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# Indoor environmental quality and comfort perception in offices


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# Abstract

Indoor environmental conditions widely affect comfort perception, well-being, health and work productivity, because people spend about 90% of their time indoor. The present work of thesis started with the investigation of Indoor Environmental Quality (IEQ) in offices, through the analysis of standards and protocols, followed by the drafting of a literature review.

The four comfort domains, thermal comfort, acoustic comfort, visual comfort and indoor air quality (IAQ) have been investigated with the aim of defining a method for the evaluation and representation of offices global comfort in space and time. An existing office in ARPA Valle d'Aosta building, located in Saint-Christophe (AO), has been chosen as case study to evaluate perceived, monitored and project related global comfort.

By means of Odeon, Echo, IDA Indoor Climate and Energy (IDA ICE) and DIALux evo software, the real indoor conditions of the office have been simulated and then, comparing results with standards requirements, a project of renovation has been carried out to improve indoor environmental conditions and thus global comfort.

A new protocol has been developed, combining the main indexes of the standards and protocols studied, to assess monitored and project related global comfort. The developed graphic representation allows to combine the results of benchmarks related to occupants' perceived comfort (findings of another thesis work) with the monitored and project related comfort, with the aim to overcome the gap between the perception of global comfort and monitored conditions.

# Abstract

Le condizioni ambientali interne hanno un grande impatto sulla percezione del comfort, sul benessere, sulla salute e sulla produttività nel lavoro, in quanto le persone trascorrono circa il 90% del loro tempo in spazi chiusi. Il presente lavoro di tesi indaga la qualità dell'ambiente interno (Indoor Environmental Quality) negli uffici, attraverso l'analisi di normative e protocolli, e la stesura di una revisione della letteratura. I quattro domini del comfort (termico, acustico, visivo e qualità dell'aria interna) sono stati studiati con l'obiettivo di definire un metodo per la valutazione e la rappresentazione del comfort globale degli uffici, nello spazio e nel tempo. Un ufficio nell'edificio dell'ARPA Valle d'Aosta, situato a Saint-Christophe (AO), è stato scelto come caso studio per la valutazione del comfort globale percepito, monitorato e di progetto. Attraverso i software Odeon, Echo, IDA Indoor Climate and Energy (IDA ICE) e DIALux evo, sono state simulate le reali condizioni interne dell'ufficio e successivamente, confrontando i risultati con i requisiti delle normative, è stato realizzato un progetto di ristrutturazione per migliorare le condizioni ambientali interne e di conseguenza il comfort globale.

È stato sviluppato un nuovo protocollo, che combina i principali indici delle normative e dei protocolli studiati, per valutare il comfort globale monitorato e di progetto. La rappresentazione grafica sviluppata consente di combinare i risultati dei questionari relativi al comfort percepito dagli occupanti (risultanti da un altro lavoro di tesi), con il comfort monitorato e di progetto, con l'obiettivo di superare il divario tra la percezione del comfort globale e le condizioni monitorate.

# Summary

# Introduction

This project of thesis has the aim to study the four comfort domains: thermal comfort, acoustic comfort, visual comfort and indoor air quality (IAQ), finding a method to evaluate and represent global comfort in offices. Global comfort significantly affects occupants' health and work productivity, but nowadays there are no protocols or standards that enable its assessment.

In this thesis, the analysis of global comfort was carried out developing the project of a case study. The office chosen is in ARPA Valle d'Aosta building, located in Saint-Christophe (AO). It was the object of another work of thesis, focused on the evaluation of comfort perception through benchmarks, compared to measured data. The result of this previous research has been useful to understand how global comfort is perceived and how to improve indoor environmental conditions.

The present thesis work started with the investigation of Indoor Environmental Quality (IEQ) in standards and protocols, followed by the drafting of a literature review, through which have been investigated the other variables able to affect global comfort. Subsequently, the office model was created and calibrated by means of the on-site monitored data in four different software: Odeon and Echo for acoustic domain simulation, IDA ICE for thermal domain, natural lighting and IAQ simulations, and DIALux evo for electric lighting simulation. In this software were simulated the real indoor conditions of the office and then, comparing results with standards requirements, a project of renovation was carried out to improve indoor environmental conditions and thus global comfort.

With the aim to quantify global comfort for the current state and the project state, a protocol was developed, combining the indexes and values from all the standards and protocols studied. Then the results were graphically represented on a scale of new comfort thresholds, defined in this thesis work, to evaluate occupants' satisfaction with indoor environmental conditions.

In particular, the topics covered by this work are introduced in the first chapter, and the main protocols' structure is presented. In the second one, the four comfort domains are presented from a physical point of view, with

an overview of the standards that codify indexes for each of them.
The third chapter is a literature review, carried out on Scopus search engine, with PRISMA method, to understand the state of art in relation to the themes of global comfort, IEQ assessment and the factors (physical and non-physical) that may affect global comfort.
In the fourth chapter, the current state of the ARPA Valle d'Aosta building office and the renovation project carried out are explained in detail, whereas in the fifth chapter, the protocol developed to evaluate, and to compare, current and project related comfort conditions is explained and applied. Results are compared with perceived comfort and represented in space and time through three different proposals.
In the sixth chapter are included discussions and conclusions on the entire thesis work, and particularly related to the new thresholds defined for comfort assessment, the variables able to affect occupants' comfort perception and the representation of global comfort.

# 1 Indoor environmental quality and global comfort

## 1.1 Introduction to the main concepts

This work began with standards and protocols analysis and with a literature review on the topic of indoor environmental quality (IEQ). It has been necessary to set some concepts with relative definitions, which have been assumed for the work that has been carried out subsequently. These concepts will be illustrated in the following paragraphs.

### 1.1.1 Indoor environmental quality

Indoor environmental quality (IEQ) is the combination of thermal, acoustic and visual conditions and indoor air quality. It represents the essential requirement for obtaining the conditions of well-being.
IEQ can be considered as the objective measure, through defined physical indexes, of the conditions characterizing a specific environment from thermal, acoustic, lighting and air quality point of view. IEQ domains are related to each other, thus the combined effect of the four domains must be considered. If requirements of one of the four domains are not respected, occupants can perceive the environment dissatisfying also from the other three aspects point of view. IEQ indexes are regulated by standards and norms at national and international levels, which establish threshold values to enable designers achieving indoor environmental optimal condition.

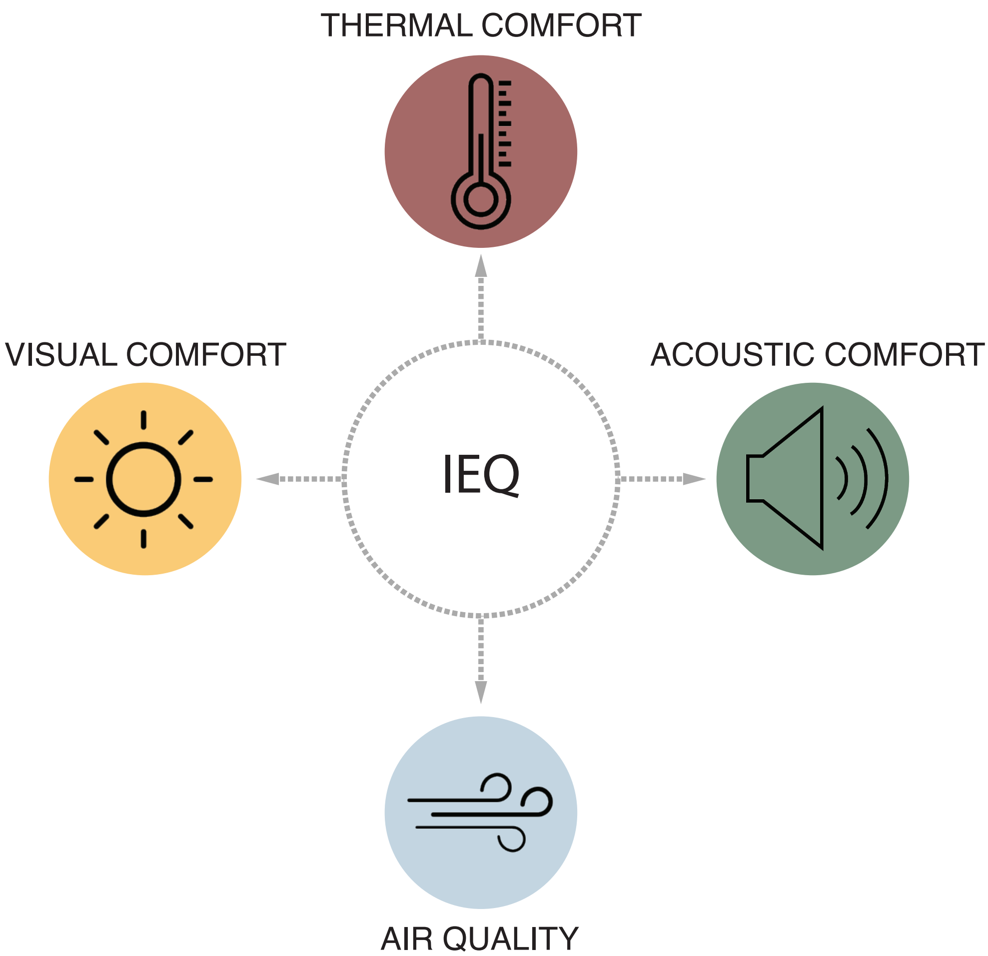


*Figure 1: IEQ domains.*

### 1.1.2 Environmental comfort perception

The concept of comfort represents the status in which subjects experience feeling of well-being and satisfaction. The large scale is the intrinsic topic of the "environment", whereas "comfort" is related to human body and its sensations. Therefore, "environmental comfort" deals with the space that surrounds the human body and is strictly linked to the perception that people have about the environment nearby themselves.
Thermal, visual and acoustic comfort, that found their origins in the building physics field, are the focus of this theme with indoor air quality, introduced more recently with the increasing awareness that buildings are source of many human diseases.

The objective evaluation of IEQ has been demonstrated to be not sufficient for the definition of the occupants' environmental comfort perception. Physiological characteristics, psychological conditions, age, gender and other personal variables along with contextual variables, like building characteristics, office characteristics and work characteristics, have strong influence on occupants' perception of the indoor environment, although are not considered in regulations yet (Zhang & de Dear, 2019)(D'Oca et al., 2018). Researchers proved that although physical requirements are met, not all the occupants consider themselves satisfied with environmental conditions (Rasheed & Byrd, 2017). Therefore, this aspect should be integrated in the updates of the regulations as it has a fundamental role in building design, usage and maintenance phases.

### 1.1.3 Well-being, health and work productivity

Indoor environmental quality and environmental comfort perception are of fundamental importance, considering the time that people spend indoor (about 90% of their life for inhabitants of industrialized areas, according to the European Commission assessment). For this reason, researchers focused on the influence of indoor environmental quality on occupants' environmental comfort perception, as well as on their well-being, health and work productivity.

As described by Lou and Ou (Lou & Ou, 2019) also office layout influences occupants' work productivity and well-being. It may favour collaboration among office colleagues, but on the other side it affects occupants' privacy and is source of uncontrolled noise. Furthermore, they demonstrated that high-density offices are less comfortable and occupants feel bothered in them.

Other factors, like reflections, luminance ratios, odours, humidity, mould, particulate matter, noise and vibration have been identified as discomfort sources (Frontczak & Wargocki, 2011).

One's feeling about oneself in relation to the surrounding environment defines the well-being. If physiological, psychological and social needs are satisfied it means that the individual well-being tends to be high (Ong, 2013). Warr in 1998 proposed three scales included in well-being definition:

pleasure to displeasure, comfort to anxiety and enthusiasm to depression. He also identified ten features influencing well-being: opportunity of personal control, opportunity for using one's skills, externally generated goals, variety, the environment, availability of money, physical security, supportive supervision, opportunity for interpersonal contact and job status in society (Ong, 2013).

The relationship between work productivity of office occupants and the environment in which they work has been studied by Heerwagen, who defined the "worker performance" as directly dependent from "motivation", "ability" and "opportunity".

*P = Motivation x Ability x Opportunity*

The "motivation" is strictly linked to the will that a person has to perform a task; he or she has to be able to perform it ("ability") and the environment in which the task is performed must be suitable ("opportunity"). The workplace directly influences the motivation and it must provide comfortable and healthy conditions (Heerwagen, 1998).

An important aspect of workplaces characteristics is to allow occupants' have direct contact with the outside world during the working day, to let workers follow their natural circadian rhythms. Moreover, buildings must be sensitive to the changing needs of people, providing them with control possibilities.

Furthermore, it is evident since decades that building systems weaknesses causing bad indoor environment conditions are able to affect human health. The concept of Sick Building Syndrome (SBS) was introduced in the 1980s. At that time causal and risk factors were not known enough yet, ventilation rates in buildings were limited and emissions from buildings materials were high. In 1983 the World Health Organization defined it firstly. The symptoms of SBS affect building occupants in relation to the time they spend indoor, causing a temporary ill-being and disappear when they leave the building. They can be various (among them eyes, nose, throat and skin irritation and neurotoxic health problems) and are related to personal and environmental variables (Azuma et al., 2017)(Dhungana and Chalise, 2019). The WHO stated that the majority of occupants should report symptoms and that there should be no relationship with occupant sensitivity or excessive exposure. Furthermore, it stated that SBS phenomenon appears without a single apparent causal factor in the building, thus symptoms are caused by the exposure to many chemical compounds that are present in a low concentration. (Godish, 2005).

Different from SBS is the “Building-Related Illness” (BRI), a real disease caused by inadequate indoor environmental conditions, that can even have fatal consequences (Esfandiari et al, 2017). It includes hypersensitivity diseases, nosocomial infections and toxic effects associated to high exposures to carbon monoxide (CO).

Nowadays many actions have been done to improve IEQ, reduce SBS and BRI (particularly ventilation rate have been increased and emissions from finishes, paintings, furnishes and other building materials have been reduced) and increase occupants’ comfort (Godish, 2005).

Wei et al. demonstrated that greater comfort leads to higher well-being and health conditions, with economic consequences and a significant increase in productivity in offices.

Furthermore, work productivity increases in relation to the level of concentration on the task to be performed. Short-term, medium-term and long-term factors can be different sources of productivity loss (Ong, 2013).

Occupants have personal expectations of satisfaction and comfort that have consequences on their work productivity. Due to this expectation they tend to act to satisfy their physiological and psychological needs and to reach their comfort level, with consequences on energy consumption (Chen et al., 2020).

## 1.2 IEQ and environmental comfort assessment

To assess occupants’ comfort perception and satisfaction with indoor environmental conditions, Post-Occupancy Evaluation (POE) method was introduced in the 1960s (Bae et al., 2020)(Choi and Lee, 2018). To realize a POE study different data are required (building properties, occupant’ feedback and IEQ parameters) that are collected through interviews and on-site measurements (Bae et al., 2020)(Choi and Lee, 2018). Nowadays it is still a widespread evaluation tool, thanks to the use of questionnaires and interviews that are an easy and cheap tool to gather information (Bae

et al., 2020).
Furthermore, in recent years, several models have been developed for monitoring and representation of indoor environmental factors and conditions, with the aim of ensuring occupants' comfort and increasing energy efficiency of buildings (Erickson and Cerpa, 2012).
Devices for the collection of subjective perception responses allow to investigate other factors that affect occupants' environmental comfort perception and to forecast it (Merabet et al., 2020).

### 1.2.1 Standards

Standards are technical documents that define characteristics (dimensional, organizational, environmental, of performance, of security, etc.) of a product, process or service, according to the state of the art approved by a recognized society. Standards are organized into different categories in relation to who developed the standard and what is the level of validity: international standard (ISO), European standard (EN) and national standard (UNI in Italy). The acronym ISO identifies the standards developed by the International Organization for Standardization. These standards are a reference applicable worldwide. Each country can adopt them as its own national regulations.
EN identifies the standards developed by CEN (Comité Européen de Normalisation) that must be compulsorily transposed by CEN member countries. These standards standardize technical legislation across Europe, so there can be no rules at national level that are not in full harmony with their content. The abbreviation UNI declares Italian national standards. If there are no other abbreviations, it means that the standard has been drawn up directly by the UNI Commissions or by the Federated Bodies.
Standards set indexes optimal values range of performance or calculation methodologies. All the regulations clearly specify the context of use: dwellings, offices, educational buildings, etc. Each of them provides a preface in which there are information about the origin of the data reported in the legislation, and an introduction in which theoretical concepts and indexes are defined, before the text of the regulation.

Standards used in this thesis work to analyse each comfort domain are listed in the following table. The only standard that defines indexes values for the four domains is EN 16798. It has been written with the aim of meeting the requirements of Directive 2010/31/EU (19$^{th}$ May 2010) on the energy performance of buildings (recast), referred to as “recast EPDB”. It specifies requirements and defines how to set parameters for building system design and energy performance calculations for four different categories.

*Table 1 : standards used to evaluate each comfort domain.*

| Comfort domain | Standards |
|---|---|
| Thermal | ASHRAE 55, ISO 7730, EN 16798 |
| Acoustic | EN 3382-3, NF S31-080, ISO 22955, EN 16798 |
| Visual | EN 12464, EN 16798, EN 17037, IES_LM-83-12 |
| Indoor air quality | EN 16798 |

### 1.2.2 Building Performance Certification Programs

The growth of the consciousness of the consequences of human activity on the environment brought to the first conference convened by the United Nations in Stockholm in 1972. The path toward sustainability moved its first steps in 1962, with Rachel Carson’s “Silent Spring”, through which were shown to people the consequences of the use of pesticide DDT; and in 1972 with the “Club of Rome” and its report “Limits to Growth”.
However, the Stockholm conference has been an important event with consequences still evident nowadays. Many other conferences have been convened and reports draft in subsequent years: the UN Commission on Environment and Development that draft the Brundtland Report (“Our Common Future”) in  which is set the principle of sustainability as “Development that meets the needs of today without compromising the ability of future generations to meet their own needs”; in 1987 the Intergovernmental Panel on Climate Change was founded and the Montreal Protocol, a treaty aimed at decrease the use of compounds responsible for the depletion of the ozone layer in the stratosphere was formulated; in 1992 the United Nations

met in Rio de Janeiro to create a partnership of cooperation for fair and sustainable development. Rio declaration and Agenda 21 were the main results of this conference. In 1997 the Kyoto Protocol, an international treaty that came into force in 2005, was draft with the aim of reducing greenhouse gases emissions, responsible for climate change.
Pursuing these goals, methods for building and environmental assessment have been established to define the quality of a building and the surrounding environment. Energy-environmental certifications go beyond the assessment of the building's energy efficiency and its associated consumption (evaluated in the energy certifications required by law) and refer to the entire life cycle of a building, evaluating the impact on the environment and on people's health throughout all its phases.
Building performance certification programs were established to provide assurance regarding the quality of buildings from the point of view of the materials used, the performance of the building systems, the indoor environmental quality and comfort four domains: thermal, acoustic, visual and indoor air quality.
Thanks to this certification, it can be ensured that the certified building meets the sustainability and quality criteria, with the aim of improving the climatic and environmental conditions.
The protocols constitute an alternative sustainability assessment system to the quantitative method which is applied with the Life Cycle Assessment (LCA).
The protocols constitute a multi-criteria evaluation based on a rating system. The application of criteria is related to the activities, context and use. If the requirements selected within the protocol are respected by the building, then points will be obtained. The sum of the points allows to obtain a final performance assessment, associated to a specific certification level. Nevertheless, there are discrepancies between the findings of different protocols, because results are represented in different ways (percentage, scores). It is, therefore, a qualitative and not a quantitative methodology.

#### 1.2.2.1 BREEAM

BRE-Environmental Assessment Method is the first rating system

developed: it was drawn up in 1990 in the UK by BRE (Building Research Establishment). It establishes standards for green building and is based on a control system for environmental and building quality certification.
Today it is one of the most widespread and used worldwide tools for the environmental assessment and classification of buildings on a voluntary basis. It establishes criteria for the design, construction and maintenance-operating phases of buildings, with the aim of reducing environmental impacts and improving energy performance. It is used in all construction sectors, from public to private (residential, school, commercial, healthcare, etc.) and can be applied to existing buildings, to be renovated buildings or newly built buildings.
BREEAM rating results are given in percentage for each category and subsequently they are summarized through a weighted average to obtain the total score.
Different percentages of the rating system are:

- Outstanding ≥ 85
- Excellent ≥ 70
- Very good ≥ 55
- Good ≥ 45
- Pass ≥ 30
- Unclassified < 30

*Table 2: the table summarizes the categories of BREEM protocol, their weight and the number of indicators for each category.*

| Category | Weight | N. of indicators |
|---|---|---|
| Energy | 19% | 9 |
| Transport | 8% | 5 |
| Pollution | 10% | 5 |
| Materials | 12.50% | 5 |
| Water | 6% | 4 |
| Land Use & Ecology | 10% | 5 |
| Health & Wellbeing | 15% | 6 |
| Management | 12% | 5 |
| Waste | 7.50% | 5 |

### 1.2.2.2 LEED

LEED (Leadership in Energy and Environmental Design) was developed in 1993 by the U.S. Green Building Council. It is a rating system that is now developed and recognized worldwide.
It is subdivided in different certification systems in relation to the urban scale, the type of building and the type of intervention (renovation or new construction). This rating system evaluates the performance and environmental impact of the building over the entire life cycle and aims to encourage an integrated design approach. It is based on the assignment of points in relation to the realization of specific design characteristics considered to be aimed in a sustainable perspective. It consists of credits divided into seven categories, listed in the following table.

*Table 3: the table summarizes the categories of LEED protocol, their weight and maximum score assigned for each category.*

| Category | Weight | Score |
|---|---|---|
| Location and transportation (LT) | 15% | 16 |
| Sustainable Sites (SS) | 10% | 10 |
| Water efficiency (WE) | 10% | 11 |
| Energy and Atmosphere (EA) | 31% | 33 |
| Materials and resources (MR) | 12% | 13 |
| Internal environmental quality (IEQ) | 15% | 16 |
| Innovation in design (ID) | 6% | 6 |

The credits to be evaluated can be chosen on the basis of the building to be evaluated, but the credit prerequisites are mandatory for the building to be certified. To define the certification level, all the scores associated to the credits are summarized, up to a maximum of 100 points.
The classification based on the score obtained is as follows:
• Certified: 40-49 points
• Silver: 50-59 scores
• Gold: 60-79 scores
• Platinum: 80-100 scores

### 1.2.2.3 WELL

The WELL Building Standard™ was developed by DELOS LCC in 2014, after years of research carried out in the medical and scientific field. It is operated by the International Well Building Institute (IWBI) and issued by the U.S. Green Building Council.
The well provides a method for integrating human health and well-being into the design, construction and management phases of buildings. Therefore, it connects building with people's health, which is the main and fundamental focus of this protocol, that concerns the physical, intellectual, emotional and social well-being of people. The WELL considers the built environment as an instrument to ensure conditions of comfort, well-being and health to occupants.
It is organized on the basis of the type of space (regularly occupied or employable) and the type of users (regular occupants or occupants).
The WELL describes health and well-being of people by breaking down the human body into its systems and consists of seven thematic areas called "concepts". During project assessment each concept is graded independently on a numerical scale. This methodology of concept by concept analysis is used to ensure that "preconditions" are satisfied, while final score is calculated based on the total "preconditions" and "optimizations" achieved.

