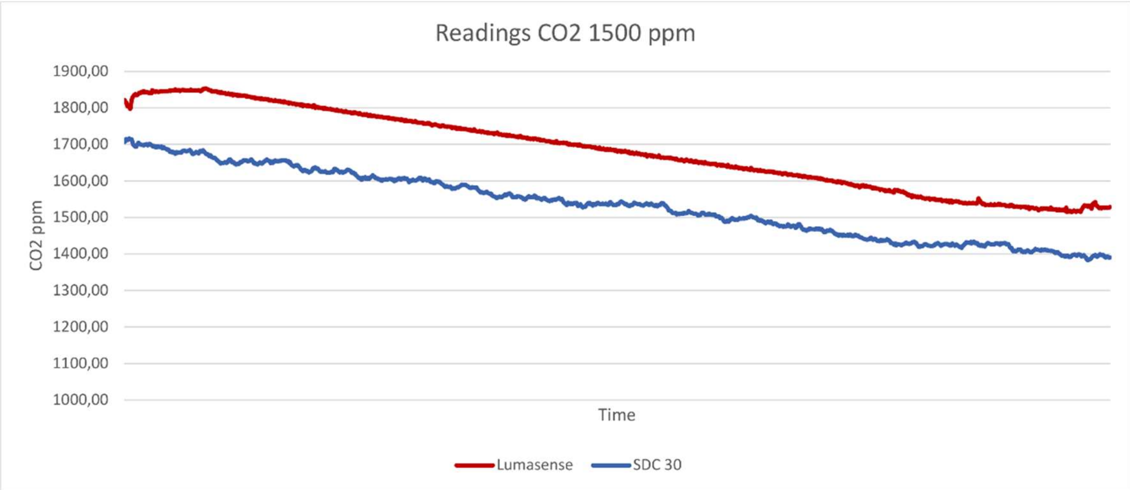


Figure 110 Sensor and reference instrument readings CO_2 1500 ppm

Table 65 Calculation of error, statistic indexes, uncertainties and acceptance limits for CO2 1500 ppm

Starting time	End time	CO_2 (ppm)		Measurement Error	E-U(X)	E+U(X)	$(x_k \bar{x})^2$	Number of measurements
16:47	14:09 (+24h)	Sensiron SSC 30	Lumasense 1512	E				n
Sampling time		1706,83	1821,05	-114,22	-150,64	-77,80	29585,23	1283
1 data/min		1708,87	1816,62	-107,75	-144,17	-71,33	30291,16	Empirical mean
		1714,92	1815,48	-100,56	-136,98	-64,14	32433,69	X
		1712,3	1807,77	-95,47	-131,89	-59,05	31496,87	1534,83
		1712,34	1804,71	-92,37	-128,79	-55,95	31511,07	Sample Variance
		1713,46	1805,37	-91,91	-128,33	-55,48	31909,95	$s^2(x)$
		1716,14	1806,08	-89,94	-126,36	-53,52	32874,61	8487,24
		1715,41	1797,99	-82,58	-119,00	-46,16	32610,43	Standard Deviation
		1714,5	1800,06	-85,56	-121,98	-49,14	32282,59	s(x)
		1714,4	1820,07	-105,67	-142,09	-69,25	32246,67	92,13
		1707,83	1828,92	-121,09	-157,51	-84,67	29930,24	Mean standard uncertainty
		1700,38	1831,22	-130,84	-167,26	-94,42	27407,98	$u_a(\bar{x})$
		1697,2	1835,21	-138,01	-174,43	-101,59	26365,18	2,57
		1696,24	1836,24	-140,00	-176,43	-103,58	26054,34	Lumasense Uncertainty
		1694,11	1838,21	-144,10	-180,52	-107,68	25371,26	u_{b1} (1%mv) [ppm]
		1694,13	1834,77	-140,64	-177,06	-104,22	25377,63	15
		1698,7	1835,04	-136,34	-172,76	-99,92	26854,55	Sensor Resolution
		1702,06	1836,57	-134,51	-170,93	-98,09	27967,07	u_{b2} [%]
		1705,02	1839,09	-134,07	-170,49	-97,65	28965,85	10
		1701,75	1841,44	-139,69	-176,11	-103,27	27863,48	Combined Uncertainty
		1700,19	1841,76	-141,57	-178,00	-105,15	27345,11	$u_c(x)$
		1700,18	1840,94	-140,76	-177,19	-104,34	27341,80	18,21030
		1698,82	1843,68	-144,86	-181,28	-108,44	26893,89	Expanded Uncertainty
		1698,25	1844,83	-146,58	-183,00	-110,15	26707,26	U(x)
		1698,28	1842,31	-144,03	-180,45	-107,61	26717,07	36,42061
		1697,81	1846,41	-148,60	-185,02	-112,18	26563,64	Coverage factor
		1699,42	1842,53	-143,11	-179,53	-106,69	27091,04	k
		1699,36	1843,19	-143,83	-180,25	-107,41	27071,30	2
		1701,15	1843,08	-141,93	-178,35	-105,51	27663,53	UPPER LIMIT
		1701,13	1844,17	-143,04	-179,46	-106,62	27656,88	UL
		1697,59	1842,42	-144,83	-181,25	-108,41	26491,98	150
		1699,4	1841,27	-141,87	-178,29	-105,45	27084,46	LOWER LIMIT
		1701,56	1842,53	-140,97	-177,39	-104,55	27800,08	LL
		1701,43	1839,74	-138,31	-174,73	-101,89	27756,75	-150
		1699,83	1841,33	-141,50	-177,92	-105,08	27226,18	guard-band factor
		1697,88	1840,45	-142,57	-178,99	-106,15	26586,47	kw
		1696,73	1848,76	-152,03	-188,45	-115,61	26212,77	2
		1694,96	1847,12	-152,16	-188,58	-115,74	25642,76	guard-band
		1695,71	1844,39	-148,68	-185,10	-112,26	25883,52	g
		1693,75	1845,10	-151,35	-187,77	-114,93	25256,70	5,14
		1692,42	1843,51	-151,09	-187,51	-114,67	24835,73	UPPER ACCEPTANCE LIMIT
		1695,41	1846,03	-150,62	-187,04	-114,20	25787,08	UAL=UL-g
		1692,19	1844,83	-152,64	-189,06	-116,21	24763,29	144,86
		1693,38	1844,66	-151,28	-187,70	-114,86	25139,23	LOWER ACCEPTANCE LIMIT
		1694,61	1843,35	-148,74	-185,16	-112,32	25530,79	LAL=LL+g
		1692,62	1844,39	-151,77	-188,19	-115,35	24898,81	-144,86
		1694,31	1845,54	-151,23	-187,65	-114,81	25435,01	
		1693,06	1845,48	-152,42	-188,84	-116,00	25037,86	
		1694,48	1846,46	-151,98	-188,41	-115,56	25489,26	
		1689,67	1845,15	-155,48	-191,90	-119,06	23976,53	
		1690,41	1846,19	-155,78	-192,20	-119,36	24206,25	
		1691,96	1846,63	-154,67	-191,09	-118,25	24690,96	
		1689,67	1845,92	-156,25	-192,67	-119,83	23976,53	
		1688,61	1846,25	-157,64	-194,06	-121,22	23649,39	
		1687,76	1846,52	-158,76	-195,18	-122,34	23388,68	
		1685,83	1846,57	-160,74	-197,16	-124,32	22802,08	
		1685,34	1846,36	-161,02	-197,44	-124,59	22654,33	
		1686,93	1846,52	-159,59	-196,01	-123,17	23135,50	
		1683,61	1847,56	-163,95	-200,37	-127,53	22136,55	
		1680,1	1847,83	-167,73	-204,15	-131,31	21104,41	
		1679,26	1846,96	-167,70	-204,12	-131,28	20861,06	
		1680,15	1847,78	-167,63	-204,05	-131,21	21118,94	
		1678,54	1848,81	-170,27	-206,70	-133,85	20653,59	
		1679,82	1848,43	-168,61	-205,03	-132,19	21023,14	

