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PROMET&O

PROactive Monitoring system for indoor EnvironmenTal quality & cOmfort

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Abstract

In the last decades, the importance of indoor environmental quality and perceived comfort in the built environment has been raised both in the scientific research field and in everyday life practice. Particularly, it has been proved that enhancing quality and comfort in the built environment allows for the improvement of, among other aspects, health, productivity and well-being. Furthermore, supporting optimal environmental conditions also allows for the implementation of Building Automation & Control Systems (BACS) and strategies for the reduction of energy consumptions. To account for the needs related to several occupants and to the built environment itself, it is fundamental to study Indoor Environmental Quality (IEQ) and Indoor Environmental Comfort (IEC) considering all the physical domains of the built environment, i.e., acoustic, thermal, visual and of air quality. IEQ is typically assessed by means of measurement campaigns using separate sensors throughout various periods. So far, only a small number of accurate multi-sensors that measure more than two or three physical quantities at the same time are available on the market. With respect to IEC, it is typically assessed by means of questionnaires but the available scientific literature only provides few results that consider the subjective perception of occupants and the IEQ monitoring at the same time.

In this thesis, an innovative methodology for IEQ and IEC assessment in office environments is explored. A new device for IEQ and IEC monitoring, which is called PROMET&O, has been designed by the Polytechnic of Turin in cooperation between the Department of Energy, the Department of Electronics and Telecommunication and the Department of Control and Computer Engineering. PROMET&O is a multi-sensor that aims at collecting objective data through the continuous monitoring of thermal, acoustic, lighting and air quality parameters, and at the same time is coupled with a touchscreen device devoted to acquire the subjective feedback of the occupants through an ad-hoc designed questionnaire. To support the identification of the design issues and the first steps of its development, two literature reviews were carried out aiming at (I) listing the premises related to the questionnaire's design in order to make it accurate, effective and engageable, and (II) deepening the measurement aspects related to the acquisition of indoor air quality quantities. Then, a practical phase of the thesis consisted in the design of the external case of the PROMET&O device in order to make it functional also in agreement with the electronic architecture issues defined. In this framework, the graphical rendering to be

implemented in the dashboard for IEQ and IEC acquisition and reporting has been determined.

To validate the proposed methodology related to IEQ and IEC, a pilot experimental study was carried out. A simplified version of the PROMET&O device, which only embeds an acoustic sensor but that is equipped with LED lights for visual feedback, was used for continuous monitoring in an office setting. Together with the sensor, the questionnaire for overall IEC assessment was administered.

Summary

1. Introduction

Today people spend almost the whole time of the day in enclosed spaces. This highlights the importance of guaranteeing an adequate Indoor Environmental Quality (IEQ) with respect to its four domains: thermal, acoustic, lighting and air quality. Indoor Environmental Quality is directly connected to the user's health, comfort and habits, and to non-physical variables (e.g., personal and behavioural). IEQ can be achieved in the built environment through the design of passive systems or through implementation of Building & Automation Control Systems (BACS). Standards and certifications developed over the years propose a vast number of possible parameters and indexes to be monitored. However, experimental investigations reported in the scientific literature mostly focus on the monitoring of only one or two domains causing a lack of a complete multi-domain approach. Another aspect is related to the perception of IEQ, which is intended as Indoor Environmental Comfort (IEC). Many studies investigated IEQ and IEC separately, and the latter has been deepened in a widely heterogeneous way. To overcome the main lacks in the IEQ and IEc assessment, this work focuses on the implementation and validation of an innovative methodology that is called PROMET&O (PROactive Monitoring system for indoor EnvironmenTal quality & cOmfort).

With a multidisciplinary approach, PROMET&O involves experts in building physics, electronic engineering and computer science engineering also to develop an innovative and accurate multi-sensor for infield monitoring of IEQ and IEC. The PROMET&O multi-sensor was designed to encourage a proactive occupants behaviour in the framework of office applications, in order to enhance health, well-being and productivity. Thanks to the possible interaction with the BACS, PROMET&O might contribute to the reduction of energy consumption in everyday life environments.

1.1. Comfort and Quality in the built environment

This thesis will heavily focus on the IEC and IEQ. The main difference between the two fields is the focus on aspects they analyse, based on the occupant feeling and perception of the environment (for IEC evaluation) and on an objective monitoring of physical parameters (for IEQ evaluation). To evaluate the IEC, it is necessary to obtain information about occupants from occupants, who must provide feedback on their condition. This is possible through surveys to collect information, questions are sent to the user subdivided by domains to which they belong: Thermal Comfort, Acoustic Comfort, Visual Comfort and Indoor Air Comfort. IEQ is instead evaluated by the monitoring of objective parameters, belonging to the Thermal Quality, Acoustic Quality, Lighting Quality and Indoor Air Quality domains. Indoor Environmental Comfort and Indoor Environmental Quality aim to guarantee to the user the best conditions depending not only on specific parameters, but on the perception one has of them.

For this reason this thesis aims to give a more comprehensive look on these topics, merging and studying together all the domains and also developing and administering a survey that will give a look into the occupant perception other than the one expected from the physical domains.

1.2. The PROMET&O approach

Today in the world there are several monitoring systems of Indoor Environmental Quality. Of these tools capable of simultaneously monitoring information about the various domains and parameters making up the IEQ, only a few are able to provide a sufficiently complete evaluation of the IEQ trend. Of these, none is able to obtain feedback from the occupant on his/her comfort situation at the same time as the environmental quality indexes. This generates a void within the market that PROMET&O aims to fill.

PROMET&O is a project developed by the Politecnico of Turin. Developed with a multidisciplinary approach involving experts in building physics, electronic engineering and IT engineering. The project aims to develop a methodology such as to put in close relationship IEC, IEQ, and PPBCv.

Designed to be placed in offices, PROMET&O has been designed as a multi-sensor able to evaluate the IEQ through a continuous monitoring of the parameters, the IEC through the proposal of a questionnaire aimed at capturing instantaneous feedback from the users, and able to perceive information on the PPBCv thanks to an access to the PROMET&O system via login.

1.2.1. *Productivity*

Studies have proven the influence of Indoor Environmental Quality on worker productivity. Although the design costs of a more performing building from an energy point of view may be higher, it has been proven that worker efficiency improvements will grant substantial economic gains over a short period, after about 2 years the initial investment can be exceeded by a factor of 60 times. This should be a clear indication proving the importance of working in an adequate environment.

Productivity increases and reduction can be closely linked to health and wellbeing, the safer the indoor environment feel the more the employee can work undisturbed, reducing health threats can on average equate to an increase of two days of work per year, that will otherwise get lost for casual sickness like flu or common colds.

Existing standards define recommended levels for thermal and lighting, addressing these two domains is simpler considering the clear effect that they can cause on an environment.

Indoor Air Quality (IAQ) is harder to evaluate possible effects on productivity, and is usually mainly linked to the Sick Building Syndrome (SBS), which is strongly considered as a cause of a poor air environment.

The effect of a poor acoustic ambience showed that Sound Pressure Level (SPL) does not strongly influence productivity, except in situations of extreme levels of noise. Studies demonstrate that an improvement of the lighting conditions makes a better perception of the acoustic environment without changing it. [4]

Overall it is estimated that, with very conservative assumptions, it is possible to reach an increase of about 0.5-5% production worth. [1]

1.2.2. *Well-being*

Most research highlights the difficulty of tying together IEQ and well-being, even if it's becoming the main point of the architecture projection. The aforementioned Sick Building Syndrome is one of the possible effects that links the occupant well-being to the Indoor Environmental Quality. It's directly linked to the Indoor Air Quality. In fact SBS' main cause is air scarce ventilation that can produce uneasiness effects, usually ranging from headache to nausea.[6,3] Another aspect of the IEQ that affects well-being is the Thermal Quality. The complex part of this domain is the variability of variables that influence the well-being, because it is not only influenced by the physical parameters like Air Temperature or Relative Humidity, but also by occupant age, gender, and clothing. Thermal preferences are also an important element that should be considered. Well-being is also strongly influenced by lighting, depending on colour range preferences of the occupants.[5]

1.2.3. Health

Indoor Environmental Quality effects on humans usually fall inside the "well-being" category, as a minor inconvenience to overcome. Although Sick Building Syndrome (SBS) usually involves a mild effect, as previously disclosed, a constant exposure to an environment rich in pollutants can have serious repercussions on health in the long run. It has been demonstrated that poor Indoor Air Quality (IAQ) conditions can generate dangerous syndromes such as cardiovascular disease or asthma. Furthermore, when the air changes in an internal environment are insufficient, the spread of airborne diseases increases drastically.[6]

1.2.4. Energy consumption

As already explained, in a pleasant environment there is a consequent increase in employee productivity and a direct greater profit; an increase in IEQ guarantees visible and considerable improvements in energy consumption. The main domain to pay attention to is Thermal Quality, in fact a small reduction in this category can lead to considerable economic savings.[1,2,3]

IAQ and lighting also engrave energy consumption with the artificial ventilation system and with the light-control. These do not have a heavy impact on consumption and consequently on costs in the short term, however ensuring constant control over long periods can lead to large savings.

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2. Indoor Environmental Comfort

As previously mentioned, all the four domains have an effect on Indoor Environmental Comfort (IEC), its evaluation is usually made by a questionnaire to collect subjective data. A literature review was carried out with three main objectives: showing the impact of the IEQ on Comfort calculation, outline the mostly used questions, and how to engage people into continuing the survey up to its finish. The review focuses primarily on how to make a compelling question and what makes a survey understandable for a wide range of people, with different levels of knowledge; explaining the correct wording, the structure and design of a compelling questionnaire. Identified questionnaires are then compared to the legislation and other studies. The paragraph 2.1 is a work in progress aimed to be published as a scientific article, for this reason the structure is similar to a literature review.

2.1. Indoor Environmental Comfort Review

2.1.1 Introduction

Indoor Environmental Comfort is one of the most important factors that a building should provide to its users. To reach this goal the legislation gives guidelines that should be followed, but laws alone generally don't give a full picture, on field experiments have the tendency to adapt these guidelines. This literature review aims to study the questionnaires that are currently used in the IEC field that proved the efficacy of their question. The correlation between the subjective and objective sides of an indoor environment is often not taken into consideration. Generally papers consider only one or two domains of the IEQ without taking into consideration the relevance that other factors might have on the wellbeing of the occupancies. This aspect has been noticed even in the sensor industry, indeed most sensors only consider one or two physical domains. Some devices capable of checking multiple domains do exist, but there is a clear market void especially in the comparison of objective monitored data and the subjective feedback.

The objective is to outline a method to develop a questionnaire making it fit in the most possible situation. It will also investigate the best graphical visualisation to develop an easy-to-understand dashboard for data collection.

2.1.1.1 General rules for questionnaires

To further understand the best way to produce a questionnaire, the literature review on articles only related to IEQ wasn't enough, so a parallel research to outline the state of the art of questionnaires is needed. In the following chapters the focus will be directed towards the correct approach to use when developing a survey in order to give to the user an understandable and clear questionnaire. This research will then be compared to the questions that will emerge from the literature review.

2.1.1.1.1 Questionnaire question

Questionnaires must follow some rules regardless of the topic, these are established to maximise the amount of usable response and reduce to minimum the rate of user confusion or misunderstandings [31,32,33]. This can be done by keeping a specific formulation and wording; the choice of the words is one of the most influential factors on the survey outcome. Questions should be characterised by:

- easy to understand
- simple
- only convey one thought at a time
- concrete
- to avoid ambiguous meaning, the question should have the least number of words with the most amount of meaning
- avoid catchwords, which is a word or phrase that is often repeated by, or becomes connected with a particular organisation, especially a political group
- avoid words with emotional connotations: that could influence the following answer depending on the emotion rather than the opinion
- temporal window: each question should convey a clear time position for the question that requires it, saying last week is to be preferred compared to usually, this to avoid different understandings of the same term
- Active/passive voice, an active voice like “complete this questionnaire only if you had any thermal discomfort last week” seems to be more engaging, easier to understand and preferable compared to a passive voice like “this questionnaire has to be completed only if you had any thermal discomfort last week”
- Leading questions, always be sure when asking personal questions that the user is from the correct group, simply by asking if the interviewed person is a worker before asking its job, by stating to jump this question in case it is not

2.1.1.1.2 Questionnaires answers

Answers should follow the same rules as the question, easy to understand, simple wording, avoid ambiguity, etc. while also:

- Demand one answer per question
- Yield truthful and accurate answers
- Accommodate all possible contingencies of a response
- Have mutually exclusive response options
- produce variability in response: if in a question with multiple choice almost all users give the same answers this might mean three things, you found a generally agreed factor, the question was written in a wrong way or most often the answer option given were to restrictive and most people answered with the close estimation which don’t give the real scope of the situation

The structure of the answers is important as much as the style of response, which can be either open ended or provide multiple options from which to choose one or more.

When an answer is composed of multiple set possibilities to choose from it is possible to give to the users a set of answers chosen by the survey developer, however there are some scales that are consistently more used for their efficacy. For example the Likert scale is one of the most used options to have a good answer, usually goes to a 5 or 7 point scale, the middle or neutral point is needed only if no previous question already excluded that possibility. The key to the Likert scale proven effectiveness is the simple point wording based on the feeling of agreement on a question, ad example “extremely satisfied, very satisfied, satisfied, indifferent, unsatisfied, very unsatisfied, extremely unsatisfied” or “strongly agree, agree, neutral, disagree, strongly disagree” are all possible likert scale, this is useful because all survey could maintain the same metric just by slightly modifying the questions.

- The McIntyre scale is often used as a way to establish thermal preference on a 3 point scale “warmer, no change, cooler” sometimes is used a 5 or 7 point even if it should only divide people In the one in comfort and discomfort to correctly evaluate later questions.
- The ASHRAE scale for the Predicted Mean Vote (PMV) is a mathematical model that use: metabolic rate, clothing insulation, air temperature, mean radiant temperature, air speed and relative humidity to evaluate the subjective thermal comfort level. The PMV index can range from -3 cold, -2 cool, -1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, to +3 hot, this range is often used as an answer scale for subjective comfort.
- Magnitude estimation: In this field answers of this kind are almost non-existent and constantly avoided, because of the highly variability, usually the user is requested to put an “X” on a line going from 0 to

100, is clear that this method might cause some error, but new research seems to favour this approach even over a Likert scale for two reason, first it allows to distinguish a larger range of perceived situation (when correctly placed), second, the intervals between levels of acceptability are measured in uniform units calibrated by the acceptability of the reference sentence, known as the 'standard', In contrast, the intervals between numbered points on a Likert scale, although numerically equal, may in fact not be treated as equal by respondents, particularly if they are associated with vague labels.[31]

2.1.1.1.3 Questionnaire structure

Easy to follow question structure: the sequence of questions must allow an easy understanding of what the topic is at the moment, a proper structure makes the questionnaire considerably harder to be misunderstood. This is especially relevant for preliminary questions, generally at the start of any survey there are some cognitive interrogation (age, sex, etc.) made to have a vague profile of possible behaviours, but some generally considered "preliminary" question could be detrimental:

- Questions that put a great strain on memory, this could influence answer of the present confronting it with a past event
- Question of a personal character, more broadly, asking any type of preference could influence all following question on the same topic
- Question related to personal wealth

If any of these types of questions are needed they are to be put near the end of a chapter going into a different topic or at the actual end of the survey.

A smooth progression through the question is fundamental to maintain a high engagement and minimise non-response, this can be achieved by:

- Choose a general form, which refers to the general structure of the questionnaire, a structured questionnaire gives a specific amount of possible answers to choose minimising open answer questions, on the other hand unstructured questionnaires behave the opposite.
- Maintain motivation to complete the questionnaires, starting with easy questions and establishing the general category of the respondents.
- Aid respondents recall: which is a question-asking strategy in which survey respondents are provided with a number of cues to facilitate their memory of particular responses that are of relevance to the purpose of the study.
- Be relevant to respondents' own records: providing a clear explanation of the importance of the data over the life of the interviewed.

The order and grouping of the question should be planned to avoid any question that could leave some influence in later parts of the survey.

Maintaining a compact visual by placing question and answers close together, also by grouping topics together, and giving a clear visual change when the topic varies, even just by changing chapter title. This is particularly needed in case of questionnaires that don't ask for full competition.

-Filter question: Their aim is to give a different path to follow depending on the answer, which is useful to only have relevant question answers and to guide the user through the survey. This should be done by providing a clear explanation on what path to follow to avoid users getting lost, which is especially true if we consider the pen and paper version.

2.1.2 Methods

2.1.2.1 Literature search

Articles were searched on the Scopus database, starting from the 2000, focussing in the indoor environment houses, schools, offices. The main keywords for the query were the four comfort domains, survey and indoor as summarised in the following scheme. From the query all the articles that showed the survey, some questions or studies that explored the influence of different human factors on the perception of comfort were selected.

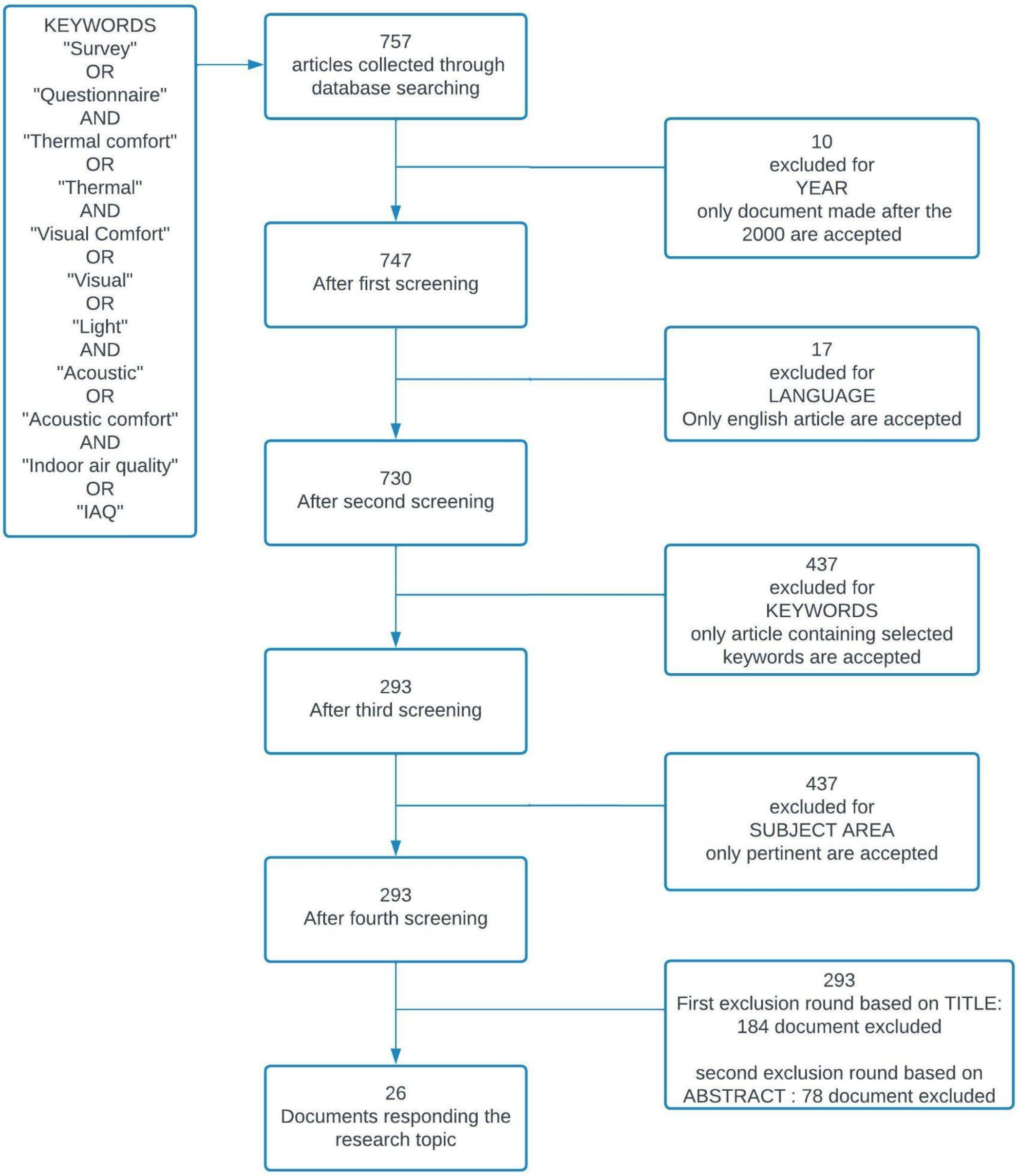

Figure 1: flowchart of the selection process that has been followed to determine the articles deemed inherent and complying to the research

2.1.3 Results

2.1.3.1 Summary of the articles

In the following table *Table 1* the chosen articles are summarised. The focus of this table is to compare for each article from the main field studied, where the studied building was located, the building's intended use and then the most interesting questions are listed with possible answers. Under the question column are shown, when given, the exact question and answer possibilities given by the article, otherwise are given the topic of the question.