*Table 4: the table summarizes the categories of WELL protocol, the maximum score assigned for "preconditions" (their achievement is mandatory) and "optimizations" (to obtain high performance value), and total score from 0 to 10.*

| Category | Preconditions | Optimizations | Total |
|---|---|---|---|
| Air | 12 | 17 | 0 - 10 |
| Water | 5 | 3 | 0 - 10 |
| Nourishment | 8 | 7 | 0 - 10 |
| Light | 4 | 7 | 0 - 10 |
| Fitness | 2 | 6 | 0 - 10 |
| Comfort | 5 | 7 | 0 - 10 |
| Mind | 5 | 12 | 0 - 10 |

#### 1.2.2.4 Protocollo ITACA

The first version of the Italian ITACA rating system, approved on January 15, 2004, was developed by ITACA ("Istituto per l'innovazione e trasparenza degli appalti e la compatibilità ambientale") and by the "Associazione nazionale delle Regioni e delle Province autonome", a working group Interregional for Sustainable Construction established in 2001.
It is an energy efficiency and energy saving related building classification for assessing its impact on the environment. It is based on indicators and verification methods that comply with technical standards and national laws.
For the application of Protocollo ITACA it is necessary to follow the steps below:

- Identification of environmental criteria to detect the environmental performance of the building;
- Definition of benchmark performance;
- Weighing of the criteria that determine the final performance score compared to the standard level.

It can be used for existing buildings to be renovated as well as for new buildings. Furthermore, each typology of building refers to its own protocol (residential, commercial, school, tertiary, industrial).
Regional versions are also envisaged: Protocollo Itaca Marche, Protocollo Itaca Puglia, Protocollo Itaca Umbria, Protocollo Itaca Piemonte, Protocollo Itaca Valle d'Aosta, Protocollo Itaca Friuli-Venezia Giulia, Protocollo Itaca Liguria, Protocollo Itaca Lazio, Protocollo Itaca Basilicata.

*Table 5: the table summarizes the categories of ITACA protocol, their weight and maximum score assigned for each category.*

| Category | Weight | Score |
|---|---|---|
| Sustainable Sites (SS) | 17% | 6 |
| Water efficiency (WE) | 43% | 15 |
| Energy and Atmosphere (EA) | 14% | 5 |
| Materials and resources (MR) | 14% | 5 |
| Internal environmental quality (IEQ) | 11% | 4 |

## 1.3 Thesis goal

The analysis of international standards and protocols reveals some limitations as they define indexes values to reach the minimum acceptable level. Furthermore, a general lack of multi domain approach on comfort assessment is evident. The evaluation of the combined effect of the four domains is fundamental for its strong influence oh health, well-being and work productivity.

Standards define indexes for each domain, defining risk avoidance values, whereas in protocols each category is codified in different ways and with different results, thus general comfort assessment is difficult to be performed. The results of this analysis show the necessity to find a new way to represent and evaluate comfort in existing building and to define new guidelines for comfort design. For this reason, with this project of thesis will be developed a graphic representation of global comfort able to compare the results of the assessment of perceived comfort (obtained through benchmarks), measured comfort (through on-site measurements) and project related comfort (through a rating system).

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# 2 The four IEQ domains

## 2.1 Thermal comfort

Thermal comfort is related to objective external stimuli, set in physics field, and subjective responses to such stimuli, dependent on personal perception and thus established on statistic basis. Standard ISO 7730 defines thermal comfort as “that condition of mind which expresses satisfaction with the thermal environment” and states that dissatisfaction can be caused by warm or cool discomfort of the body as a whole, or by unwanted cooling or heating of one part of the body. Because of different personal perception, it is not possible to define a thermal environment able to satisfy everybody but is possible to define thermal environments predicted to be able to satisfy a specific percentage of occupants.

From an objective point of view, thermal comfort can be defined as the state of thermal neutrality, in which human body thermal accumulation is zero, with almost inactive behavioural thermoregulation mechanisms (absence of chills or sweating) and vasomotor thermoregulation mechanisms (absence of vasoconstriction or peripheral vasodilation). Thermal neutrality depends on micro-climate, which affects heat exchanges between the person and the environment and is defined by a set of environmental indexes.

The main factors that must be considered when defining thermal environmental conditions are:

- Building thermal characteristics
- Heat and vapour source
- Climate conditions
- Air conditioning system performance
- Activities and use of a space.

Whereas physical indexes for thermal comfort assessment are:

- Air temperature [°C]
- Average radiant temperature [°C]
- Relative humidity [%]

- Air velocity [m/s]
- Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD)

Air temperature is measured with an instrument (such as dry bulb thermometer) that has to be in thermal balance with air and without thermal exchanges with other elements through radiation.
Average radiant temperature is the weighted average of surface temperatures delimiting the environment including the effect of incident solar radiation.
Air temperature and average radiant temperature are the two main factors that influence heat sensation. If the body is exposed to cold surfaces, a sensitive amount of heat is emitted in the form of radiation to these surfaces, producing a feeling of cold.
Relative humidity, expressed in percentage, is the ratio between the partial pressure of the water vapor in the air and the maximum water vapor pressure that can be had at that temperature.

$$\varphi a = pa/pvs \; [\%] \tag{1}$$

It's the relation between the quantity of water vapor in a volume of air and the maximum quantity that it could contain, at the same condition of temperature and pressure. Maximum water vapor pressure depends on air temperature.
Air velocity depending on the direction is measured in two different ways. For one-way flow paddle anemometers are used, whereas if the direction is unknown, omnidirectional sensors are used.
Operative temperature represents the uniform temperature of an environment in which an occupant would exchange for irradiation and convection the same thermal power of the thermally non-uniform environment under examination.
Human body can exchange mass, heat and work, thus it could be considered as a thermodynamic system and analysed its energy balance.

$$S = M - W - E_{res} - C_{res} - C - R - E - K \tag{2}$$

Where:

S: amount of thermal energy or internal energy variation of human body in the unit of time [W];

M: metabolic energy [W];

W: mechanical power that human body exchange with environment [W];

$E_{res}$: energy exchange through respiration as latent heat [W];

$C_{res}$: thermal power exchanged in respiration as sensitive heat [W];

C: thermal power exchanged for convection [W];

R: thermal power exchanged for radiation [W];

E: thermal power exchanged for evaporation from the skin [W];

K: thermal power exchanged for conduction [W].

To verify the condition of homeothermy S must be equal to zero, thus:

$$M - W - E_{res} - C_{res} - C - R - E - K = 0 \tag{3}$$

$$M - W = E_{res} + C_{res} + C + R + E + K \tag{4}$$

In 1970, Povl Ole Fanger conceived the first model about thermal comfort, expressed through two indexes PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied).

The PMV is based on the solution of the energy balance equation of the human body and correlates the thermal sensation to a vote relating to the perception of the environment. In the same environment there could be different subjective responses, due also to differences in clothing insulation and metabolic rate. Metabolic rate is the thermal power generated by metabolic reactions referred to the unit of surface of the body. It is connected to the level of physical activity performed by the individual and its value increases as the physical activity practiced increases. For the metabolic rate is used the technical unit of measurement met (1 met = 58 W/m$^2$).

Therefore, to obtain an objective result, PMV index must be considered. It is the average of predicted subjective responses of occupants. It is evaluated with a scale of 7 points: from - 3 (cold) to + 3 (hot), where zero represents the neutral condition.

PMV is an average value and the dispersion of the data around this average

is rather high, due to highly variable subjective responses. For this reason, Fanger introduced another index, through which is possible to take this distribution into account: the PPD, that represents the predicted percentage of occupants unsatisfied (the ones that vote ± 2 or ± 3).
The main factors causing local discomfort are unwanted cooling or heating of occupant's body, drafts, abnormally high vertical temperature differences between floor and head.
Reliability of Fanger's model is affected by environment ventilation typology. It has been proven that PMV is not reliable for naturally ventilated buildings, because it was studied in air-conditioned climate chamber. Therefore, to overcome this limitation, in 1998 Gail S.Brager and Richard J.de Dear proposed an alternative thermal comfort model, the so called "adaptive comfort model", that was adopted by international standards for naturally ventilated buildings. They stated that people are not passive recipients of thermal environment, but they interact with environmental system, thus the adaptation to thermal environment is related to three different processes: behavioural adjustment, physiological acclimatization and psychological habituation or expectation (Brager and de Dear, 1998). Their studies highlight the distinction between responses in air-conditioned and naturally ventilated buildings. The innovative aspect of adaptive approach model of thermal comfort was received and declined, by Nicol ed Humphreys, in EN 16798.

### 2.1.1 Standard framework

The main standards that regulate thermal comfort are ASHRAE 55, EN 16798 and ISO 7730.
ASHRAE 55 deals with indoor thermal environmental factors and personal factors combined to set indoor thermal environmental conditions acceptable for most of the occupants. The addressed environmental factors are: temperature, thermal radiation, humidity, air speed; whereas the personal factors are: clothing insulation and metabolic rate.
Standard EN 16798 states that criteria for the thermal environment in heated and/or mechanical cooled buildings shall be based on the thermal comfort indexes PMV-PPD, with assumed typical levels of activity and typical values

of clothing thermal insulation (winter and summer). Based on the selected criteria a corresponding design operative temperature interval shall be established. Criteria for local thermal discomfort such as draught, radiant temperature asymmetry, vertical air temperature differences and floor surface temperatures shall also be considered when designing buildings.
Standard ISO 7730 enables the analytical determination of indoor thermal conditions by setting thermal indexes (like operative temperature and air velocity) values and of thermal comfort through the calculation of PMV and PPD values, set by this standard for different categories.

## 2.2 Acoustic comfort

In the design phase acoustic component is usually neglected compared to aesthetics, functionality and performed choices. Thermal and visual comfort, through which is possible to reduce energy consumption, have a direct impact on economical aspect, while acoustic comfort represents a physical condition where a person, in a specific environment, experiences a sense of well-being.
Conditions are considered comfortable not with complete absence of noise, but with the balance of different acoustic conditions. Well-being or ill-being, from an acoustic point of view, is not only determined from the level of noise in a room. Acoustic comfort is affected by the levels and the nature of the sound experienced in a space; therefore, silence is not necessarily associated to a real sense of acoustic well-being.
Providing acoustic comfort consists in minimizing intruding noise, ensuring satisfaction in workspace, avoiding discomfort, stress, tiredness and even certain pathologies.
A proper sound design in workplace helps to improve concentration and productivity, to enable a better communication and to block unwanted noise. If occupants are satisfied with the environment, they are more productive, happier and healthier.
Open spaces, due to their layout, present many problems from acoustic point of view, such as noise and distraction, lack of privacy, stress, greater risk of illness. The most relevant problem is the irrelevant speech noise, that is difficult to be controlled because is caused by conversations between

colleagues, telephone calls, laughter.
Sound propagates in the air as a plan wave, characterized by a specific frequency and a wavelength, for this reason sound pressure is the variation of the static air pressure.
Sound pressure level is the main index for sound evaluation. Expressed in dB, it is the logarithmic scale of the pressure variation, thus it is obtained from the sound pressure generated from a source and the reference pressure.

$$L_p = 10\log(p_2/p_0)\ [dB] \quad (5)$$

It is measured with a noise meter and a microphone highly performing. The frequencies perceived by human auditory system are between 20 Hz and 20000 Hz. Pure sound is characterized on a specific frequency, while sound pressure level is distributed in frequency spectrum (generally divided into octave thirds).

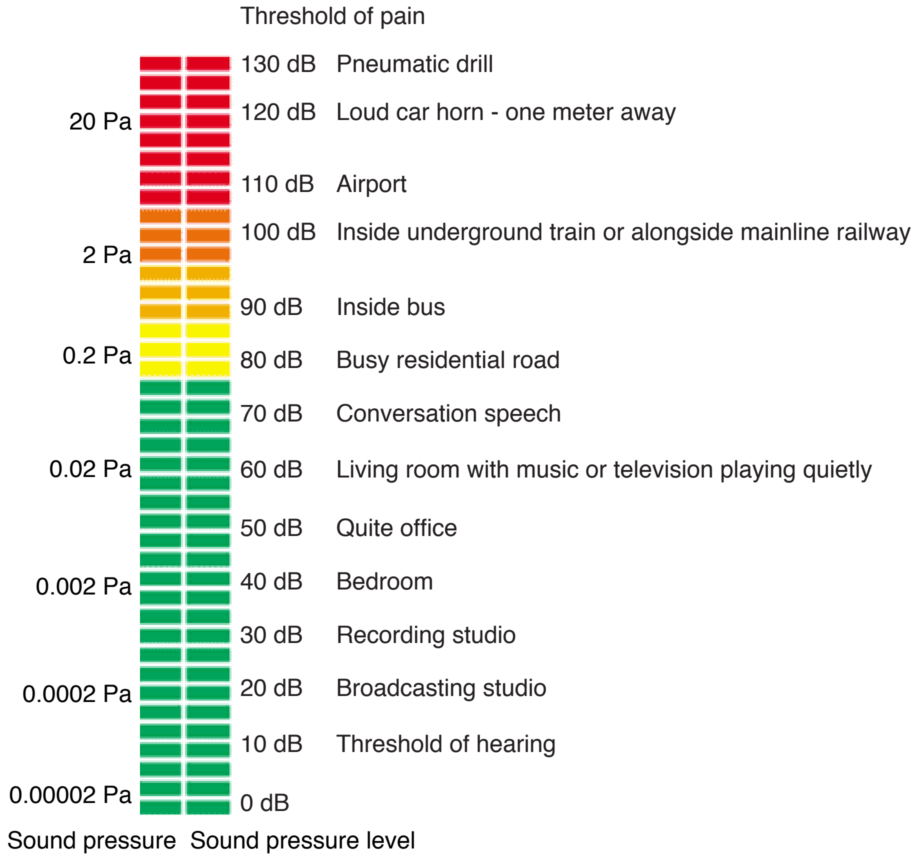


*Figure 2: Sound Pressure Levels (SPL). Source: Pro Audio Files*

Sound wave in presence of an obstacle will be absorbed, transmitted, and reflected, according to the material properties. For this reason, sound pressure level is influenced by the materials and the shape of the office. This index is strongly related to acoustic comfort perception, because to each sound pressure level corresponds a different perception and strength.
Total noise level is the sound pressure level of the overall noise. It results from the logarithmic sum of external noise (noise from road, airborne and railway) and internal noise (caused by equipment and premises) and other noise sources that occupants cannot control.
To evaluate external noise are used two indexes: the level of insulation provided by the facade ($D_{nT,A,Tr}$) and $L_{50}$ measured inside the room between 9.00 a.m. and 6.00 p.m. for 1 hour on a working day.
An appropriate sound insulation system can ensure acoustic comfort.
Equipment noise can be permanent, when the equipment is operating for a period greater than 50% of the usage time of the room, or intermittent, if the noise is not permanent. The latter is described by the maximum value of 1 s short $L_{Aeq}$ throughout measuring duration ($L_{max}$).
Another index useful to evaluate acoustic conditions in office space is reverberation time. It is the duration, in seconds, required for the sound level to fall by 60 dB when the noise source is instantaneously interrupted, in a specific room. Indoor environment with a source and reflective surface, generate a semi reverberant field (NF S31-080).

$$\tau_{60} = 0,163\ V/A\ [s] \tag{6}$$

As shown in Formula 6, reverberation time depends on volume and area of the space, thus geometry strongly influences acoustic conditions.
Another important index to evaluate acoustic comfort, especially in an open space, is spatial decay rate, that is slope in decibels of the spatial sound decay curve within a given distance range, when the distance from the source doubles.
Furthermore, in a multi-level building it is important to measure impact noise, caused by the impact between the floor and an object.

### 2.2.1 Standard framework

The main standards that regulate acoustic comfort are NF S31-080, EN 3382-3, ISO 22955 and EN 16798.
The first one is a French standard that specifies acoustic requirements according to different levels (standard, efficient, highly efficient) for different types of areas in office buildings.
EN 3382 is an international standard divided in three parts: performance spaces, reverberation time in ordinary rooms, and open plan offices. The third part specifies a measurement method, in which numerical results indicate acoustic performance of open space.
Standard ISO 22955 is a technical guidance to achieve acoustic quality of open spaces, more specifically this document is used for refitting projects, renovation or change/add activities.
Standard EN 16798 provides values to limit the sound pressure level due to mechanical equipment and to set sound insulation requirements for the noise from outside and adjacent rooms.

## 2.3 Visual comfort

Visual comfort is a subjective response to the quantity and quality of light within a space. Causes of visual discomfort can be not enough or too much light and significative changes in light levels or sharp contrast, because human eyes adapt to light levels.
The concept of visual comfort involves different themes, such as aesthetic and light quality, views of outside space, absence of glare, activities to be carried on without excessive effort.
Visual environment assessment requires the analysis of different factors:

- Sources of light (natural or electric)
- Distribution of light within the space (colour and intensity)
- Perception of visual comfort

From a physiological point of view, light has a direct effect on the regulation of circadian cycle, with impact on biological functions, such as sleep, mood, and alertness.

Lighting sources (sun or light bulb) emit propagating energy, of which a limited range of wavelengths, included between infrared and ultraviolet, is perceptible to the human eye as light. Human perception of light is determined by the amount of radiation energy that enters the eye.

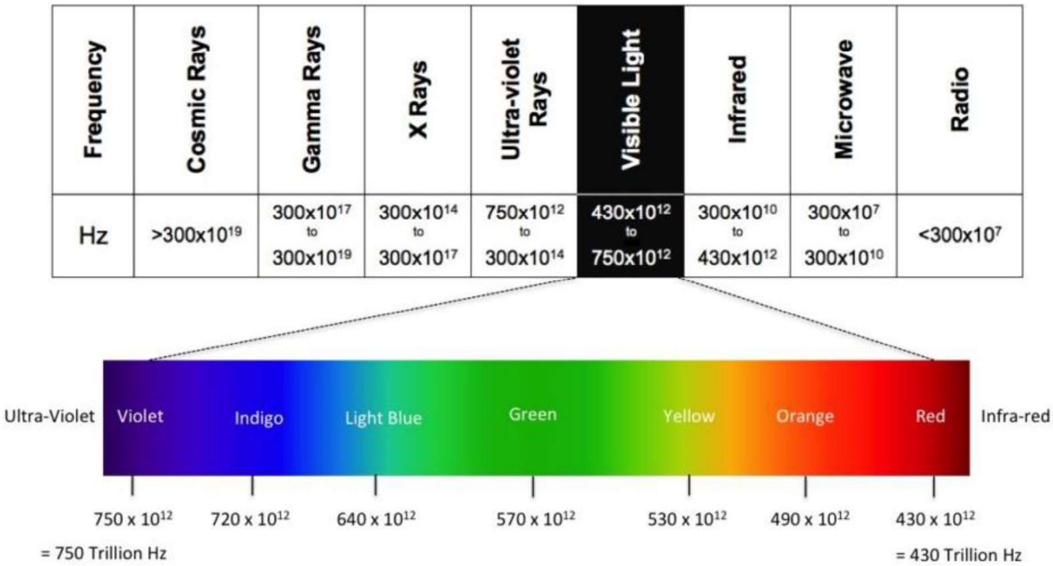


*Figure 3 visible light spectrum. Source: Simone M. Matthews - Universal Life Tools*

Illuminance is one of the photometric indexes. It permits to measure illuminance level on a work surface, with the aim to understand visual condition for a specific activity. It is the result of the ratio between the luminous flux on a surface and the surface itself.

If illuminance is not homogeneous on the surface the comfort will be not ensured, thus the other important index for visual comfort assessment is illuminance uniformity. Important variations of illuminance can cause annoyance.

Human eyes perceive the surfaces for their luminance, it is the luminous flux emitted or reflected from a lighting surface, thus the photometric measure of the luminous intensity per unit area of light in a given direction. Therefore, it represents how the surface of an object brights, for this reason relevant luminance differences can cause discomfort.

Moreover, glare is caused by an intensity of light in the visual field that is usually greater than the intensity of light that is adapted to the eyes. To assess the discomfort glare caused directly from the luminaires is evaluated

the unified glare rating index.
Correlated colour temperature (CCT) is the measure of light source colour appearance, defined by the proximity of the light source chromaticity coordinated to the blackbody locus, as a single number rather than the two required to specify a chromaticity.
Colour rendering index (Ra) provides information about the quality of the colour rendering of a light source.
In recent years, a great attention has been given to new indexes to evaluate natural lighting, moving toward dynamic daylighting metrics. U.S. Green Building Council codified two metrics indexes in LEED v4, also described in IES_LM-83-12: Spatial daylight autonomy ($sDA_{300,50\%}$) and Annual sunlight exposure (ASE). They describe daylight performance.
Spatial daylight autonomy defines the percentage of floor area that receives at least 300 lx for at least 50% of annual occupied hours.
The second one, Annual sunlight exposure is the percentage of an analysis area that exceeds a specified direct sunlight illuminance level more than a specified number of hours per year. In particular, $ASE_{1000,250h}$ is the percentage of an analysis area that exceeds illuminance level of 1000 lx for more than 250 hours per year.
Daylight glare probability represents the vertical illuminance at eye level, related to source luminance size and location, view direction and background luminance (Shen and Tzempelikos, 2014). It is the most recent index used to evaluate glare from daylight, resulted by experimental data in private office spaces involving human test subjects.
Knowing more about light and how to control it is important for its direct influence on health and well-being.

### 2.3.1 Standard framework

Standards that define visual comfort indexes are: EN 12464, EN 16798, EN 17037, IES_LM-83-12.
EN 12464 provides indexes for electric illuminance in workplaces, defining values to ensure lighting quality and quantity.
Illuminance level required by EN 16798 shall be obtained by daylighting (according to the daylight availability), electric lighting or a combination of

both (calculated only for the occupied hours).
EN 17037 defines indexes to reach, through natural lighting, proper visual level to carry on activities indoor, avoiding glare.
IES_LM-83-12 was created to describe dimensions of daylighting performance. It has the aim to define a consistent calculation methodology that would allow to compare in a consistent manner multiple design alternatives and climatic locations.