The graph in Fig.115 makes clear the sensor's unsuitability for measuring CO_2 concentration under such conditions. Almost all of the values do not meet the lower limit. The most suitable choice could be, either a calibration procedure, or replacement of the sensor itself, with one possessing better performance characteristics.

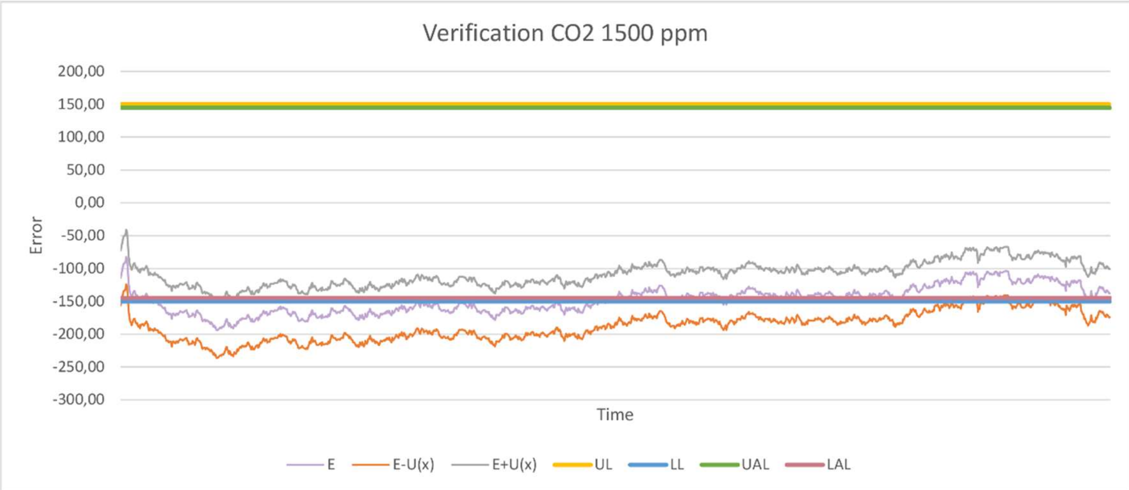


Figure 111 Calibration verification with a confidence level of 95% at CO_2 1500 ppm

2500 ppm

SDC 30 was tested under CO_2 concentration conditions of about 2500 ppm. The test lasted 23 hours and 15 minutes, totaling a data sample of 1396. Adopting the same methods as before and taking into account the previously listed influence parameters, the combined uncertainty of 27.41 ppm was first calculated, and consequently the extended uncertainty in the confidence interval of 95.4 percent was calculated to be 54.82 ppm.

Table 66 Calculation of error, statistic indexes, uncertainties and acceptance limits for CO_2 2500 ppm