Table 1: summary of the reviewed articles

ARTICLE	COMFORT FIELD	INTENDED USE	LOCATION OF THE STUDY	TYPE OF QUESTION	QUESTIONS	HOUR OF INTEREST
[1]	Thermal, IAQ	gym, (Others)	Canada	Physiological	-"How satisfied were you with the temperature today?". answer on 5 points: warm, slightly warm, neutral, slightly cool, cool, -"how satisfied were you with the air quality in the gymnastics centre today(i.e. stuffy/stale air,odour)?". answer on 5 points: very poor, poor, neutral, good, very good.	10.00 - 18.00 Free
[2]	Thermal	University	U.S.A	Physiological	-"How does the room feel?". Answer on 5 points: cold, chilly, perfect, warm, hot.	24 - 24 Free
[3]	Thermal	Office	Singapore	Physiological	question about thermal comfort not better explained, answers on a 7 point scale following PMV.	8.00 - 17.00 Free
[5]	Thermal, IAQ, Visual, Acoustic	School		Physiological	-How satisfied are you with the indoor climate today?. Response on 5 points, described qualitatively by smileys without further definitions. -Multiple choice question in which to highlight your discomfort from: "Too warm; Too cold; Draft; Poor air quality; Noise; Poor lighting; Other".	9.00 - 18.00 Free
[4]	Thermal	Office	Norway	Physiological	Unspecified question about thermal comfort, Answer on a 7 points PMV scale, unspecified question about temperature preference on a 3 points on the McIntyre scale: more falls, no variation , colder Checklist for clothing.	8.00 - 17.00 Free
[6]	Thermal	University	Italy	Physiological	Question about thermal comfort not better explained	8.00 - 17.00 Free
[7]	IAQ	Office	Cina	Physiological, Contextual	Basic information: Gender, age, daily working hours, illness history -question about Odours: Stuffy odour, mould odour, pungent odour -question about Symptoms: Headache, fatigue,dizziness, breathing difficulty, tight chest, blocked nose, dry, tinnitus -"When leaving Office When leaving the Office buildings, the symptom changes?"	9.00 - 17.30 Free
[8]	Visual	School	Cina	Physiological, Behavioural, Contextual	-"The first thing that I notice upon my entrance to a class is its window?" -"I will immediately notice a window if it causes glare or provides abundant light." -"During lecture courses, I prefer to close curtains because the light annoys me" -"During lecture courses, I prefer to open curtains only if there is no intense light coming in." Answers on a 5 point scale from strongly agree to strongly disagree.	10.00, 14.00 Mandatory
[14]	IEQ	Office	Corea	Physiological	0. Personal workspace description. 1. Satisfaction with the amount of space available. 2. Satisfaction with visual privacy in the workspace. 3. Satisfaction with the workspace interaction with coworkers. 4. Satisfaction with workspace temperature. 5. Satisfaction with workspace air quality. 5. Satisfaction with workspace air quality. 6. Satisfaction with workspace lighting (illuminance). 7. Satisfaction with the visual comfort of lighting 8. Satisfaction with noise level. 9. Satisfaction with sound privacy. (ability to hold conversations without your neighbours overhearing and vice versa) 10. Overall satisfaction with personal workspace.	9.00-17.30 Free
[9]	IAQ, SIAQ	Residential	Sweden	Physiological	"Have you been bothered by the following factors in your dwelling?". 1. Draught; 2. Too high room temperature; 3. Unstable room temperature; 4. Too low room temperature; 5. Stuffy air; 6. Dry air; 7. Unpleasant odour;8. Dust and dirt. Answers on 4 points: yes, sometimes; no, never.	-----
[15]	Thermal, IAQ, Visual, Acoustic	Residential	Canada	Physiological, Behavioral, Contextual	-Question on: Age, Length of stay, Rental choice, Number of occupants, Average indoor time, Smoking indoors, Pet keeping, IEQ, Indoor thermal satisfaction now, IEQ problems, Thermostat or fan control, long term thermal satisfaction, Radon, Mould, Indoor air quality now, Indoor air quality problems, long term air quality, lighting condition now, long term lighting satisfaction, speech privacy,	-----
[16]	Thermal, IAQ	Residential	Italy	Physiological	-"How satisfied are you with the temperature in your apartment?" -"How satisfied are you with the air quality in your apartment?" -"How satisfied are you with the amount of light (natural and artificial) in your apartment.?" -"How satisfied are you with the sound privacy in your apartment (ability to have conversations without your neighbours overhearing and vice versa). Answers on a 5 points Likert scale from "very satisfied" a "dissatisfied".	At start and end, 3 week apart
[17]	Thermal, IAQ	Residential	France	Physiological, Behavioral, Contextual	The first questionnaire asks about the occupants of the apartment, the use of maintenance for the ventilation system, the use of heating systems, the average period of opening of windows, the presence of smokers, the state of fixtures, if detergents or other pollutants are used (incense, candles, pesticides, perfumes). The second questionnaire asks about perceived air pollution, acoustic thermal comfort and the reasons for possible discomforts.	One questionnaire at the end of every week.

ARTICLE	COMFORT FIELD	INTENDED USE	LOCATION OF THE STUDY	TYPE OF QUESTION	QUESTIONS	HOUR OF INTEREST
[18]	IAQ	Residential	Taiwan	Physiological, Contextual	Question on: Sex, age, allergic history, family history, time spent in the home, Information on the residential, building style, construction year, number of stories, causes of the renovation, floor area, floor materials, ventilation system. Indoor environment conditions and living style, number and kind of pets, use of insecticide, aromatics and/or incense, amount of tobacco smoking, surrounding outdoor environments, kinds of the site surrounding the house.	The questionnaire were done one per week
[19]	Thermal, IAQ, Visual, Acoustic, IEQ	University	Italy	Physiological, Physical	Question on: gender, age, How do you rate global comfort in the classroom?Comfort categories in the last hour, How do you rate thermal comfort in the classroom? How do you rate the air quality in the classroom?, How do you rate visual comfort in the classroom?, How do you rate acoustic comfort in the classroom?, answers on a 5 point scale from very poor a very good	Subjective every hour on a voluntary basis
[20]	Thermal, IAQ, Visual, Acoustic	University	Belgium	Physiological, Behavioral, Contextual	Personal data, general feeling, View, Visual comfort, thermal comfort, Adaptation control, User interaction, Acoustic comfort	2 times, 2 weeks apart in the autumn at 14.00 Mandatory
[21]	Thermal, IAQ, Visual, Acoustic	University	Indonesia	Physiological, Physical	-Rate the level of temperature as: "very cold", "cold", "comfort", "hot", "very hot" -Determine their feeling about relative humidity as "very dry", "dry", "comfort", "humid", "very humid" -Rate the level of noise which is rated in 5 scales such as: "too silence", "silence", comfort, "noisy", "too noisy"	-----
[22]	Visual	University	Italy	Physiological	Apart from the initial information (gender and age), the questionnaire is composed of 14 closed-ended questions on a 11 point Likert scale.	Usually around 10.30 and 12.30 depending on weather.
[23]	Visual	Other:	Sweden	Physiological, Behavioral, Contextual	Questions on: Lighting condition, visual symptoms, daylight, illuminance , glare,flicker, work space, work object, work postures.	intervals of 2-3 weeks, time not specified
[24]	IEQ	Office	Nederland	Physiological, Contextual	How satisfied are you with the following condition? Temperature, air quality, humidity, view outside, lighting, daylight, noise, overall comfort.	working hours not better explained.
[25]	Thermal	Office	France	Physiological, Contextual	Thermal preference was assessed using a seven-point scale: 'a lot more cooler', 'more cooler', 'a bit more cooler', 'no change', 'a bit more warmer', 'more warmer' and 'a lot more warmer'. Thermal satisfaction was evaluated using two levels: 'satisfied' and 'dissatisfied'. In addition, students' activity level was determined using a five-point scale: 'seated quiet', 'standing relaxed','light activity', 'medium activity' and 'high activity'.	-----
[26]	Visual	School	Iran	Physiological, Behavioral, Contextual	Daylight availability on the desk, amount of view through the window, quality of the view, is the sun shining directly into your eyes?, how the sun feels, mark the degree of glare that you may experience, overall assessment over visual comfort, indicate how you behave in case of excessive sunlight	3 times per day at 9.00, 11.00 and 13.00 Mandatory
[27]	Visual	Office	japan	Physiological, Behavioural, Contextual	-"How is the brightness on your desk, do you feel uneasy about the lack of uniformity on your desk?", -"Do you feel uneasy about the reflection on your desk?", -"Do you feel uneasy about the reflection on displays?" -"Do you have task lighting?, -"How often do you use ceiling illumination?" -"How often do you use shading such as venetian blinds?", -"How is the brightness in your whole workspace?, -"How do you feel about the atmosphere in your workspace?, -"Are you satisfied with the light environment in your workspace?	working hours not better explained
[28]	Thermal	Residential	Japan	Physiological, Contextual	Thermal sensation; thermal evaluation, thermal preference, personal acceptability	10 and 16 free
[29]	Thermal	Residential	Portugal	Physiological, Contextual	Level of satisfaction with the quality of daylight, level of thermal comfort during winter, level of thermal comfort during the summer, when the thermal discomfort is more present, what do you use to adjust the thermal comfort?What kind of heating do you use, is the air usually stuffy.	-----
[30]	Thermal comfort	Residential, Office, School, (Other)	Madagascar	Physiological	Thermal sensation, humidity sensation, air movement sensation, Thermal satisfaction, thermal preference, thermal comfort	-----

Table 2: Interactions of satisfaction over individual characteristic (table taken form [10])

	Gender	Age	Country of origin	Height, weight	Fitness	health	Job	Psychological behaviour stress
Thermal sensation	O	O		O	O	O		O
Satisfaction with temperature	X							
Thermal comfort	O	O	O	O	O			
Acceptability of thermal environment	O	O			O		X	
Neutral temperature	X		X					
Perception of temperature	O	O					0	
Neutral temperature Impact on perception of air quality	X							
Satisfaction with air quality	X							
Perception of air quality	O	O						
Subjective air quality Impact on visual	O	X						X
Satisfaction with visual environment	O							
Visual satisfaction	X	X					X	
Satisfaction with lighting							O	O
Impact on acoustic conditions								
Satisfaction with acoustic environment	O							
Acoustic dissatisfaction and disturbance			X					
Ranking of conditions	X							
Adverse perception	X		X				X	
Overall satisfaction							X	X

Table 2 is instead obtained by another literature review [10] where the "X" indicates a proven effect of the given sensation-perception (in the first column) with the corresponding condition (in the first row), in opposition the "O" indicates interactions that are not connected.

2.1.3.2 Thermal Comfort

Compared to the other field the thermal studies are considerably more frequent, most papers in the review considers this field: with sixteen papers talking about Thermal Comfort one was conducted in a gym, six in residential buildings, two in a school, three in offices and five in universities. Regardless of the different use of the building or the outside condition, questions remain generally similar. The most used variation of question are "*How satisfied were you with the temperature today*" [1], *How satisfied are you with the indoor climate today*" [5], "*How satisfied are you with the temperature in your apartment*" [16], "*Rate the thermal level of temperature*" [21], "*Level of thermal comfort during the winter*" [29], all question want to receive essentially the same response about the instantaneous perception that the receiver of the survey has in one moment in time. Considering that the questions are the window that users have over the people interested in them [33] using an active and cordial voice that remains serious but friendly seems to be the best option. Time position is often overlooked but is a needed information. On this type of question, is noticeable a trend on the possible answers, usually on a 5 or 7 point scale either using a Likert scale on preference or on a ASHRAE scale on feeling like "cold, cool, slightly cool, neutral, slightly warm, warm, hot" or a Bedford scale on preference like "much to warm, too warm, comfortably warm, comfortable, comfortably cool, too cool, much too cool. Another often asked subject revolves around the preference of condition, "*usually do you prefer which type of environment?*" This can be a tricky question, most questionnaires [15] put this type of question at the chapter start, however this could influence opinion on later thermal questions, the preferred answering scale is the McIntyre, but is often used as a 5 or 7 point instead of 3.

2.1.3.3 Indoor Air Comfort

Air quality as a topic has recently seen an increase in popularity due to the covid pandemic. Indoor Air Comfort (IAC) was always considered the main cause of many indoor illnesses like the Sick building syndrome-SBS which is considered to be caused by some airborne chemical compound like VOCs. Of eleven papers on IAC one was conducted in a school, one in an office, four in a university and five in a residential building. Understanding the perception that people have over IAC is considerably less straightforward compared to thermal comfort, this is visible in the questions, all articles seem to choose a different approach. Same deal for the answers stile and scale, some article directly ask if the user if they feel the presence of radon or other airborne pollutants [15], which can be difficult to evaluate, other approach instead try understand the current air quality by asking about some possible symptoms and smells that are usually link to poor air quality. This method seems to yield the best result [7]. Some possible questions can be: "*Over the day have you smell any of these odours?*", multiple answers are possible between "stale air, Stuffy odour, mould odour, pungent odour" or question on symptoms: "*do you usually suffer From one of this symptoms: Headache, fatigue, dizziness, breathing difficulty, tight chest, blocked nose, dry, tinnitus*" and "*by leaving the structure does the symptoms change: yes, no*". This approach Is clearer for the user and provides a higher level of correlation with the objective measurements. If for consistency or other reasons it is preferable to use *a set answer scale, another option that proved to be effective is by asking "how do you feel about the air quality?*" and the question can be done on a 5 point Likert scale from very good to very poor, this method however does not explain clearly what is considered good and bad air, putting this decision only on the user's side.

2.1.3.3 Visual Comfort

The visual comfort is generally considered a necessity by the legislation, on offices or public structures regulating a minimum of 500 lux on the desk, in the residential field we only have some suggestion. The questions for indoor visual comfort usually are "*Are you satisfied with the visual comfort at the moment/usually?*"[27] Answers on a 5 point scale from very poor to very good, "*Do you usually see disturbing glares*?"[26] answers on 5 scales from never to always, or "*What is your desk-table-walls brightness?*"[27] answer on a 5 point scale from very bright to very dark. These questions are good at establishing the general subjective preferences and situation of the user, but are often not enough. Other possible question ask about what the user have in relation with light sources (windows, tv-pc screen light, etc.) some questions can be like: "*during the day I prefer to close the windows*", "*during the day I prefer to open the windows*", : "*during the day I prefer to open the windows only if there is no intense lighting coming in*", "w*hen I am closer to windows I tend to turn light on more*", "*when I am further from windows I tend to turn light on mor*e", "the *first thing that I do when entering the room is turning the light on*"[8] the scale is usually a 5 point Likert. These questions proved to be the most various between the articles; general questions are usually similar while specific questions vary considerably.

2.1.3.4 Acoustic Comfort

Indoor acoustic comfort is one of the most annoying to users primarily for the feeling of impotence on reducing the noise pollution that has a source outside the houses. From the review the most used question resulted in the usual general assessments like: "*how do you rate your acoustic comfort*" [19] from too silent to too noisy or satisfied dissatisfied, another often used question for the residential aspect is "*Are you satisfied with your sound privacy?*"[16] From dissatisfied to satisfied. The research on subjective acoustic indoor comfort is usually integrated in other research but the questions are consistent between papers.

2.1.4 Questionnaire administration

To receive a compelling answer from the interviewed question wording and an easy to follow structure composition is only the first step. The next one will be choosing a period and time of the day where the user should submit the answer. from the literature review is visible how there are two category of questionnaire for :

"Free answer": this type doesn't give any time stamps where it is possible to answer. (but generally try to remember the hour of the answer by digital means) The freedom of this approach is best used on a large population where the sample size can dilute over all the studied period, to work correctly this method will require a visible stand and some means to create awareness towards the initiative.

"Mandatory answers": this typology gives instead an exact time window where the questionnaire should be done. Can be further divided in 2 sections, one option is to give a time window or give an exact hour to answer, and can be done one or multiple times in a day.

The literature review give a wide range of possible hours where they made their population answer the mandatory questionnaire, this hour variability can be linked to the physical domain studied:

Thermal: give a clear preference over the working hour of the day, usually considered around 8.00 AM to 8.00 PM, although there is interest in the season, some study monitor for months an environment, submitting questionnaires on a weekly basis.

Visual: questionnaires regarding the visual are forced to be inconsistent due to climatic conditions. All surveys should be answered during comparable situations, multiple studies where forced to take answers only on specific days ignoring others, overall the preferred study period is around 9.00 to 13.00.

Air quality: this domain does not seem to be a key factor when deciding administration times over the other domain. This can vary depending on the place of the study and if there are some considerable pollution emitters in the vicinity like sizable roads or factories. Regardless the most frequent administration times are working hours

Acoustic: similarly to the previous domain acoustic is generally not a predominant factor for the administration's time. As previously its relevance depends directly from the severity of noise caused near the studied indoor. This usually makes the administration times around the working hours.

2.1.5 Graphical style

Questionnaires need to be understandable under every aspect, the wording field was already discussed in the previous chapters analysing the best practices, in a similar way the graphical side is the one that gives the charm and sets the tone to the entire work. Is the first impact that a user has over the questionnaire before reading any question. These chapters are considered both a paper and digital approach but we primarily will focus on the latter type.

From the reviewed articles only few had or showed a meaningful approach to this topic. Most paper based questionnaires prefer the typical style made by a question followed by a series of possible answers with a square for each where it is possible to draw a mark to give the answers, but there are a few notable exceptions.