## 2.4 Indoor air quality

Indoor air quality became one of the comfort domains since the discovery of 20th century about illnesses related to not adequate indoor environmental conditions (Ong, 2013).
Indoor air quality is considered acceptable when there are no specific pollutants in harmful concentrations, according to the criteria established by the competent authorities, and at least 80% of the occupants express satisfaction with it.
Attention to IAQ has grown with time, and it is now recognized the relationship between bad air quality and people's health, well-being and work productivity. As previously mentioned, (see paragraph 1.1.3) the concept of Sick Building Syndrome (SBS) was introduced in the 1980s and the World Health Organization attributes great importance to this theme. Symptoms of SBS like eyes, nose, throat and skin irritation affect building occupants in relation to the time they spend indoor, causing a temporary ill-being and disappear when they leave the building.
Office buildings are exposed to elevated bio effluent levels related to high occupation densities and inadequate ventilation, pollutants emissions from buildings materials, furniture and equipment, contamination of AHUs by organisms/biological products that can cause illnesses like hypersensitivity pneumonitis or legionnaires' disease, exposure to resuspended surface dusts.
Therefore, air quality is strongly related to the presence of pollutants indoor and should be kept under control by means of source control, ventilation, filtration and/or air cleaning, as stated in standard EN 16798.

The main sources of pollutants in indoor environment are:

- Outdoor air
- People (during the respiratory process, carbon dioxide, water vapor and organic substances are introduced into the environment)
- Pets
- Plants
- Tobacco smoke
- Equipment
- Furnitures
- Building materials
- Cleaning products
- Cooling and ventilation building systems

Whereas the main air pollutants are:

- Carbon dioxide ($CO_2$)
- Carbon monoxide (CO)
- Formaldehyde
- Particulate matters ($PM_{2.5}$, $PM_{10}$)
- Volatile Organic Compounds (VOCs)
- ETS (tobacco smoke)
- $NO_x$
- $NO_2$
- $SO_x$
- Benzene
- Aromatic hydrocarbons

Carbon dioxide varies with the seasons that affect the frequency of aeration of the premises by opening the windows. Carbon monoxide, produced by incomplete combustion of carbon-containing materials, is colourless, odourless, tasteless and flammable. Formaldehyde is a colourless, flammable gas, found in buildings materials, insulating materials and finishings. $PM_{10}$ are defined as inhalable particles and have a diameter of less than 10 µm and their effects affect mainly the upper airways of the respiratory system. $PM_{2.5}$ are finer particles, with a diameter of less than 2.5 µm, they can reach the respiratory system inferior. VOCs are toxic by inhalation and exposition, with chronic or acute effects. In some conditions of temperature and relative

humidity, they are nutrients for moulds and bacteria, sources of MVOC (Microbial Volatile Organic Compounds) that contain micro toxins.
Another important dangerous gas for human health is radon. The danger is linked to dacay products of gas, which accumulate in respiratory ways, in bronchia and lungs. In buildings it is exhaled from underground and some materials. The concentration changes in function of building structure and that of soil. The risk is higher in low-rise buildings, closed to ground and with poor ventilation.

### 2.4.1 Standard framework

Standard EN 16798 provides design criteria for indoor air quality.
It recommends design ventilation air flow rates when designing any type of ventilation system (including mechanical, natural and hybrid ventilation systems), considering the pollutant emissions rates left after source control.
In the standard are defined three methods for the definition of design parameters for indoor air quality: the method based on perceived air quality; the method based on the use of limit values for substance concentration; the method based on predefined ventilation air flow rates.
Design ventilation air flow rates, design $CO_2$ concentrations and WHO Indoor Air Quality guidelines are present in this standard.

## 2.5 References

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# 3 Literature review

## *Indoor Environmental Quality in offices and its effect on office occupants' comfort, well-being and work productivity: A review*


### 3.1 Abstract

People spend about 90% of their time in closed spaces and indoor environmental conditions have effects on their comfort, well-being, health and work productivity. This literature review has the aim to understand more about Indoor Environmental Quality in office buildings and its effect on occupants' global comfort perception. Workplace comfort perception has in fact a great influence on work productivity. Standards define the minimum performance level for indoor conditions and do not consider the combined effect of IEQ factors, thus ensuring discomfort avoidance but do not guarantee well-being. To assess occupants' comfort, Post-Occupancy-Evaluation surveys were introduced in the 1960s which are based on questionnaire that collect occupants' individual responses about their satisfaction with indoor environmental conditions. Parameters for each IEQ domain were analysed and selected in this review, among the ones defined by the most recent Building Certification Programs and standards, with the aim to understand what indexes affect comfort perception and how to represent global comfort. Research is moving towards desk monitoring systems of IEQ factors which also collect occupants' feedbacks with the aim to best detect the reference values based on subjects' perception.

## 3.2 Keywords

Global comfort, Indoor Environmental Quality, offices, work performance

## 3.3 Introduction

Indoor Environmental Quality (IEQ) is a remarkably investigated topic in the recent literature due to the time that people spend indoors [1]. According to the European Commission assessment [2], people spend about 90% of their time in closed spaces, thus research focused on the influence of indoor conditions on occupants' comfort, well-being, health and work productivity [3] [4] [5] [6] [7].

IEQ involves thermal, acoustic and lighting conditions and Indoor Air Quality (IAQ), which are codified in many international standards. However, people's perception of comfort indoors can be also influenced by non-physical factors, which are not included in regulations [6] [8] [9] [10] [11], such as age, context of growth, gender. Recently, scholars have investigated this theme. Choi and Moon [5], Lou and Ou [6] demonstrated that office layout, non-IEQ factors, air quality, thermal, acoustic and lighting conditions, significantly affect occupants' comfort perception. Rasheed and Byrd [7] instead demonstrated that although the physical requirements are achieved, not all the occupants are satisfied.

In the 1960s Post-Occupancy Evaluation (POE) method was introduced to analyse user's comfort perception and satisfaction with indoor environmental conditions [12] [4]. Nevertheless, some researchers investigated the reliability of POE surveys [13], as example Rasheed and Byrd [7], in their review identified many bias which can modify survey results, such as experimenter expectancy, social desirability, novelty effect.

Frontczak et al. [14] investigated the relationship between occupants' satisfaction and environmental conditions, stating that POE is a widespread evaluation tool to assess occupants' comfort perception. Questionnaires and interviews are cheaper and easier ways to gather information, compared to other methods. Furthermore, benchmarks have been developed for the evaluation of building occupants' perception of indoor environment through the collection of datasets in POE projects [12], such as Building Occupants Survey System Australia (BOSSA), SPOES (Sustainable Post-Occupancy Evaluation Surveys).

The great importance of IEQ evaluation is demonstrated in the studies of Azuma et al. and of Parbati and Manisha, which focused on the sick building syndrome (SBS) symptoms, those symptoms of illness that affect building occupants in relation to the time they spend indoor. SBS symptoms, firstly defined in 1983 by the World Health Organization, can be various (among them ocular, respiratory and cutaneous) and are related to personal and environmental variables [15] [16].

Candido et al. demonstrated that occupants' well-being and work productivity can be supported by a correct office design.

Access to daylight, outdoor environment and nature should be guaranteed: the positive impact of biophilia on workers' satisfaction and well-being has been ascertained [17].

Standards do not concern these non-IEQ variables, but define IEQ indexes to assess air quality, thermal, acoustic and lighting conditions of the workspace. Norms such as EN 16798, EN 7730, ASHRAE 55, EN 12464-1, EN 3382-3, NF S31-080, EN 22955 establish threshold values of the main indexes which are used as guidelines by designers to achieve indoor habitability level.

Wei et al. review [18] detected the most important parameters for thermal comfort evaluation, which are room operating temperature, indoor air temperature, relative humidity of indoor air and air speed. Noise level and reverberation time are instead the most applied parameters for acoustic comfort, while for visual comfort the level of illuminance, daylight factor and spatial autonomy of daylight are usually assessed [18]. Ventilation speed (outdoor air feed rate), TVOC, formaldehyde, $CO_2$, CO, $PM_{10}$, $PM_{2.5}$, ozone, benzene and radon are the main parameters for indoor air quality.

The literature shows that researchers show a growing interest in Building Performance Certification Programs which give specific scores to the different comfort domains. As Wei et al. stated in their review, LEED sets 47% of credits for IAQ and 35% for lighting environment, whereas BREEAM, DGNB, ITACA, LiderA and NABERS assign to each domain similar credits: 25-33% for IAQ, 17-33% for thermal environment, 17-33% for lighting environment and 17-22% for acoustic environment [18]. On the other side, the WELL protocol, is organised in ten concepts that influence the quality of indoor environment. Nevertheless, recently also LEED and BREEAM have expanded their credit structure, considering social and economic well-being, safety and security. Figure 4 shows the weights given to the four comfort domains by the main Building Performance Certification Programs. Concerning the WELL protocol, the weight percentages for the four environmental factors were rescaled with respect to their original values since they represent only four out of seven aspects.

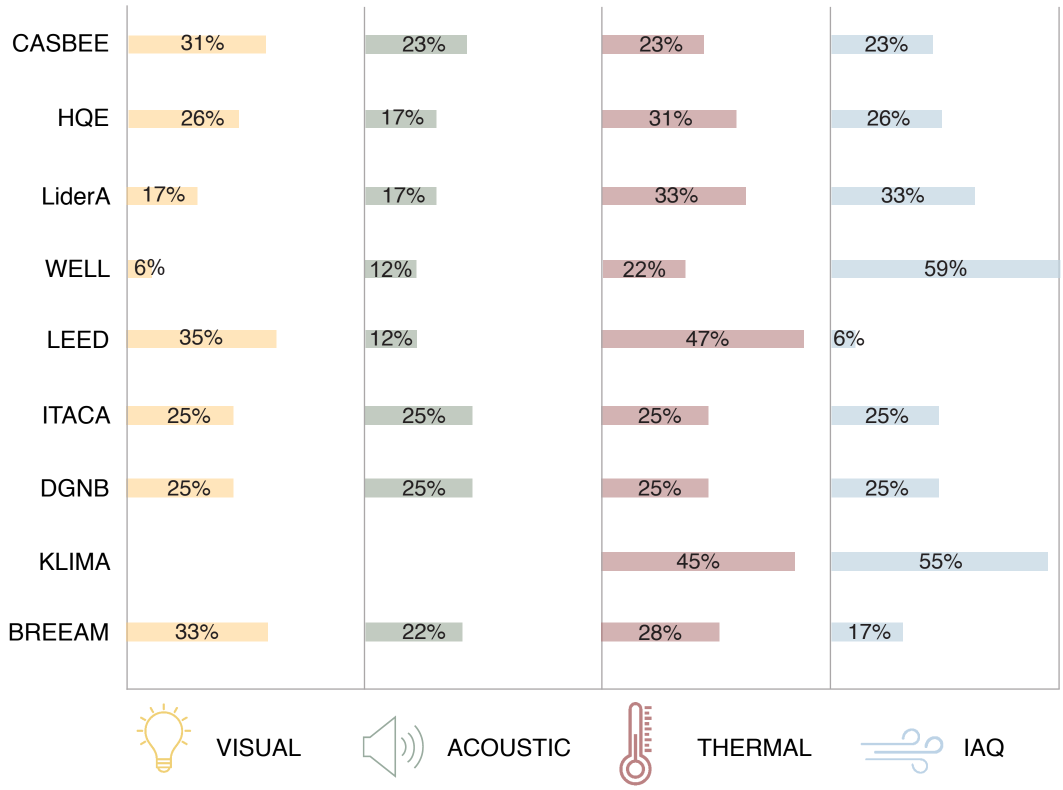


*Figure 4: weights given to the four comfort domains by the main Building Performance Certification Programs. Concerning the WELL program, the weight percentages for the four environmental factors were rescaled with respect to their original values, so that their sum is equal to 100%.*

Researchers analysed the relation between non-IEQ variables and occupants' comfort perception, identifying the factors that influence comfort of people in offices indoor environment, such as age, socio-economic status, season, climate and social-psychological factors [8]. The study by D'Oca et al. [9] highlighted that occupants' real or perceived control over their indoor environment affects their comfort perception, i.e. the possibility to have adaptive opportunities increases occupants' perceived comfort. Occupants' perception and behaviour have also a significant impact on building energy consumption [1] [19]. As stated by Sakellaris et al. [20], personal control on building systems allows reaching a comfortable and productive environment, reducing energy consumption in buildings.

Devices for monitoring and representing the indoor environmental factors have been developed to assess indoor environmental conditions [21]. A great number of studies have been carried out on the monitoring of single comfort domain and only a limited number investigated the combined effect of more than one aspect, due to the high cost of environmental measurements [23] [24]. As far as comfort representation is concerned, virtual reality is an adequate representation system of physical environments to study subjective perception of thermal comfort and consequently to set thermal conditions [27].

Thanks to devices for data collection of subjective responses it is also possible to forecast the comfort conditions [22]. Occupants' perception was analysed in the study of Lee et al., that developed an intelligent feedback request algorithm, thanks to the collection of responses through participatory interfaces designed to be effective but not intrusive [25]. Ascertained the correlation between comfort perception and environmental parameters, Antoniadou et al. developed a new Integrated Personalizes Comfort Model of Office Buildings (IPCMOB) index to quantify this relation [26].

Findings of this overview reveal that a considerable number of studies analyse IEQ factors, non-IEQ factors and their effects on occupants' global comfort. The literature suggests that the collection of occupants' feedback, combined with IEQ monitoring, enables to change environmental conditions and guarantee energy savings and occupants' well-being. In particular, the following paragraphs include the description of the research method applied for each objective, then the results related to the IEQ perception and assessment, the analysis of the main IEQ indexes and the other factors that affect comfort perception and the different ways to monitor and represent comfort.

### 3.3.1 Scope and research objectives

This literature review concerns studies that dealt with the indoor environmental factors and their effects on occupants' comfort, well-being, health and productivity in offices, considering the influence of personal and contextual variables.

Four research objectives, resumed in Table 6, have been identified to examine the aforementioned themes and answer to questions regarding IEQ, through the definition of keywords:

- How is IEQ perceived and evaluated?
- What are the main IEQ indexes?
- What are the main factors that influence the comfort perception?
- How is IEQ represented in space and time?

*Table 6: research objectives with related questions and keywords used for the research.*

| Objectives | Questions | Keywords |
| --- | --- | --- |
| Perception and assessment of IEQ | How is IEQ perceived and evaluated? | "Multidimensional comfort", "Overall comfort", "IEQ", "Discomfort", "Office" AND "Workplace", "Work environment", "Cross-modal effect", "Combined effect" |
| IEQ indexes | What are the main IEQ indexes? | "IEQ index", "IEQ parameter", "Office" AND "Work environment" |
| Factors which influence the IEQ perception | What are the main factors that influence the comfort perception? | "IEQ", "Indoor Environmental Quality", "Indoor environment", "Contextual variable", "Office" AND "Workplace", "Work environment", "Contextual factor", "Psychosocial factor", "Context" |

| | | |
|---|---|---|
| Representa-tion of global comfort | How is IEQ represented in sp ace and time? | “Combined comfort”, “Multidimensional comfort”, “Representation”, “Office” AND “Overall comfort”, “Global comfort”, “Workplace”, “Work environment”, “Visualization”, “Graphic” |

The first research question is on occupants’ comfort perception in their workspace and IEQ assessment tools. IEQ compliance (thermal, acoustic, lighting conditions and air quality) is verified by indexes that are simulated at the buildings design phase and verified through monitoring and with the post occupancy evaluation. IEQ indexes values which guarantee the minimum functional level of comfort in workplaces have been investigated with the second research question.

Global comfort perception is also influenced by other factors not related to the indoor environment, but which significantly affect occupants’ well-being and health. With the third question, the research focuses on studies conducted to analyse contextual and personal factors that influence occupants’ comfort perception.

The last objective of this research aims at investigating the literature state-of-the-art related to the representation of simultaneously monitored aspects of global comfort. Findings demonstrate that techniques have been already developed, but more effort shall be paid to the development of apps which monitor IEQ quantities and collect personal feedback on comfort perception.

## 3.4 Material and methods

The method applied in this review, portrayed in Figure 5, Figure 7, Figure 8 and Figure 9, followed the rules of the “Preferred Reporting Items for Systematic Reviews and Meta-Analyses” (PRISMA) [28]. The research, carried out with the Scopus search engine, has been focused on the four above mentioned objectives for which a total of 641, 106, 703, 179 papers have been selected, respectively. The selection of the main articles has been carried out with the criteria explained in the following section and brought to analyse 17, 6, 20 and 11 papers, respectively.

### 3.4.1 Selection process

The first step of the selection process has been the definition of keywords for each objective in order to start the articles research. These first choices were based on the contents acquired on the theme of IEQ, thanks to a general literature survey [23][14][1]. The first research did not yield enough results, thus an additional research was needed, with different keywords shown in Figure 5, Figure 7, Figure 8, Figure 9, to better understand the state of the art of the different issues.

For each objective, the inclusion criteria that allowed to refine the results were the following:

- Only articles and reviews;
- Only articles published in the last five years;
- Only articles written English.

Furthermore, articles concerning nursing and management were excluded, as well as the articles with abstracts not related to the IEQ theme. After the entire text reading other papers were excluded because their text was not in compliance with the research purpose.

## 3.5 How is IEQ perceived and evaluated in offices?

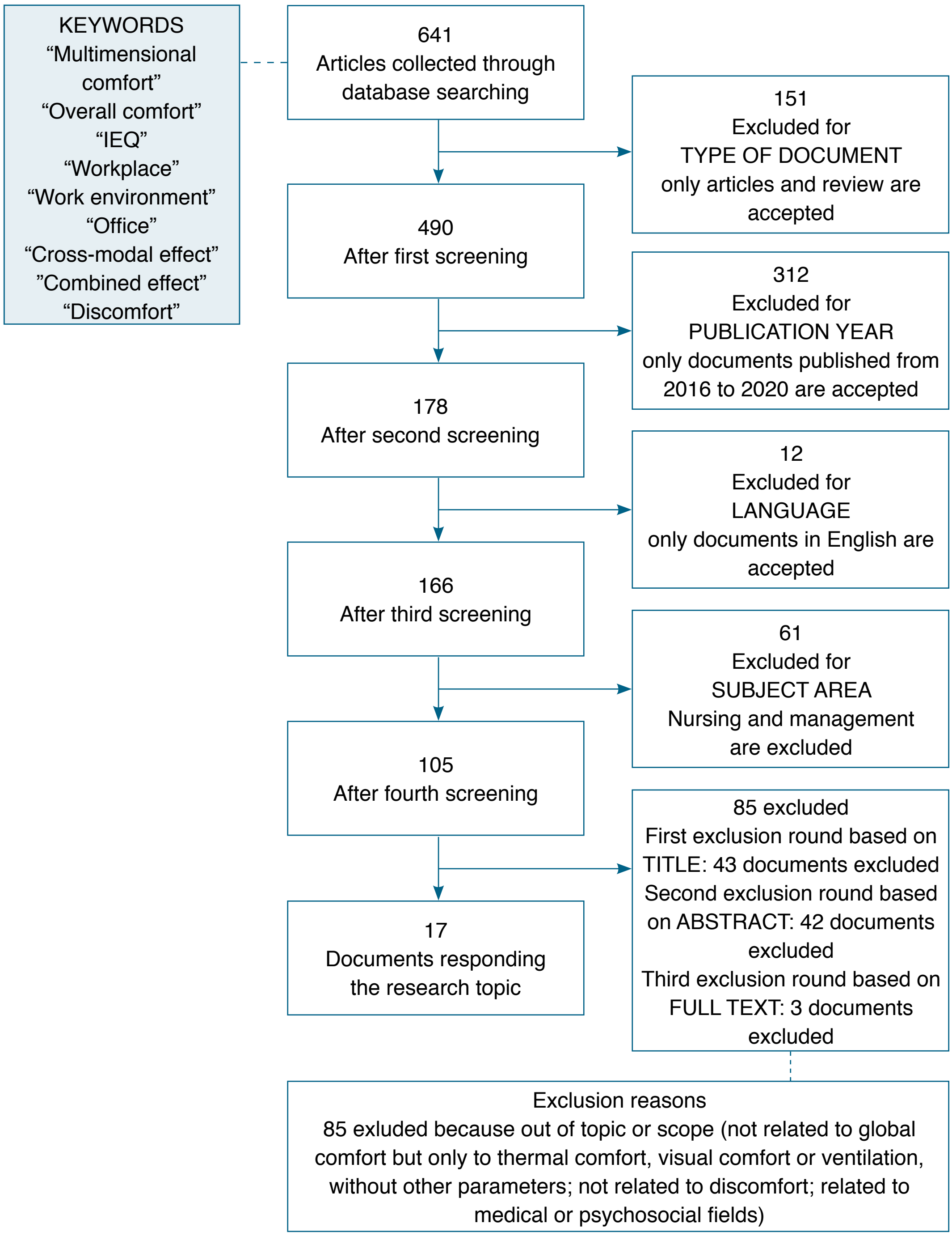


*Figure 5: flowchart of the selection process that has been followed to determine the articles deemed inherent and complying to the research question “How is IEQ perceived and evaluated in offices?”.*

Figure 5 shows the articles selection process (described in paragraph 0) followed for the first research objective. In open-plan offices IEQ conditions (thermal, lighting and acoustic environment and air quality) and non-IEQ factors affect occupants' comfort, health, behaviour and work performance [6][5].

### 3.5.1 Occupants' comfort perception of IEQ factors

Thermal environment is one of the most important factors associated with global comfort [29] [30]. Occupants' well-being and work productivity are negatively affected by non-adequate indoor temperature [5]. Lighting influences occupants' visual perception in relation to office tasks, hence standards recommend different illuminance levels. Natural lighting is preferred to artificial lighting and considerably influences occupants' psychological well-being [5]. A study carried out from 13 workplace buildings in Minnesota, between 2015 and 2017, demonstrated that occupants were more satisfied with the quantity of artificial lighting than its adjustability. In addition, occupants were more satisfied with lighting environment when sitting within 4.57 m of a window and when equipped with neutral colour artificial lighting [31].

Acoustic environment affects occupants' perception of comfort. Noise disturbance (traffic noise, machine noise and irrelevant speech noise) is a significative source of distraction and disorder in open-plan offices, affecting occupants' well-being and work productivity [5]. Candido et al. [32] demonstrated that workers' privacy and speech intelligibility are not adequately ensured in open-plan offices, causing productivity reduction. A survey conducted from December 2015 to March 2016 in University Open-plan Research Offices in China, highlighted that work productivity in UOROs is mainly affected by acoustic environment conditions, particularly by conversation noise [30].

Indoor air quality also significantly affects occupants' satisfaction with IEQ conditions, work productivity and well-being. Air freshness may injure occupants' wellness, affecting their mood, sensation of time course, of visual attentional capture and speed of information processing [5].

### 3.5.2 Post-Occupancy Evaluation (POE)

The Post-Occupancy Evaluation (POE) method has been introduced in the 1960s to evaluate occupants' perception of their indoor environment, well-being and satisfaction with IEQ. POE studies require different data (building properties, users' feedback and IEQ parameters) that are collected through interviews and on-site IEQ measurements [12][4].