Starting time	End time	CO_2 (ppm)		Measurement Error	E-U(X)	E+U(X)	$(x_k - \bar{x})^2$	Number of measurements
12:24	11:39 (+24h)	Sensiron SSC 30	Lumasense 1512	E				n
Sampling time		2785,33	2637,57	147,76	92,93	202,58	133378,30	1396
1 data/min		2789,67	2642,44	147,23	92,41	202,06	136567,16	Empirical mean
		2787,11	2647,52	139,59	84,77	194,41	134681,62	X
		2788,51	2658,12	130,39	75,56	185,21	135711,15	2420,12
		2789,59	2658,50	131,09	76,26	185,91	136508,04	Sample Variance
		2785,51	2658,29	127,22	72,40	182,05	133509,81	$s^2(x)$
		2780,64	2656,76	123,88	69,06	178,71	129974,63	36893,82
		2778,65	2664,19	114,46	59,64	169,29	128543,72	Standard Deviation
		2782,14	2670,64	111,50	56,68	166,33	131058,44	s(x)
		2779,04	2675,39	103,65	48,82	158,47	128823,53	192,08
		2776,75	2684,52	92,23	37,41	147,05	127184,92	Mean standard uncertainty
		2775,33	2690,20	85,13	30,30	139,95	126174,10	$u_a(\bar{x})$
		2772,72	2695,18	77,54	22,72	132,37	124326,72	5,14
		2771,43	2702,01	69,42	14,60	124,25	123418,68	Lumasense Uncertainty
		2772,18	2708,40	63,78	8,95	118,60	123946,20	u_{b1} (1%mv) [ppm]
		2769,27	2716,16	53,11	-1,72	107,93	121905,68	25
		2765,65	2718,02	47,63	-7,20	102,45	119390,94	Sensor Resolution
		2765,75	2725,46	40,29	-14,53	95,12	119460,06	u_{b2} [%]
		2759,56	2734,86	24,70	-30,12	79,53	115219,47	10
		2760,25	2737,70	22,55	-32,27	77,38	115688,38	Combined Uncertainty
		2758,85	2745,73	13,12	-41,71	67,94	114737,97	$u_c(x)$
		2756,34	2751,20	5,14	-49,68	59,97	113043,85	27,41219
		2751,93	2751,74	0,19	-54,64	55,01	110097,84	Expanded Uncertainty
		2752,85	2763,22	-10,37	-65,20	44,45	110709,21	U(x)
		2753,82	2764,31	-10,49	-65,32	44,33	111355,65	54,82438
		2755,79	2769,23	-13,44	-68,27	41,38	112674,31	Coverage factor
		2754,75	2777,27	-22,52	-77,34	32,31	111977,20	k
		2753,18	2782,51	-29,33	-84,16	25,49	110928,93	2
		2749,33	2788,14	-38,81	-93,64	16,01	108379,19	UPPER LIMIT
		2747,35	2793,72	-46,37	-101,19	8,46	107079,44	UL
		2738,23	2796,40	-58,17	-112,99	-3,34	101193,94	250
		2737,66	2800,66	-63,00	-117,82	-8,17	100831,62	LOWER LIMIT
		2741,68	2807,16	-65,48	-120,31	-10,66	103400,80	LL
		2746,04	2810,61	-64,57	-119,39	-9,74	106223,81	-250
		2752,15	2812,85	-60,70	-115,52	-5,87	110243,88	guard-band factor
		2753,59	2816,23	-62,64	-117,47	-7,82	111202,20	kw
		2756,65	2824,05	-67,40	-122,22	-12,58	113252,40	2
		2759,08	2824,71	-65,63	-120,45	-10,80	114893,84	guard-band
		2760,75	2832,08	-71,33	-126,16	-16,51	116028,76	g
		2761,82	2834,38	-72,56	-127,38	-17,74	116758,85	10,28
		2758,95	2836,67	-77,72	-132,55	-22,90	114805,73	UPPER ACCEPTANCE LIMIT
		2756,7	2841,59	-84,89	-139,72	-30,07	113286,06	UAL=UL-g
		2755,6	2845,97	-90,37	-145,19	-35,54	112546,79	239,72
		2754,65	2849,85	-95,20	-150,02	-40,37	111910,28	LOWER ACCEPTANCE LIMIT
		2758,12	2851,27	-93,15	-147,97	-38,32	114243,96	LAL=LL+g
		2757,6	2854,05	-96,45	-151,28	-41,63	113892,71	-239,72
		2754,57	2859,08	-104,51	-159,34	-49,69	111856,76	
		2753,11	2857,22	-104,11	-158,94	-49,29	110882,30	
		2755,77	2858,21	-102,44	-157,26	-47,61	112660,88	
		2755,45	2864,93	-109,48	-164,31	-54,66	112446,17	
		2756,1	2867,34	-111,24	-166,06	-56,41	112882,52	
		2757,44	2870,01	-112,57	-167,40	-57,75	113784,74	
		2752,29	2869,63	-117,34	-172,17	-62,52	110336,87	
		2751,81	2872,64	-120,83	-175,65	-66,00	110018,22	
		2750,55	2874,33	-123,78	-178,61	-68,96	109183,95	
		2750,44	2877,28	-126,84	-181,67	-72,02	109111,26	
		2750,56	2881,44	-130,88	-185,70	-76,05	109190,56	
		2747,86	2879,03	-131,17	-186,00	-76,35	107413,47	
		2747,55	2886,30	-138,75	-193,57	-83,93	107210,37	
		2746,4	2888,92	-142,52	-197,35	-87,70	106458,60	
		2746,7	2885,26	-138,56	-193,39	-83,74	106654,46	
		2743,16	2886,90	-143,74	-198,57	-88,92	104354,80	

As shown in both Tab.67 and Fig.116, the sensor tends to underestimate the actual values read by the reference instrument, even more than the previous cases. This results in the higher uncertainty compared with the previous CO_2 concentration conditions.

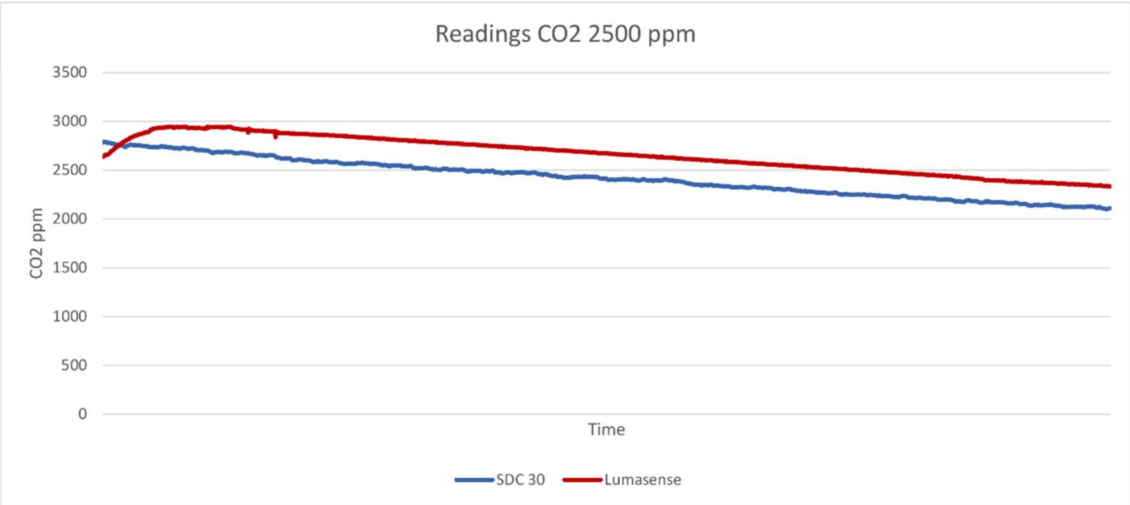


Figure 112 Sensor and reference instrument readings CO_2 2500 ppm

The graph in Fig.117 makes clear the sensor's unsuitability for measuring CO_2 concentration under such conditions. Almost all of the values do not meet the lower limit. The most suitable choice could be, either a calibration procedure, or replacement of the sensor itself, with one possessing better performance characteristics.