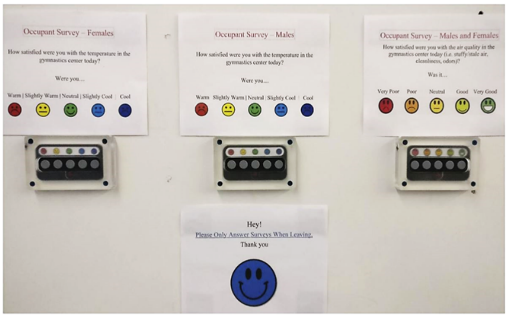

Figure 2: A method to conduct longitudinal studies on indoor environmental quality and perceived occupant comfort. (Figure taken from [1])

This is an example of a hybrid between the paper and the digital approach, answers are taken by an array of buttons colour coded to the relative smile, this is made to attract people into answering. In this article surveys were done in a school gym so the playful nature of the colored smiles is appropriate and could create interest.

Figure 3: Occupant thermal feedback for improved efficiency in University buildings. (Figure taken from [2])

This example shows another colour coded answer style, this questionnaire was only digital, made for a college and had only a few questions on thermal comfort given by a more serious and minimal style with a consistent colour scheme.

Figure 4: Design and in-field testing of a multi-level system for continuous subjective occupant feedback on indoor climate. (Figure taken from [4])

This example is also digital based, and proves of great help to value correct graphical styles depending on the situations. The question in the "D" image says "How satisfied are you with the indoor climate today" and offers a scale of possible answers made by emoji. This questionnaire was done in an office, the paper itself gives some interesting feedback given by the interviewed workers: "People are messing with the tablet stand and zooming in at one smiley face and so on." and "Maybe it would be better to use simple grades or dice/star ratings instead of the smiley faces."

This feedback shows how some graphical choices need to match the questionnaire setting, in a school environment smiley faces can be considered acceptable, but while studying an office or a place where is possible to predict that the majority of its occupants will be adults, then is preferable to utilise a more serious approach. The questionnaire set the idea that the interviewed have over the interviewing, maintaining colourful but serious and minimal graphics help the interviewed to take the questionnaire with more seriousness when giving a response.

In Figure 4 a display is shown where it is possible to choose a lever to express discomfort, the icons give a simple but exhaustive indication about the concept of the button, while avoiding being too informal.

2.1.6 Conclusions

The aim of this review was to bring together the subjective and objective fields in a way not often faced. A main point of this review was to find the correct wording which is fundamental to reach the reader in a compelling and clear way. The researched questions show a link with the regulations even though the questionnaires were not directly made from it. From all the found questions those structured in a similar way to the given rules proved to be more effective, but exceptions weren't rare. Articles usually don't focus on the received feedback, so understanding the rate of success and retention that each question can obtain is complex to evaluate.

Questionnaires are still the best way to evaluate IEC, some aspects proved to be more influential than others, both on user’s comfort and user’s involvement to the questionnaires:

- Context seems to be one of the main influencing points on questionnaires;
- The scale to evaluate Comfort is also a factor affecting people's participation. Some studies conducted in schools [5] pointed out that the PMV scale seems easier to understand for children;
- The perceived comfort is strongly influenced by the user expectation on a specific environment [30];

Actually there isn't a unique methodology to produce a perfect questionnaire everywhere applicable, with the literature review above discussed was possible to outline the method used to develop the PROMET&O questionnaire to obtain a feedback on the subjective comfort.

2.2. IEC for PROMET&O

To evaluate the IEC, PROMET&O multi-sensor proposes a questionnaire to express the global comfort perceived for each domain.

The answers respond to a percentage value of comfort for each domain. The formula to obtain IEC index is below indicated:

(Thermal Comfort + Acoustic Comfort + Indoor Air Comfort + Visual Comfort) / 4 = IEC [%]

The will to avoid arbitrary choices in the representation or the use of scales that could be less understandable has led to the decision to give comfort in percentages from 0 to 100 for ease of understanding for all. The following paragraphs will explain the conversion for each domain, the questions that will be shown are taken directly from the final survey developed for PROMET&O which will be further explained in chapter 4.

2.2.1. Thermal Comfort

Thermal Comfort is that condition of mind which expresses satisfaction with the thermal environment. The comfort perceived can vary from person to person, but from legislation and literature it was possible to define a mathematical algorithm that could give a value to express the Thermal Comfort. To describe the Thermal Comfort was used the Thermal Comfort Model, given by legislation (EN 16798-1:2019).

In the following table are shown the parameters considered for Thermal Comfort calculation in PROMET&O.

Table 3: Conversion table from sensor data to Thermal Comfort used in PROMET&O

COMFORT DOMAIN		**THERMAL COMFORT**	
		TC	
		%	
THRESHOLD / TEMPORAL RANGES		0-100%	All temporal ranges
SAMPLING TIME		-	
REPORT TIME		30 s	
COMPLIANCE AT REPORT TIME		Adaptive Thermal Comfort Model	
VISUALIZATION TIME	compliance overall temporal ranges	Adaptive Thermal Comfort Model	

Where:

Threshold / Temporal Range - range of data returning

Sampling Time - Time in which the sensor acquires the physical data

Report Time - Time in which the monitored data is sent to the server

Compliance at report time - Compliance to the legislation over a set number of samples values.

Visualisation time - Time in which the monitored data is shown

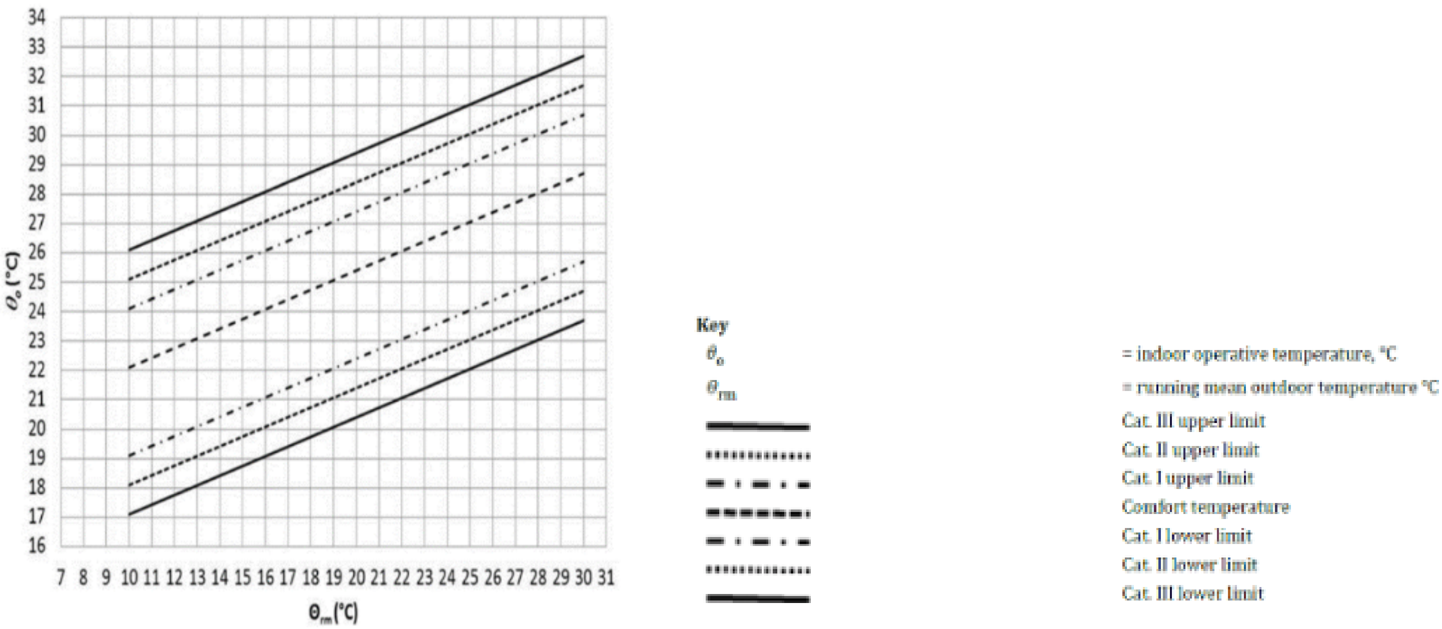

Figure 5: Adaptive Thermal Comfort Model (figure taken from [35])

This model crosses the running mean outdoor temperature which is the arithmetic mean of outside temperature over the last 30 days and the indoor operative temperature:

This formula is a simplification for indoor environments considering Air Temperature equal to the Operative Temperature (T_a = T_o) and an indoor air speed inferior to 0.3 m/s, with metabolic rate between 1.0 and 1.3 while not in direct sunlight, which are generally always true in an office. The comfort percentage is then calculated by considering how many samples are within the acceptable region (upper limit 1 and lower limit 1) in the last 100 samples; that amount is the thermal comfort percentage.

To evaluate the Thermal Comfort, PROMET&O multi-sensor aims to propose to the users a questionnaire containing two questions to evaluate the level of discomfort.

First question is a general question regarding if there are any dissatisfaction in the environment the user is (only one option is checkable at time):

1) Please indicate on the following scale how YOU feel NOW
- ☐ Hot
- ☐ Warm
- ☐ Slightly worm
- ☐ Neutral
- ☐ Slightly cool
- ☐ Cool
- ☐ Cold

Below are indicated the level of percentage in which the answers are converted to express a TC value

Table 4: Conversion from question answer to comfort values used in PROMET&O.

"+3 Hot"	25%
"+2 Warm"	50%
"+1 Slightly warm"	75%
0 Neutral	100%
-1 Slightly cool	75%
-2 Cool	50%
-3 Cold	25%

This question has been chosen because of its simplicity and the similarity to legislation questions. The words “you” and “now” have been put as capital letters to further explain the importance of the subjective feeling in that moment, so it’s possible to have a time position where it is possible to compare the objective thermal situation with the perceived feeling. The answers to this question follows the PMV scale.

The second question (only one option is checkable at time):

2) Please indicate on the following scale how YOU find the AIR VELOCITY in your environment NOW

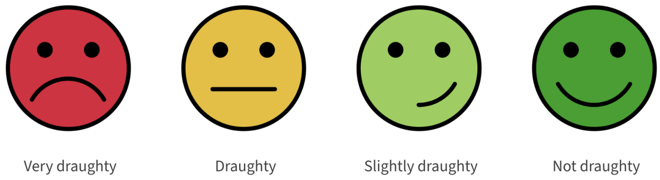

Figure 6: Representation of dashboard selectable options in the questionnaire

Table 5: Conversion from question answer to comfort values used in PROMET&O.

Very draughty	25%
Draughty	50%
Slightly draughty	75%
Not draughty	100%

This question was mainly selected by the similarity to the legislation with the addition of the time coordinate "NOW" in order to ensure its clarity and avoid misunderstandings by users.

It is important to add that Air Velocity is considered as a parameter influencing the Thermal domain and not the IAQ domain because it has a strong effect on the perceived temperature. To analyse IAC is preferable checking bad smells.

2.2.2. *Acoustic Comfort*

Acoustic comfort is that condition in which the user experiences a sense of well-being related to the hearing conditions. In the following table where are shown the values regarding Sound Pressure Level and Acoustic Comfort with their respective algorithms used to calculate the percentage of expected comfort, considering: “xt” the expected comfort percentage at a given time, “n” the number of records that satisfy the legislation and “n. Samples values” the total data recorded.

Table 6: Conversion table from sensor data to Acoustic Comfort used in PROMET&O

COMFORT DOMAIN		**ACOUSTIC COMFORT**		**Sound Pressure Level**	
		AC		SPL	
		%		dB(A)	
THRESHOLD / TEMPORAL RANGES		0-100%	All temporal ranges	≤ 40 dB(A)	All temporal ranges
SAMPLING TIME		-		22 kHz	
REPORT TIME		1 s		1 s	
COMPLIANCE AT REPORT TIME		AC = Compliance SPL in report time [%]		Compliance SPL in report time (xti) [%] = (nSPL·100)/n. sampled values	
VISUALIZATION TIME	**compliance in real time**	AC = Compliance SPL at RT [%]		5 s -> 5 percentage values Compliance SPL in RT [%] = (xt1 + xt2)/2	
	compliance over 3h	AC = Compliance SPL in 3 h [%]		3 h -> 2160 percentage values (every 5 s) Compliance SPL in 3h [%] = (xt1 + xt2 + … + xt2160)/2160	
	compliance over 12h	AC = Compliance SPL in 12 h [%]		12 h -> 4 percentage values (every 3 h) Compliance SPL in 12 h [%] = (xt1 + xt2 + xt3 + xt4)/4	
	compliance over 24h	AC = Compliance SPL in 24 h [%]		24 h -> 2 percentage values (every 12 h) Compliance SPL in 24 [%] = (xt1 + xt2)/2	
	compliance over 3d	AC = Compliance SPL in 3 d [%]		3 d -> 3 percentage values (every 24 h) Compliance SPL in 3 d [%] = (xt1 + xt2 + xt3)/3	
	compliance over 1w	AC = Compliance SPL in 1 w [%]		1 w -> 7 percentage values (every 24 h) Compliance SPL in 1 w [%] = (xt1 + xt2 + … + xt7)/7	
	compliance 1m	AC = Compliance SPL in 1 m [%]		1 m -> 31 percentage values (every 24 h) Compliance SPL in 1 m [%] = (xt1 + xt2 + … + xt31)/31	

To evaluate the Acoustic Comfort, PROMET&O multi-sensor aims to propose to the users a questionnaire containing one question to evaluate the level of discomfort, and another question useful to highlight the problem source not the comfort.

1) Please indicate on the following scale how YOU find the NOISE in your environment NOW

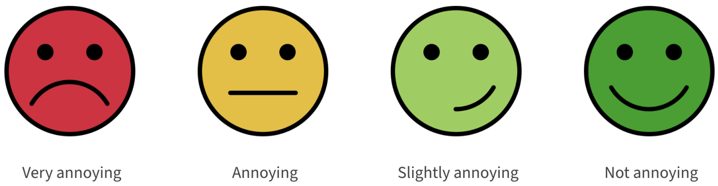

Figure 7: Representation of dashboard selectable options in the questionnaire

Table 7: Conversion from question answer to comfort values used in PROMET&O.

Very annoying	25%
Annoying	50%
Slightly annoying	75%
Not annoying	100%

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

- ☐ Building system
- ☐ Computer, printer, other equipments
- ☐ People chatting
- ☐ Road traffic
- ☐ Other noise from the outside
- ☐ Other
- ☐ None

The first question has been chosen following the legislation, the second aims to detect the noise source highlighting it as a discomfort cause. In other environments the second question has to be modified and adjusted inserting the typical sources of noise present in a different ambient.

2.2.3. Visual Comfort

Visual comfort is that condition of satisfaction of visual requirements expressed by the user. In an indoor environment should always guaranteed 500 lx on the desk level; this value is used as reference for the the following table where are shown the values regarding illuminance and visual comfort with the respective formula to calculate the percentage of expected confort considering: “xt” the expected comfort percentage at a given time, “n” the number of records that satisfy the legislation and “n. Samples values” the total records from the sensors.

Table 8: Conversion table from sensor data to Visual Comfort used in PROMET&O.

<table>
<tr><th colspan="2" rowspan="3">COMFORT DOMAIN</th><th colspan="2">Illuminance</th><th colspan="2">VISUAL COMFORT</th></tr>
<tr><td colspan="2">E</td><td colspan="2">VC</td></tr>
<tr><td colspan="2">lx</td><td colspan="2">%</td></tr>
<tr><th colspan="2">THRESHOLD / TEMPORAL RANGES</th><td>Writing, typing, reading, data processing ≥ 500 lx</td><td>All temporal ranges</td><td>0-100%</td><td>All temporal ranges</td></tr>
<tr><th colspan="2">SAMPLING TIME</th><td colspan="2">1 s</td><td colspan="2">-</td></tr>
<tr><th colspan="2">REPORT TIME</th><td colspan="2">30 s</td><td colspan="2">30 s</td></tr>
<tr><th colspan="2">COMPLIANCE AT REPORT TIME</th><td colspan="2">Compliance E in report time (xti) [%] = (nE·100)/n. sampled values</td><td colspan="2">VC = Compliance E in report time [%]</td></tr>
<tr><th rowspan="7">VISUALIZATION TIME</th><th>compliance in real time</th><td colspan="2">1 min -> 2 percentage values
Compliance E in RT [%] = (xt1 + xt2)/2</td><td colspan="2">VC = Compliance E in RT [%]</td></tr>
<tr><th>compliance over 3h</th><td colspan="2">3 h -> 180 percentage values (every 1 min)
Compliance E in 3h [%] = (xt1 + xt2 + … + xt180)/180</td><td colspan="2">VC = Compliance E in 3 h [%]</td></tr>
<tr><th>compliance over 12h</th><td colspan="2">12 h -> 4 percentage values (every 3 h)
Compliance E in 12 h [%] = (xt1 + xt2 + xt3 + xt4)/4</td><td colspan="2">VC = Compliance E in 12 h [%]</td></tr>
<tr><th>compliance over 24h</th><td colspan="2">24 h -> 2 percentage values (every 12 h)
Compliance E in 24 [%] = (xt1 + xt2)/2</td><td colspan="2">VC = Compliance E in 24 h [%]</td></tr>
<tr><th>compliance over 3d</th><td colspan="2">3 d -> 3 percentage values (every 24 h)
Compliance E in 3 d [%] = (xt1 + xt2 + xt3)/3</td><td colspan="2">VC = Compliance E in 3 d [%]</td></tr>
<tr><th>compliance over 1w</th><td colspan="2">1 w -> 7 percentage values (every 24 h)
Compliance E in 1 w [%] = (xt1 + xt2 + … + xt7)/7</td><td colspan="2">VC = Compliance E in 1 w [%]</td></tr>
<tr><th>compliance 1m</th><td colspan="2">1 m -> 31 percentage values (every 24 h)
Compliance E in 1 m [%] = (xt1 + xt2 + … + xt31)/31</td><td colspan="2">VC = Compliance E in 1 m [%]</td></tr>
</table>

To evaluate the Visual Comfort, PROMET&O multi-sensor aims to propose to the users a questionnaire containing three questions to evaluate the level of discomfort:

1) Please indicate on the following scale how YOU find the VISUAL in your environment NOW

Figure 8: Representation of dashboard selectable options in the questionnaire

Table 9: Conversion from question answer to comfort values used in PROMET&O.

Very uncomfortable	25%
Uncomfortable	50%
Slightly uncomfortable	75%
Not uncomfortable	100%

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

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

3) Please indicate 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

The first question was chosen following the legislation while the second aims to better define the origin of glare. PROMET&O multi-sensor is designed to be placed in offices, and despite an office is often adequately lighted, glare sources are one of the most disturbing possibilities in Visual Comfort. In case of a different environment, the answers have to be adjusted.

The last question asks a subjective preference instead of a feeling. The legislation imposes a minimum Illuminance needed to work without Visual Issues, but not aways is enough. Some activities might prefer a higher or lower amount of light.

2.2.4. Indoor Air Comfort

To evaluate the IAQ, various parameters are checked for which the maximum achievable by legislation are identified according to the exposure times to them. The following tables show these pollutants with the respective formula for calculating the percentage of expected Indoor Air Comfort considering: "xt" the percentage of comfort expected at a given moment, "n" the number of records that satisfy the regulation and "n. Sample Values" the total records from the sensors.