As Bae et al. demonstrated with their 11-year-benchmark study, different typologies of POE surveys have been applied throughout the years. These surveys may be designed for a broader scope of investigation, or for a specific IEQ domain. The POE projects through which a great number of responses have been collected, enabled to develop large datasets and create IEQ benchmarks, with closed questions, to estimate building occupants' perception of indoor environment [12].

Developed benchmarks, summarized in Table 7, are the Center of the Built Environment (CBE), the Building Use Studies (BUS), the Work Environment Diagnosis Instrument (WODI) toolkit, developed by The Dutch Center for People and Buildings that is based on the percentages of satisfied respondents instead of the averaged scores. The CBE results demonstrated that respondents were mostly dissatisfied with acoustic quality followed by thermal comfort [12] while the WODI results demonstrated that indoor climate, lighting, and acoustics had the highest percentage of dissatisfaction, particularly personal control of temperature has been evaluated as the least satisfactory factor.

The Building Occupants Survey System Australia (BOSSA) benchmark was based on responses from occupants in 18 workplace buildings, and classified individual spaces as the most unsatisfactory factor, followed by noise distraction, privacy, and connection to outdoor environment. The SPOES (Sustainable Post-Occupancy Evaluation Surveys) benchmark, realized with building occupants mean scores collected in 11 years, showed that workers were satisfied with most of IEQ factors, and furthermore that adjustability of thermal conditions was the least satisfactory factor followed by the possibility to limit undesired sounds and to control overall privacy, and temperature [12].

The research by Kang et al. [33] done by the Center for Building Performance and Diagnostics (CPBD) at Carnegie Mellon University by means of the

National Environment Assessment Toolkit (NEAT), collected POE surveys in more than 1600 workstations in 64 buildings. The relationship between measured and perceived IAQ indexes, such as Carbon Monoxide (CO), Carbon Dioxide ($CO_2$), Total Volatile Organic Compounds (TVOC), and particulates ($PM_{2.5}$, $PM_{10}$), was evaluated. The concentration level of $CO_2$ is difficult to be detected by people, being it odourless and colourless, thus it can affect occupants' health, causing sick building syndrome.

Providing operable windows, dedicated exhaust, individual return air diffuser density and low-medium partition height, is able to ensure good indoor air quality [33].

The literature review of Rasheed and Byrd [7] showed that not all the occupants consider themselves satisfied, although physical conditions comply with regulations indications, because of their different cultures and past experiences that influenced their expectations. For this reason, a scientific indication of comfortable environment is still investigated. They anyway highlighted the insufficiency of self-evaluation tool, demonstrating that occupant's IEQ perception is affected by bias that can alter the research findings. The bias can be the hawthorn effect, the placebo effect, the experimenter expectancy effect, the social desirability, the novelty effect, the perceived productivity and the error related to singular questions.

Nevertheless, POE represents a widespread evaluation tool to assess occupants' satisfaction with indoor environment. In Figure 6 is summarized the process for IEQ assessment based on POE survey, including subjective responses on occupants' comfort perception and objective on-site measurements of IEQ parameters. The aim of this data collection is the improvement of indoor environmental conditions to increase users' satisfaction, obtain energy savings and reducing operational costs.

*Table 7: IEQ benchmarks for the assessment of occupants' perceived comfort, health and work productivity. Sources of data (number of buildings and of respondents) from which benchmarks have been developed and results obtained thanks to occupants' responses.*

| IEQ benchmark | Data source for benchmark creation | Occupants' responses results |
|---|---|---|
| Center of the Built Environment (CBE) | 215 buildings 34,169 respondents | Respondents were mostly dissatisfied with acoustic quality followed by thermal quality. |
| Work Environment Diagnosis Instrument (WODI) | 19 organizations ≥7000 respondents | Indoor climate, lighting, and acoustics had the highest percentage of dissatisfaction. |
| Building Occupants Survey System Australia (BOSSA) | 50 buildings | Workstation quality as the most unsatisfactory factor, followed by noise distraction, privacy, and connection to outdoor environment. |
| Sustainable Post-Occupancy Evaluation Surveys (SPOES) | 41 buildings 2836 respondents | Workers were satisfied with most of IEQ factors. Adjustability of thermal conditions was the least satisfactory factor followed by the possibility to limit undesired sounds and to control overall privacy, and temperature. |
| Building Use Studies (BUS) | Buildings compared to this benchmark continue to update it. | - |

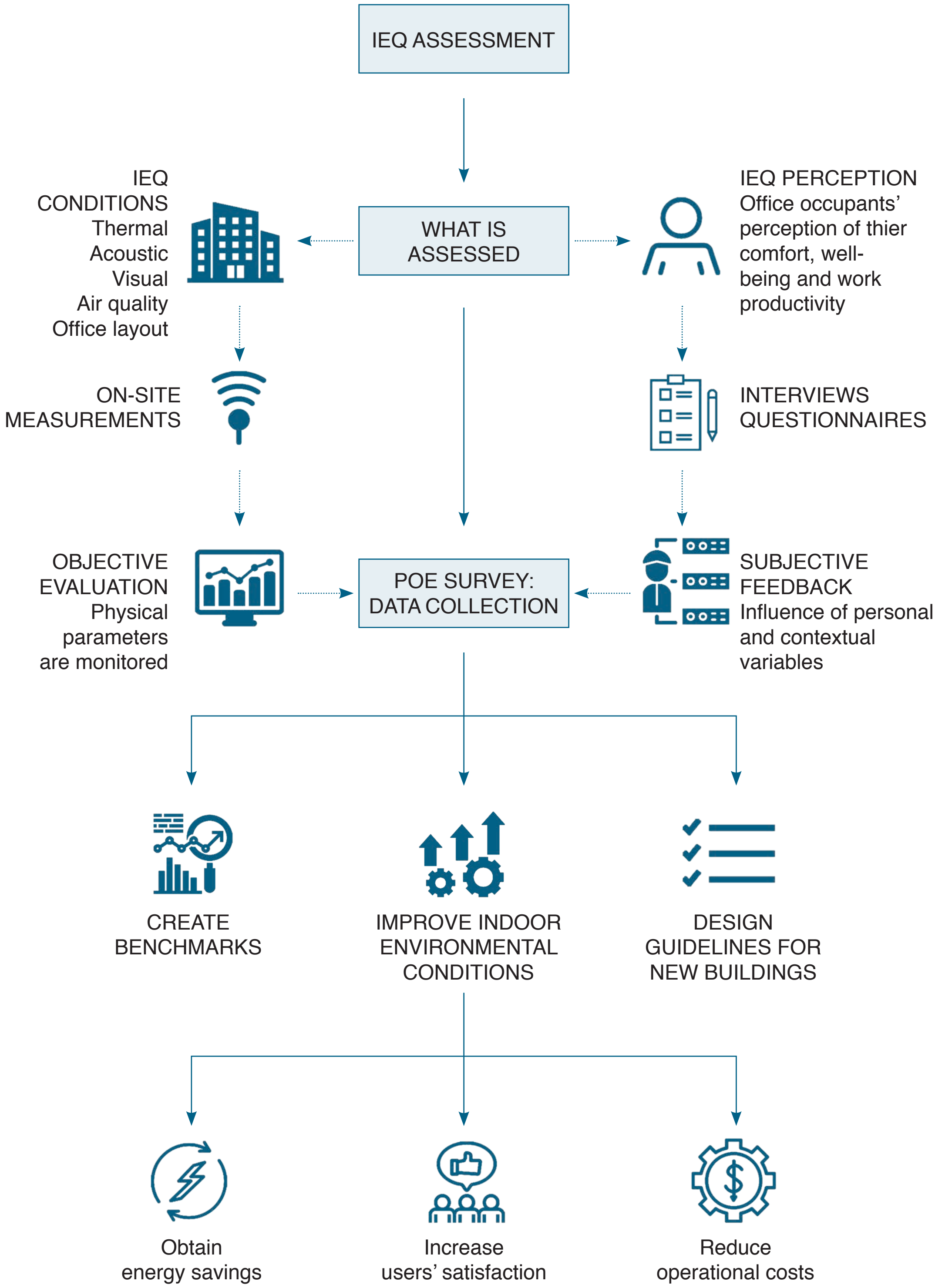


*Figure 6: process followed for IEQ assessment through objective measures and subjective responses with the post occupancy evaluation (POE). Outcomes of the process are highlighted.*

### 3.5.3 Design guidelines

Aware that offices interior design affects human health, researchers studied the relationship between IEQ and humans to find out design guidelines [17]. Candido et al. noticed that a workplace design regarding location of stairs, sit–stand desk use and attractive walking routes, that allows occupants to move repeatedly, favours their physical activity and musculoskeletal comfort. Activity-based working has been defined by Leesman's Team in 2017 as a business strategy that pursues occupant's comfort not forcing them to stay in a single desk location [34].

Furthermore, access to nature, daylight and outdoor environment should be ensured to reduce stress and improve positive mood and wellness of office workers. Their findings demonstrated that biophilia positively affects occupants' productivity and well-being [17].

In another study, Candido et al. stated that occupants' work productivity increases in open-plan offices endowed with areas subdivision based on the activities to be carried out, favouring a minimization of noise disturbance. Office aesthetic and maintenance and comfortable furnishings have positive influence on workers' satisfaction and comfort [32].

## 3.6 What are the main IEQ indexes?

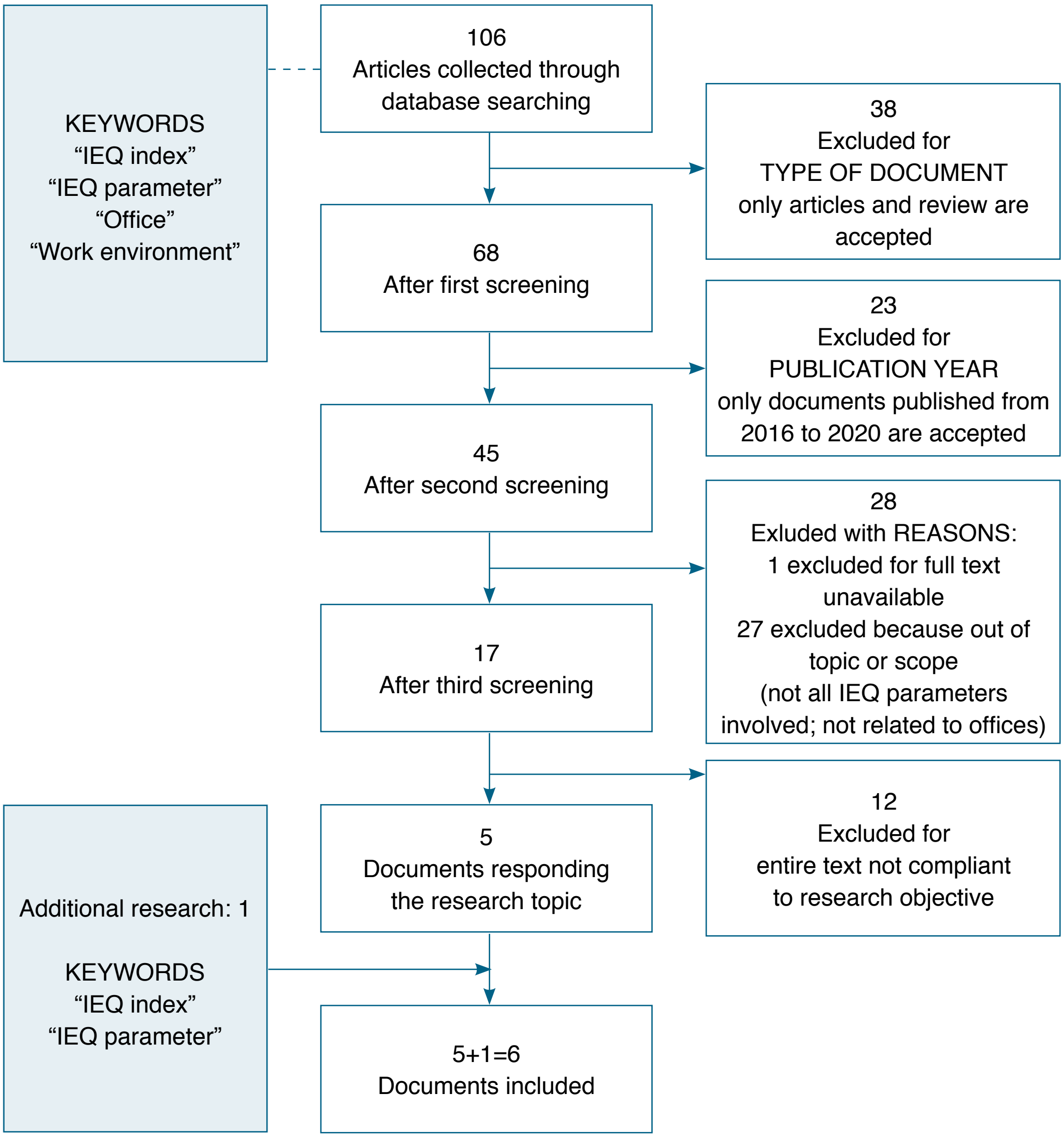


*Figure 7: flowchart of the selection process that has been followed to determine the articles deemed inherent and complying to the research question "What are the main IEQ indexes?".*

The research approach, shown in Figure 7, provided articles regarding IEQ indexes. IEQ indexes related to indoor air quality, thermal, lighting and acoustic environments are set and differently organised in Technical Standards and Building Performance Certification Programs for each IEQ domain.

Indoor air quality importance was originated from discoveries of twentieth century, that demonstrated its correlation with illnesses [35], thus IAQ indexes are defined by WHO guidelines. The other three comfort domains indexes, defined by Standards, derived from physics studies and WHO guidelines. For IAQ and thermal conditions, standards related to single IEQ aspect do not distinguish indexes values for office layout. Standard EN 12464 [36] for visual comfort is organised in tasks, because each activity requires a different level of lighting conditions, instead ISO 3382-3 [37] and NF S31-080 [38] for acoustic comfort provide values for different office types.

### 3.6.1 IEQ indexes in international Standards

Table 8 shows indexes which are fundamental for the assessment of indoor comfort conditions, selected from international Standards, WHO guidelines and Level(s) (the results of an European framework study for sustainable building [40]), divided for different office typologies. Three typologies of workplaces were identified: single office, shared office (from two to five people) and open space.

*Table 8: IEQ indexes and their thresholds defined by international standards.*

| Parameter | Single office | Shared office | Open space | Reference |
|---|---|---|---|---|
| THERMAL COMFORT | | | | |
| PPD* | | | | |
| Category I | PPD < 6% | PPD < 6% | PPD < 6% | |
| Category II | PPD < 10% | PPD < 10% | PPD < 10% | EN 15251 |
| Category III | PPD < 15% | PPD < 15% | PPD < 15% | |
| Category IV | PPD > 15% | PPD > 15% | PPD > 15% | |
| PMV* | | | | |
| Category I | -0.2<PMV<+0.2 | -0.2<PMV<+0.2 | -0.2<PMV<+0.2 | |
| Category II | -0.5<PMV<+0.5 | -0.5<PMV<+0.5 | -0.5<PMV<+0.5 | EN 15251 |
| Category III | -0.7<PMV<+0.7 | -0.7<PMV<+0.7 | -0.7<PMV<+0.7 | |
| Category IV | PMV<-0.7, +0.7<PMV | PMV<-0.7, +0.7<PMV | PMV<-0.7, +0.7<PMV | |
| $T_{op}$ in unoccupied hours | 16 < $T_{op}$ < 32°C | | 16 < $T_{op}$ < 32°C | EN 16798 |

| | | | | |
|---|---|---|---|---|
| $T_{op}$ | $20 < T_{op} < 26°C$ | | $20 < T_{op} < 26°C$ | EN 16798 |
| | Cooling season: 24.5 ± 1.0°C | | Cooling season: 24.5 ± 1.0°C | EN 7730 |
| | Heating season: 22.5 ± 1.0°C | | Heating season: 22.5 ± 1.0°C | EN 7730 |
| Relative humidity | 25 %< RH <60% | | 25 %< RH <60% | EN 16798 |
| Air velocity | Cooling season: < 0.1 m/s | | Cooling season: < 0.12 m/s | EN 7730 |
| | Heating season: < 0.16 m/s | | Heating season: < 0.19 m/s | EN 7730 |
| INDOOR AIR QUALITY | | | | |
| Ventilation rate | < 1 l/(s m²) | | < 0.8 l/(s m²) | N. Dodd et al. |
| Ventilation rate for $CO_2$ emission | 0.96 l/(s m²) | | 0.53 l/(s m²) | EN 16798 |
| $CO_2$ concentration (above outdoor) | < 500 ppm | | < 500 ppm | WHO guidelines value-EN 16798 |
| CO* | 15 min. mean: 100 mg/m³ | 15 min. mean: 100 mg/m³ | 15 min. mean: 100 mg/m³ | WHO guidelines value |
| | 1 h mean: 35 mg/m³ | 1 h mean: 35 mg/m³ | 1 h mean: 35 mg/m³ | |
| | 8 h mean: 10 mg/m³ | 8 h mean: 10 mg/m³ | 8 h mean: 10 mg/m³ | |
| | 24 h mean: 7 mg/m³ | 24 h mean: 7 mg/m³ | 24 h mean: 7 mg/m³ | |
| ACOUSTIC COMFORT | | | | |
| Total noise level | $L_{50}$≤55dB | $L_{50}$≤55dB | $L_{50}$≤55dB | NF S31-080 |
| | 35≤$L_{50}$<45 dB | 35≤$L_{50}$<45 dB | 40<$L_{50}$<45 dB | |
| | 30<$L_{50}$<35 dB | 30<$L_{50}$<35 dB | 40<$L_{50}$<45 dB | |
| | | | $L_{A,eq,T}$≤55dB | ISO 22955 |
| | | | $L_{p,A,S,4m}$≤48dB | ISO 3382-3 |
| - external noise | Standard level: $D_{nT,A,tr}$≥30 dB | Standard level: $D_{nT,A,tr}$≥30 dB | Standard level: $D_{nT,A,tr}$≥30 dB | NF S31-080 |
| | Efficient level: $D_{nT,A,tr}$≥30 dB $L_{50}$≤35dB | Efficient level: $D_{nT,A,tr}$≥30 dB $L_{50}$≤35dB | Efficient level: $D_{nT,A,tr}$≥30 dB $L_{50}$≤35dB | |
| | Highly efficient level: $D_{nT,A,tr}$≥30 dB $L_{50}$≤30dB | Highly efficient level: $D_{nT,A,tr}$≥30 dB $L_{50}$≤30dB | Highly efficient level: $D_{nT,A,tr}$≥30 dB $L_{50}$≤30dB | |
| -equipment noise | Standard level: $L_{Aeq}$≤45 dB | Standard level: $L_{Aeq}$≤45 dB | Standard level: $L_{Aeq}$≤45 dB | NF S31-080 |
| Reverberation | Standard level: / | Standard level: $T_r$≤0.6s | Standard level: $T_r$≤0.8s | NF S31-080 |
| | Efficient level: $T_r$≤0.7s | Efficient level: $T_r$≤0.6s | Efficient level: 0.6<$T_r$<0.8s | |
| | Highly efficient level: $T_r$≤0.6s | Highly efficient level: $T_r$≤0.5s | Highly efficient level: $T_r$≤0.6s | |
| | | | $T_r$≤0.8s | ISO 22955 |
| Impact noise | Standard level: $L'_{nTw}$≤62 dB | Standard level: $L'_{nTw}$≤62 dB | Standard level: $L'_{nTw}$≤62 dB | NF S31-080 |

| | | | | |
|---|---|---|---|---|
| | Efficient level: $L'_{nTw} \leq 60$ dB | Efficient level: $L'_{nTw} \leq 60$ dB | Efficient level: $L'_{nTw} \leq 60$ dB | NF S31-080 |
| | Highly efficient level: $L'_{nTw} \leq 58$ dB | Highly efficient level: $L'_{nTw} \leq 58$ dB | Highly efficient level: $L'_{nTw} \leq 58$ dB | |
| Insulation from internal airborne noise | Standard level: $D_{nT,A} \geq 35$ dB | Standard level: $D_{nT,A} \geq 35$ dB | Standard level: $D_{nT,A} \geq 30$ dB | NF S31-080 EN16798 |
| | Efficient level: $D_{nT,A} \geq 40$ dB | Efficient level: $D_{nT,A} \geq 40$ dB | Efficient level: $D_{nT,A} \geq 35$ dB | |
| | Highly efficient level: $D_{nT,A} \geq 45$ dB | Highly efficient level: $D_{nT,A} \geq 45$ dB | Highly efficient level: $D_{nT,A} \geq 40$ dB | |
| Spatial decay | | | 7dB | ISO 3382-3 |
| | | | Standard level: 2 dB If decay not applicable: $T_r \leq 1.2$s | NF S31-080 |
| | | | Efficient level: 3 dB If decay not applicable: $T_r \leq 1$ s | |
| | | | Highly efficient level: 4 dB If decay not applicable: $T_r \leq 0.8$ s | |
| | | | >6 dB | ISO 22955 |
| Distraction distance | | | 5 m | ISO 3382-3 |
| VISUAL COMFORT | | | | |
| Electric Lighting | | | | |
| Illuminance in working areas | 500 lx | | 500 lx | EN 16798 |
| Illuminance in working areas* | 300≤E≤3000 lx at desk height | 300≤E≤3000 at desk height | 300≤E≤3000 at desk height | N. Dodd et al. |
| Illuminance on the task area* | | | | EN 12464 |
| T1 | 300 lx | 300 lx | 300 lx | |
| T2 | 500 lx | 500 lx | 500 lx | |
| T3 | 750 lx | 750 lx | 750 lx | |
| T4 | - | 300 lx | 300 lx | |
| T5 | 200 lx | 200 lx | 200 lx | |
| T6 | 500 lx | 500 lx | - | |
| Unified Glare Rating* | | | | EN 12464 |
| T1 | UGR ≤ 19 | UGR ≤ 19 | UGR ≤ 19 | |
| T2 | UGR ≤ 19 | UGR ≤ 19 | UGR ≤ 19 | |
| T3 | UGR ≤ 16 | UGR ≤ 16 | UGR ≤ 16 | |
| T4 | - | UGR ≤ 22 | UGR ≤ 22 | |
| T5 | UGR ≤ 35 | UGR ≤ 35 | UGR ≤ 35 | |
| T6 | UGR ≤ 19 | UGR ≤ 19 | - | |
| Illuminance Uniformity* | | | | EN 12464 |
| T1 | U ≥ 0.4 | U ≥ 0.4 | U ≥ 0.4 | |

| | | | | |
|---|---|---|---|---|
| T2 | U ≥ 0.6 | U ≥ 0.6 | U ≥ 0.6 | EN 12464 |
| T3 | U ≥ 0.7 | U ≥ 0.7 | U ≥ 0.7 | |
| T4 | - | U ≥ 0.6 | U ≥ 0.6 | |
| T5 | U ≥ 0.4 | U ≥ 0.4 | U ≥ 0.4 | |
| T6 | U ≥ 0.6 | U ≥ 0.6 | - | |
| Colour rendering index* | | | | EN 12464 |
| T1 | CRI ≥ 80 | CRI ≥ 80 | CRI ≥ 80 | |
| T2 | CRI ≥ 80 | CRI ≥ 80 | CRI ≥ 80 | |
| T3 | CRI ≥ 80 | CRI ≥ 80 | CRI ≥ 80 | |
| T4 | - | CRI ≥ 80 | CRI ≥ 80 | |
| T5 | CRI ≥ 80 | CRI ≥ 80 | CRI ≥ 80 | |
| T6 | CRI ≥ 80 | CRI ≥ 80 | - | |
| Natural lighting | | | | |
| Daylight factor | DF > 2% | DF > 2% | DF > 2% | EN 17037 |
| Vertical facades daylight factor* | $DC_{a,j} \geq 6$ % | $DC_{a,j} \geq 6$ % | $DC_{a,j} \geq 6$ % | EN 16798 |
| | 6 %>$DC_{a,j}$≥4 % | 6 %>$DC_{a,j}$≥4 % | 6 %>$DC_{a,j}$≥4 % | |
| | 4 %>$DC_{a,j}$≥2 % | 4 %>$DC_{a,j}$≥2 % | 4 %>$DC_{a,j}$≥2 % | |
| | $DC_{a,j} < 2$ % | $DC_{a,j} < 2$ % | $DC_{a,j} < 2$ % | |
| | $DC_{a,j} \geq 2$ % | $DC_{a,j} \geq 2$ % | $DC_{a,j} \geq 2$ % | N. Dodd et al. |
| Spatial daylight autonomy* | | | | IES_LM-83-12 |
| Nominally accepted | sDA > 55% | sDA > 55% | sDA > 55% | |
| Preferred | sDA > 75% | sDA > 75% | sDA > 75% | |
| Annual sunlight exposure* | | | | IES_LM-83-12 |
| Nominally accepted | ASE < 7% | ASE < 7% | ASE < 7% | |
| Clearly acceptable | ASE < 3% | ASE < 3% | ASE < 3% | |
| Daylight glare probability* | | | | EN 17037 |
| Daylight glare mostly not perceived* | DGP≤0.35 | DGP≤0.35 | DGP≤0.35 | |
| Daylight glare perceived not disturbing* | 0.35<DGP≤0.4 | 0.35<DGP≤0.4 | 0.35<DGP≤0.4 | |
| Daylight glare often disturbing* | 0.4<DGP≤0.45 | 0.4<DGP≤0.45 | 0.4<DGP≤0.45 | |
| Daylight glare intolerable* | DGP≥0.45 | DGP≥0.45 | DGP≥0.45 | |