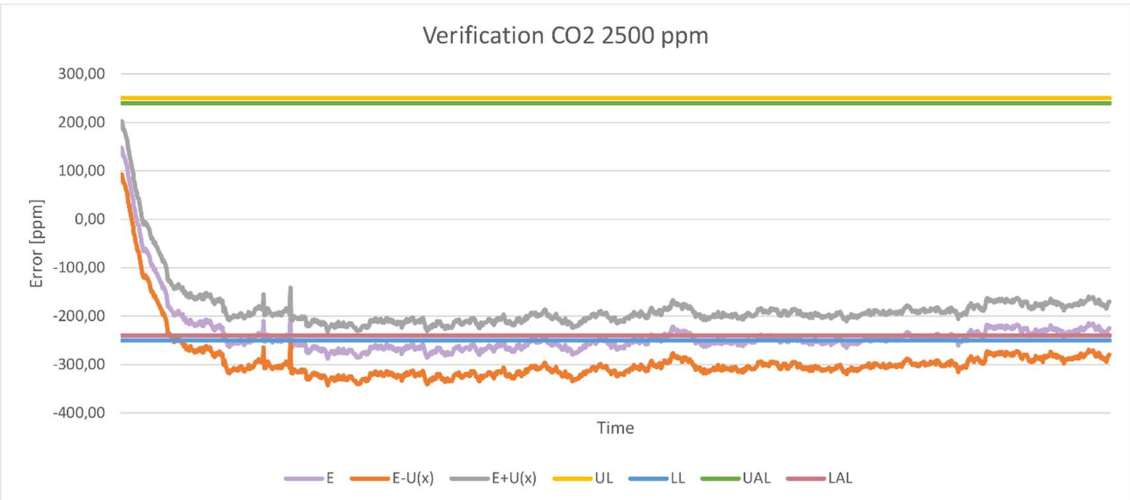


Figure 113 Calibration verification with a confidence level of 95% at CO_2 2500 ppm

CALIBRATION RESULTS

Through Matlab software, an appropriate code was generated to find the calibration function that could characterize the SDC 30 CO_2 sensor. The calibration function of the measurement chain was based on 4 data collected at 2500ppm, 4 data at 1500ppm, 4 data at 500ppm. Specifically, the data used are as follows:

Table 67 CO_2 data used for calibration

CO_2 ppm		2500			
Device	Reference	2785.33	2789.67	2788.51	2788.11
	Sensor	2637.57	2642.44	2658.12	2647.52
CO_2 ppm		1500			
Device	Reference	1821.05	1816.62	1815.48	1807.77
	Sensor	1706.83	1708.87	1714.92	1712.3
CO_2 ppm		500			
Device	Reference	440	444	445	443
	Sensor	438.72	445.72	449.04	447.22

Fig.118 shows on the y-axis the value of the measurement with the sensor in calibration, and on the x-axis the reference value given by the instrument. The blue dots indicate the experimental values, i.e., the measured value in relation to the actual value, while the magenta line represents the linear calibration function, obtained by minimizing the sum of the square root of the difference between the function and the experimental values.

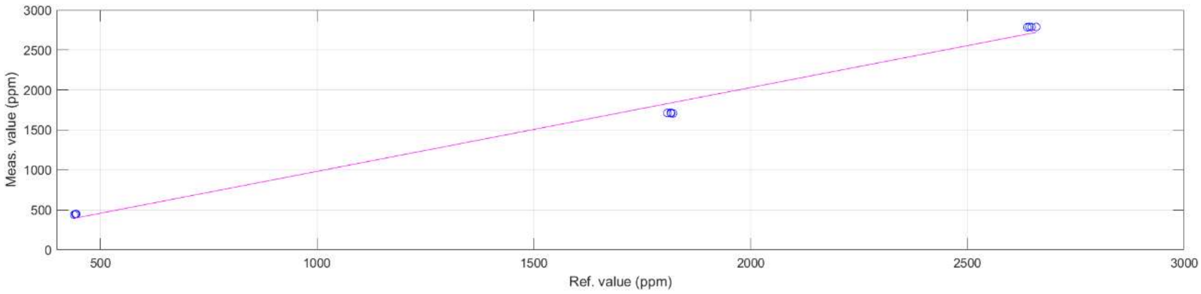


Figure 114 Calibration relation plotted through Matlab

Through the polyfit function, the polynomial that fits the data set previously shown in Tab.68 was found. The angular coefficient (m), that is, the slope of the calibration line, results in 1,049, while the intercept (q) equals -67,142. So the calibration function results:

$$y = 1{,}049 \cdot x - 67{,}142$$

The residual fitting error of about 136 ppm is shown in Fig.119. This uncertainty value is added to the uncertainty of the reference instrument, which is 1%. This results in an expanded uncertainty (Uadj(CO_2)) of 136+1% m.v.

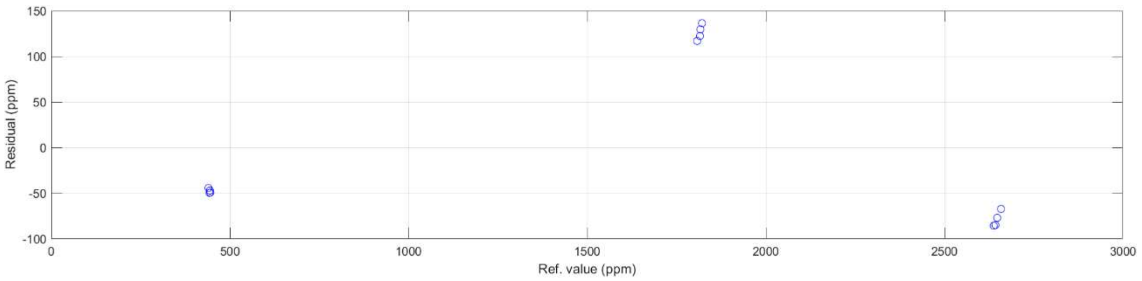


Figure 115 Residuals over reference value plotted through Matlab

Next, the relative humidity measurement chain was verified by comparing 8 additional data:

Table 68 CO_2 data for calibration verification

		CO_2 ppm							
Device	Reference	2725.46	2734.86	1706.83	1708.87	1714.92	444	446	447
	Sensor	2765.75	2759.56	1821.05	1816.62	1815.48	444.55	443.12	442.15

The following results are shown in fig.120:

Axis y= Error (%)

Axis x= reference value (%)

Blue continuous line= extended measurement uncertainty of the characterized chain

Red symbols= are the data obtained before characterization

Green symbols= data obtained after characterization

The results show that the procedure was successful as all green symbols fall within the uncertainty range required by the previously imposed CMRs.