Table 10: Conversion tables from sensor data to Air Comfort used in PROMET&O.

<table>
<tr><th rowspan="3">COMFORT DOMAIN</th><th colspan="2">Carbon monoxide</th><th colspan="2">Carbon dioxide</th><th colspan="2">Nitrogen dioxide</th><th colspan="2">Particulate matter</th></tr>
<tr><th colspan="2">CO</th><th colspan="2">CO_2</th><th colspan="2">NO_2</th><th colspan="2">PM2.5</th></tr>
<tr><th colspan="2">mg/m3</th><th colspan="2">ppm</th><th colspan="2">µg/m3</th><th colspan="2">µg/m3</th></tr>
<tr><td rowspan="4">THRESHOLD / TEMPORAL RANGES</td><td>15 min. mean ≤ 100 mg/m3</td><td>RT</td><td rowspan="4">≤ 800 ppm</td><td rowspan="4">All temporal ranges</td><td rowspan="2">1 h mean ≤ 200 µg/m3</td><td rowspan="2">RT, 3h, 12h, 24h, 3d, 1w</td><td rowspan="2">24 h mean ≤ 25 µg/m3</td><td rowspan="2">RT, 3h, 12h, 24h, 3d, 1w</td></tr>
<tr><td>1 h mean ≤ 35 mg/m3</td><td>3h</td></tr>
<tr><td>8h mean ≤ 10 mg/m3</td><td>12h</td><td rowspan="2">Annual mean ≤ 20 µg/m3</td><td rowspan="2">1m</td><td rowspan="2">Annual mean ≤ 10 µg/m3</td><td rowspan="2">1m</td></tr>
<tr><td>24 h mean ≤ 7 mg/m3</td><td>24h, 3d, 1w, 1m</td></tr>
<tr><td>SAMPLING TIME</td><td colspan="2">3 s</td><td colspan="2">3 s</td><td colspan="2">3 s</td><td colspan="2">3 s</td></tr>
<tr><td>REPORT TIME</td><td colspan="2">1 min</td><td colspan="2">1 min</td><td colspan="2">1 min</td><td colspan="2">1 min</td></tr>
<tr><td>COMPLIANCE AT REPORT TIME</td><td colspan="2">1 min. -> 20 sampled values</td><td colspan="2">1 min. -> 20 sampled values</td><td colspan="2">1 min. -> 20 sampled values</td><td colspan="2">1 min. -> 20 sampled values</td></tr>
</table>

<table>
<tr><th rowspan="3">COMFORT DOMAIN</th><th colspan="2">Particulate matter</th><th colspan="2">Total Volatile Organic Compounds</th><th colspan="2">Formaldehyde</th><th colspan="2">INDOOR AIR QUALITY</th></tr>
<tr><th colspan="2">PM10</th><th colspan="2">TVOC</th><th colspan="2">CH_2O</th><th colspan="2">IAQ</th></tr>
<tr><th colspan="2">µg/m3</th><th colspan="2">µg/m3</th><th colspan="2">µg/m3</th><th colspan="2">%</th></tr>
<tr><td rowspan="2">THRESHOLD / TEMPORAL RANGES</td><td>24 h mean ≤ 50 µg/m3</td><td>RT, 3h, 12h, 24h, 3d, 1w</td><td rowspan="2">≤ 500 µg/m3</td><td rowspan="2">All temporal ranges</td><td rowspan="2">30 min. mean ≤ 100 µg/m3</td><td rowspan="2">All temporal ranges</td><td rowspan="2">0-100%</td><td rowspan="2">All temporal ranges</td></tr>
<tr><td>Annual mean ≤ 20 µg/m3</td><td>1m</td></tr>
<tr><td>SAMPLING TIME</td><td colspan="2">3 s</td><td colspan="2">3 s</td><td colspan="2">3 s</td><td colspan="2">-</td></tr>
<tr><td>REPORT TIME</td><td colspan="2">1 min</td><td colspan="2">1 min</td><td colspan="2">1 min</td><td colspan="2">1 min</td></tr>
<tr><td>COMPLIANCE AT REPORT TIME</td><td colspan="2">1 min. -> 20 sampled values</td><td colspan="2">1 min. -> 20 sampled values</td><td colspan="2">1 min. -> 20 sampled values</td><td colspan="2">IAQ compliance in report time (xti) [%] = (nCO + nCO2 + nNO2 + nPM2.5 + nPM10 + nTVOC + nCH2O)·100/(20+20+20 +20+20+20+20)</td></tr>
</table>

VISUALIZATION TIME	Compliance for all air pollutants
compliance in real time	Compliance IAQ in RT (xti) [%] = Compliance IAQ in report time
compliance over 3h	3 h -> 180 percentage values (every 1 min) Compliance IAQ in 3h [%] = (xt1 + xt2 + … + xt180)/180
compliance over 12h	12 h -> 4 percentage values (every 3 h) Compliance IAQ in 12 h [%] = (xt1 + xt2 + xt3 + xt4)/4
compliance over 24h	24 h -> 2 percentage values (every 12 h) Compliance IAQ in 24 [%] = (xt1 + xt2)/2
compliance over 3d	3 d -> 3 percentage values (every 24 h) Compliance IAQ in 3 d [%] = (xt1 + xt2 + xt3)/3
compliance over 1w	1 w -> 7 percentage values (every 24 h) Compliance IAQ in 1 w [%] = (xt1 + xt2 + … + xt7)/7
compliance 1m	1 m -> 31 percentage values (every 24 h) Compliance IAQ in 1 m [%] = (xt1 + xt2 + … + xt31)/31

To evaluate the Indoor Air Comfort, PROMET&O multi-sensor aims to propose to the users a questionnaire containing two questions to evaluate the level of discomfort:

1) Please indicate on the following scale how YOU find the AIR QUALITY in your environment NOW

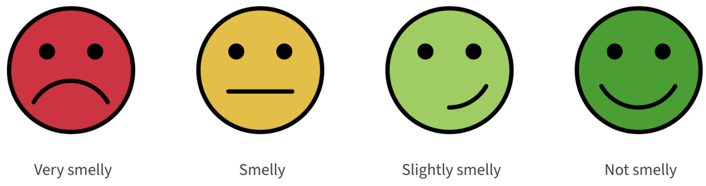

Figure 9: Representation of dashboard selectable options in the questionnaire

Table 11: Conversion from question answer to comfort values used in PROMET&O.

Very smelly	25%
Smelly	50%
Slightly smelly	75%
Not smelly	100%

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

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

Evaluating the subjective situation for IAQ is a complex task because generally people have a completely different perception on this topic. The one that should be the most consistent is the perceived smell like in the first question, but even this can change considerably depending from person to person.
The second question wants to better understand the possible pollutants choosing between some easy to differentiate options that can be found in an office.

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3. Indoor Environmental Quality

Indoor Environmental Quality (IEQ) describes the conditions in a confined space, usually indicated inside the building environment. It's the combination of Indoor Air Quality (IAQ), and Thermal, Acoustic and Visual conditions. Indoor Environmental Quality is the essential requirement to obtain the conditions of well-being for the occupants.

Instead of the Indoor Environmental Comfort (IEC) threatened in the chapter 2, that is the representation of the subjective comfort for occupants, IEQ is considered as an objective measure defined by physical indexes: a percentage mathematically obtained as the average calculation of the four domains' percentage of quality.

$$(TQ + AQ + IAQ + VQ) / 4 = IEQ\ [\%]$$

Is important to note that even if IEQ can reach elevated values, all the domains are strictly connected to each other so it is fundamental that all the indexes have to respect their own requirements or the occupants can perceive the whole environment as dissatisfying.

Thermal, Acoustic, Visual and IAQ are regulated by standards and norms defined at national or international level, which establish threshold values to maintain occupants in safety and comfort.

3.1. Thermal, Acoustic and Visual Quality

3.1.1. Thermal Quality

To carry out the Thermal Quality have to be monitored four environmental parameters, those define the characteristics present in a specific environment in function of the thermal domain. To those have to be added two personal factors, straightly directed with the occupants. Both environment and personal parameters can be related by algorithms given by law.

- *Air Temperature*

It's considered as the temperature of the air's environment, measured in degrees Celsius (°C) and indicated as (T_a). It's the most known physic quantity of Thermal Comfort. To a mean user, usually it's wrongly the only parameter associated with the Thermal Comfort.

- *Relative Humidity*

Relative Humidity is the ratio between the actual amount of water vapour in the air and the maximum amount of water vapour that the air can hold at that air temperature. It's measured in percentage [%]. Indicated by (RH).

- *Mean Radiant Temperature*

Thermal radiation is the heat radiated from warm objects. Radiant heat may be present if there are heat sources in an environment.

- *Air velocity*

Air velocity is a parameter described by the speed of the air moving across the user.

- *Clothing insulation*

A personal factor that calculates the comfort of the user considering how he or she is dressed.

- *Work rate / metabolic heat*

The other personal factor calculated in function of the physical work done by the user. It's is related even with physical characteristics of a person, like weight, size, age or sex.

3.1.2. Acoustic Quality

The only parameter monitored for the acoustic domain is the Sound Pressure Level (SPL). Sound Pressure Level is the result of the variations of air pressure changes achieved by the sound waves. It's measured in dB(A) and it's also called (SPL).

3.1.3. Visual Quality

To carry out the light monitoring the main parameters that can be monitored are:

- *Illuminance*

It is the quantity of light or luminous flux falling on a surface. It is measured in lux [lx], expressed as lumen per metre square.

- *Luminance*

Luminance typically describes the intensity of emitted light, it is the luminous intensity projected on a given area and direction.

- *Brightness*

Brightness is what we perceive when lumens fall on the rods and cones of our retina, it cannot be measured like luminance, but it can be scaled in percentages.

3.2. IAQ Review

Given that there is no univocal approach to evaluate the Indoor Air Quality either on the methods of data collection or on the parameters monitored, a review of the scientific literature was carried out aimed at describing and identifying main pollutants. These will then be monitored by PROMET&O multi-sensor.

3.2.1. Introduction

The search for spaces that meet sufficient comfort characteristics for occupant well-being is becoming central to the building industry.
People today spend about 90% [4,5,7,14,16,18] of their time in confined spaces, like homes, offices, schools, or vehicles (both as private and public vehicles [14,16]). Therefore, it becomes increasingly important to adapt enclosed spaces to minimum standards to ensure the well-being and health of the occupants [16].
In the building industry, the concepts of energy efficiency and indoor environmental quality are the main topics today, as buildings are required to provide a comfortable and healthy indoor environment with minimal energy consumption. [12]

Indoor Environmental Quality (IEQ) is the synthesis of the performance of thermal comfort, indoor air quality, lighting, and acoustics [13], which directly reflects on occupants' health.
In the following discussion, we will delve into the field of air quality being not only a topic of great interest for todays and future design policies, but especially as it is an area that is being explored more in the last decade it lacks a single and scientifical agreed upon approach for evaluating it.

Poor air quality directly affects health with symptoms such asthma, allergy, cardiovascular disease, neurological effects, lethargy, headache, and fatigue [4,19]. These symptoms are directly related to the human-building relationship and are known as Sick Building Syndrome (SBS) [13].
They not only directly affect the lives of the occupants but also affect their productivity; this has been confirmed both within schools [7] and offices [13].
Although there is no unambiguously established method of approach to comprehensively assess indoor air quality, the main pollutants responsible for the above symptoms are reported by WHO with their respective maximum imposed parameters.

These have been updated since 2005, in 2021 as follows [22]:

- PM10: the annual value increases from 20 to 15 μg/m^3, the 24-hour value from 50 to 45 μg/m^3
- PM2.5: annual value increases from 10 to 5 μg/m^3, 24-hour value from 25 to 15 μg/m^3
- Nitrogen dioxide: annual value increases from 40 to 10 μg/m^3, and a 24-hour value of 25 μg/m^3 is introduced

- Ozone: a seasonal peak value of 60 µg/m^3 is introduced
- Sulphur dioxide: the 24-hour value is increased from 20 to 40 µg/m^3 carbon monoxide: a 24-hour value of 4 µg/m^3 is introduced

To the pollutants set by WHO as mainly harmful and consequently to be controlled to meet the limits imposed, volatile organic compounds (VOCs) such as [4,14] should be added:
Formaldehyde; Benzene; Tetrachloroethylene; Octane; Ethylbenzene; p,m-xylene; o-xylene; 1,2,4-trimethylbenzene; Toluene; Styrene; a-pinene; d-limonene; Naphthalene ; 1,2,3-trimethylbenzene; Chloroform.
Unlike CO2, NO2, P2.5, Pm2.5, Pm10, O3 and SO2; no parameters are defined for VOCs as there is not enough toxicological data to date to estimate the risk on human health [16], however, they remain linked to symptoms on par with the previously mentioned pollutants.

3.2.2. Methods

The main objective of this literature review is to analyse and synthesise the literature works from 2010 to date to identify and list which are the main polluting factors inside buildings, which were the common elements of application in the various case studies during the research phase, and the identification of a single overall value that can express the comfort related to IAQ (preferably expressed as a percentage value).

Selection process
The following literature review was carried out by the PRISMA's method, whose checklist: title, abstract, introduction, methods, discussion and conclusions. Through the support of the database in Scopus, it was possible, by setting a set of input parameters, to select articles useful for research around IAQ.
Once the papers that responded to the first stage of selection based on keywords were collected, articles were included or excluded from the review using the criteria shown in Table 1. Subsequently, papers that passed the first selection were further investigated through a full-text review so as to eliminate less relevant articles from the search and add supportive articles to support the thesis. The selected articles mainly deal with the major pollutants responsible for occupant symptoms. Since there is no one-size-fits-all approach, the search was extended to generic case studies (such as homes, offices, schools, and indoor swimming pools) to draw a common thread.
From a starting point set by the first 1369 articles, we arrived at 80 articles, reduced to 19 once we filtered out the most relevant ones a posterior to reading the title and abstract. Posterior readings and articles were included to aid the research work.
Below is the table illustrating the process that led to the selection of the articles used.

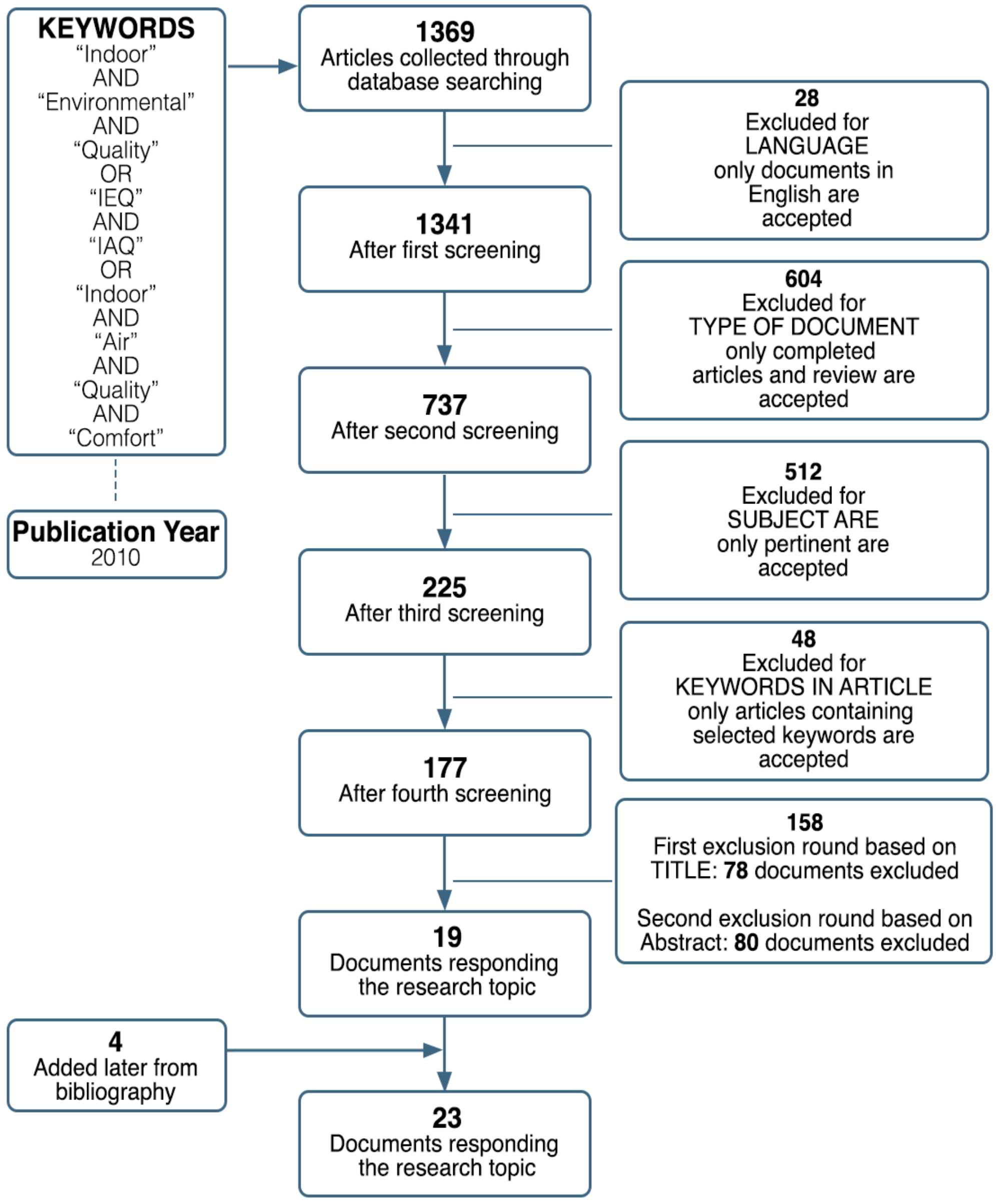


Figure 10: flowchart of the selection process that has been followed to determine the articles deemed inherent and complying to the research

Selected articles
The selected articles are heterogeneous in terms of pollutants analysed, geographic areas of interest, building use, and timing of obtaining data, all schematized according to Table 2 and Table 3.
Some articles, being useful reviews to build the basis for what follows and not directly owning case studies addressed, were not fully included in the schematization in Table 2 and Table 3.
The articles dealt mainly with case studies in Europe, two in the US [3,13,18], one in the UK [6], one in South Africa [5] and one in Japan [19].

Table 12: Building usage in review article.