** Parameters specified for the different office typologies by authors and not by standards indications.*

*T1 Filing, copying, etc.*
*T2 Writing, typing, reading, data processing, CAD workstations.*
*T3 Technical drawing.*
*T4 Conference and meeting rooms.*
*T5 Reception desk.*
*T6 Archives.*

The indexes monitored for thermal comfort assessment are Predicted Percentage Dissatisfied, Predicted Mean Vote, room operating temperature, relative humidity and air velocity, whereas ventilation rate, ventilation rate for $CO_2$ emission, $CO_2$ and CO concentration are defined by IAQ regulations. Noise levels, reverberation time, insulation, spatial decay and distraction distance are the indexes evaluated for acoustic environmental quality. For visual comfort is necessary to differentiate between electric lighting and natural lighting: levels of illuminance, unified glare rating, illuminance uniformity and colour rendering index are assessed for electric lighting, whereas, daylight factor and dynamic indexes as spatial daylight autonomy, annual sunlight exposure, daylight glare probability are used to evaluate natural lighting.

### 3.6.2 Relation between IEQ indexes and occupants' comfort and well-being

Wei et al. [18], in their review, analysed fourteen Green Building certification schemes and highlighted the parameters used to evaluate IEQ. Findings of the research showed ninety parameters, grouped in thermal, acoustic, visual and air quality, with different weight. Thermal and air quality domains had a greater weight on the IEQ (27% and 34% respectively) followed by acoustic and visual (17% and 22% respectively). Wei et al. highlighted that greater comfort leads to a better state of well-being and health, with economic consequences and a significant increase in productivity in offices. Frontczak and Wargocki, analysed the connection between well-being, health and indoor conditions. Findings showed different factors, related to comfort, that may cause stress: reflections, luminance ratios, odours, humidity, mold, particulate matter, noise and vibration [43]. The research of Bluyssen instead showed a discrepancy between the requirements proposed by the current Standards and the perceived occupants' comfort. The review includes research of the last twenty years, demonstrating attention paid to the quality of indoor space. The assumption of the research is that regulation of physical aspects is not sufficient [11], due to the fact that standards are focused on single aspects of comfort, without considering that users are exposed to these stimuli simultaneously [43].

## 3.7 What are the main factors that influence the comfort perception?

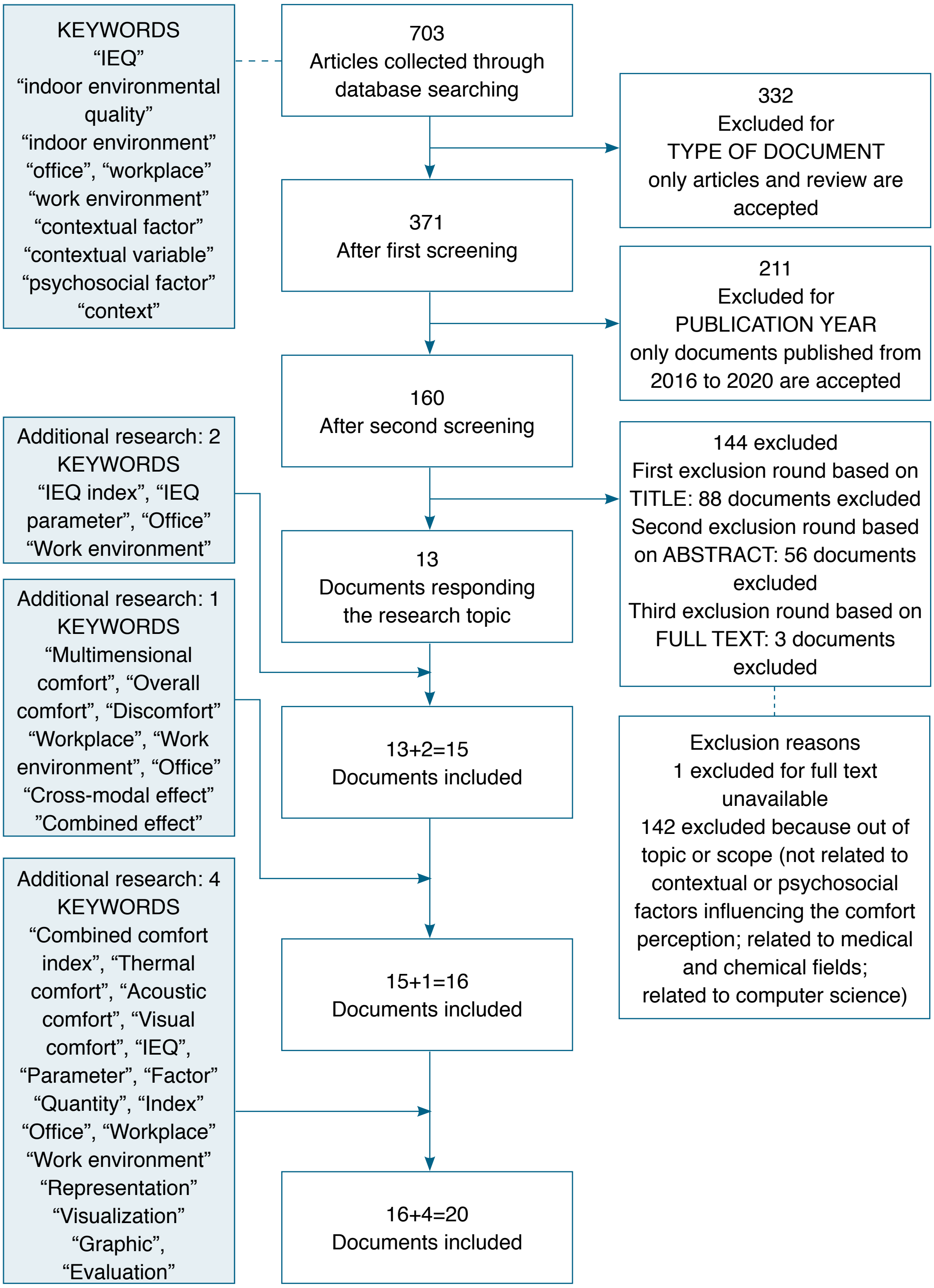


*Figure 8: flowchart of the selection process that has been followed to determine the articles deemed inherent and complying to the research question “What are the main factors that influence the comfort perception?”.*

Figure 8 shows the selection process of the articles in answer to the third research question "What are the main factors that influence the comfort perception?". Findings show the presence of other variables able to influence comfort perception: contextual and personal.

### 3.7.1 Contextual and personal variables

Global comfort in workplaces is influenced by contextual variables, with effect on health, well-being and work productivity, organized by authors in Table 9 in five main categories: "Building characteristics", "Office characteristics", "Work characteristics", "Occupants' control on building systems and environment" and "Environmental characteristics". Occupants' global comfort is affected also by personal variables, grouped in five main categories presented in Table 10: "Physiological", "Location", where with the subcategory "Context of growth" is meant birthplace, country related customs and traditions, "Psychological", "Social status", "Work related variables".

*Table 9: main contextual variables that influence occupants' comfort and well-being in workplaces.*

| **Contextual variables** | | | |
|---|---|---|---|
| Category | Variable | Affected comfort and well-being aspects | Reference |
| Building characteristics | Building typology | Thermal comfort | [8] |
| | Building orientation | Thermal comfort; visual comfort * | [39] |
| | External view | Well-being* | [39] |
| Office characteristics | Office type | Thermal comfort, visual comfort, acoustic comfort, air quality* | [40] [30] [41] |

| | | | |
|---|---|---|---|
| Office characteristics | Office layout | Thermal comfort, visual comfort, acoustic comfort, air quality* | [42] |
| | Workspace location | Thermal comfort, visual comfort, acoustic comfort, air quality* | [39] [6] [30] |
| | Workstation | Visual comfort, thermal comfort | [6] |
| | Amount of space | Well-being* | [43] [44] |
| | Access to daylight | Visual comfort; well-being* | [42] |
| | Proximity from a window | Thermal comfort, visual comfort, acoustic comfort, air quality* | [39] |
| | Ventilation mode | Thermal comfort | [8] |
| | Visual privacy | Well-being* | [43] [44] |
| Work characteristics | Lack of privacy | Well-being* | [30] |
| | Work task | Thermal comfort, visual comfort, acoustic comfort, air quality* | [30] |
| | Occupancy hours | Thermal comfort, visual comfort, acoustic comfort, air quality* | [41] |
| | Building automation | Thermal comfort, visual comfort, acoustic comfort, air quality* | [42] |
| | Ease of use and knowledge of how to operate | Well-being* | [9] |
| | Operable windows | Well-being* | [9] |
| | Blinds and shades | Visual comfort; thermal comfort * | [9] |

| | | | |
|---|---|---|---|
| Occupants' control on building systems and environment | Glare control | Visual comfort; thermal comfort * | [45] |
| | Noise management | Acoustic comfort * | [45] |
| | Adjustable thermostats | Thermal comfort * | [9] |
| | Artificial lighting | Visual comfort * | [9] [41] |
| | Number of people access to IECs | Well-being* | [41] |
| | Level of IEC accessibility | Well-being* | [41] |
| Environment characteristics | Climate | Thermal comfort | [9] [8] |
| | Season | Thermal comfort | [8] |
| * *Variable mentioned in the articles, but comfort domain specified by the authors.* | | | |

*Table 10: main personal variables that influence occupants' comfort and well-being in workplaces.*

| **Personal variables** | | | |
|---|---|---|---|
| Category | Variable | Affected comfort and well-being aspects | Reference |
| Physiological | Age | Thermal comfort, visual comfort, acoustic comfort, air quality* | [46] [40] [9] [10] [8] [6] [39] [41] |
| | Gender | Thermal comfort * | [6] [10] [8] [6] [34][39] [41] [9] |
| | Weight | Thermal comfort | [10] |
| | Body composition | Thermal comfort | [8] |
| | Visual acuity | Visual comfort | [47] |
| Location | Context of growth | Thermal comfort * | [30] |
| Location | Country of residence | Thermal comfort * | [41] |

| | | | |
|---|---|---|---|
| Psychological | Preference towards natural lighting | Visual comfort | [47] |
| | Preference towards thermal environment | Thermal comfort | [8] |
| | Attitude towards thermal environment | Thermal comfort | [8] [41] |
| | Expectations towards thermal environment | Thermal comfort | [8] |
| | Interaction with others | Well-being* | [41] |
| Social status | Social conditions | Well-being* | [8] [41] |
| | Economic conditions | Well-being* | [8] |
| | Personal culture | Well-being* | [41] |
| | Lifestyle | Well-being* | [10] |
| Work-related variables | Tenure (number of years in the workplace building) | Thermal comfort, visual comfort, acoustic comfort, air quality* | [10] [41] |
| | Hours per week spent in the workplace | Thermal comfort, visual comfort, acoustic comfort, air quality* | [10] |
| | Work position | Thermal comfort, visual comfort, acoustic comfort, air quality* | [41] |

* *Variable mentioned in the articles, but comfort domain specified by the authors.*

Kang et al. identified the individual factors, such as age, gender, birthplace, seat position and work activity that influence occupants' perception of IEQ. Sensitivity to artificial lighting, natural lighting and office noise depend on

age, while sensitivity to ventilation and temperature changes in relationship to gender [30].
Results from the study of Zhang and de Dear revealed a difference in thermal comfort perception related to the gender. The same thermal environment is perceived colder by females than by males and thermal sensitivity is higher in females. Humidity sensibility and air movement are no differently perceived in relation to the sexes. Furthermore, under the same thermal environment, occupants have lower thermal sensation during winter in all the contexts. Considered the same internal thermal conditions, those who are in warmer climates tend to be colder than those in harsh climates, in all the contexts. The ability to adapt to climatic conditions is more accentuated in females than in males [8].
The study of Bae et al. endorses the aforementioned findings. Results show that males tend to be more satisfied with thermal, acoustic, electric lighting and privacy conditions than females. Another factor that influences IEQ perception is age: younger (18-34 years) and older (+55 years) groups are more fulfil with IEQ conditions than middle-aged group (35-54 years). Those who have worked in the same workplace for less than 2 years and that work less than 20 hours per week are more satisfied with IEQ factors, in particular acoustic quality, cleanliness, maintenance and privacy [10].
Inadequate environmental conditions equally affect health, with effects summarized in Table 11, although they are perceived by occupants differently in relation to personal variables.

*Table 11: personal variables that affect comfort perception and cause discomfort with effects on health.*

| Personal variables | Comfort aspect | Effects on health |
|---|---|---|
| Gender<br>Age<br>Body composition<br>Context of growth<br>Socio-economic factors<br>Psychological factors<br>Work type<br>Control | Thermal conditions | Itchy, watery eyes, headaches, throat irritation, feeling of fatigue, respiratory symptoms [45] [46] |
| | Indoor air quality | Headaches, eyes, skin, nose, and throat irritation, asthma, allergies, bronchitis, and chronic obstructive pulmonary disease, cancer, fatigue [45] [46] [16] |
| | Acoustic conditions | Headaches, vocal fatigue, hoarseness, dry throat, higher systolic and diastolic blood pressure, changes in heart rate, hypertension, fatigue [45] [46] |
| | Visual conditions | Changes in circadian rhythms, decrease of immune functions, alertness, headaches, diabetes, heart disease, hormonal problems, fatigue [45] [16] |

The study conducted by Choi and Moon demonstrated once again the relationship between non-IEQ factors and occupants' comfort. Findings of this study proved that the "Senior" group preferred lower work surface illuminance level and lower air velocity, compared to "Mid-Age" and "Junior groups", confirming the previous assumption related to the influence of age on comfort perception. Furthermore, workstation plays a key role in occupants' satisfaction: those who sat in perimeter areas were more satisfied with higher reading zone illuminance levels and air velocity than occupants in the centre area [6].

### 3.7.2 Occupants' control on building systems and consequences on energy consumption

Further focus is dedicated to accessibility to IECs, that defines the real control that occupants have on building systems [46]. Many researchers investigated the relationship between subjects' perceived or real control over their indoor environment and their comfort and overall satisfaction.

Occupants that perceive a higher control on the indoor environment were up to 85% more satisfied than the ones who perceived a lower control [9].

Furthermore, occupants' comfort was increased by the chance to have adaptive opportunities and they appreciated digital control technologies, although a reduced automation of building systems was preferred, and did not appreciate voice-based controls [47]. On the other hand, people with different backgrounds and past experiences have different expectation towards their office indoor environment. Their actions done to reach their comfort level, through the adaptation of indoor conditions thanks to the control on building systems, may increase energy consumption [48] [49].

Therefore, energy consumption can be reduced providing comfortable conditions in workplaces.

The study of Zhang and de Dear [8] highlighted that the analysis of the influence of these non-physical factors on workers' comfort allows to understand the relation between occupants and indoor environment, encourages the search of an optimal design that guarantees comfort and well-being, and aims at reducing energy consumption.

## 3.8 How is IEQ represented in space and time?

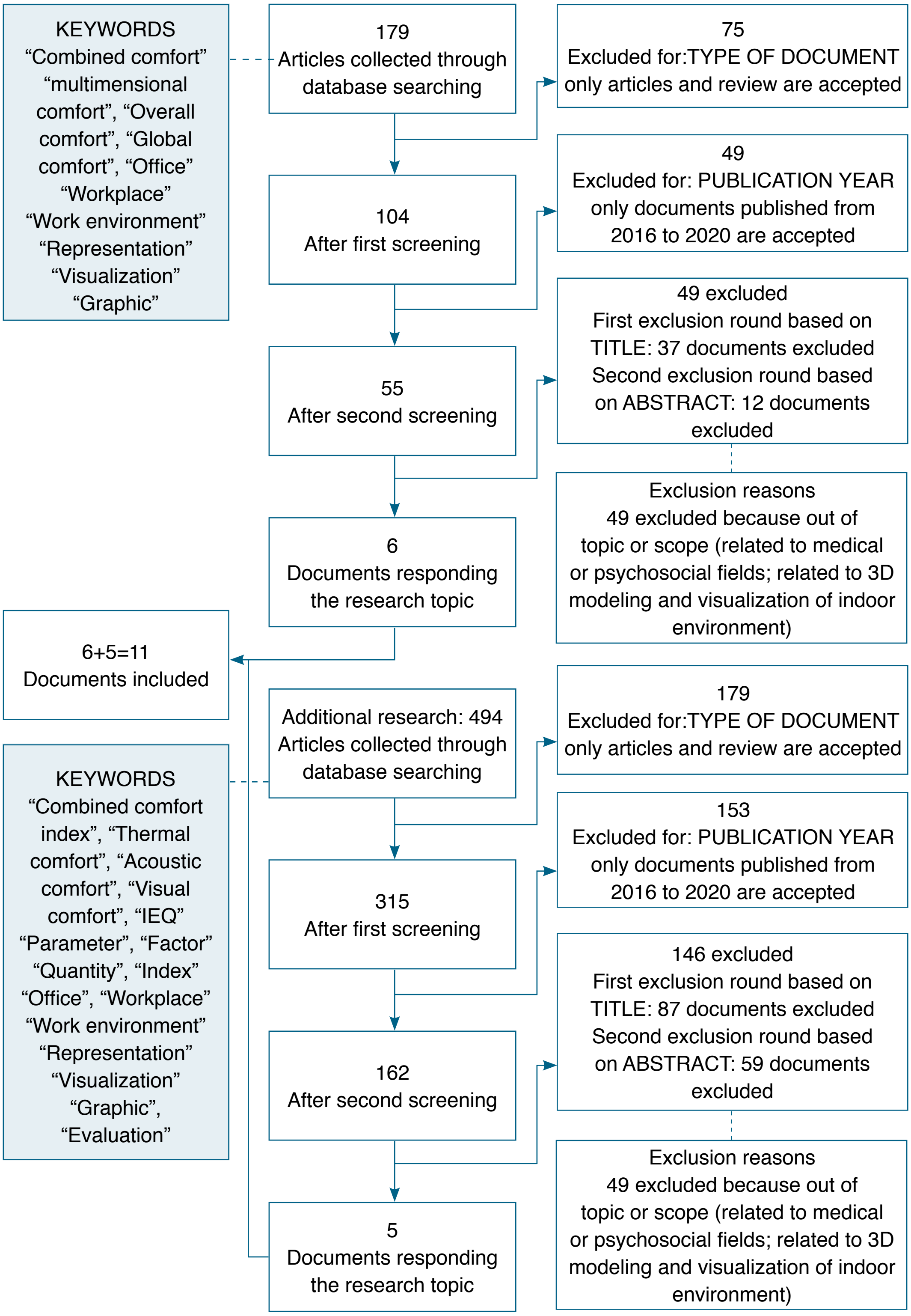


*Figure 9: the flowchart describes the selection process that has been followed to determine the articles deemed inherent and complying to the research question “How is IEQ represented in space and time?”.*

Figure 9 shows the selection process of articles inherent to the fourth research question "How is IEQ represented in space and time?".

In recent years, studies focused on indoor comfort, attempting to develop strategies to evaluate comfort and to set up building systems. Studies of concretely developed tools are summarized in  Table 12. The literature shows that the majority of the analyses are static, like the model proposed by ASHRAE [22]. Merabet et al. reported that the static analysis of parameters does not permit to assess occupants' comfort perception. Their main purpose was to measure comfort through a network of wireless sensors. Thanks to this prototype it is possible to forecast users' comfort and perception of the environment, considering human factors (age, gender, body mass index) along with environmental variables. This model allows the development of systems able to dynamically change indoor environmental conditions, adapting them to the user preferences [22].

Parkinson et al. measured simultaneously the parameters of environmental quality in real time with SAMBA, a continuous monitoring system. It combines a set of hardware with sensors integrated and software platform that allows to analyse and visualize data related to the IEQ performance, even by non-scientists. SAMBA will be able to provide the world's largest research database of building IEQ performance, which will be a resource for benchmarking the performance of individual buildings.