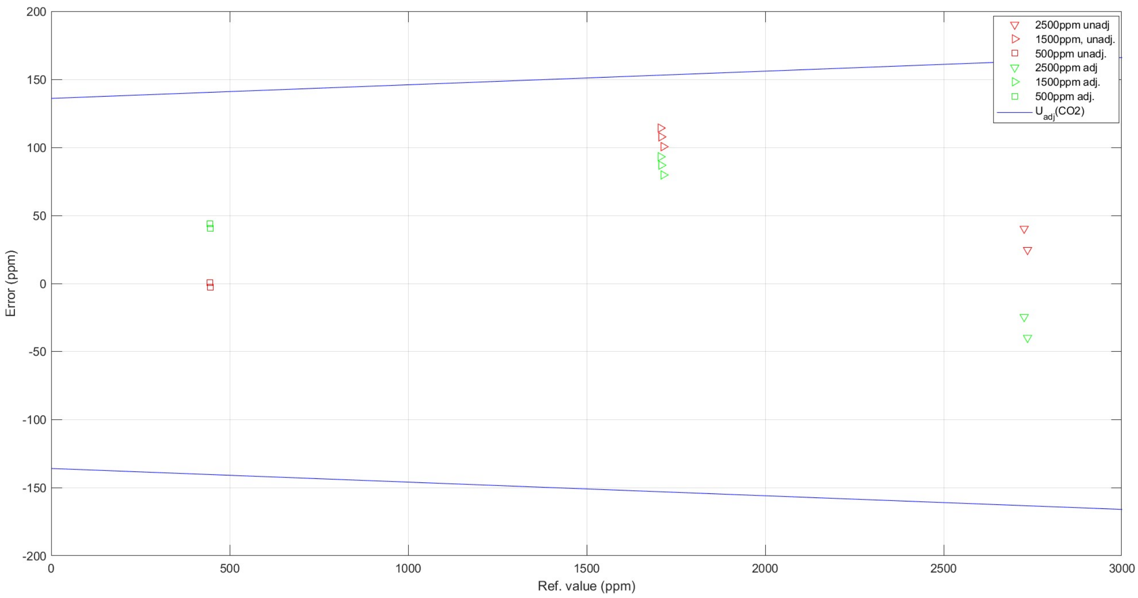


Figure 116 Adjusted error Uadj(RH) plotted though Matlab

The newly characterized data (green asterisk) are shown in the graph in Fig.121, where they are related to the pre-characterization data (red asterisk).

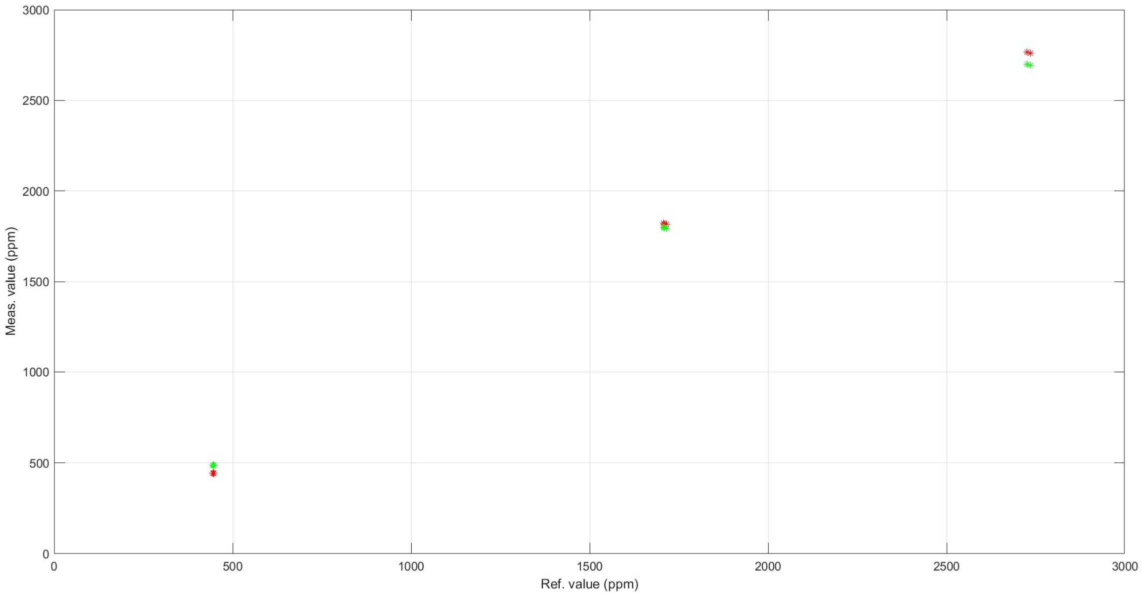


Figure 117 CO_2 *Data before and after metrological characterization*

3.6.5 Acoustic: Sound Pressure Level Sensor

The measurements on the sound pressure level (SPL) sensor, ST-IMP34DT05, have been performed at INRIM (Istituto Nazionale di Ricerca Metrologica) in Turin.The first phase consisted of analysing the behaviour of the single low cost sensor. The procedure involved a sequential comparison in an anechoic chamber with a class A reference microphone, BK4191 from the company Brüel & Kjæl. Its characteristics show a sensitivity of 0.01276 V/Pa. This instrument, in particular, requires recalibration every time before use. In this specific case, a Brüel & Kjæl calibrator was used, at a frequency of 1 kHz and a sound pressure level of 94 dB. The ambient conditions in which the measurement was carried out were as follows:

- Air temperature: 22°C
- Relative humidity: 60%
- Atmospheric pressure: 98.301 kPa

Initially, the microphone was placed inside the anechoic chamber (V=3,5 m^2) on a pole stand, at a height of 1.5m from the ground and a distance of 2.5cm from the center of the pole (Fig. 122).

A second microphone was placed inside the anechoic chamber to check the stability of the signal, as required by regulations. Both were connected via a USB cable to an external PC, which was used to monitor the data from both the reference microphone (channel 1) and the verification microphone (channel 2).