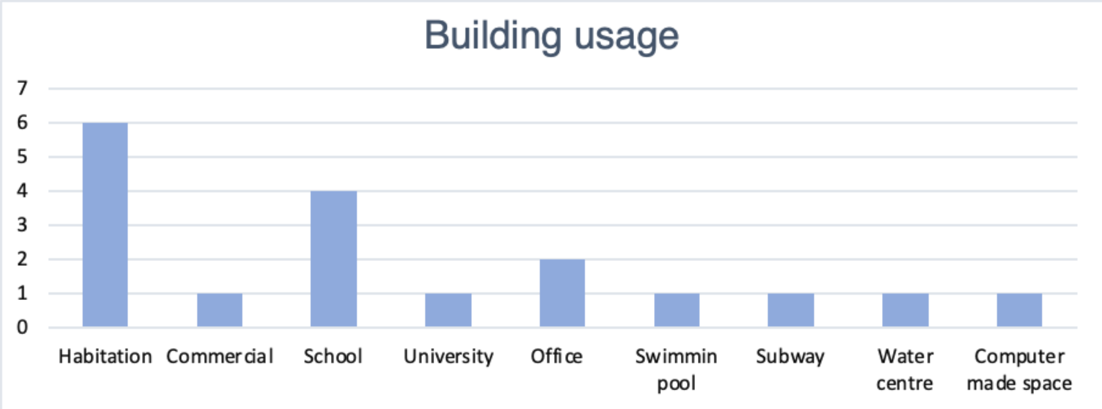
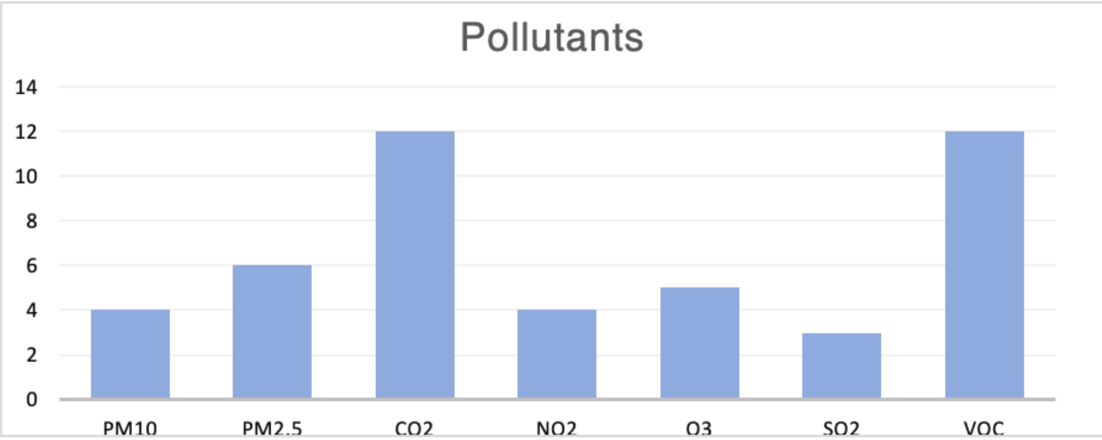


Table 13: Typology of pollutants studied in review article.



As can be guessed from the data contained in Table 3, most of the studies within the articles selected for review placed the focus on CO2 and VOCs as the main causes of adverse human symptoms. NO2 and SO2, on the other hand, were the least addressed pollutants being more difficult to obtain instrumentation to measure them.

Smoke and its effects
It has been noticed that smoke is one of the key components of Indoor Air Quality pollution, the tobacco's burning and the combustion of the cigarette generates almost all the pollutants analysed during the review.

In addition to symptoms closely related to (active) smoking such as cancer, coronary heart disease, respiratory disease, and stroke [21], it has been demonstrated [1,16] how smoking not only raises the level of indoor pollutants, but also adversely affects outdoor environments (such as front door, balconies and streets) in the immediate vicinity of the building frequented by smokers. This happens not only in buildings where smokers are resident [1,16].

So, to define a list of the most important and dangerous pollutants, only cases where occupants don't smoke were analysed to obtain a better view of the indoor air quality conditions

3.2.3. Pollutants

Carbon Dioxide
Among the pollutants included in the ONU list, CO_2 is the main greenhouse gas. This contributes the largest share of total emissions, suffice it to say that in the United States in 2020 it accounted for 79% of total emissions [20]. It is produced, 94% [20], by the combustion of fossil fuels depending on the type of fuel (gas or liquid).

Carbon Monoxide
A very harmful pollutant due to its high toxicity, made dangerous above all by its characteristics that make it colourless and odourless. Today its presence as a pollutant is not deepened monitored even though the ONU imposes particularly stringent limits

Particulate Matter
With particulate matter we refer to a mixture of solid particles and liquid droplets found in the air. PM can be of different sizes, it goes from 10 microns to 2.5 microns (or even smaller). Largest particles, such as dust, dirt, soot, or smoke, are large or dark enough to be seen with the naked eye. Others are so small they can only be detected using an electron microscope.
Particulate matter poses human health to a great risk because it can be collected in lungs or in the upper respiratory tract causing disease to lungs, asthma or bronchitis, reaching even to premature deaths in case of long exposures.

Nitrogen Dioxide
NO_2 is a toxic gas that irritates the respiratory system and mucous membranes, if taken in large quantities it can generate pathologies such as bronchitis, allergies and irritation.
It is a pollutant known mostly as secondary, it plays a fundamental role in the formation of photochemical smog.

Volatile Organic Compounds

The other main pollutants are VOCs - Volatile Organic Compounds, these are characterised and generated by the materials in buildings and the habits of the occupants. The formaldehyde (CH_2O) is a VOC, it's considered one of the most impactful to human health so it's usually considered as a pollutant to itself.

According to the Minnesota Department of Health these are divided into three categories depending on their derivation:

Building materials

- Paint, varnishes, caulks, adhesives
- Carpet, vinyl flooring
- Composite wood products
- Upholstery and foam

Home & Personal Care Products

- Air fresheners, cleaning products
- Cosmetics
- Fuel oil, gasoline

Activities

- Smoking
- Dry cleaning, photocopiers
- Cooking, hobbies
- Burning wood

3.2.4. Conclusions

The presence of pollutants in indoor environments is capable of generating evident discomfort in the occupants. Bad smells, stagnant air and mild breathing difficulties are the first presentation of SBS, quickly leading to symptoms such as headache, tiredness, confusion or lethargy.

In offices this leads to a productivity reduction, increase of the stress [22] and increase in costs due to worse productivity, increase in health care costs and increase in attendance at work.

The identification of pollutants, the study of them, the capacity to monitor and the causes that these can cause have already been a reason for studying and deepening air quality for a long time. In 2020, with the outbreak of COVID-19, interest in the subject grew exponentially; to date, however, there is no uniqueness in the methodology that allows the unequivocal definition of the parameters that guarantee the occupants to minimise their health risks.

Many countries rely on ONU standards, which are not always stringent enough with respect to the presence of pollutants in cities (especially in metropolitan cities).
Scholars are now in agreement on the production of a unique IAQ certification such that this can define standards that reduce the risk on people's health and well-being.

In conclusion, the review was aimed at defining the main, known and dangerous pollutants in a unique list. These were used as the parameters to be monitored for the calculation of the Indoor Air Quality index.

3.3. IEQ for PROMET&O

Considering that the design of the PROMET&O multi-sensor was driven by the desire to place it in office environments, through the analysis carried out in the previous chapter was possible defining all the parameters that PROMET&O multi-sensor aims to monitor.

Those are divided in two macro-group listed below:

Directly monitored by the multi-sensor

T_a - RH - SPL - TVOC - CH_2O - NO_2 - CO_2 - CO - PM2.5 - PM10 - E

Obtained by mathematical calculations

Thermal Comfort - Acoustic Comfort - Visual Comfort - Indoor Air Quality

The four domains are used to calculate the IEQ percentage value with the formula already discussed in the previous paragraph 3.0, where it's calculated as the arithmetic average of the four domains.

All the parameters divided by the respective domains are analysed below, the tables show the information that will be contained within the PROMET&O dashboard which will show the data monitored by the multi-sensor (chapter 4).

3.3.1. Thermal Monitoring

To carry out the Thermal Monitoring in the PROMET&O multi-sensor only two parameters will be considered: Air Temperature and Relative Humidity.

These have been chosen because in addition to being the best-known quantities, in an office environment it is probable that these are the parameters with which employees (on average hypothesised as not accustomed to the quantities of technical physics) can more easily interact for the purposes of a more comfortable environment for them.

Furthermore, the air velocity, being in an indoor environment, was excluded from the objective monitoring, but it's included as a subjective question inside the questionnaire.

Table 14: Acceptable threshold for Thermal Quality.

PARAMETER			RANGE ON ORDINATE AXIS OF THE GRAPH	THRESHOLD	TEMPORAL MEAN ON GRAPH	REFERENCE	DEFINITION
Air temperature	T_a	°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	%	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 characterise the relative humidity of the environment

3.3.2. *Acoustic monitoring*

The only parameter monitored for the acoustic domain is the Sound Pressure Level (SPL).

In the following table are collected the information about Sound Pressure Level. Those will be uploaded in the design phase in the PROMET&O multi-sensor's dashboard.

Table 15: Acceptable threshold for Acoustic Quality.

PARAMETER			RANGE ON ORDINATE AXIS OF THE GRAPH	THRESH OLD	TEMPORAL MEAN ON GRAPH	REFERENCE	DEFINITION
Sound Pressure Level	SPL	dB(A)	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.

3.3.3. *Light monitoring*

Illuminance (E) is the only parameter directly monitored by PROMET&O multi-sensor. Luminance and glare, on the other hand, are the focus of the questions in the questionnaire for calculating Visual Comfort.

In the following table are collected information about Illuminance. Those will be uploaded in the designing phase in the PROMET&O multi-sensor's dashboard.

Table 16: Acceptable threshold for Visual Quality.

PARAMETER			RANGE ON ORDINATE AXIS OF THE GRAPH	THRESHOLD	TEMPORAL MEAN ON GRAPH	REFERENCE	DEFINITION
Illuminance	E	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

3.3.4. IAQ monitoring

Defining all the parameters to be monitored, a table containing all the information about the pollutants was created.

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. []

Given the absence of a single regulation at national or European level that defines the pollutants and the standards that they must comply with, in order to select the main pollutants, which are then included in the monitoring by the PROMET&O multi-sensor, a literature review was carried out to list and define the main pollutants.

Table 17: Acceptable threshold for Air Quality.

PARAMETER			RANGE ON ORDINATE AXIS OF THE GRAPH	THRESHOLD	TEMPORAL MEAN ON GRAPH	REFERENCE	DEFINITION
Carbon monoxide	CO	mg/m3	0-200 mg/m3	15 min. mean ≤ 100 mg/m3	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/m3	1 h mean ≤ 35 mg/m3	3h		
			0-50 mg/m3	8h mean ≤ 10 mg/m3	12h		
			0-50 mg/m3	24 h mean ≤ 7 mg/m3	24h-3d-1w-1m		
Carbon dioxide	CO_2	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	µg/m3	0-500 µg/m3	1 h mean ≤ 200 µg/m3	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 µg/m3 (0.1 ppm). It is one of the principal nitrogen oxides associated with combustion sources.
			0-100 µg/m3	Annual mean ≤ 20 µg/m3	1m		
Particulate matter	PM2.5	µg/m3	0-100 µg/m3	24 h mean ≤ 25 µg/m3	RT-3h-12h-24h-3d-1w	EN 16798	Particulate matter is a mixture of solid particles and liquid droplets found in the air. PM2.5 : fine inhalable particles, with diameters that are 2.5 micrometres or smaller.
			0-50 µg/m3	Annual mean ≤ 10 µg/m3	1m		
Particulate matter	PM10	µg/m3	0-200 µg/m3	24 h mean ≤ 50 µg/m3	RT-3h-12h-24h-3d-1w	EN 16798	Particulate matter is a mixture of solid particles and liquid droplets found in the air. PM10 : inhalable particles, with diameters that are 10 micrometres or smaller
			0-100 µg/m3	Annual mean ≤ 20 µg/m3	1m		
Total volatile organic compounds	TVOC	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	0-200 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.

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4. PROMET&O

The main point of this thesis was the design of the PROMET&O multi-sensor. The PROMET&O multi-sensor aims to collect objective data belonging to the four domains of Indoor Environmental Quality (IEQ). The uniqueness of the multi-sensor compared to the main competitors on the market is the ability to also collect subjective data on the comfort perceived by users in the indoor environment.

The PROMET&O logo has been decided starting from the project's name:

It takes its name from Prometheus, in Greek mythology is the Titan god of fire. Prometheus is best known for stealing fire from gods and giving to humanity, for it his name is associated with technology development and knowledge.

For it, to combinate the idea of ecology with Prometheus iconography, the logo is:

Figure 11: PROMET&O's logo

There the four leaves, simulating a fire, represent the four Indoor Environmental Quality domains (respectively from left to right Thermal, Visual, Acoustic and Air Quality).

4.1. General Design Issues

4.1.1. Requirements and needs analysis

To approach the design of PROMET&O multi-sensor was essential to define which were the main needs and requirements.

Main points of attention were:

Physical quantities measured

The physical quantities measured according to standards and laws that define the parameters to be respected, the conditions of comfort and the information that will be provided to users via PROMET&O.

Instrument morphology

The PROMET&O multi-sensor aims to be a manageable instrument, with a modern design that doesn't conflict with all the sensors' needs. It has to be the smallest as possible, with many holes on it to obtain the right airflow for the sensor's best monitoring.

In it are required different type of support to be placed in different environments in different ways:

- Rubbering base, to be placed over flat surfaces
- Vertical hook, to be hung on the wall
- Rod hook, to be lifted by a rod

Visual feedback

To help the users to understand the level of Indoor Environmental Quality without interacting with an IT dashboard, it is important that the multi-sensor can give a visual feedback of the IEQ to allow the user to take action on the problem.

Graphic rendering dashboard of the data obtained

To allow the user to receive all the information about the monitored and calculated data by the PROMET&O multi-sensor, it is fundamental that the multi-sensor will be designed with an IT dashboard that collects all data, with more suggestions on parameters and hints to improve the IEQ.

4.1.2. Benchmark analysis

Defined the requirements and needs, the market was analysed to define a table of the minimum performance already present on it. Many competitors were identified, but only two multi-sensors were chosen because of their popularity and high performances and similarity on PROMET&O multi-sensor in developing:

1) *SAMBA*

Figure 12: SAMBA multi-sensor. (Figure taken from [3])

SAMBA is a new multi-sensor to approach the IEQ monitoring. It's based on a small, low-cost, desk-based multi-sensor for thermal comfort (Air Velocity and Radiant Temperatures, air speed and humidity), acoustics (Sound Pressure Level), lighting (Illuminance) and air quality (Carbon Dioxide, Carbon Monoxide, Total Volatile Organic Compounds, Formaldehyde and Particulate Matter).

SAMBA is designed to be placed in any HVAC (Heating, Ventilation and Air Conditioning) zone of complex commercial buildings. Various IEQ indices and compliance metrics are calculated in real-time before being presented to an online IEQ dashboard to which the building user has access.

2) *AirCare*

Figure 13: AirCare multi-sensor (figure taken from [4])

AirCare is an Italian project that directly focuses on air quality and comfort control, but analyses and monitors also the thermal, acoustic and visual domains.

The following Excel table was produced to correlate the design intentions of PROMET&O multi-sensor with the characteristics already present on the market.

Table 18: Comparison between PROMETE&O and the main competitors.

			PROMET&O	AirCare	SAMBA
DETECTABLE MEASURES	Thermal comfort	Air Temperature	Yes	Yes	Yes
		Globe temperature	No	No	Yes
		Air velocity	No	No	Yes
		Relative Humidity	Yes	Yes	Yes
	Acoustic comfort	Sound pressure level	Yes	Yes	Yes
	Indoor Air Quality	Carbon Dioxide	Yes	Yes	Yes
		Carbon Monoxide	Yes	No	Yes
		Particulate Matter 10	Yes	Yes	No
		Particulate Matter 2.5	Yes	Yes	No
		Formaldehyde	Yes	No	Yes
		Nitrogen Dioxide	Yes	No	No
		TVOC	Yes	Yes	Yes
		Atmospheric Pressure	No	Yes	No
	Visual Comfort	Illuminance	Yes	Yes	Yes
	Electromagnetic quality	Electrosmog	No	Yes	No
GENERIC SPEC.	Sensor case details	single case	Yes	Yes	No
		LED light	Yes	No	No
		Vertical hook	Yes	Yes	No
		Rubberized base	Yes	Yes	Yes
		Rod hook	Yes	No	No
		dimensions h x l x w [cm]	In development	10 x 10 x 7	19 x 9 x 9 (main) 9.5 x 9.5 x 9.5 (satellite)
		Battery	No	Yes	No

Physical quantities measured

Particular attention was given to the measurements detected by the multi-sensors already present on the market.

As it's shown in the table, the respective measures of Acoustic Comfort and Visual Comfort, respectively, the Sound Pressure Level (SPL) and the Illuminance (E) are monitored by both AirCare and SAMBA.

In the case of Thermal Comfort, global temperature and air velocity are measured only by SAMBA, instead of Air Temperature (T_a) and Relative Humidity (RH).

Significant differences are found in the IAQ branch, where PROMET&O aims to be the multi-sensor with the highest number of pollutants measured in correlation to the studies previously carried out on Indoor Air Quality.

Is important to note that AirCare can also monitor the electromagnetic quality by measuring the electrosmog present in the air. This feature is not required in PROMET&O multi-sensor, but it's not excluded that can be implemented in the future.

Figure 14: SAMBA multi-sensor. (figure taken from [3])

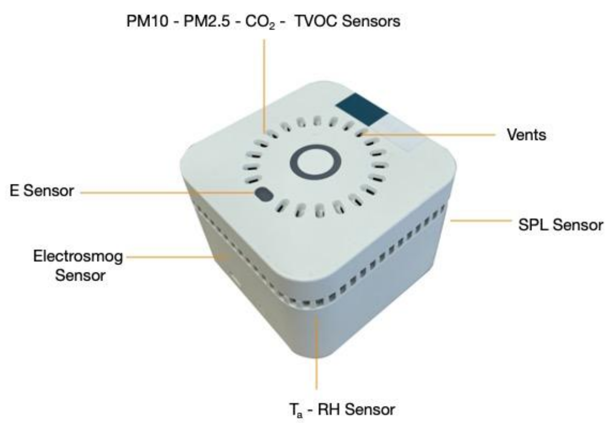


Figure 15: AirCare multi-sensor.

Morphology

The morphological structure was an element of particular attention for what subsequently was the design-phase of the PROMET&O multi-sensor case.

As shown in the upper table about SAMBA and AirCare dimensions, it was found that:

- SAMBA is made up of two distinct elements connected by wire, the first containing the largest number of sensors inside (called “main”) with dimensions of 19x9x9 [cm]; the second (called "satellite") with dimensions of 9.5x9.5x9.5 [cm].
- AirCare has a small structure, with a square base, having dimensions of 10x10x7 [cm].

Defined AirCare as more practicable thanks to its smaller dimensions and easier customizable, it was deeply analysed even in its inside characteristics. Inside AirCare was noticed that it presents two different Printed Circuit Board (PCB) where the sensors can be attached; this feature allows the design of a smaller case in only one element. It’s important to note that SAMBA has been developed with the intention of being placed in commercial sites, so it doesn't aim to be flexible in the placement, instead of PROMET&O and AirCare (principally designed for offices).