### 3.8.1 Thermal comfort evaluation and representation

Results of the analyses of the last five years show that great attention has been given to thermal comfort. In their study Lee et al assumed the concept that thermal comfort is a mental condition and the only way to measure it is to investigate occupants' reliable responses regarding thermal environment satisfaction. An effective data collection method requires time, continuity and the ability to update data over time, thus it is invasive, but the reduction of its frequency or the use of based on voluntary employee participation questionnaires would be untrusted [25].

A large number of studies investigated methods for the collection of occupants' feedback, in order to set up and update models, which require a great amount of data. The gathering of responses, through participatory

interfaces, led to the development of an intelligent feedback request algorithm, to capture the user's thermal preferences. Data are collected from voluntary feedback and requested feedback, with the aim of limiting to when strictly necessary the feedback requested and relying mainly on participatory feedback. It is therefore an effective but less intrusive tool [25].
The literature provides an example of a participatory method for collecting and analysing users' assessments, combined with simultaneous temperature measurements, with spatial resolution at room level. TrojanSense was developed by Konis et al. with the aim to improve comfort conditions and energy performance of buildings. The system can be used to increase the accuracy of thermal preference predictions and provide data on the perception of thermal comfort over time [50].
Erickson and Cerpa created a gather of thermal comfort perception data in an university building, thus modified thermal conditions according to occupants' feedbacks and reported the results of 100% of occupants satisfied and an energy saving of 0.01% in 5 months [21].
The study of Li et al. analysed post-occupancy assessments and constant measurements of thermal conditions in four air-conditioned office buildings in Sydney, Australia. Results show that thermal comfort, considered a long period, is influenced by pronounced temperature variations and significant changes in daily temperature. This study underlines that continuous monitoring is needed for the evaluation of thermal comfort [51].
Antoniadou et al. developed a new Integrated Personalizes Comfort Model of Office Buildings (IPCMOB) index, to define a personalized comfort approach in offices. The IPCMOB involves three different aspects: the characteristics of the building, the environmental conditions and users' behaviour [26]. Although they are based on thermal comfort analysis, these studies demonstrate the importance of collecting occupants' feedback and creating models.

*Table 12: tools developed by researchers for IEQ monitoring and for the development of interfaces to collect users' feedback regarding their comfort perception.*

| Authorship | Study | Results | Reference |
|---|---|---|---|
| Merabet GH et al. (2020) | Development of a prototype consisting of a network of wireless sensors to measure comfort, and of a model for thermal comfort prediction. | With this model predictions were reached in 33 of 41 data entries. In 80.49% of the points the model is accurate. | [22] |
| Larsen TS et al. (2020) | Development of IEQ-Compass to holistically evaluate IEQ, measuring 16 parameters. With "IEQ Design Compass" it is possible to communicate results and identify IEQ problems. | Results are presented with two different levels of detail in relation to two different groups of users: professionals or a wider audience, which includes building users. | [41] |
| Lee S et al. (2020) | Development of an intelligent occupant feedback request algorithm to obtain comfort-related responses and creation of a participatory user interface. | The user interface receives occupants' thermal preference responses when they want to send them and asks for occupants' responses only when necessary. | [25] |
| Konis K et al. (2019) | Development of TrojanSense, a tool that integrates wireless Bluetooth Low Energy (BLE) proximity beacons integrated in buildings that can monitor temperature and automatically require occupants' feedback. | The system can be used to increase thermal preference predictions accuracy and provide data on thermal comfort perception over time. | [50] |

| | | | |
|---|---|---|---|
| Antoniadou P et al. (2018) | Development of a new Integrated Personalizes Comfort Model of Office Buildings (IPCMOB) index. | Findings of this study demonstrate that is necessary to determine and assess the correlation between environmental parameters and users' perceived comfort. | [26] |
| Tiele A et al. (2018) | Development of a low cost, portable, battery-powered monitoring device to monitor the variations of IEQ parameters in indoor working environment. | Temperature, humidity, $PM_{2.5}$, $PM_{10}$, TVOC (× 3), $CO_2$, CO, IAQ, illuminance and sound levels are monitored with this tool. The overall IEQ percentage is determined through a scoring system with which the recorded measurements are evaluated. | [3] |
| Parkinson T et al. (2018) | Development of SAMBA, a tool for continuous monitoring of IEQ parameters from occupants' workstation. | Data related to office buildings IEQ parameters can be efficiently acquired, presented to occupants and used by building operators and facility managers. | [24] |

### 3.8.2 Virtual models reliability

The use of virtual models to study human behaviour is useful at the design phase, but the creation of a physical test bench, that contributes to comfort conditions and satisfaction of the indoor environment, presents difficulties [27].

The study of Ozcelik and Becerik-Gerber compared virtual and physical environments to evaluate aspects related to the influence of thermal stimuli on the selected response variables (such as actual versus perceived indoor

air temperature, thermal comfort and satisfaction, number and type of interactions) demonstrating that there is no difference between physical and virtual environments in the field of thermal comfort [27]. Tiele et al. created a low cost, portable, battery-powered monitoring device for IEQ. This tool is based on monitoring the variations of IEQ parameters in indoor working environment for 10-minute averaging period. The overall IEQ percentage is determined through a scoring system with which the recorded measurements are evaluated, thanks to the development of a customized IEQ index. The advantages are related to the ease of construction and the flexibility that allows the implementation with other sensors [3].
Monitoring systems of indoor conditions, such as SAMBA, demonstrate that this new approach provides a better evaluation of IEQ, that improves the energy performance of the building [47] [48] and the indoor environment. These systems represent a starting point for the acquisition of comfort data within office buildings, which will be part of a database for future scientific investigations through the definition of ranges and for evaluations for comparisons between the performance of buildings [24].

## 3.9 Discussion and conclusion

This literature review presents the findings of different methodological approaches to IEQ assessment for the definition of occupants' comfort conditions, through the identification of four main research questions. The following paragraphs include the definition of new comfort ranges, able to guarantee global comfort in workplaces, considering variables able to affect comfort perception, and then the monitoring of IEQ parameters and the representation of results.

### 3.9.1 Standards as minimum performance level for risk avoidance

Standards set thresholds for physical factors of IEQ. Particularly, EN 16798 [52] defines parameters for the indoor environment of single domains of comfort and establishes settings for design, heating, cooling, ventilation and lighting environment. Nevertheless acoustic environmental parameters are

not defined in this standard, that refers to other regulations.
Figure 10 shows new threshold to evaluate comfort, considering that indoor environmental settings, defined by current regulations, permit to avoid discomfort and ensure functional indoor conditions [53].
Protocols and standards were set to evaluate physical conditions of the indoor environment, not considering occupants' perception, owing to the great influence of demographic and contextual factors, that cannot be objectively quantified [9] [8]. However, in recent years, building performance protocols have given specific attention to comfort factors through scores assignment to each domain [12] [18].
French acoustics standard NF S 31-080 [53] defines acoustic values for three different ranges of performance, overcoming the concept of comfort linked to a definition of well-being as risk avoidance, to guarantee different flexible ranges of comfort (starting from the satisfaction of minimum requirements). The "standard" level is the minimum threshold, that does not guarantee acoustic comfort, the "efficient" level ensures good and comfortable working conditions, the "highly efficient" level regards the maximum acoustic performance level, related to wellness and comfort [38]. It is a qualitative notion related to office activity and use, in relation to the different typologies of tasks and workplaces. With these different comfort ranges, it may be possible to guarantee indoor environmental conditions in relation to occupants needs and office tasks, and satisfy customer requests, with different design solutions.

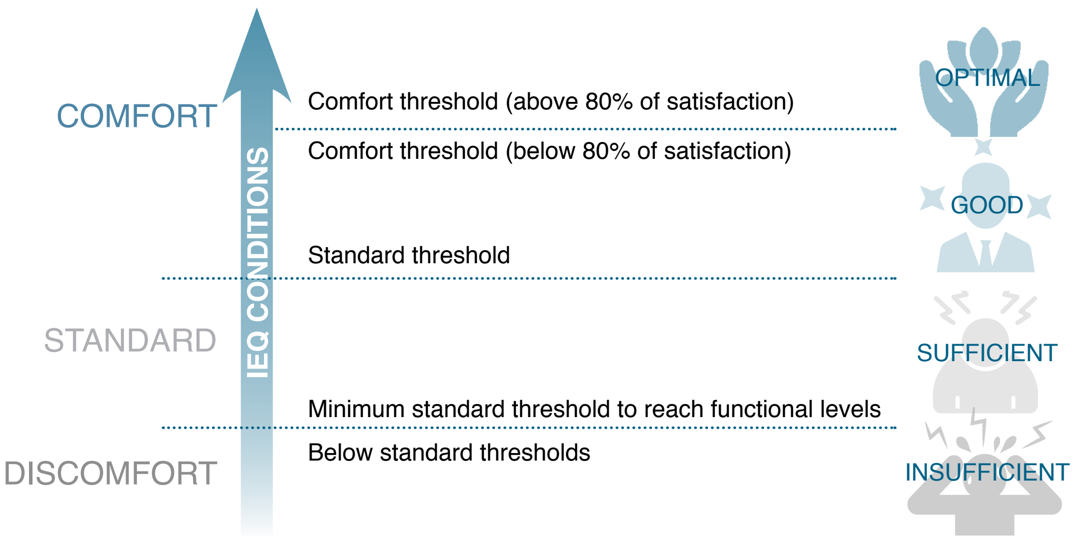


*Figure 10: occupants' experience of IEQ in workplaces (adapted from [54]).*

### 3.8.5 Occupants' comfort perception

Occupants' perception of their workplace is related to measurable physical factors (regulated by standards) that differently affect their comfort, in relation to the influence of contextual and demographic factors.
To analyse non-IEQ factors, evaluation instruments, such as POE survey, were developed [46] [6] [13]. The reliability of subjective feedbacks collected through this instrument has been investigated, because it is based on occupants' responses about personal comfort perception [55] [33] [4] [31]. It is a widespread tool, although it is necessary to conduct objective measurements for physical environment assessment to implement subjective feedbacks data [56] [7].
Control on building systems is an important psychological aspect that influences the perception of indoor environment, with important consequences on employee's well-being and work productivity [46]. Therefore, the availability of adaptive opportunities has been proven to increase occupants' perceived comfort [9] [20].
Occupants' actions, aimed at obtaining personal comfort level, have also a direct impact on energy consumption of office building. [47] [48] [57].
An optimal design could ensure occupants' health, comfort and well-being and the optimization of energy expenditure. A solution proposed by Altomonte et al. suggests the implementation of "flexible and adaptable settings", that can change over time and in relationship to occupants' needs [53].
Contextual variables and personal variables, shown in Table 9 and Table 10 respectively, and design solutions (access to nature, daylight and to outdoor environment) influence workers productivity and workplace perception [17] [32].
The personal variables mostly mentioned in the reviewed articles, as having the greater impact on employees' indoor environment perception, are: age, gender and context of growth.
These key personal variables can be new guidelines for the definition of different ranges of comfort, in relation to occupants and their tasks. New methods for assessing the interactions between IEQ aspects and contextual and personal factors may be useful to implement regulations [58].

### 3.8.6 Representation and monitoring of indoor environmental conditions

Monitoring systems of IEQ that combine multiple sensors in only one tool, can be used for this purpose, through an extensive assessment of the conditions that cause harmful effects on health and affect occupants' comfort and well-being [3].
Findings from reviewed articles highlight the scarcity of models assessing dynamically tracked parameters and employees' comfort perception, not providing the possibility to change the building settings [50] [27] [26] [59]. In the research field, interfaces and apps monitoring combined effect of IEQ factors and giving information about global comfort perception, are rather used as a support tool [22] [25] [51]. In fact, recent apps, are limited to providing occupants' feedback in relation to a single domain. The process shown in Figure 11 foresees the use of interfaces to collect occupants' feedback regarding IEQ, combined with a sensor that constantly and simultaneously monitors comfort parameters, to guarantee global comfort in the workplace, increasing the productivity of employees and achieving energy savings. New measuring tools and devices, that consider the dependence of environmental perception on personal variables, may be helpful for the definition of new performance levels of standards.

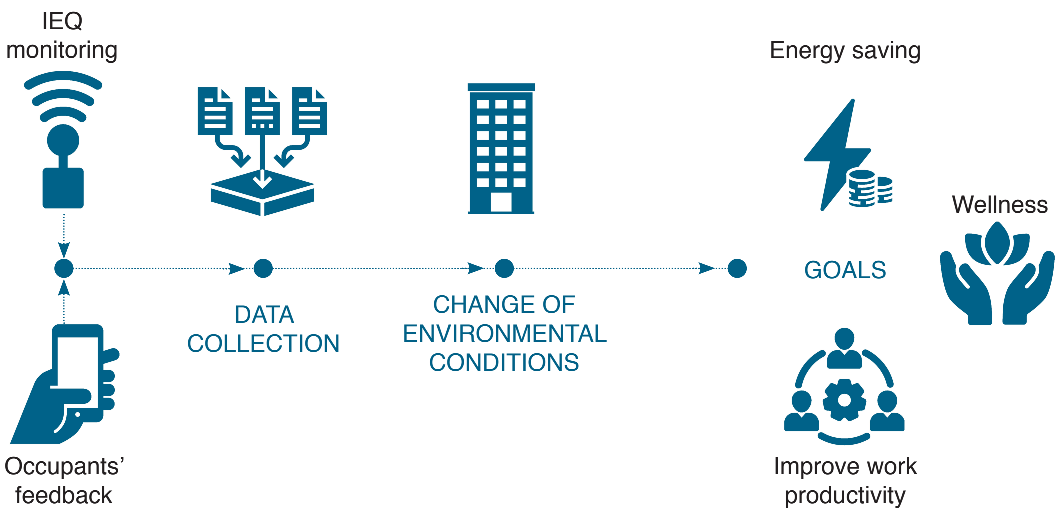


*Figure 11: outcomes of the process related to IEQ assessment based on objective monitoring, occupants' feedback, data collection and interaction with the environmental conditions.*

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## 3.10 List of abbreviations including units and nomenclature

BLE Bluetooth Low Energy
BOSSA Building Occupants Survey System Australia
BREEAM BRE Environmental Assessment Method
BUS Building Use Studies
CBE Center of the Built Environment
CO Carbon Monoxide
$CO_2$ Carbon Dioxide
CPBD Center for Building Performance and Diagnostics
DGNB Deutschen Gesellschaft für Nachhaltiges Bauen
IAQ Indoor Air Quality
IECs Indoor Environmental Controls
IEQ Indoor Environmental Quality
ITACA Istituto per la Trasparenza, l'Aggiornamento e la Certificazione degli Appalti
IPCMOB Integrated Personalizes Comfort Model of Office Buildings
LBC Living Building Challenge
LEED Leadership in Energy and Environmental Design
NABERS National Australian Built Environment Rating System
NEAT National Environment Assessment Toolkit
PMV Predicted Mean Vote
POE Post-occupancy evaluation
PPD Predicted Percentage of Dissatisfied
SAMBA Sentient Ambient Monitoring of Buildings in Australia
SBS Sick Buildign Syndrome
SPOES Sustainable Post-Occupancy Evaluation Surveys
TVOC Total Volatile Organic Compounds
UORO University Open-plan Research Office
WHO World Health Organization
WODI Work Environment Diagnosis Instrument

# 4 The project of comfort

The aim of this section of the thesis has been to assess indoor environmental conditions of the current state of an office, chosen as case study, to subsequently achieve an improvement in conditions and a higher comfort range, among the ones identified through the previous research and study, by means of a redevelopment project.
The assessment of indoor environmental conditions of the office has been performed through the realization of the office model in simulation software for each domain: Odeon and Echo software for the acoustic domain, IDA ICE software for thermal, visual and air quality domains and DIALux evo for electric lighting. On-site monitored data were used to calibrate the office model in each software. Once these steps have been completed and the simulation data of the current state have been obtained, the office project for the improvement of indoor environmental conditions has been done.
The survey of the office and the monitoring of internal environmental conditions were carried out in the thesis work “Qualità dell’ambiente interno e comfort globale: misure in campo ed analisi nella sede dell’ARPA della Valle d’Aosta” of the student Niccolò Oggiani, with supervisors Prof. Marco Masoero and Prof. Arianna Astolfi (Oggiani, 2020). Data necessary for the calibrations have been taken from this thesis work.

## 4.1 Project workflow

To realise this work five main steps have been followed:

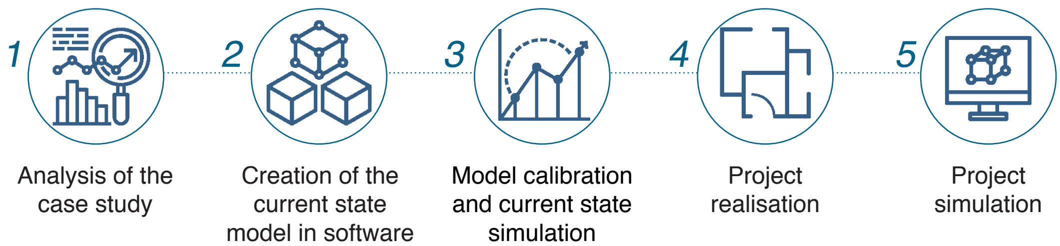



*Figure 12: project workflow.*

The first step has been the analysis of the case study. The data of the office that are presented in the theses of N. Oggiani are related to morphology, building systems, internal gains and occupancy hours at the moment in which the analysis was done. The data he monitored and processed have been used to realize the model and its calibration on the software.
The calibration is a tool used to create a model on software as close to real conditions as possible, thus allows to reduce the differences among simulated model and reality. It requires input data based on the choice of the useful parameters needed to frame the case studied. The mostly used approach is the empiric one, based on the modification of the undetermined or hypothesized parameters “by trial and error”.
The analysis of regulations, protocols and literature review carried out allowed to identify the parameters to be evaluated for determining the comfort conditions within the office, for each domain.

*Table 13: indexes simulated through the software.*

| Software | Simulated indexes | | Unit |
|---|---|---|---|
| Odeon | Reverberation time | $T_r$ | s |
| Echo 8.1 | Sound insulation of façade | $D_{nTw}$ | dB |
| | Sound insulation of internal walls | $D_{2m,nTw}$ | dB |
| IDA ICE 5.0 | Indoor operative temperature | $T_{op}$ | °C |
| | Predicted mean vote | PMV | - |
| | Predicted percentage of dissatisfied | PPD | % |
| | Relative humidity | RH | % |
| | $CO_2$ concentration | $CO_2$ | ppm |
| | Daylight factor | DF | % |
| | Spatial daylight autonomy | $sDA_{300,50\%}$ | % |
| | Annual sunlight exposure | $ASE_{1000,250h}$ | % |
| DIALux evo | Average Illuminance | E | lx |
| | Illuminance uniformity | U | - |
| | Unified Glare Rating | UGR | - |

## 4.2 Case study

The office under study is located in the first floor of the headquarters of ARPA Valle d'Aosta (Agenzia Regionale per la Protezione dell'Ambiente Valle d'Aosta) in Saint-Christophe (AO).

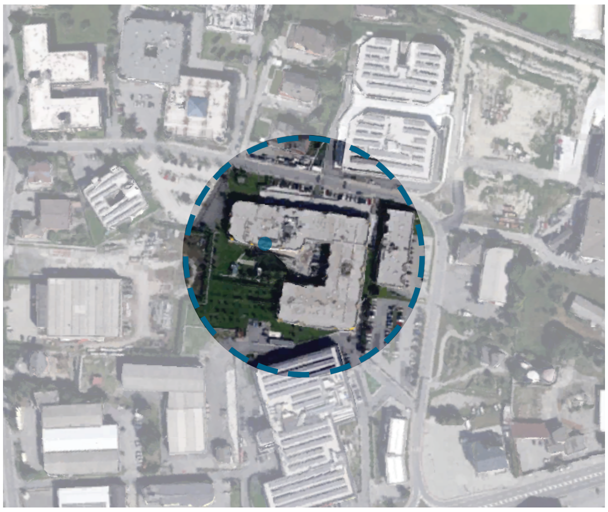


Figure 13: orthophoto of ARPA Valle d'Aosta.

LOCATION

Country: Italy

City: Saint-Christophe (AO)

Latitude: 45.735° N

Longitude: 7.351° E

Altutude above see: 552.0 m

Climate zone: E

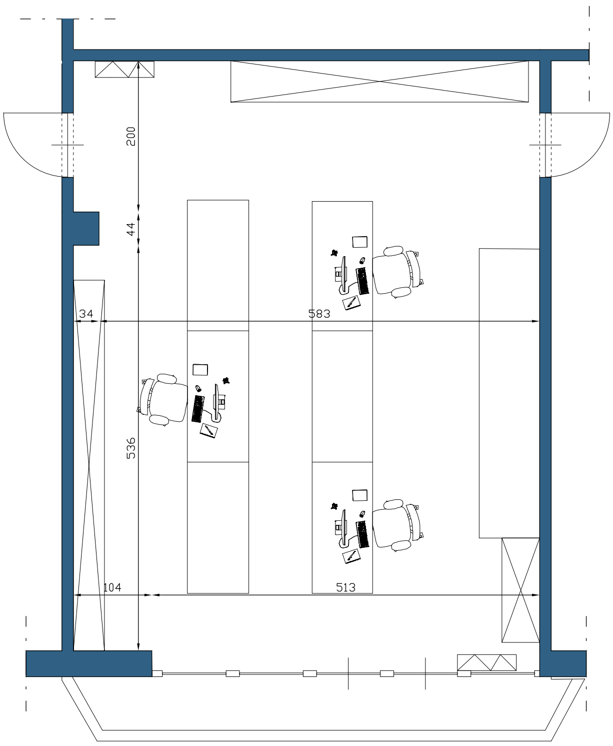



Figure 14: office plan, first floor, scale 1:100.

BUILDING

Construction years: 2002-2005

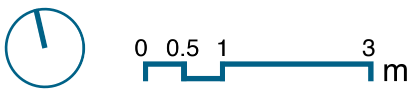
OFFICE UNDER STUDY

First floor plan

Volume: 130 $m^3$

Floor surface: 49 $m^2$

The office faces south, towards the internal courtyard. Opposite, at a distance of 5 meters, there are two trees.