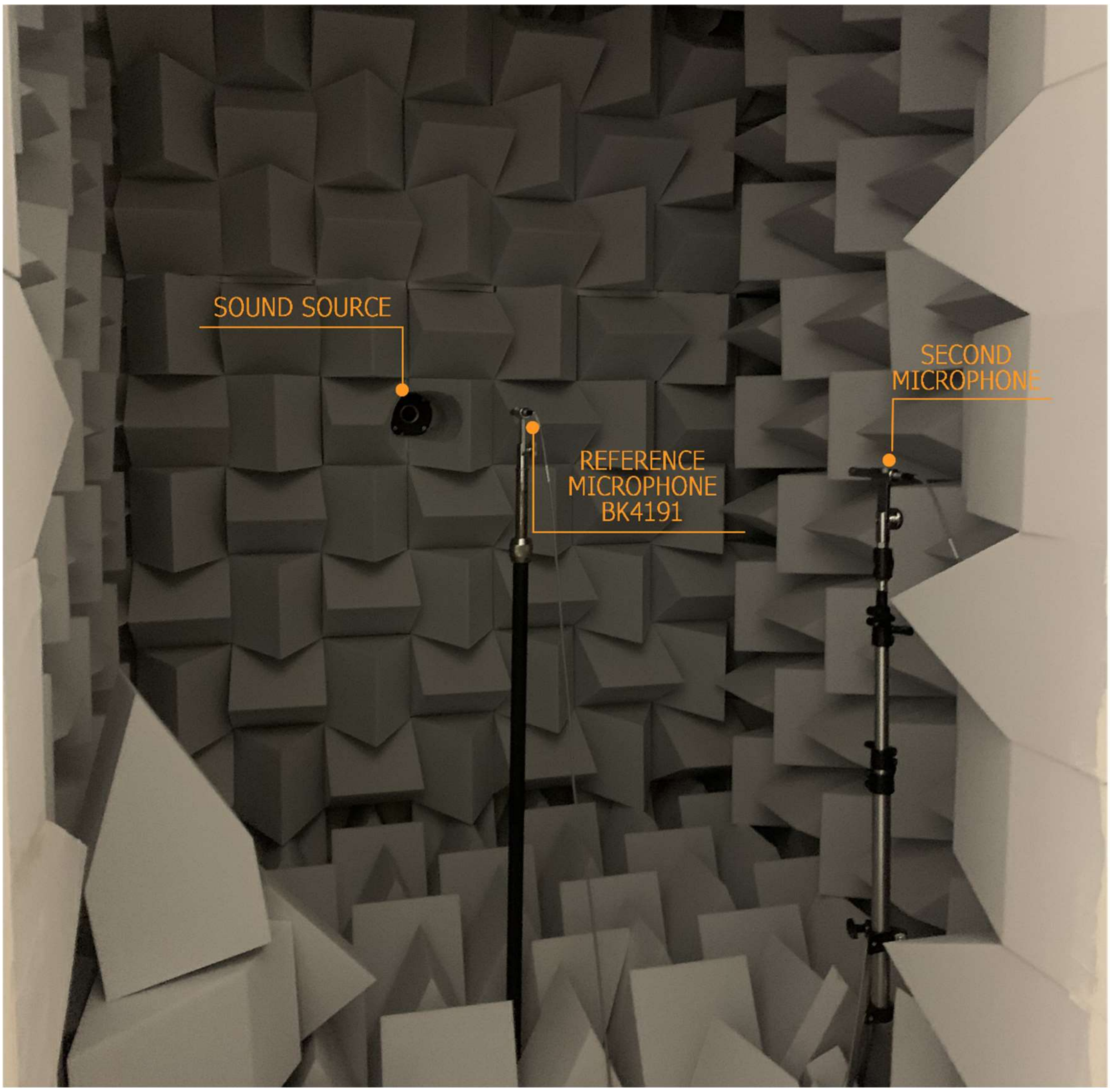


Figure 118 Reference microphone inside the anechoic chamber

The acoustic signal was transmitted inside the chamber by a generator, according to frequencies in one third octave from 500Hz to 12500 Hz, as these were considered the most reasonable within the range of use of PROMET&O (500 Hz, 630 Hz, 800 Hz, 1000 Hz, 1250 Hz, 1600 Hz, 2000 Hz, 2500 Hz, 3150 Hz, 4000 Hz, 5000 Hz, 6300 Hz, 8000 Hz, 10000 Hz, 12500 Hz).

The acquisition time of the Equivalent Level measurement corresponds to 4 seconds. This data was extrapolated as an Excel file.

Subsequently, the reference microphone was removed from the anechoic chamber to accommodate, in an equivalent position, the MEMS sensor to be monitored. In order to facilitate the maintenance of a stable position, as well as the normal position relative to the source inside the chamber, the sensor was first housed in a cylindrical fork-shaped support, concave, but closed laterally, to avoid resonance influences (Fig.123).

Figure 119 SLP sensor housed in a cylindrical fork-shaped support

It was then placed on the rod. Via two cables, the microphone was connected to the core board, which in turn was connected to the PC.