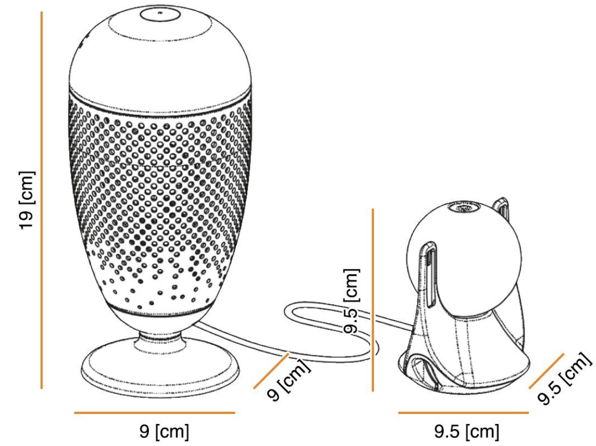


Figure 16: SAMBA device (figure taken from [1])

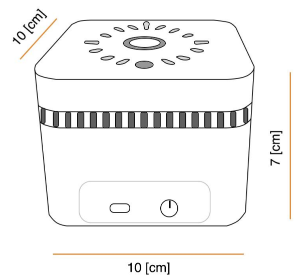


Figure 17: AirCare device (graphical representation made by the authors)

Visual feedback

Although the possibility of having feedback on the Indoor Environmental Quality by interfacing solely with the AirCare and SAMBA multi-sensors (without the support of external dashboards) is not a present feature, in the design of the PROMET&O multi-sensor it was defined as a fundamental feature that has to be added.

As a result, LED lights were implemented in the case design to indicate the percentage of Indoor Environmental Quality for an instant visual feedback.

Obtained data reporting dashboard

Once the physical components of the multi-sensor had been defined, attention moved to the graphic rendering for the return of the acquired data, consequently the SAMBA and AirCare screens were analysed, defining their main strengths and weaknesses.

Figure 18: SAMBA dashboard visualisation. (figure taken from [2])

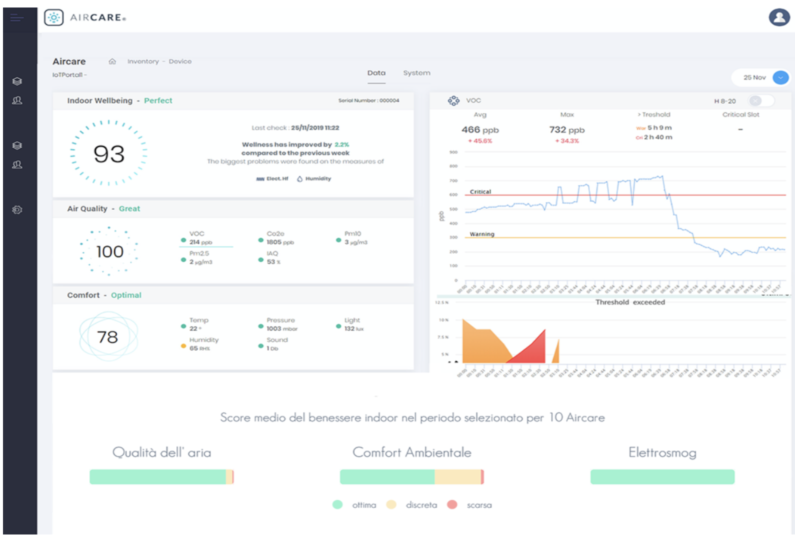


Figure 19: AirCare - dashboard visualisation. (figure taken from [4])

The main elements identifiable from the dashboards above are:

- Comforts are graphically displayed with speedometers indicating the percentage,
- Customisable graphs showing the trend of the data collected at variable time intervals are inserted in the main view,
- The Indoor Environmental Quality is represented as the most important data, and therefore the value is placed in the most visible point of the respective dashboards.

On the other hand, negative elements were found in both the dashboards:

- Low level of users engagement due to the data representation that is too complex for a naïve user

4.2. Occupant engagement strategies for the dashboard design

In drafting the PROMET&O subjective feedback monitoring questionnaire, it was essential to ensure that users could express their discomfort/comfort without getting bored in the long period.

One of the main elements of attention when designing a questionnaire is the retention rate, especially when monitoring an office with busy workers who are free to provide feedback when they prefer [6]. For this reason the questionnaire must be easy to understand and fast to complete. It has to be included inside a simple and intuitive system (like a dashboard or a paper), because a complex one discourages user interest.

To increase user involvement, it is also possible to make the questionnaire feel like a game [6], therefore it is advisable to give the dashboard some utility even when the questionnaire is not being carried out. It is possible to provide the user with a form of reward from completing the questionnaire [6], this will allow the user to perceive time as an investment capable of having something.

People are expected to provide feedback especially when they are feeling uncomfortable, so it is important to show to the user that the answers given have been captured and reported inside a more complex visualisation system, such as graphs or tables. Graphical details are used to facilitate the user to provide feedback. [6]

From those analysis, was possible to outline guidelines for PROMET&O questionnaire:

- Simple and fast to be completed ;
- Intuitive dashboard to insert the questionnaire in,
- Implementation of feedbacks from the questionnaire back to the user,
- Allowing the user to see their responses while browsing through tables and graphs.

4.3. Multi-sensor development

The analyses carried out and addressed in paragraph 4.1.2 were followed by the design phase of the multi-sensor mainly focusing on the electronic field. In order to capture the physical quantities and communicate those data to the PoliTo server, the Department of Electronics and Telecommunications of Politecnico di Torino designed the electrical architecture of the multi-sensor. After the definition of the elements that will compose the multi-sensor their specifics and needs were used to define the main elements for PROMET&O multi-sensor's case design.

Below the general scheme of the PROMET&O multi-sensor is represented:

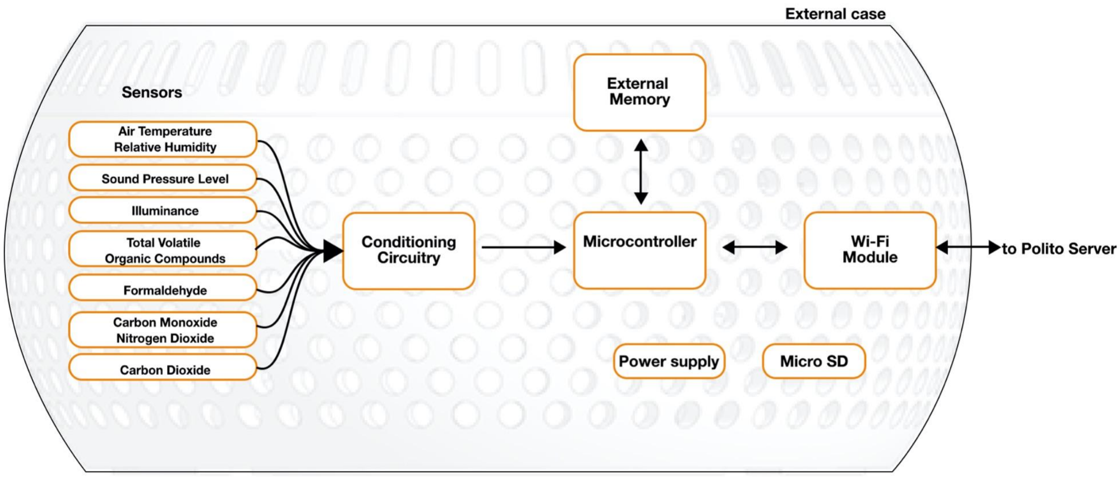


Figure 20: Scheme of the multi-sensor components under development.

All the elements that have to be placed inside the multi-sensor's case, under the PCBs grounding on the base of PROMET&O. These are not of such dimensions as to affect the actual final dimensions of the case, however they need to be careful during the design phase of the same to prevent their presence from coming into conflict with the positioning of the sensors, subjected to much more stringent needs.

The Microcontroller is the "hearth" of the electronic field for PROMET&O. The limited availability of this element on the market due to the effects of the pandemic led to slowdowns in the design of the case.

Is important to clarify that all the topics discussed in this chapter are in an early development stage, they are correct at the time of this thesis, but they could be easily subjected to change.

4.3.1. Hardware

The first phase of the design of the PROMET&O multi-sensor case was the definition of the sensors considering the following parameters:

- Cost
- Dimensions
- Accuracy
- Measurement range

As regards the accuracy and the measurement range, the reference standard was considered the WELL protocol, depending on the physical size. In addition to these parameters, the following were also considered when choosing the sensors:

- Availability on the market
- The type of interface, particularly if analog or digital.
- The response time, which is the amount of time it takes for the sensor to adapt to a sudden alteration of the measured quantity.
- Current consumption, which should be minimised for any implementations battery-operated futures and to limit overheating problems.

Thermal sensor

The research on the market of sensors for temperature and relative humidity has given as results sensors with characteristics very similar to each other.

The SHT41 (Sensirion) was chosen since its accuracy is closest to the required one and allows both parameters at the same time. The SHT41 is wire connected. To have the best measurements is required to be placed away from the PCB, power supply or any parts that could generate heat, for this reason it will be mounted on the top part of the case, near some opening on the side that will allow a constant air flow to a best monitoring.

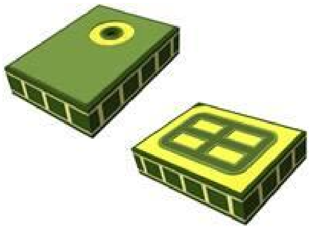
Figure 21: SHT41 sensor. (figure taken from [5])

Acoustic sensor

The digital sensor IMP34DT05 is a microphone used to monitor the Sound Pressure Level. The microphone must be positioned in the centre of the multi-sensor to best return the measurements acquired. It's wire connected.

The IMP34DT05 was preferred because it provides the digital output, so it simplified the design phase.

To allow a better sound reception for the microphone, PROMET&O multi-sensor's case should have many holes in its side.



A calibrator is placed over the sensor by the support of a plastic cylinder placed on top of it so the case has to be shaped to allow the hooking of the cylinder in the correct position. That provides the possibilities of an easier calibration of the acoustic sensor.

Figure 22: IMP34DT05 sensor. (figure taken from [5])

Light sensor

To carry out the light monitoring the Illuminance (E) is the only parameter measured. For this quantity another specification is added:

how much the spectral response of the sensor is similar to the relative visibility curve of the human eye (photopic vision).

Regarding accuracy, a value of 5% was initially considered, lowered to 10% due to the lack of sensors on the market that meet this specification.

The OPT4001 and the VEML7700 meet both the specification on the human eye visibility curve and the measurement range; it has been decided to prefer the latter, as it has a greater maximum range than the others taken into account consideration.

VEML7700 is wire connected and has to be positioned on the top of the case on a flat and horizontal surface.

It’s the only visible sensor and it has to be placed over the sound sensor.

Figure 23: OPT4001 sensor. (figure taken from [5])

Air quality sensors

Carbon Monoxide (CO) and Nitrogen Dioxide (NO_2)

The sensors for these quantities are mainly of the electrochemical type, they are based on a chemical reaction of the gas in question. These types of sensors have strong dependencies on the temperature and on the presence of other gases of a species similar to that of interest (phenomenon called cross-sensitivity).As far as Carbon Monoxide is concerned, Spec sensors' 3SP_CO_1000 was chosen as the manufacturer has reported on the datasheet a list of the cross-sensitivities they measure, and graphs of the dependence with temperature are shown. This allows you to have more information during the metrological characterization phase.

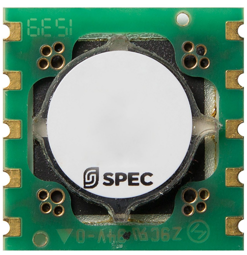
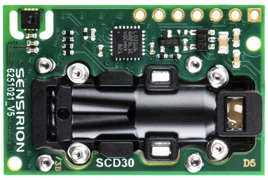


Figure 24: 3SP_CO_1000 sensor (figure taken from [5])

Furthermore, the market availability of the other sensors is limited.

For the nitrogen dioxide, the respective sensor from Spec sensors was chosen for the reasons already stated above.

Carbon dioxide (CO_2)



Among the various possibilities, the SCD30 was chosen for its best accuracy, the main focus for PROMET&O's project.

Figure 25: SCD30 sensor. (figure taken from [5])

Particulate Matter 10 (PM10) and Particulate Matter 2.5 (PM2.5)

It was decided for the SEN54, despite its large dimensions and current consumption compared to the other sensors, it allows measuring the TVOCs. Although the use of a specific sensor for TVOCs is foreseen, this allows a comparison between the result of the latter and the SEN54.

Figure 26: SEN54 sensor. (figure taken from [5])

Total Volatile Organic Compounds (TVOC)

The ZMOD4410 was chosen because of a lower cost despite having the same characteristics.

Figure 28: ZMOD4410 sensor. (figure taken from [5])

Formaldehyde (CH_2O)

Sensirion SFA30 has been chosen for the accuracy values and the current consumption. In addition, the market availability of competitors to date is scarce.

Figure 29: ZMOD4410 sensor. (figure taken from [5])

Those sensors presents same electrical characteristics:

- Are wire connected
- Have to stay in the side of PROMET&O multi-sensor’s case to get enough air
- Don’t generate any conflicts with other sensors

The only need all IAQ sensors have is a constant flow of air that shouldn't surpass 1 [m/s]. That condition is considered always satisfied in an indoor environment.

In the following table are collected all the information about the chosen sensors indicating accuray and dimensions:

Table 19: Summary of sensor used for PROMET&O.

PHYSICAL QUANTITY	PRODUCER - PART NUMBER	MEASUREMENT RANGE	ACCURACY	DIMENSIONS WxLxH (mm)
Air Temperature Relative Humidity	Sensirion -SHT41	-40 °C - 125 °C / 0 % - 100 %	± 0.2 °C / ± 2 %	1.5 x 1.5 x 0.54
Illuminance	Vishay - VEML7700	0 - 120000 lux (max)	10%	6.5 x 2.35 x 3
Carbon Monoxide	Spec sensors -3SP_CO_1000	0 - 1000 ppm	± 2.75 nA/ppm (of sensitivity)	20 x 20 x 3.8
Nitrogen Dioxide	Spec sensors - 3SP_NO2_5FP	0 - 5 ppm	± 10 nA/ppm (of sensitivity)	20 x 20 x 3.8
Carbon Dioxide	Sensirion - SCD30	0 - 40000 ppm	± (30 ppm) ± 3 % (in range of 400 - 10 000 ppm)	35 x 23 x 7
Particulate Matter 10 Particulate Matter 2.5	Sensirion - SEN54	0 - 1000 µg/m3	PM2.5: ± 10 % PM10: ± 25 %	52.3 x 43.3 x 22.3
Total Volatile Organic Compounds	Renesas - ZMOD4410	0 - 30 ppm (max)	± 15 %	3 x 3 x 0.9
Formaldehyde	Sensirion - SFA30	0 - 1 ppm	± 20 ppb or ± 20 %	42 x 24 x 5.5
Sound Pressure Level	ST - IMP34DT05	Frequency response: 100 – 10000 Hz	Not declared	3 x 4 x 1

Components

Ended the sensors-decision phase, other components and their needs were described

- A ON/OFF bottom, clickable from the outside.
- The battery charger hole to make the multi-sensor connected by wire with the electricity
- LED Lights for visual feedback, designed to be shown on the top of the case.

All of those tools have to be wire connected to the PCB.

PCB

Once all the sensors and components were decided, the designing phase started by developing the Printed Circuit Board (PCB).

PCB is used to connect all the electronic components (including sensors). It has been the main element used to start the development of PROMET&O multi-sensor's case.

To contain all the elements the PCB was designed starting from all the sensors and components dimensions and needs. The result is a circle with a diameter of 14[cm] and 2 [mm] of height. The PCB has to be elevated from the base of the case and needs 4 [cm] of heigh pertinence.

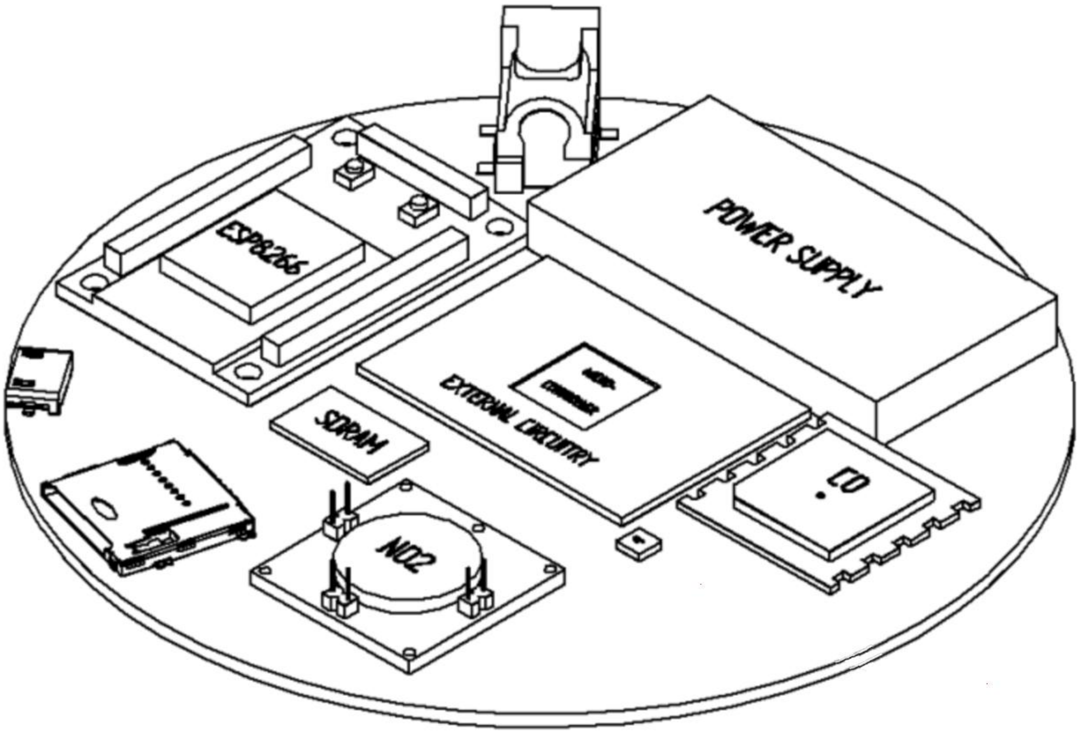


Figure 30: PCB - sensors positioning hypothesis

4.3.2. *Case*

The PROMET&O multi-sensor's case was designed to be a small and functional multi-sensor with an attractive design.

Designed to be printed with a 3D filament printer, the case was designed as four different pieces connectable to each other screws:

1) *The top*

It's made up of two pieces, the cover and the transparent element.

The top ring is the element that will close the case; it will contain the LED lights for visual feedback, so it's designed with transparent pieces.

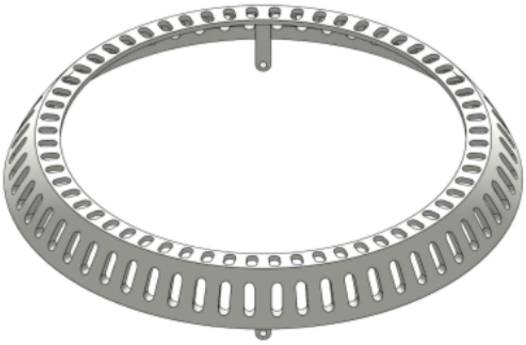


Figure 31: 3D view of the case

The cover is placed over the body. It holds PROMET&O's logo, the four domain symbols and the "IEQ" word as they are shown in the dashboard.

When the case is closed the ring and the cover part leave a hollow part on the side where some LED light can find a place that will be used to indicate the IEQ percentage by gradually emulating the percentage of comfort as shown in the dashboard in that moment.