### 4.2.1 Office features

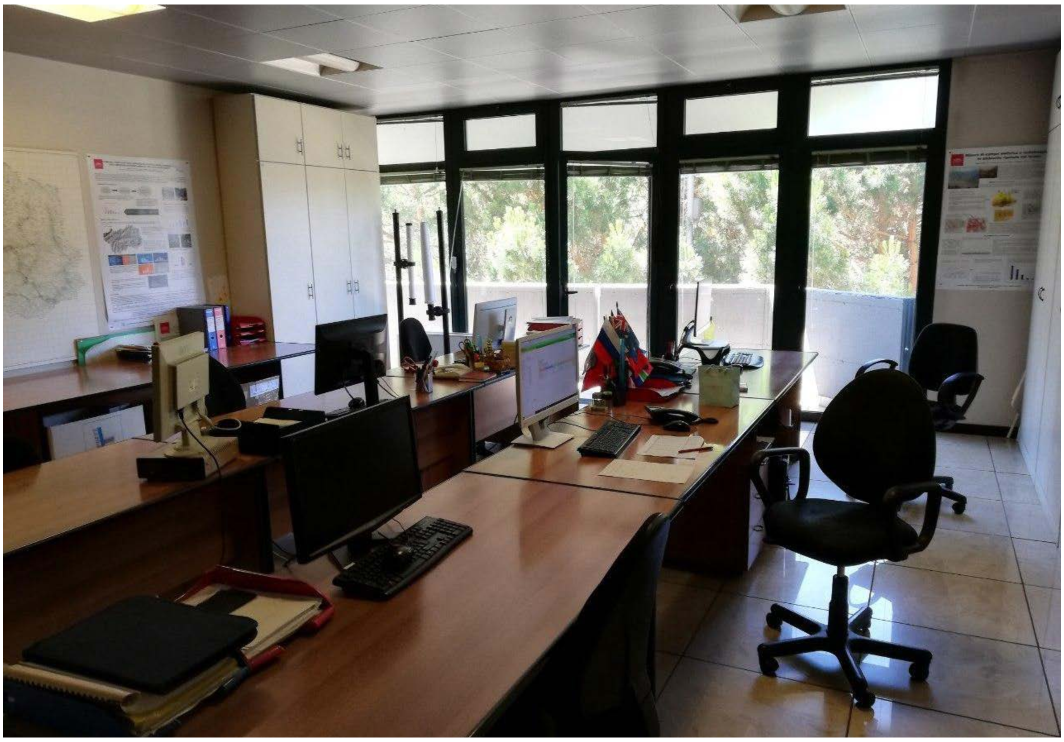


*Figure 15: photo of the office. Source: "Qualità dell'ambiente interno e comfort globale: misure in campo ed analisi nella sede dell'ARPA della Valle d'Aosta" (Oggiani, 2020).*

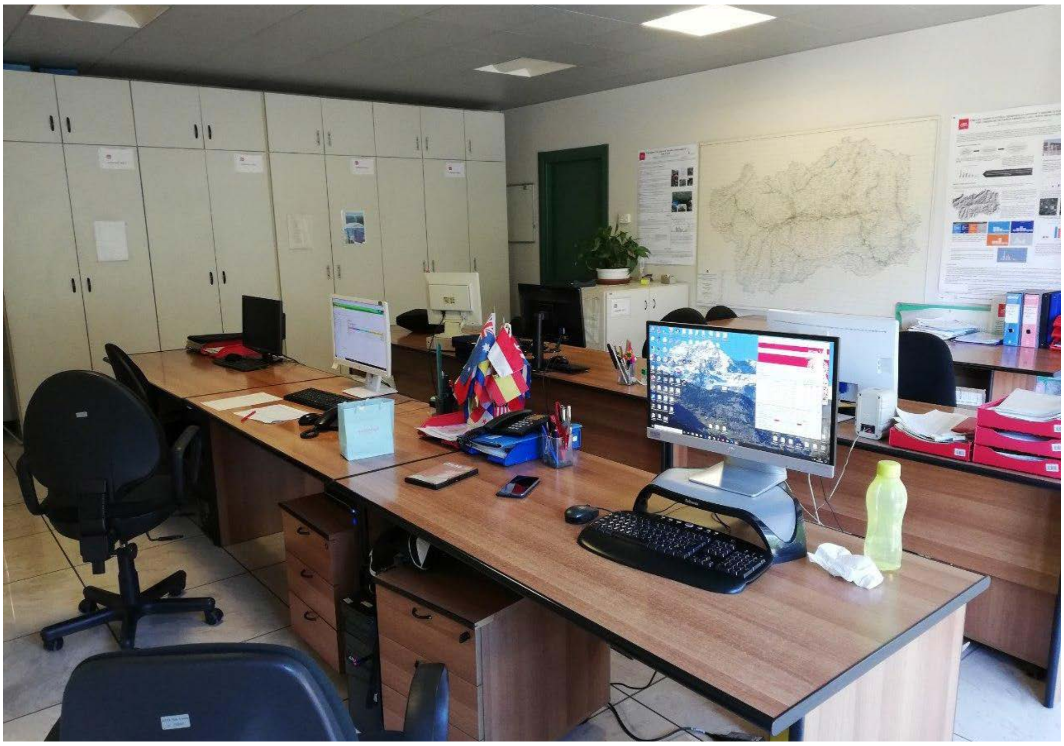


*Figure 16: photo of the office. Source: "Qualità dell'ambiente interno e comfort globale: misure in campo ed analisi nella sede dell'ARPA della Valle d'Aosta" (Oggiani, 2020).*

*Figure 17: office view.*

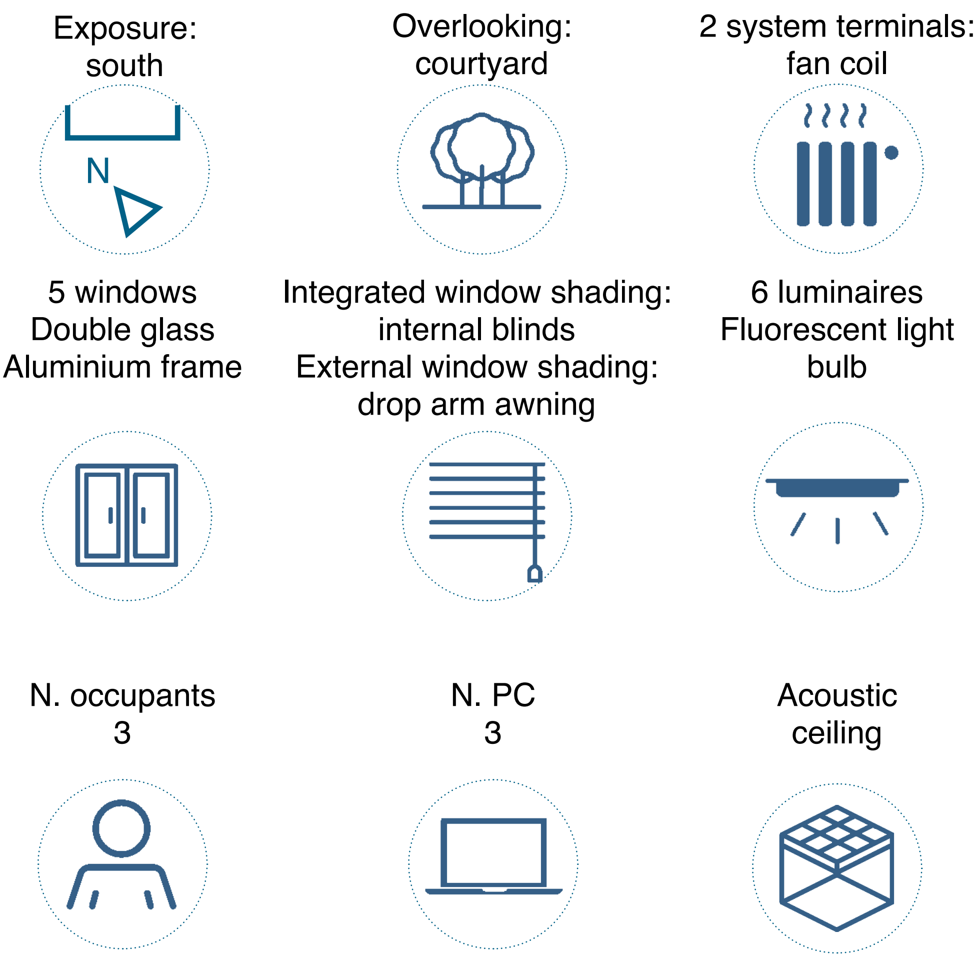



*Figure 18: Survey features presented in "Qualità dell'ambiente interno e comfort globale: misure in campo ed analisi nella sede dell'ARPA della Valle d'Aosta" thesis (Oggiani, 2020).*

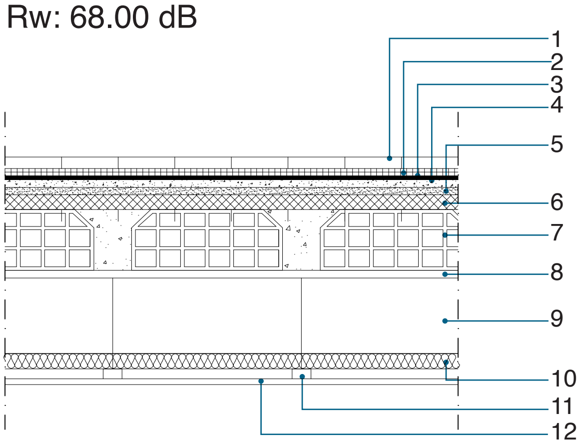
### 4.2.2 Opaque and transparent envelope

The office stratigraphy of opaque envelope has been composed using the information about construction typology, period of construction of the building (years 2002-2005) and by means of the UNI 11552:2014, because specific data on materials and layers thicknesses were not available.
The only available information was related to the typology of stratigraphy: concrete panels have been used for this building construction. Furthermore, it is known that false ceiling with a layer of fiberglass insulation has been added after the building construction in the roof package.
Starting from this knowledge, in standard UNI 11552:2014 have been detected the most proper stratigraphy for each technology package.
The only information owned about windows is that are made up of two glasses and by aluminium frame.

#### 4.2.2.1 Abacus scale 1:20

**ROOF**

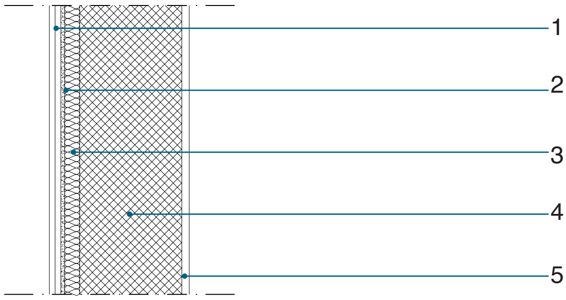
Thikness: 60.00 cm
U-value: 0.44 W/(m2K)
Rw: 68.00 dB




| | | |
|---|---|---|
| 1. | Outdoor flooring | 3.0 cm |
| 2. | Polystyrene insulating panel | 2.0 cm |
| 3. | Bituminous waterproofing membrane | 1.0 cm |
| 4. | Concrete screed | 2.0 cm |
| 5. | Cement mortar | 2.0 cm |
| 6. | Reinforced concrete | 4.0 cm |
| 7. | Concrete beams-brick blocks | 16.0 cm |
| 8. | Render | 2.0 cm |
| 9. | Air | 20.0 cm |
| 10. | Fibreglass | 4.0 cm |
| 11. | False ceiling structure | 2.5 cm |
| 12. | Gypsum | 1.5 cm |

## EXTERNAL WALL

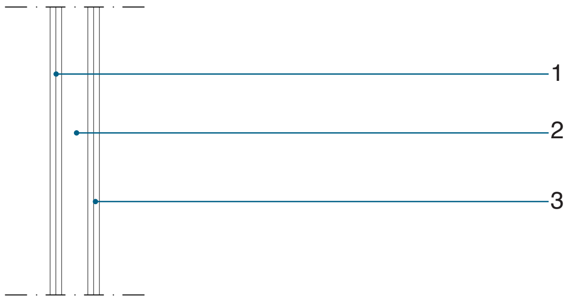
Thikness: 37.00 cm
U-value: 0.58 W/(m2K)
Rw: 35.80 dB




| | | |
|---|---|---|
| 1. | Gypsum | 3.0 cm |
| 2. | Cement mortar | 1.0 cm |
| 3. | Fibreglass | 4.0 cm |
| 4. | Concrete | 27.0 cm |
| 5. | Render | 2.0 cm |

## INTERNAL WALL

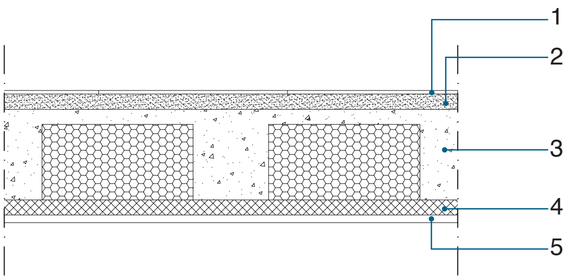
Thikness: 13.00 cm
Rw: 42.90 dB




| | | |
|---|---|---|
| 1. | Gypsum | 3.0 cm |
| 2. | Air | 7.0 cm |
| 3. | Gypsum | 3.0 cm |

## INTERNAL SLAB

Thikness: 31.00 cm
Rw: 51.00 dB




| | | |
|---|---|---|
| 1. | Ceramic tiles | 1.0 cm |
| 2. | Cement mortar | 4.0 cm |
| 3. | Concrete screed | |
| 4. | Predalles lattice slab (concrete, EPS) | 24.0 cm |
| 5. | Render | 2.0 cm |

#### 4.2.2.2 Window properties

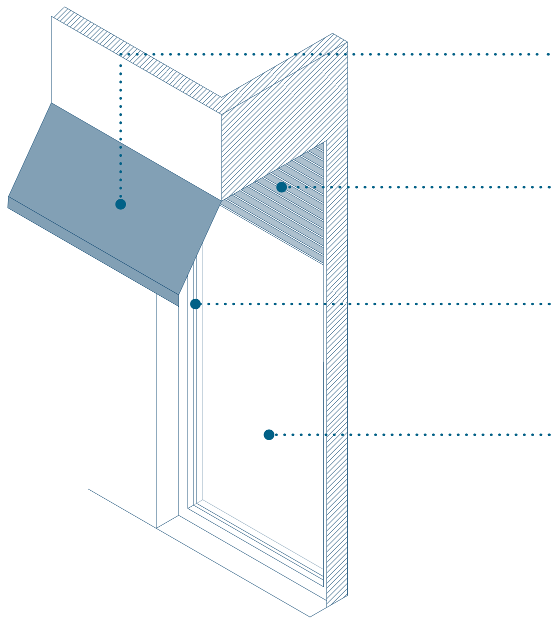



*Figure 19: current state window and shadings properties*

### 4.2.3 Data monitoring

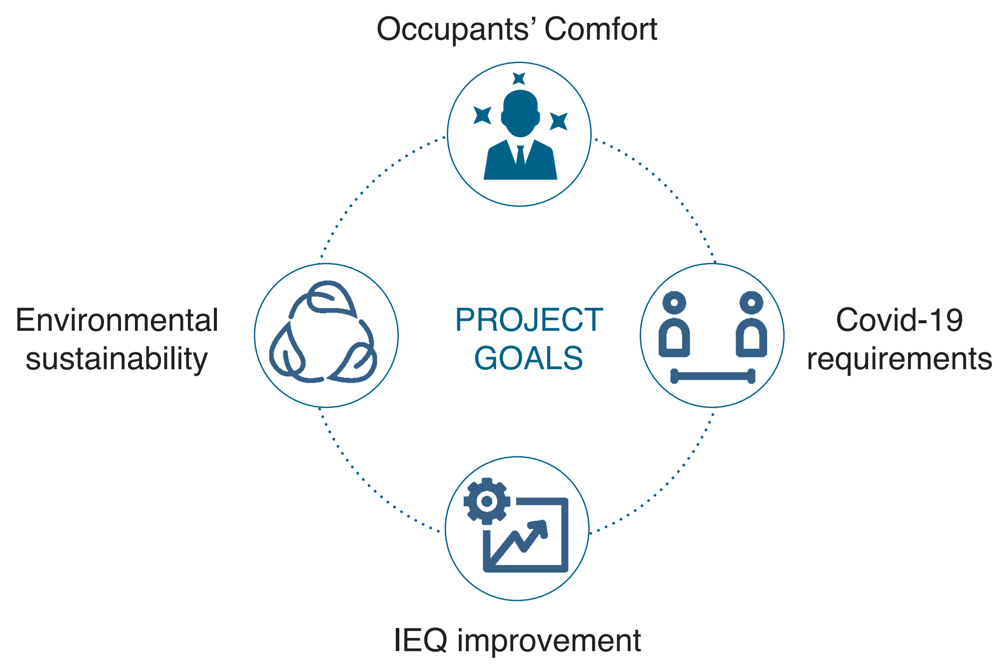
The measurements taken from the thesis work "Qualità dell'ambiente interno e comfort globale: misure in campo ed analisi nella sede dell'ARPA della Valle d'Aosta" (Oggiani, 2020) are related to the physical quantities that are used to evaluate indoor comfort, with reference to standard EN 16798. The monitoring period is between 18/08/2020 and 03/09/2020. The period of daily employment by workers is between 9:00 and 17:00, from Monday to Friday.
The measurements were differentiated into two types: continuous measurements and punctual measurements. The former refers to physical quantities monitored over the working hours for three consecutive days in all three weeks. The punctual measurements, on the other hand, refer to physical quantities monitored in three specific days (18/08/2020, 24/08/2020 and 02/09/2020) and used to obtain the environmental indexes present in the legislation and useful for the assessment of indoor environmental comfort.

It must be noticed that the monitoring survey was carried out during the Covid-19 pandemic period, thus air conditioning system was kept switched off to reduce the circulation of the virus.
In Table 14 are presented the physical parameters monitored.

*Table 14: punctual and continuous monitoring of physical parameters. Source: "Qualità dell'ambiente interno e comfort globale: misure in campo ed analisi nella sede dell'ARPA della Valle d'Aosta" (Oggiani, 2020).*

| THERMAL DOMAIN | | |
|---|---|---|
| Indoor air temperature | $T_i$ [°C] | Punctual and continuous measure |
| Outdoor air temperature | $T_o$ [°C] | Continuous measure |
| Indoor relative humidity | $RH_i$ [%] | Punctual and continuous measure |
| Outdoor relative humidity | $RH_o$ [%] | Continuous measure |
| Mean radiant temperature | $T_{mr}$ [%] | Punctual measure |
| Air velocity | $V_a$ [m/s] | Punctual measure |
| INDOOR AIR QUALITY | | |
| $CO_2$ concentration | $CO_2$ [ppm] | Punctual measure |
| Volatile organic compounds | VOC [µg/m$^3$] | Punctual measure |
| Particulate matter: $PM_1$, $PM_{2.5}$, $PM_{10}$ | $PM_1$, $PM_{2.5}$, $PM_{10}$ [µg/m$^3$] | Punctual measure |
| ACOUSTIC DOMAIN | | |
| Equivalent continuous sound pressure level | $L_{,A,eq}$ [dB(A)] | Punctual and continuous measure |
| Reverberation time | $T_{30}$ [s] | Punctual measure |
| VISUAL DOMAIN | | |
| Average illuminance | E [lx] | Punctual measure |

## 4.3 Office project



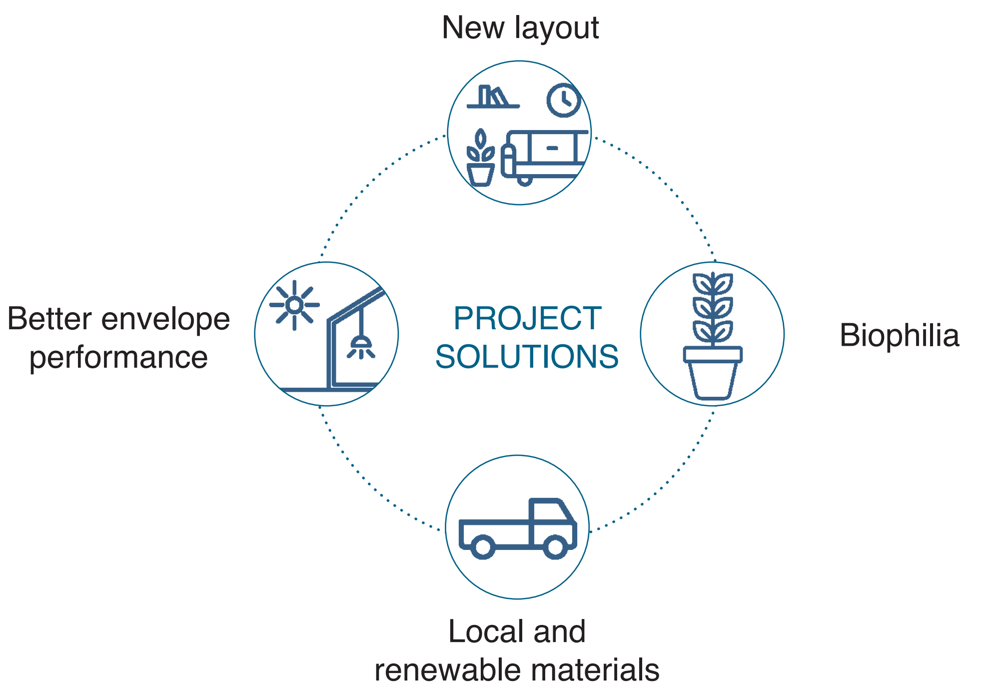
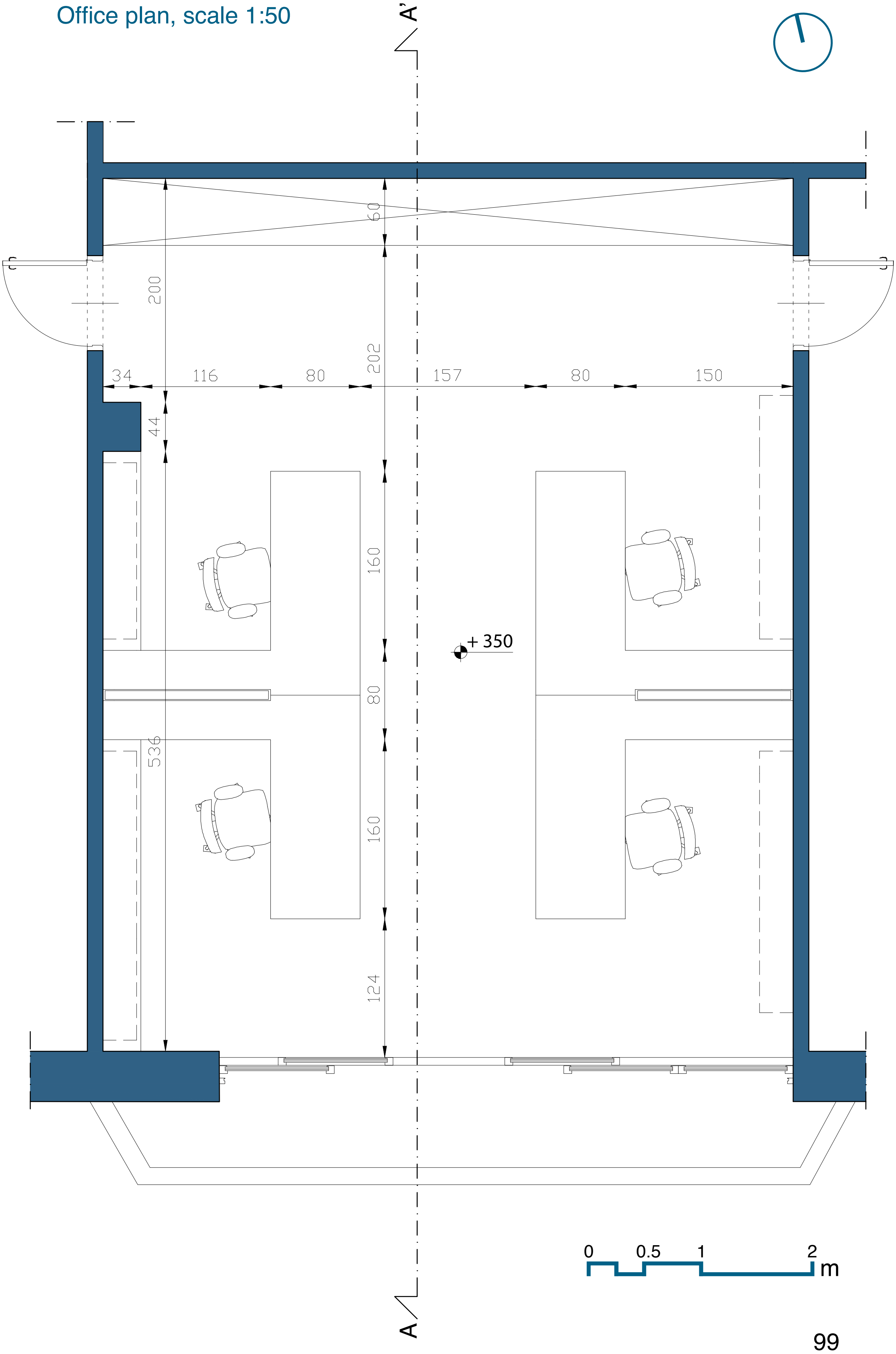