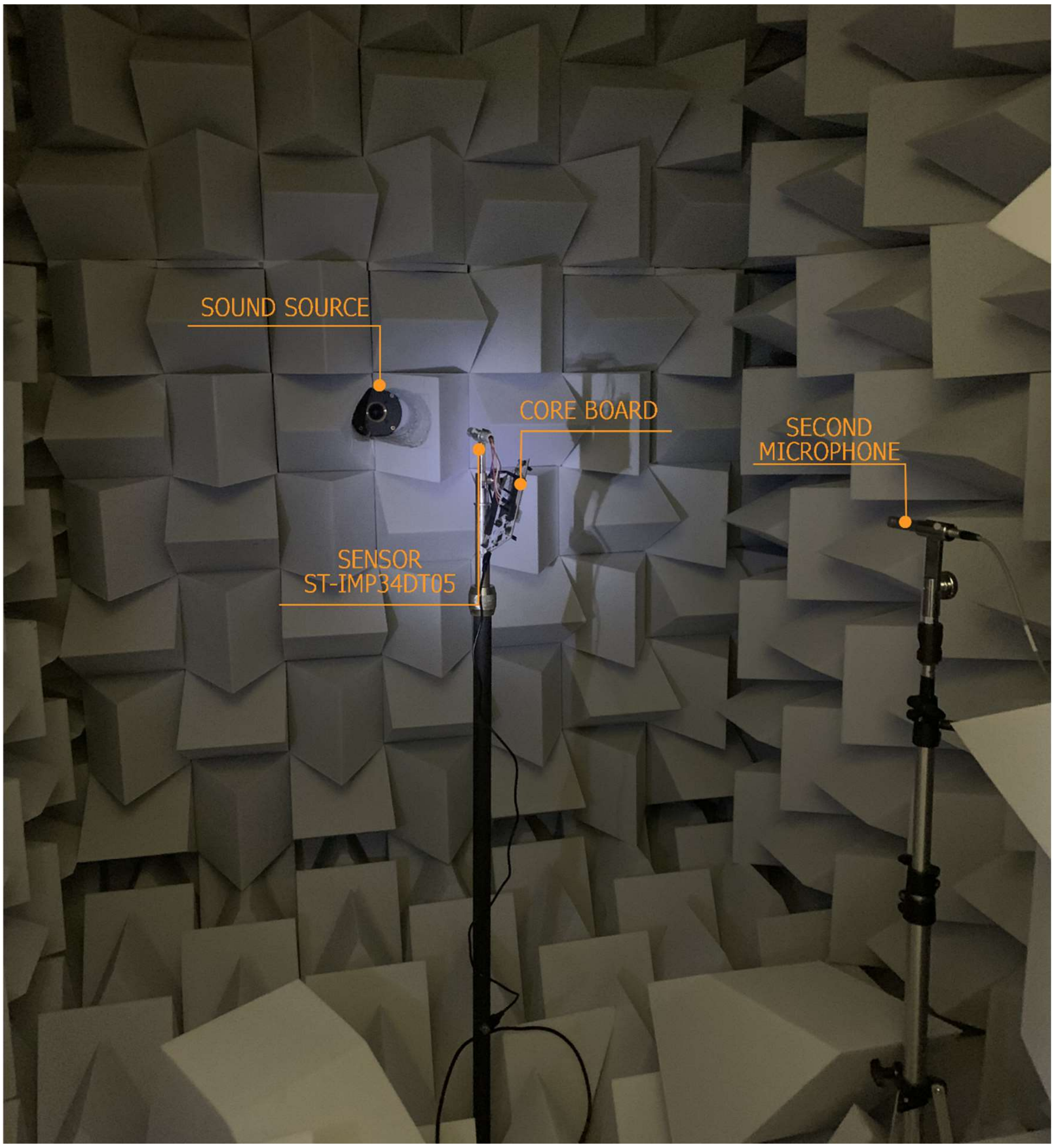


Figure 120 SLP sensor inside the anechoic chamber

For each acoustic signal, which was generated in the same way as the previous procedure, via a MATLAB function, data was collected every second for 4 seconds. The control microphone was used again, and, similarly to the first step, the equivalent level data was sampled and saved as an Excel file.

Unfortunately an code error occurred, making the measurements unsuitable to be used.

3.6.6 Discussion Of The Results: A Comparison With Samba

The results obtained revealed a general need for metrological characterization of low-cost sensors. In fact, with the exception of the temperature sensor, which was even verified in the 99.7 percent confidence interval, the sensors for relative humidity, illuminance, and CO2 concentration were not verified, i.e., their effective metrological characteristics did not meet the required metrological specifications.

For all quantities, it is possible to state that their expanded uncertainty U(x) increases as the measured quantity increases. In particular, the illuminance sensor is not suitable for measurements under natural light conditions, which can reach illuminance levels even higher than 10000 lux. The CO2 sensor also shows exponential growth in uncertainty as the concentration increases. The RH sensor, on the other hand, maintains an almost constant uncertainty as the humidity value increases, although the reference values and those read by the sensor deviate widely from each other already.

Many considerations can be made about the illuminance sensor:

- Sensor 1 demonstrates worse behavior than sensor 2. Besides being a plausible fact, since the nominal uncertainty stated by the manufacturer may differ from sensor to sensor, the cause could be traced to excessive stress, mainly of a thermal nature, which the sensor was subjected to during assembly.
- Other evidence lies in the fact that the illuminance values recorded by the sensor housed in the gray support, are always lower than those recorded by the sensor when housed in the white support. As previously stated, this could be reflections and scattering of light on the support itself. At a later stage the medium could be printed in a darker color, or alternatively the inner walls could be covered with black tape or paper.
- When tilted 30° from horizontal, the sensor tends to behave better than when tilted 60°. The cause could lie on the generation of additional shadows on the sensor, caused by the holder itself containing the sensor. So the less light will be normally incident on the sensor, the worse its performance will be.

- Measurements taken with covers of different flaring confirmed that the one at 60° from vertical, allows the sensor to perform better, although with poorer results than when the sensor is fully uncovered. In the next stage then, the case design will undergo a modification of the top cover. The opening intended for the illuminance sensor will no longer be at 90° but at 60°.

LOW COST MULTISENSOR SAMBA: A CALIBRATION COMPARISON

As stated in chapter 2.2.1, one of PROMET&O's main competitors is the low-cost multisensor SAMBA. After ascertaining their similarities and differences, both in terms of the parameters monitored and the interface with which the results are communicated to the user, a technical comparison of the way in which the sensors are calibrated and the results regarding their uncertainties became necessary. Drawing on the literature provided by the developers of the multisensor, the following considerations emerged.

100 low-cost indoor environment quality monitoring devices (SAMBA) were calibrated in order to calculate the standard error of the estimate. The mathematical model used was a Monte Carlo simulation, or multiple probability simulation. Although the SAMBA system is less accurate than laboratory reference instruments, it is sufficiently accurate for the purpose of monitoring environmental quality.

The calibration was carried out in a controlled climate chamber environment, taking into consideration the ranges in which the multisensor is required to operate, established by NABERS (National Australian Built Environment Rating System), rather than the full range of the sensors. The behaviour of the SAMBAs with respect to the simultaneously measured reference instruments was simulated by regression analysis.

Thermal

On the thermal side, five SAMBA sensors were calibrated in a small wind tunnel for comparison with an omnidirectional thermal anemometer with an accuracy of ± 0.02m/s. It measures air velocity with a sampling time of 1 second. Air temperature and relative humidity data are sampled every 10 s, against an instrument with accuracy ± 0.3°C, ±3%. The analysis ranges were:

- T_a, T_{glob}= 17°C ÷ 27°C
- RH= 20% ÷ 70%
- V_a= 0.01 ÷ 0.45 m/s

The data was then averaged over 3 minutes.

Indoor Air Quality

From the point of view of air quality, the SAMBAs were placed inside an sealed chamber (79x19x19) with a reference instrument, whose accuracy for CO_2 readings is equal to 3% of the reading or ±50 ppm, while for CO readings it is equal to 5% of the reading or ±1 ppm. The chamber also has an inlet port to insert gases, an outlet port and a fan to mix the air. The parameters analysed were:

- CO_2 in the calibration range 500-2000 ppm, with 6 calibration points;
- CO in the calibration range 0.0-15.0 ppm, with 6 calibration points;
- Particulates in the calibration range 0.000-0.100 µg/m3, with 10 calibration points;
- HCHO (Formaldehyde) in the calibration range 0-500 ppb, with 10 calibration points.