Figure 32: 3D view of the case

2) *The body*

The main structure element follows the Printed Circuit Board form. Convexed in the centre to let a better positioning of the sensors on its inside, it presents many holes to let sensors get enough air from the environment.

Figure 33: 3D view of the case

3) *The base*

It’s the place where the most sensors are placed and where the PCB will be fixed on, supported by four hooks . This element presents a soft rubber base to better stick to any horizontal surface, a groove that can be used to hang the multi-sensor on a wall, and is also used to block the sensor on poles that are used in the field testing. Thanks to the base shape and grooves it is possible to 3D print a unique support for any need.

Figure 34: 3D view of the case

As it follows, the PROMET&O multi-sensor's case is so composed, these views present a schematic summary of the pieces and the position of the various components.

Axonometric view

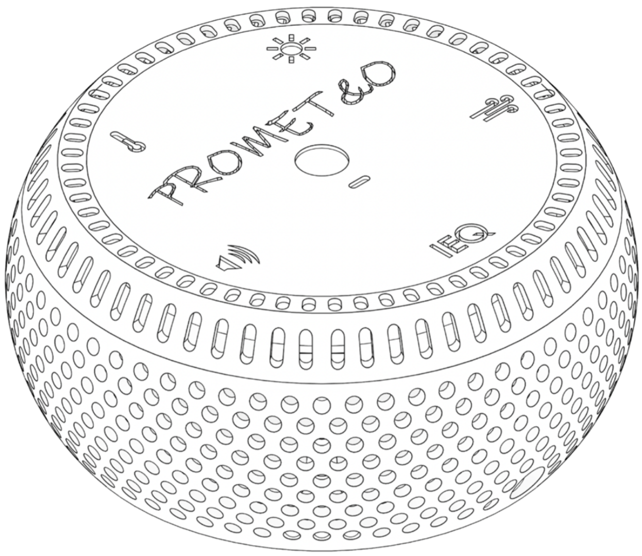


Figure 35: schematic 3D axonometric view

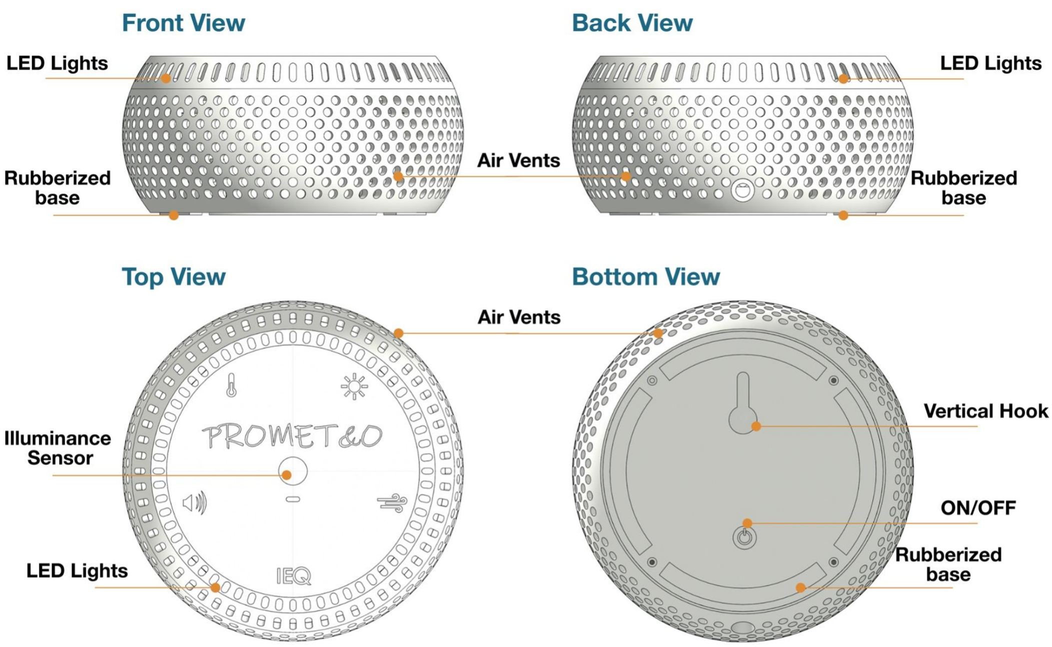


Figure 36: schematic 3D views of the case

Section view

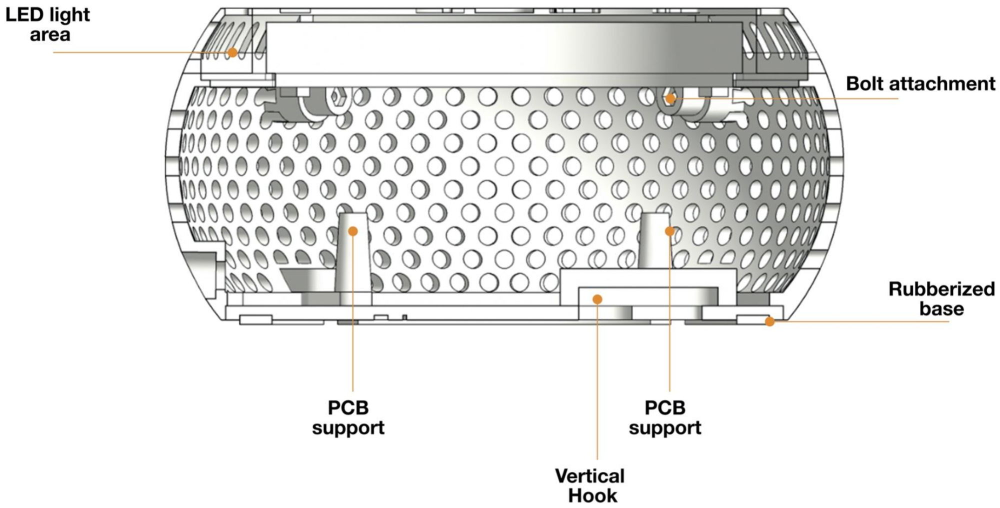


Figure 37: schematic 3D view of the case

4.4. Subjective survey structure

The design of the PROMET&O multi-sensor was followed by the development of the IT dashboard capable of returning the data acquired and collecting the subjective feedback by the occupants.

To design the PROMET&O multi-sensor dashboard, was previously defined the structure that the subjective questionnaire proposed by the application should have.

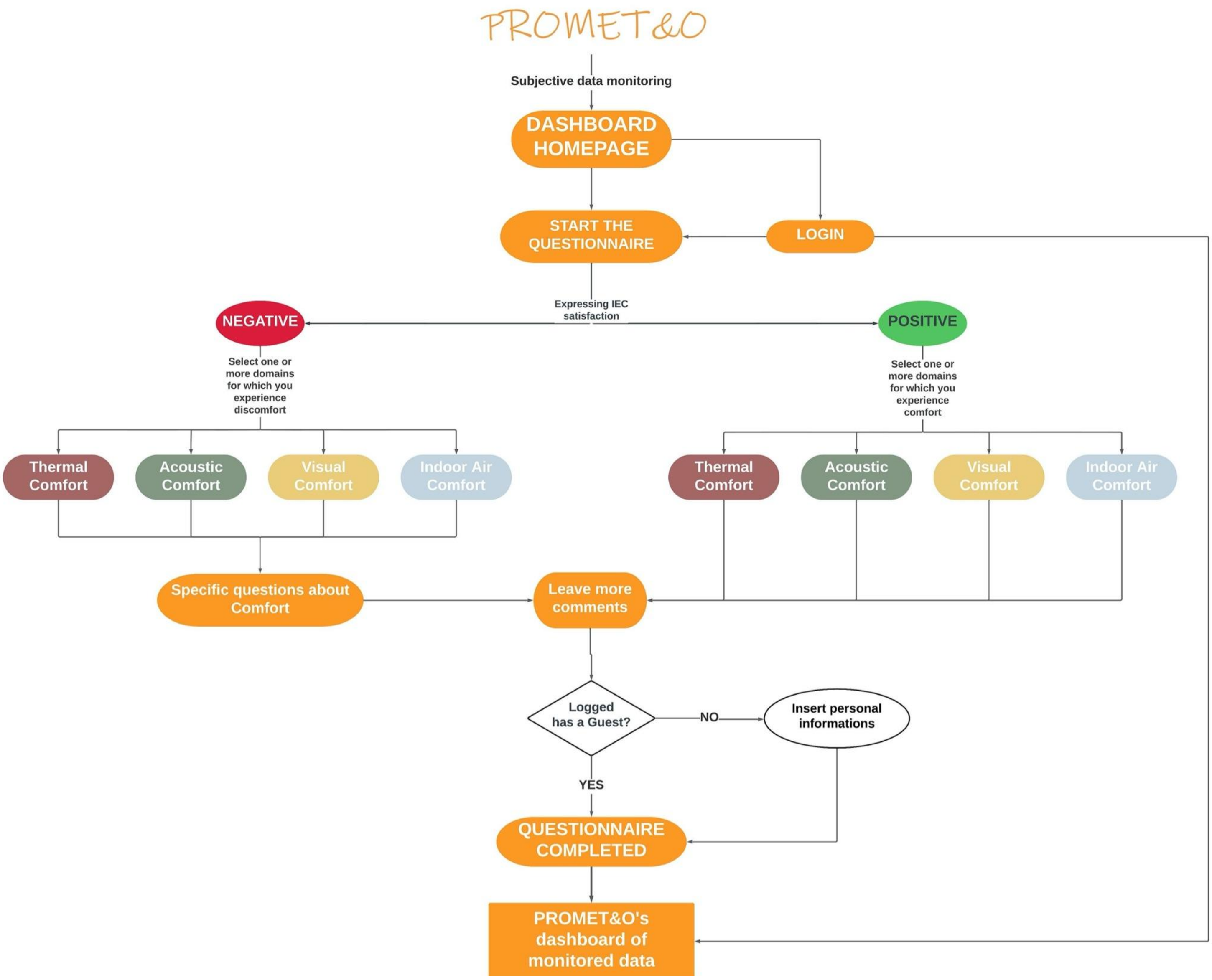


Figure 38: Flowchart of the subjective questionnaire possible actions

The dashboard was developed in both languages English and Italian.

In the following paragraph is explained the architecture of PROMET&O monitoring system to obtain IEC and IEQ values to show to occupants.

To obtain IEQ data the PROMET&O multi-sensor aims to be placed in a specific environment to monitor the parameters previously listed.

To evaluate the IEC instead the user has to carry out a questionnaire in the PROMET&O application.

Both obtained data of IEC and IEQ will be shown in the dashboard accessible only by previous **Login**.

To report the IEC feedback the user can log in the PROMET&O multi-sensor application as User (by previous registration) or as Host. It is possible to **Login** or **Start the questionnaire**. If the user is already registered, the **Login** button will switch to **Dashboard**, to see all the objective and subjective data monitored by PROMET&O.

If **Login** is pressed it is possible to register (if not already done) to the app by inserting PPBC variables (Personal, Physiological, Behavioural, and Contextual).

By clicking **Start the questionnaire** the user is sent to the questionnaire, where it is possible to select the subjective satisfaction of Indoor Environmental Quality (from bad to nice depending on colour).

If the answer is positive (light green and green smiley) the questionnaire will ask which domains the user is mostly satisfied with, leaving then the possibility of leaving more comments and information.

If the answer is negative (yellow and red smiley) the questionnaire moves to a dashboard containing the four domains of Indoor Environment, respectively Thermal - Acoustic - Visual - IAQ where it is possible to select up to all domains to express a discomfort.

To this follow specific questions for the domain. The questions are divided by belonging domain, and will show up only if the domain in question has been selected. All the domains questions have multiple choices.

Once the portion of the questionnaire referring to the domains has been completed, the questionnaire will end, allowing the user to leave other comments. By pressing **Complete** the questionnaire will be officially completed.

Is always admitted to press the **Home** button, but if it's clicked during the progression of the questionnaire, answers will not be acquired.

4.5. Dashboard development

4.5.1. Subjective data reporting

Below are represented many views of the subjective questionnaire, taken as screenshot of the actually working PROMET&O app.

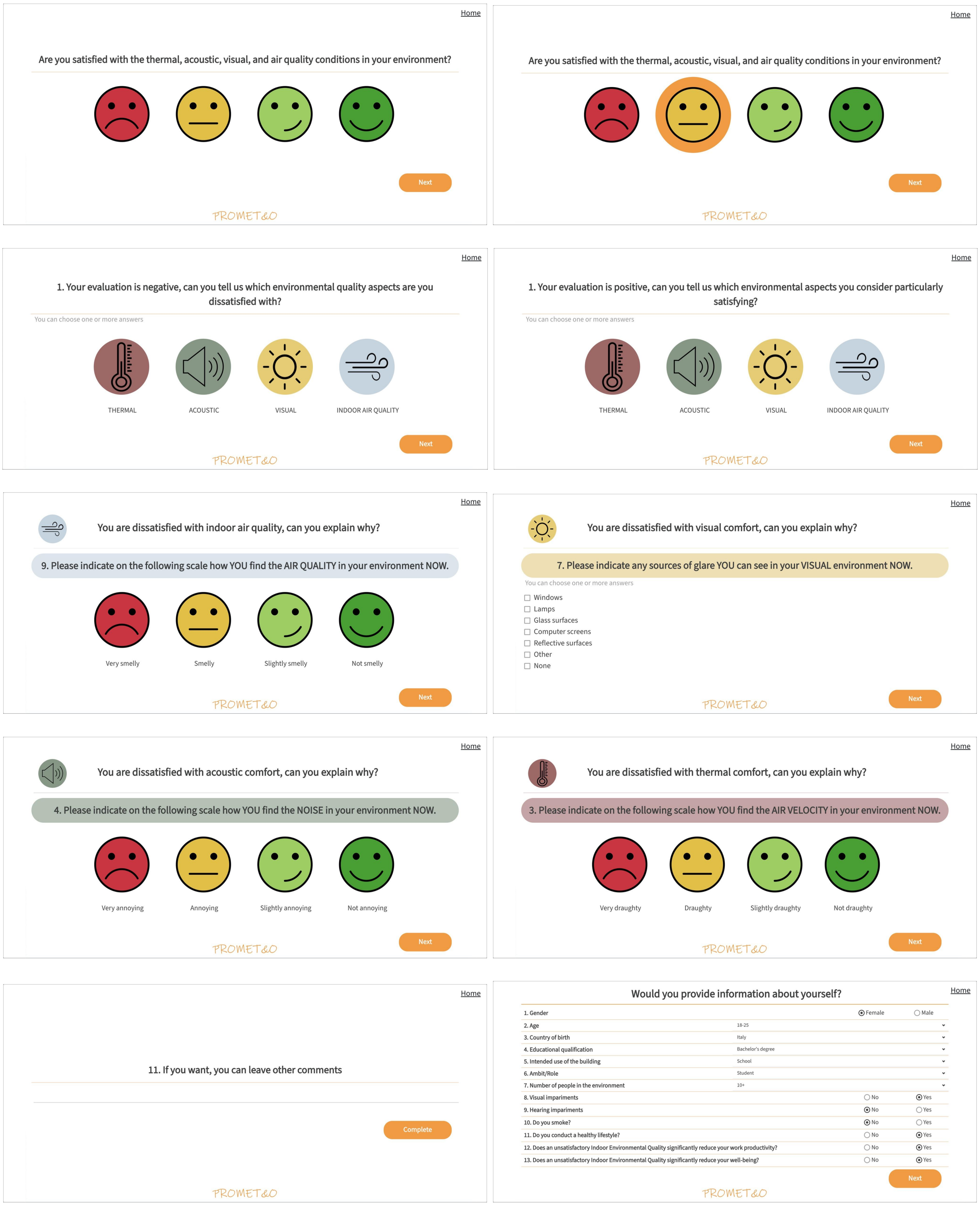


Figure 39: examples of dashboard view of the subjective questionnaire

4.5.2. *Objective data reporting*

The objective monitored data dashboard was designed using PowerPoint software support. Once the design phase was completed it was given to the IT engineering team which created it in the form of a website. The sheet (widescreen 16:9) was divided into two macro areas containing on the left a static banner that could contain variable information on the selected data, on the right the data collected.

Figure 40: PROMET&O dashboard - Main page

To make the screen more interactive in order to keep the interest of the user alive without compromising the ease of understanding, it was possible to show the data of the various domains at the click of each speedometer, while to view all the values at the same time it was inserted the same feature in the IEQ speedometer. The image placed in the centre will represent the multi-sensor placement environment.

Figure 41: PROMET&O dashboard - Relative Humidity (RT) selected

As you can see, in the box on the left the name of the clicked data and the respective description are updated at the same time as the interaction occurred in the portion on the right.

Furthermore, in order not to overload the information screen, the data are represented on the right with the nomenclature in a contracted version, and only on the left the name is fully displayed.

Figure 42: PROMET&O dashboard - Indoor Environmental Quality selected

Having determined the general setting of the dashboard, the buttons that modify the data displayed according to time frames prior to Real Time (RT) have been inserted.

The Home button, on the other hand, takes the user to the home screen where you can access the subjective questionnaire on environmental comfort.

Figure 43: PROMET&O dashboard - Main page selected

While the comforts are expressed in percentages, the measured values are expressed in the respective units of measurement defined by legislation.

The regulations also define the comfort (or safety) reference ranges for the data, these are represented in the box on the left, followed by the real-time value if RT is selected as a time frame.

Figure 44: PROMET&O dashboard - Relative Humidity (RT) selected

If other time frames were selected (I.E. 3h), the box would be updated containing no longer the real-time value but the mean value with respect to the selected time.

The standard deviation, 10th percentile, and 90th percentile are also added as additive information.

Figure 45: PROMET&O dashboard - Relative Humidity (3h) selected

The **More** button was subsequently added to allow the user to receive additional information about the domain or the measure selected. This feature has been implemented through pop-up banners to not excessively weigh down the box on the left with information not always requested.

Figure 46: PROMET&O dashboard - Relative Humidity (RT) selected

When clicked:

Figure 47: PROMET&O dashboard - More button for Relative Humidity (RT) selected

Likewise, the **Hints** function has been implemented to obtain suggestions in order to improve the comfort or quality of the selected data.

Unlike the information contained in the box on the left, **Hints** and **More** are not necessarily obtained by law.

Figure 48: PROMET&O dashboard - Relative Humidity (3h) selected

When clicked:

Figure 49: PROMET&O dashboard - Hints button for Relative Humidity (RT) selected

To complete the display without having to overload the initial screen, the possibility of displaying the graphs has been implemented using the **Show the graphs** button.

Figure 50: : PROMET&O dashboard - Relative Humidity (3h) selected

When the **Show the graphs** button is clicked (becoming **Hide the graphs**), the right portion of the screen changes, leaving room for the graph, representing the trend of the measurements in the various selected time frames.

To avoid misunderstandings between the information displayed in the graph and the data represented, the box on the left no longer shows the information as in the case of **Show the graphs** disabled.

The **Hints** and **More** keys give way to a legend indicating subjective comfort and reference range visualisation and to the **Compare the graphs** key.

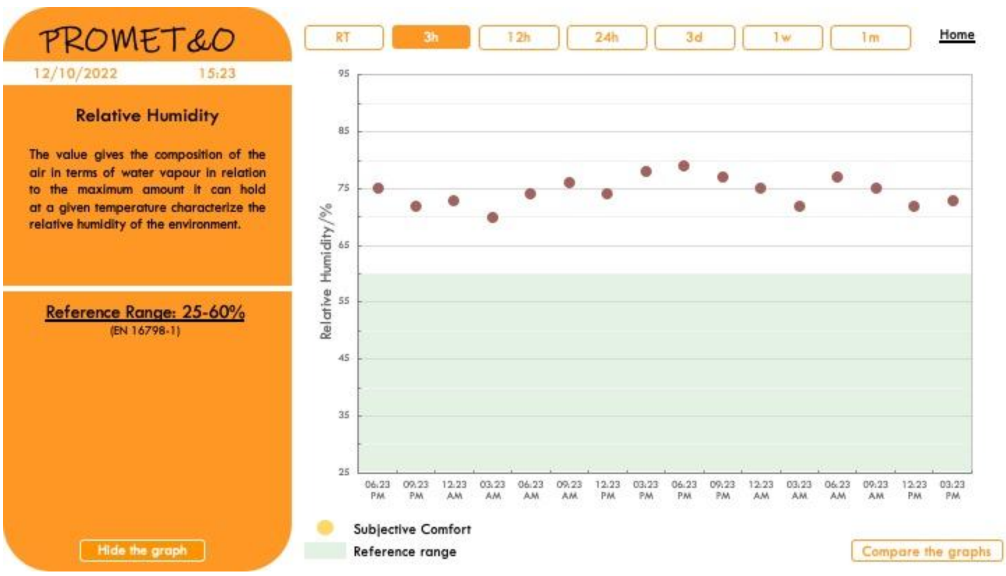


Figure 51: PROMET&O dashboard - Graph of monitored Relative Humidity (3h) selected

By clicking the **Compare the graphs** button, the entire screen changes enabling the ability to simultaneously view up to four graphs, which can be selected according to a double principle:

1) Same value in different time frames

Figure 52: PROMET&O dashboard - Graphs compared

2) Same time frame for different values

Figure 53: PROMET&O dashboard - Graphs compared

4.5.3. Graphs' design phase

The design for the representation of the data was created using Excel support within which, through the use of data generated randomly by the program itself, the graphs that will be displayed in the dashboard once completed were hypothesised.

The only difference between graphs is given from a line that links data in **Show the graphs**, that is not present in other temporal frames.

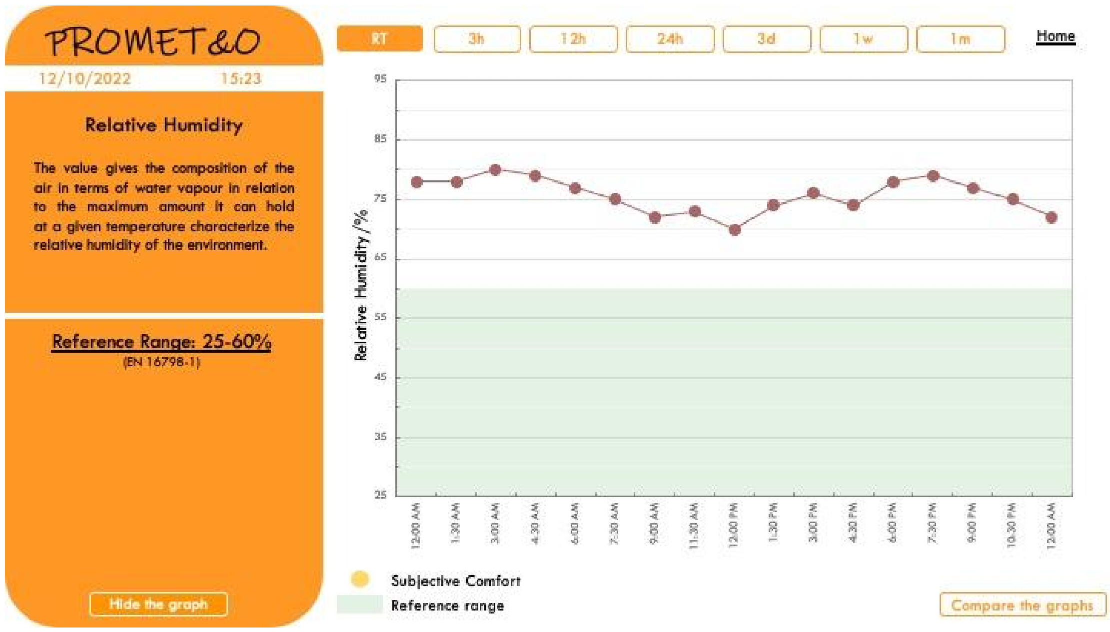


Figure 54: PROMET&O dashboard - Relative Humidity (RT) graph selected

The reference range (standards of comfort by law) is shown by a green band under the graph.

No reference range is visible in the Comforts' graphs because those aren't officially given by law.

The amount of data represented on abscissa axis in reference to each time frame is indicated as follows:

RT - 17 shown values each 5 minutes.

3h - 16 shown values each 3 hours to represent last 3 days

12h - 14 shown values each 12 hours to represent last week

24h - 14 shown values each day to represent 2 passed weeks

3d - 14 shown values each 12 hours to represent 6 passed weeks

1w - 12 shown values each week to represent 3 passed months

1m - 12 shown values each month to represent the passed year

4.5.4. Hints & More

A uniqueness within the PROMET&O dashboard is the possibility that the user, even if not related to the subject of Building Physics, can obtain additional information on the monitored parameters. This information are called Hints and More.

As previously mentioned, both will be viewable by clicking on the respective buttons which will open pop-ups over the screen.

The information contained in the pop-ups will be collected from legislation, protocols or literature.

I.E.

Thermal Comfort:

Hint - 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.

More - 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 the lower airways.

Carbon Monoxide:

Hint - Overconcentration of CO can be avoided using in a proper way all devices running on fossil fuels and by ensuring fresh air flow into your indoor space. (WHO)

More - Carbon monoxide is an odourless, colourless, and tasteless gas caused by incomplete combustion. It is poisonous and potentially lethal. (IQAir)

References

[1] Parkinson, T., Parkinson, A., & de Dear, R. (2019). Continuous IEQ monitoring system: Context and development. *Building and Environment*, *149*, 15–25. https://doi.org/10.1016/j.buildenv.2018.12.010

[2] Parkinson, T., Parkinson, A., & de Dear, R. (2015). Introducing the SAMBA indoor environmental quality monitoring system. *Living Learn*, 1139-1148.

[3]https://www.sydney.edu.au/research/research-impact/shaping-the-future-of-indoor-spaces.html

[4] https://www.aircare.it

[5] https://www.mouser.it

[6] Viola, F., & Idone Cassone, V., (2017). *L'arte del Coinvolgimento,* Hoepli. 8820378272

5. Pilot study for the PROMET&O methodology

The PROMET&O multi-sensor, as illustrated in the previous paragraph, is accompanied by a dashboard for data return and by the case containing all the electronic elements. Because of the world shortage of microprocessors that followed the Covid-19, the multi-sensor's validation suffered a setback. The application containing the questionnaire for subjective feedback has instead reached a state of progress such as to allow it to be validated in the field.

To define the guidelines for an in field application, completed with the procedures that have to be followed subsequently when the PROMET&O multi-sensor will be completed, a sensor for acoustic monitoring was used as a replacement, flanked by the PROMET&O questionnaire.

5.1. Acoustic sensor

The Speech and Sound SEMaphore (SEM) is an acoustic sensor that can collect the Sound Pressure Level (SPL) in an environment and then show it on an app for phone or pc in a real time chart. The main feature of the sensor is the possibility to return visual feedback with the changes of LED lights depending on the perceived noise.

The SEM sensor compares the mean value of the SPL monitored in a set time range to the last value obtained in the same set time range. The visual feedback is below explained:

- A green light shows a constant noise level in the environment,
- A switch from the green light to a yellow light will show an increase of the mean SPL from the last mean calculated value in the passed same time range,
- A switch from green to red or from yellow to red light will show a harder increase of the mean SPL from the last mean calculated value in the passed same time range.

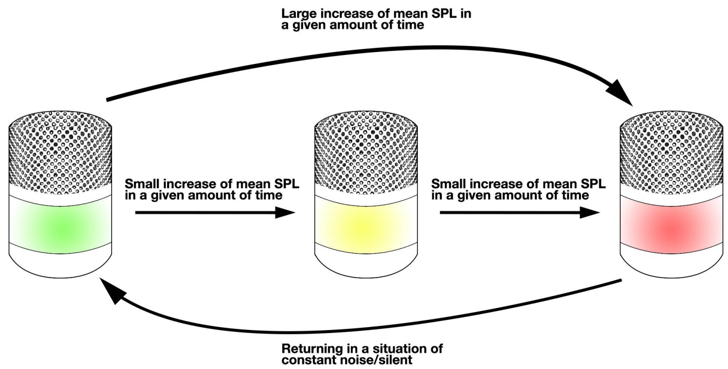


Figure 55: Schematition Speech and Sound SEMaphore light transition

5.1.1. Acoustic sensor calibration

The Speech and Sound SEMaphore's calibration took place in the anechoic chamber of the Polytechnic of Turin, to ensure no external sound could be earable. Then the SEM was opened by removing the top of its case and the calibrator was placed over it. When the calibration started a specific sound at exactly 94 dB was constantly emitted. By using a plastic cylinder the microphone of the SEM was connected to the calibrator speaker. Once the test finished it was possible to check on the SEM dashboard the difference between the dB perceived by the microphone and the stated 94 dB emitted from the calibrator. This difference is the error that a specific microphone has, knowing the error is possible to calculate the correct dB value that a specific sensor should register.

Figure 56: Speech and Sound SEMaphore - calibration

5.1.2. Acoustic sensor testing

Is important to note that SEM was designed for office-use, in calm/silent environments. In offices the discomfort for employees is mostly caused from instant noises (like a closing door or something falling to the ground). In noisy environments a great increase in the monitored SPL can cause a small variation in the discomfort perceived; in opposition in a calm environment small variations are instead perceived as annoying. To understand the difference between a calm or a noisy environment, multiple test were done before the in field application:

- In a silent room SEMs were positioned to cover a similar area where people around were working and the mean noise level was around 30-40 dB(A), fluctuations were scarce but extremely noticeable. After some testing, it has been noticed how a green to yellow difference of 4 dB(A) and a green to red difference of 10 dB(A) were good indicators. When people spoke with an average intensity the sensors flickered from green to yellow light but not too often, just as a visual reminder of not to exceed that voice tone; while loudspeaker, door shutting and other annoying activities showed a red feedback.

- On the other hand in a loud room populated with freely speaking and working students the recorded mean SPL was around 55-65 dB(A). There a change of 4 dB was noticed as hardly reachable while 10 dB of difference were never reached, so after more tests it was concluded that 3 dB difference for green to yellow light and 6 from green to red light were the best indication of the noise variations.

Figure 57: SEM - In site testing [photography]

5.2. In field monitoring and Survey application

Field testing of SEMs and the subjective questionnaire took place in the Intesa SanPaolo offices in Milan, in Paolo Ferrari Square. The monitoring phase lasted for the four consecutive weeks of November in which seven SEMs monitored the acoustic environment of two offices: four SEMs were placed in the Community Room and three in the Bench Room. The sensors started to monitor from 9:00 PM to 5:00 PM. In each office were placed mobile WI-FI routers to constantly connect SEMs to the internet, sending monitored data to the PoliTo network. Each SEM was accompanied by a tablet containing the app to access to PROMET&O's subjective questionnaire; those remained constantly connected to the battery charger to avoid shutdowns.

The two offices were chosen because they fit perfectly our objective, they can fit up to 10-12 people each; they are generally used for pc work but there also is an almost constant stream of calls for reunions, logistics, hiring new members etc. This generates alternating periods of silence and noise.

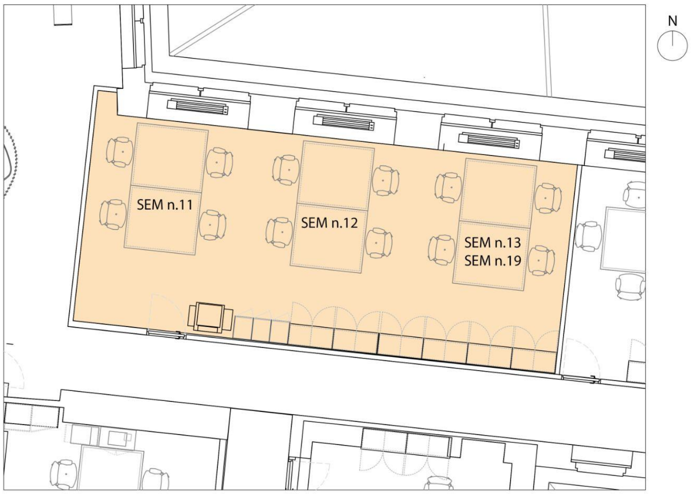


Figure 58: Community room

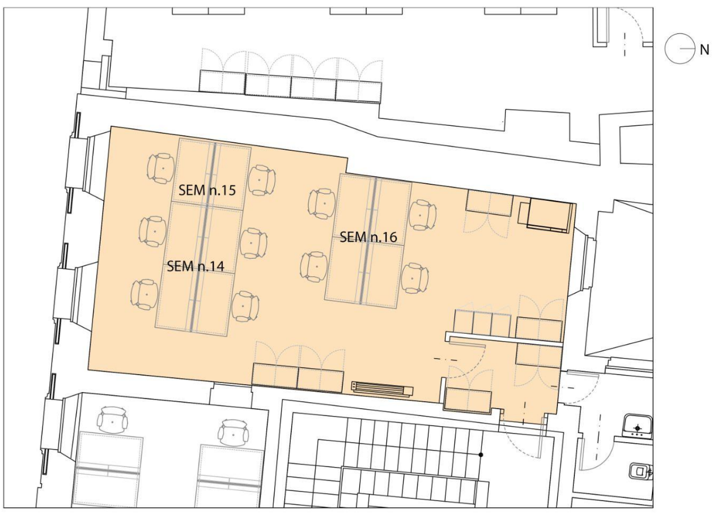


Figure 59: Bench room

Once the timing and places for monitoring have been defined, the parameters set for SEMs were indicated.

In the following table is proposed an example of SEMs' parameters settings used during the monitoring. The cells containing the parameters changed during the experimentation are indicated in yellow.

Table 20: Example of SEM setting over time.

PERIOD	SEM PARAMETERS	
WEEK 1 and day 1 of WEEK 2	Light change period (s)	1
	Measurement period (s)	5
	Percentile (%)	50
	Red threshold (dB)	8
	Yellow threshold (dB)	4
	Min. deviation reset(dB)	4
	Clear period (s)	60
	Instantaneous alert level (dB)	90
	Maximum red level (dB)	65
	Minimum green level (dB)	35
Day 2 of WEEK 2 (2022-11-15)	Light change period (s)	1
	Measurement period (s)	5
	Percentile (%)	50
	Red threshold (dB)	10
	Yellow threshold (dB)	5
	Min. deviation reset(dB)	5
	Clear period (s)	60
	Instantaneous alert level (dB)	90
	Maximum red level (dB)	65
	Minimum green level (dB)	35

When the monitoring period started, a table was prepared day after day with information regarding the operating status of each SEM, giving a report of any problems.

Table 21: Example of the report table.

SEM. Number	Already connected to the Network	Reboot	Start	First battery check	Time	Last battery check	Time	MORE
11	N	N	-	-		0%	17:10	Not working
12	Y		11:03	86%	12:00	84%	17:10	
13	Y		11:04	100%	12:05	100%	17:17	

While the objective monitoring of the acoustic side took place to define guidelines that PROMET&O will follow, the PROMET&O questionnaire for subjective feedback was validated. To involve the employees for an active participation in the project, sheets containing information on the tests were placed in the offices. The presence of the various figures linked to the project also tried to offer explanations regarding the needs and methods for data acquisition (especially regarding the use of the tablet to provide feedback on perceived comfort).Even though the monitoring period has not ended, it is possible to indicate the critical issues noted during the presence in the offices. The offices often did not have the expected number of people, many of the employees in fact preferring remote work were absent, and the few present were not particularly collaborative in the compilation phase.

Although from the questionnaire compilations that were compiled in the presence of a figure linked to the project it was possible to assume that the questionnaire is easily understandable for a naïve user.

6. Conclusions

In this thesis, an innovative methodology for IEQ and IEC assessment in office environments is explored. A new device for IEQ and IEC monitoring, which is called PROMET&O, has been designed by the Polytechnic of Turin. PROMET&O is a multi-sensor that aims at collecting objective data through the continuous monitoring of thermal, acoustic, lighting and air quality parameters, and at the same time is coupled with a touchscreen device devoted to acquire the subjective feedback of the occupants through an ad-hoc designed questionnaire.

The main outcomes that result from the implementation of the PROMET&O methodology and multi-sensor can be summarised below:

- Indoor Environmental Comfort

The IEC field is complex and studies are still ongoing. From the literature review it can be understood that surveys remain the primary method used to collect subjective feedback. Standardisation through legislation guidelines is not absent, but in the studied articles many variations are preferred, which make it difficult to describe a single method to approach the matter. Through the analysis carried out it was possible to outline some guidelines (e.g., administration strategies and device, possible rewards) on how to obtain subjective feedback on the various domains compounding the IEC for PROMET&O multi-sensor.

- Indoor Environmental Quality

Guaranteeing proper Indoor Environmental Quality is a fundamental point of architectural design. Poor environmental conditions can lead to discomfort and can cause illness to the occupants. Obtaining a compelling value to express the Indoor Environmental Quality and the possibility of an instant visual feedback for the occupant is becoming fundamental to allow them to know how to interact directly with the building. The literature is getting more aware about the actual impact that each domain has on the others. It could interact with BACS such as the HVAC system to constantly guarantee the best condition for the occupants, increasing productivity and keeping energy consumptions to the minimum level.

- The PROMET&O multi-sensor

The PROMET&O system aims at monitoring and calculating a large number of IEQ parameters, and at acquiring subjective feedback from the occupants. From the progress described so far, it can be summarised that:

The multi-sensor will be implemented shortly according to the methods described; the guidelines for application in the field will be adapted according to what was obtained from the SEM's experimentation;

The case may be subject to changes depending on the availability of some components.

The graphic design of the dashboard that returns the monitored objective data has been completed, this has to be connected to the multi-sensor once the prototypes of the device will be completed.

- The PROMET&O questionnaire

The subjective questionnaire has been tested in the field. It has been designed based on a standardised method for acquiring subjective feedback that allows constant data recording without excessively burdening employee habits. As the experimental campaign is still in progress, the analysis of the data collected will probably lead to changes especially in the administration of the questionnaire to employees if a level of collaboration will be too low compared to the expectations.

6.1. Future developments

The primary objective for the future is to develop prototypes of PROMET&O multi-sensor which will be validated in laboratory and in field to verify any limitations of the device, its accuracy, effectiveness, or any defects. The PROMET&O prototypes will be used within an experimental campaign in cooperation with the Italgas RETI SPA group to monitor the Indoor Environmental Quality and Comfort of its offices.

In the future PROMET&O might be used to inform the Building & Automation Control System (BACS) to automatically adjust the indoor environment quality in relation to perceived user comfort.