Visual

From a visual point of view, to limit the error due to differences in distance and angle of incidence between the light source and the sensor, the SAMBA was equipped with a light pipe placed between the two devices. The reference instrument adopted was a luxmeter with an accuracy of ± 2% of the reading. The data is sampled in the range of 0-1600 lux, and averaged over 1 minute for a total of 4 values.

Acoustic

Acoustically, the SAMBA was placed near a monitor providing an acoustic signal in the frequency range of 100Hz to 1600KHz, together with a reference sound level meter with ±0.10dB accuracy. SPL data in dB were averaged over 1 minute for a total of 7 values, in the range of 40 to 70 dBA.

Results

In the thermal area, the SAMBA measurements are within the tolerance range of the regulations. Air quality results vary more. The calibration responses are linear with the exception of the SPL parameter, which is underestimated between 45 and 55 dB, and the E parameter, which is overestimated after 750 lx, so further calibration is needed to improve linearity, either through software or hardware modifications.

Comparison with PROMET&O

The table below (Tab. 70) shows the different results among sensor standard error of estimate (SEE) both for PROMET&O and SAMBA for 3 of the physical dimension:

Table 69 A comparison between PROMET&O and SAMBA results

SENSORS	PROMET&O		SAMBA
	SEE		SEE
AIR TEMPERATURE	T= 30°C	± 0.008°C	± 0.05°C
	T= 20°C	± 0.008°C	
	T= 10°C	± 0.006°C	
RELATIVE HUMIDITY	RH= 22%	± 0.06 %	± 0.12%
	RH= 39%	± 0.04 %	
	RH= 75%	± 0.07 %	
	RH= 94%	± 0.03 %	
CARBON DIOXIDE	CO_2= 500 ppm	± 0.4 ppm	± 2 ppm
	CO_2= 1500 ppm	± 2.57 ppm	
	CO_2= 2500 ppm	± 5.14 ppm	

It is noticeable that the Temperature and Relative Humidity sensors used for the PROMET&O device, up to date, have a higher accuracy than those used for the SAMBA device. The CO2 concentration detection sensor of PROMET&O, on the other hand, deviates from the expected operation, performing worse than the sensor used for SAMBA.

4. CONCLUSIONS

The PROMET&O project stems from the need to bring together the objective and subjective/perceptual aspects of indoor environmental monitoring. In addition, on the European scenario, new directives, such as the EPBD, draw attention to the concept of energy efficiency, as well as quality of the indoor environment, making mandatory for new buildings the inclusion of an indoor environment monitoring system.

On the subjective front, a questionnaire was developed to collect data inherent in the user's perceived comfort, provided through tablets or smartphones. In addition, a dashboard, i.e., a subjective interface for viewing the collected data, was adopted to engage the user in the monitoring campaign. Both tools were validated by asking expert and nonexpert users to evaluate them and leave additional comments or suggestions. In fact, in the process, some changes were made both on the visualization of graphs and ways of selecting the monitored parameters and on some questions in the questionnaire itself.

On the objective front, a low-cost multisensor has been developed that can monitor some physical quantities, such as: Air Temperature, Relative Humidity (thermal domain), Illuminance (visual domain), Sound Pressure Level (acoustic domain), CO2, CO, NO2, Formaldehyde, TVOC, PM 2.5 and PM 10 (air quality domain). Each physical quantity corresponds to its respective low-cost sensor with its own uncertainty value, declared by the manufacturer ($MEMC_{nom}$ Measuring Equipment Metrological Characteristics). In fact, each sensor is calibrated by the manufacturer before being put on the market. As stated in the scientific literature, while low-cost sensors have opened the way for environmental monitoring to an increasing number of people, careful attention must be paid to the results obtained, bearing in mind that these are not particularly accurate sensors.

A large portion of the following thesis work, focused on the metrological issue, addressing the process of metrological verification and in some cases actual metrological characterization. First, it was necessary to establish the metrological requirements (CMR Customer Metrological Requirement), resorting to standards and regulations (WELL, ISO,...). Then, by comparing the datasheet of each sensor with the respective requirement to be met, it was determined in advance whether the sensor needed an adjustment step before calibration verification. Specifically, the sensor of illuminance, sound pressure level, NO_2, PM 2.5 and PM 10 have metrological characteristics ($MEMC_{nom}$) lower than the required ones (CMR).

For temperature, relative humidity, and CO_2 sensors, the following verification procedure was followed: by comparing the single low-cost sensor with an accurate reference instrument, the actual metrological characteristics of the sensor ($MEMC_{eff}$) were delineated, calculating its uncertainty (u_a) using a probabilistic method and resorting to a Type A evaluation procedure (ISO/IEC Guide 98-3:2008 GUM 1995) to arrive at an expanded uncertainty (U(x)). Should the $MEMC_{eff}$ meet of requirements imposed at the design stage, at a confidence level of at least 95.4 percent, representing the percentage of probability that the measured value falls within the range, the sensor is declared verified and does not require subsequent characterization. In contrast, in the case where the actual characteristics did not meet the requirements, MatLab software was used for the adjustment procedure. First step was to generate a calibration line, through the polyfit function, which allows generating a curve that approximates the data, and thus the measurement points. Then the residual standard error with respect to the reference value was calculated, which, when added to the uncertainty of the reference instrument itself, gives the adjusted extended measurement uncertainty (Ux(adj)). Finally, it was verified that with the new calibration function and the new extended uncertainty, the new values met the requirements.

The results obtained show that only the temperature sensor can be used without using an adjustment process. In general, for all quantities, it is possible to state that their expanded uncertainty U(x) increases as the measured quantity increases.

4.1 FUTURE DEVELOPMENTS

In the immediate term, PROMET&O will pursue metrological verification of the remaining sensors, as well as that of the complete multisensor. At the same time it will proceed with case modification and printing of 11 prototypes. This will be followed by field validation of the multisensor at the Italgas RETI SPA offices in Turin, Italy, for both IEQ and IEC monitoring. It is expected that further developments may enable PROMET&O to communicate to Building & Automation Control Systems (BACSs) the changes to be made on the quality of the indoor environment depending on the comfort perceived by the user.

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