*Figure 20: project goals and project solutions.*

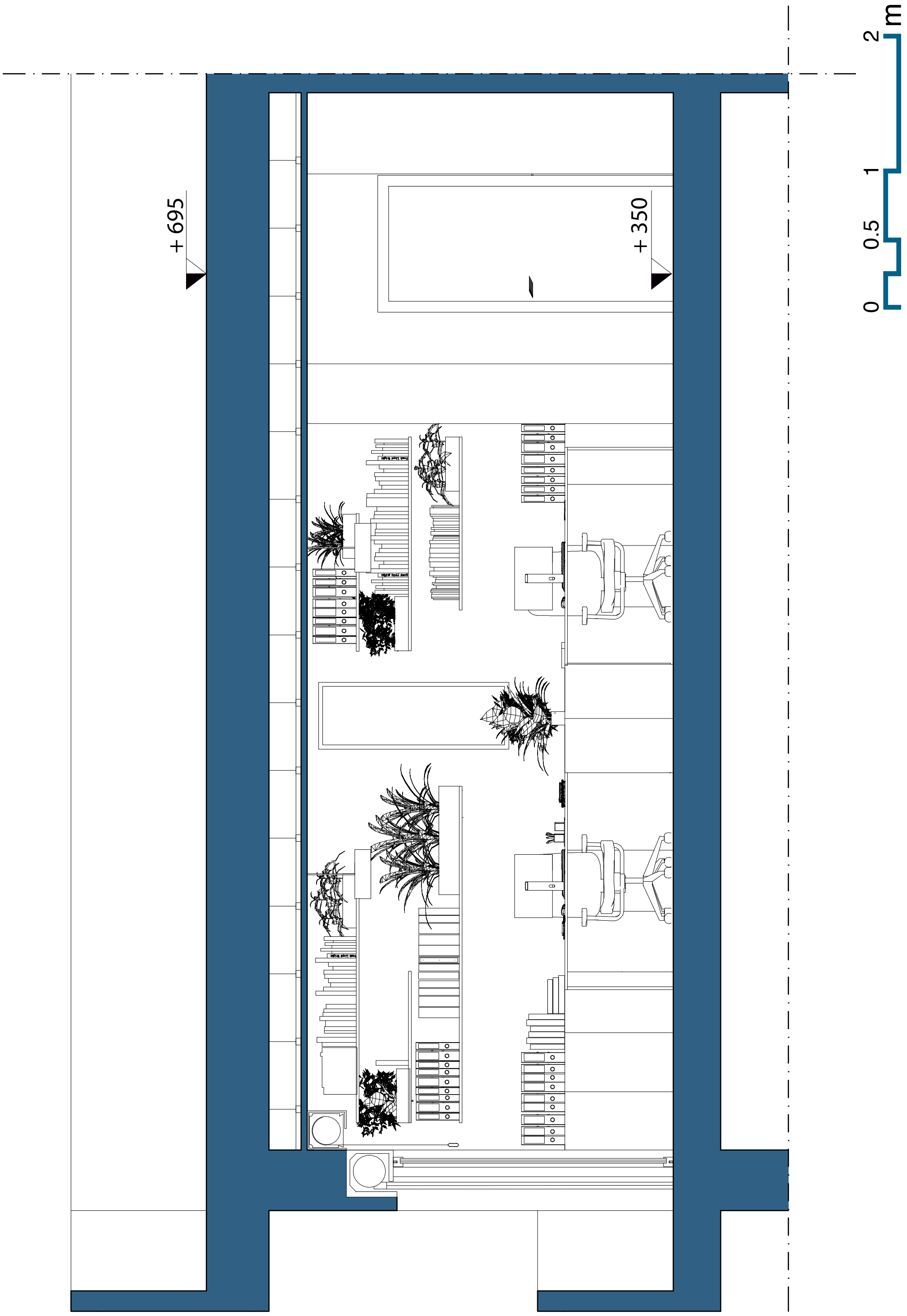
The office project was carried out to achieve the level of comfort in all the four domains, ensuring its maintenance where it was already achieved with the current state. For this reason, the critical issues and needs relating to single domains have been taken into consideration and have been combined to obtain a unitary improvement. In this work of thesis, building systems have not been dimensioned.
Given the historical period in which this thesis work was carried out, the new needs that arose from the spread of Covid-19 were also taken into consideration. The required social distance is at least one meter according to UNI 11534:2020, for front and side distances. Therefore, differentiated flows, low levels of density and spacing of the desks were fundamental for guaranteeing the maintenance of workers' safety conditions. However, thanks to the project, an increase in occupants' number from three to four can be expected.
The choice of materials was also driven by new needs that arose in the last year: the topic of biophilia has been subject of great attention by research for the improvement of indoor office conditions. For this reason, desk plants have been put to separate desks from each other and provide workers with privacy, contact with nature and distancing. The use of materials and colours that can bring back to nature, as well as the possibility of having direct contact with the outside space are, today more than ever, necessary requirements in office spaces.
Equally important is environmental sustainability topic, a decisive guide in the choice of materials. The search for low-emission materials, derived from renewable sources and produced in Valle d'Aosta, to reduce emissions associated to transportation from the factory to the worksite, has been pursued.
The project consists in the realization of an external coat and in the insulation of the roof. The choice fell on these solutions, that allow to avoid demolitions, to make the most of the existing stratigraphy, reduce the amount of work required and reduce the amount of waste material produced, with a view to environmental and economic sustainability. The windows have also been changed to achieve better performance.
The insulating material, used to improve indoor conditions, is cellulose fibre in panels, excellent thermal insulating thanks to its porous structure, able to reduce heat dispersion. These panels are breathable and hygroscopic, with

a good soundproofing power and in addiction do not contain substances irritant or dangerous for health. The raw material is paper recycled, thus the energy expenditure to produce it is very low. During the process an antiparasitic and fireproofing treatment is carried out, however it is a no-toxic and ecologic material.
In order to reduce the environmental impact due to transportation, for the furniture and floor, larch was chosen. It is a wood widely used in Valle d'Aosta.
Walls, realized with gypsum, have colours able to recall nature.
The ceiling, with excellent acoustic performance, is realized with a mono slab, for esthetic reason, avoiding joint points. Desks orientation is chosen to favor better illuminance and to guarantee outside view, while shelves are near the wall between the two doors, to leave wide space in the center.
Office layout is thought to be flexible and comfortable, able to create different scenarios that meet the necessities of the employers.

## Office plan, scale 1:50



## Section AA’, scale 1:50



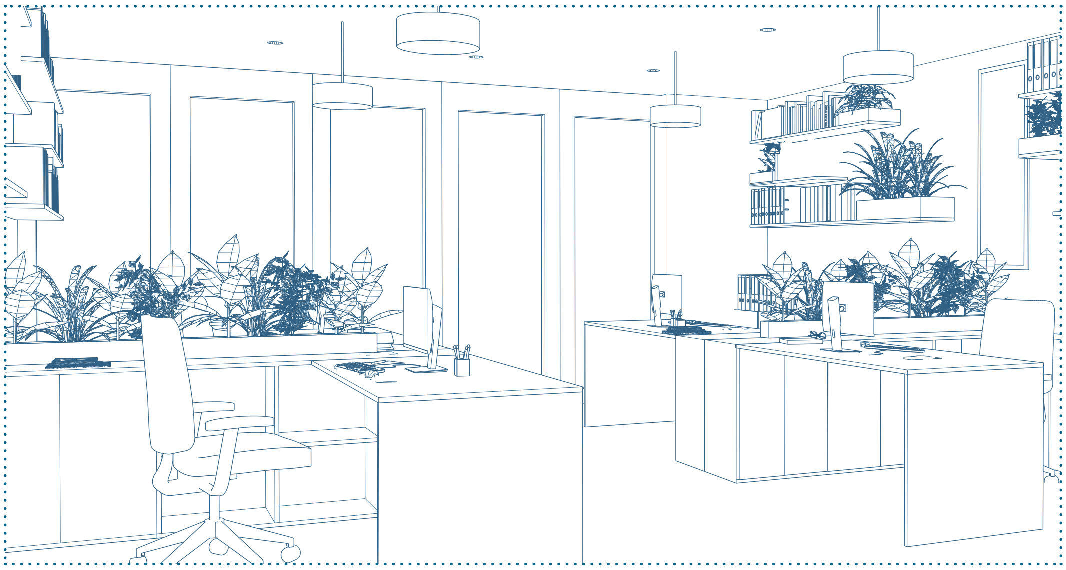


*Figure 21: office view.*

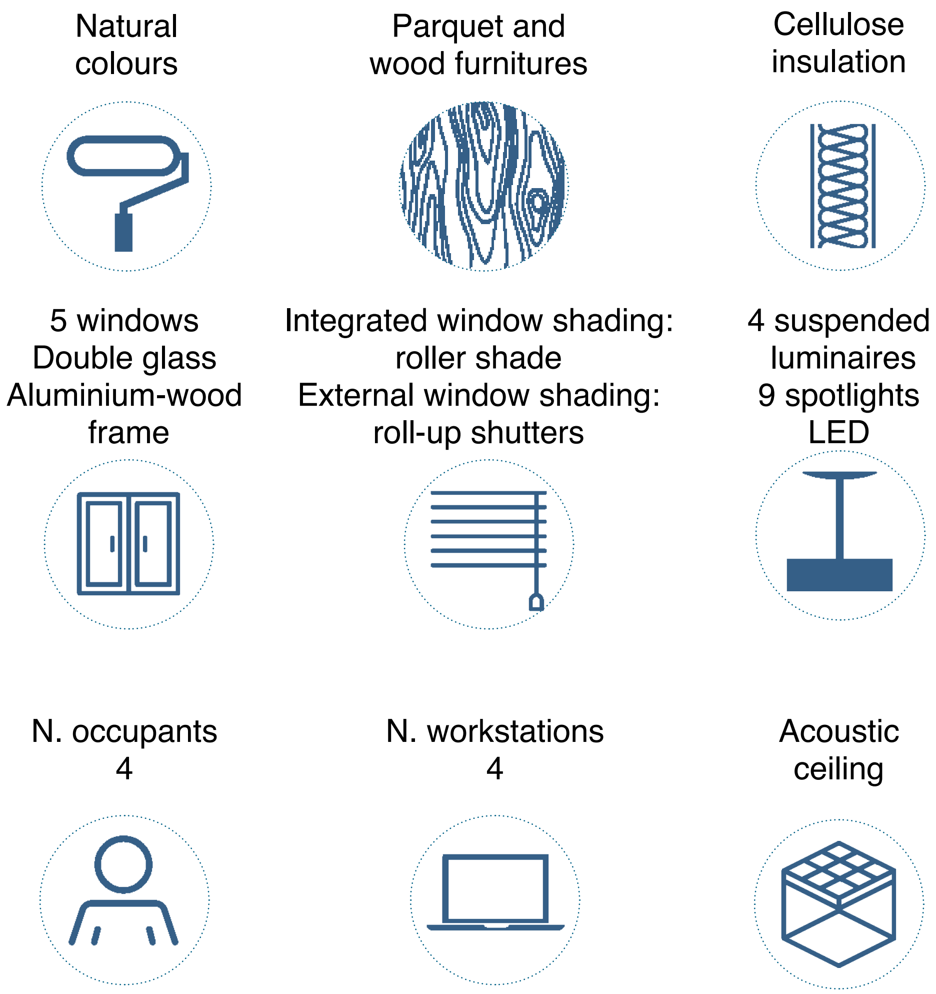


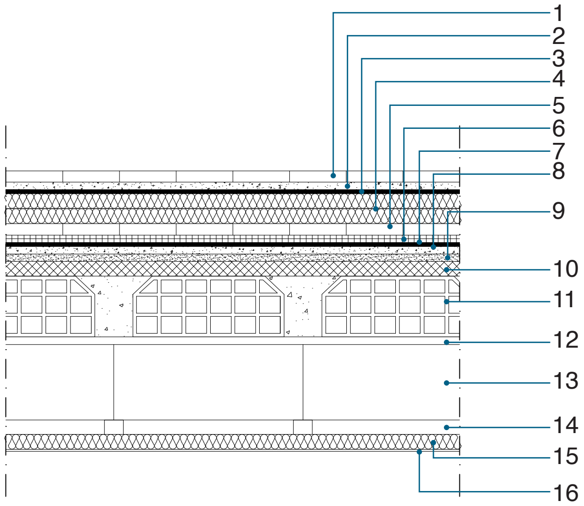

*Figure 22: office features*

## 4.3.1 Opaque and transparent envelope

### 4.3.1.1 Abacus scale 1:20

ROOF

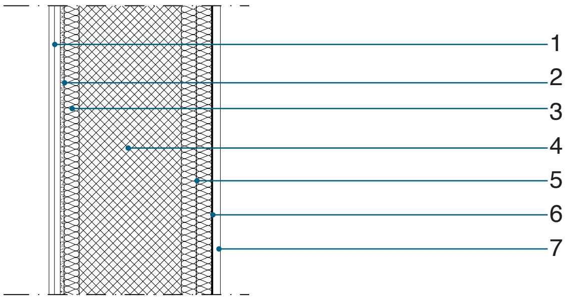
Thikness: 74.30 cm
U-value: 0.22 W/(m2K)
Rw: 68.00 dB




| | | |
|---|---|---|
| 1. | Outdoor flooring | 3.0 cm |
| 2. | Cement mortar | 2.0 cm |
| 3. | Bituminous waterproofing membrane | 1.0 cm |
| 4. | Cellulose insulation | 8.0 cm |
| 5. | Outdoor flooring | 3.0 cm |
| 6. | Polystyrene insulating panel | 2.0 cm |
| 7. | Bituminous waterproofing membrane | 1.0 cm |
| 8. | Concrete screed | 2.0 cm |
| 9. | Cement mortar | 2.0 cm |
| 10. | Reinforced concrete | 4.0 cm |
| 11. | Concrete beams-brick blocks | 16.0 cm |
| 12. | Render | 2.0 cm |
| 13. | Air | 20.0 cm |
| 14. | False ceiling structure | 3.8 cm |
| 15. | Mono Acoustic panel (rockwool) | 4.0 cm |
| 16. | Render Mono Acoustic | 0.5 cm |

## EXTERNAL WALL

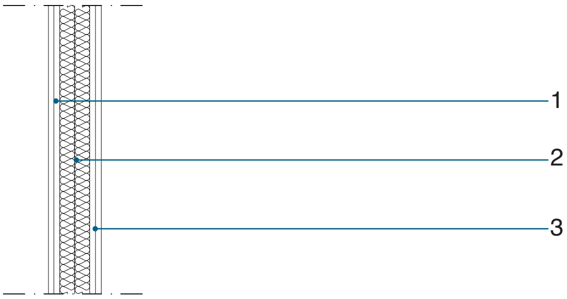
Thikness: 45.00 cm
U-value: 0.25 W/(m2K)
Rw: 47.00 dB




1. Gypsum 3.0 cm
2. Cement mortar 1.0 cm
3. Fibreglass 4.0 cm
4. Concrete 27.0 cm
5. Cellulose insulation 8.0 cm
6. Bituminous waterproofing membrane 1.0 cm
7. Render 2.0 cm

## INTERNAL WALL

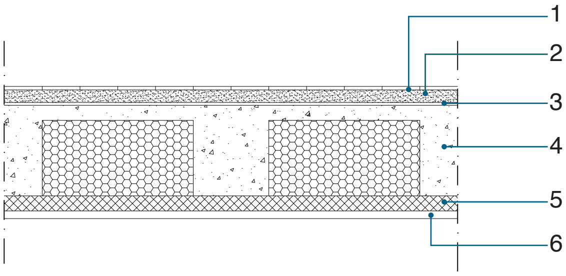
Thikness: 14.00 cm
Rw: 59.4 dB




1. Gypsum 3.0 cm
2. Cellulose insulation 8.0 cm
3. Gypsum 3.0 cm

## INTERNAL SLAB

Thikness: 35.00 cm
Rw: 51.00 dB




1. Parquet 1.0 cm
2. Cement mortar 3.0 cm
3. Acoustic mat 0.7 cm
4. Concrete screed
5. Predalles lattice slab (concrete, EPS) 24.0 cm
6. Render 2.0 cm

#### 4.3.1.2 Window properties

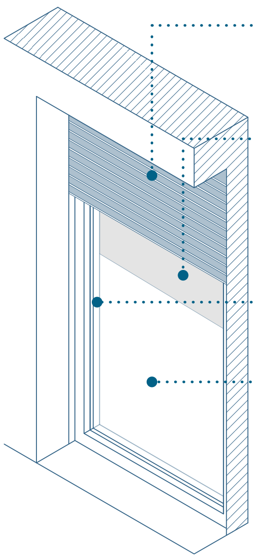



*Figure 23: project window and shadings properties*

For the project two different kinds of luminaires have been chosen, in order to ensure the illuminance level (lx) on desks required by standard EN 16798 for the specific visual task of this office (writing, typing, reading, data processing) and in order to provide the possibility to have general lighting when occupants don't have to perform that specific visual task. Suspended luminaires and spotlights have been put as shown in Figure 24. The former are at 1.45 m height above desks, the latter are embedded in the false ceiling.

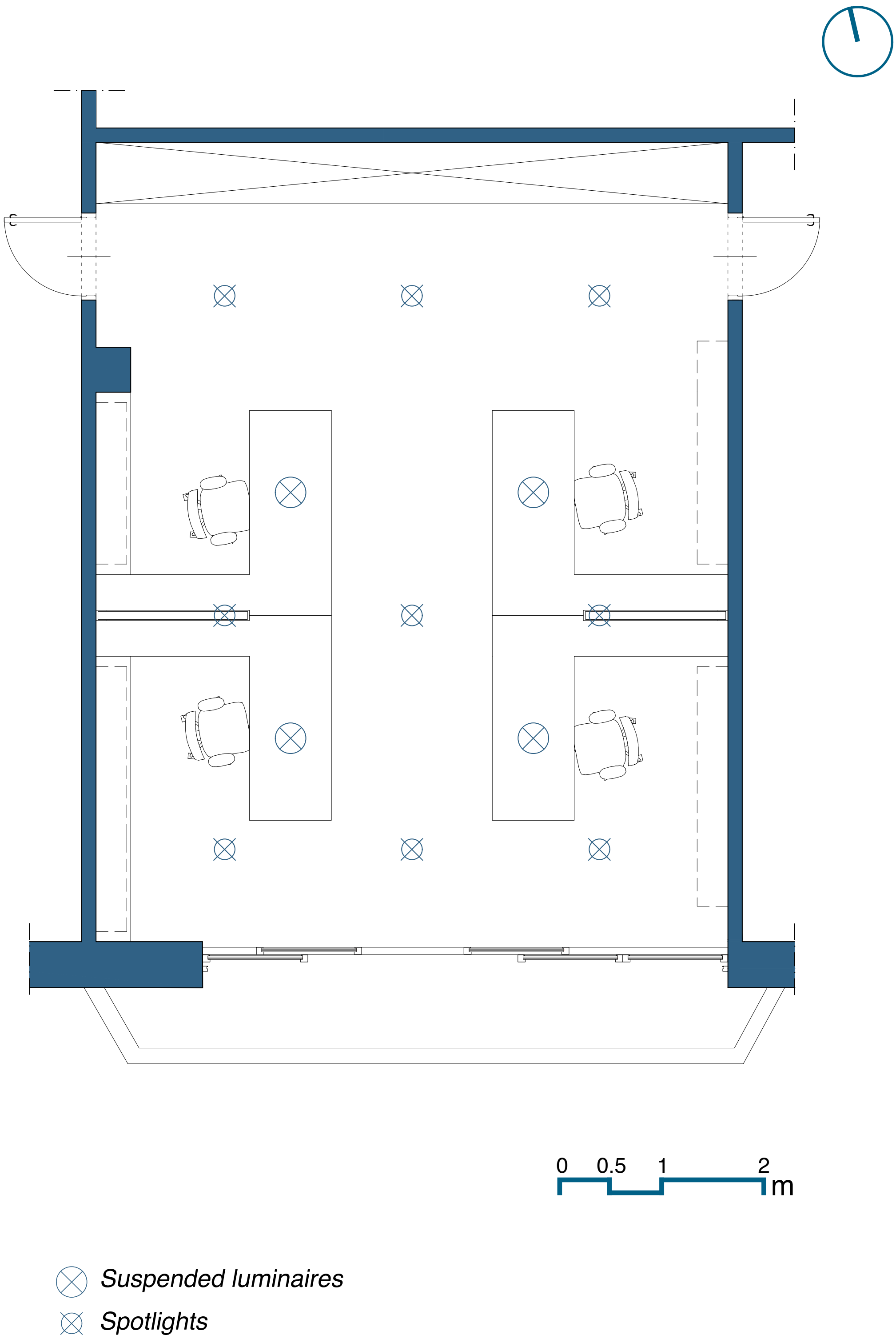



*Figure 24: luminaires positioning scheme*

Due to the presence of two different kinds of luminaires, many scenarios of electric lighting are possible. Three of them are then presented.

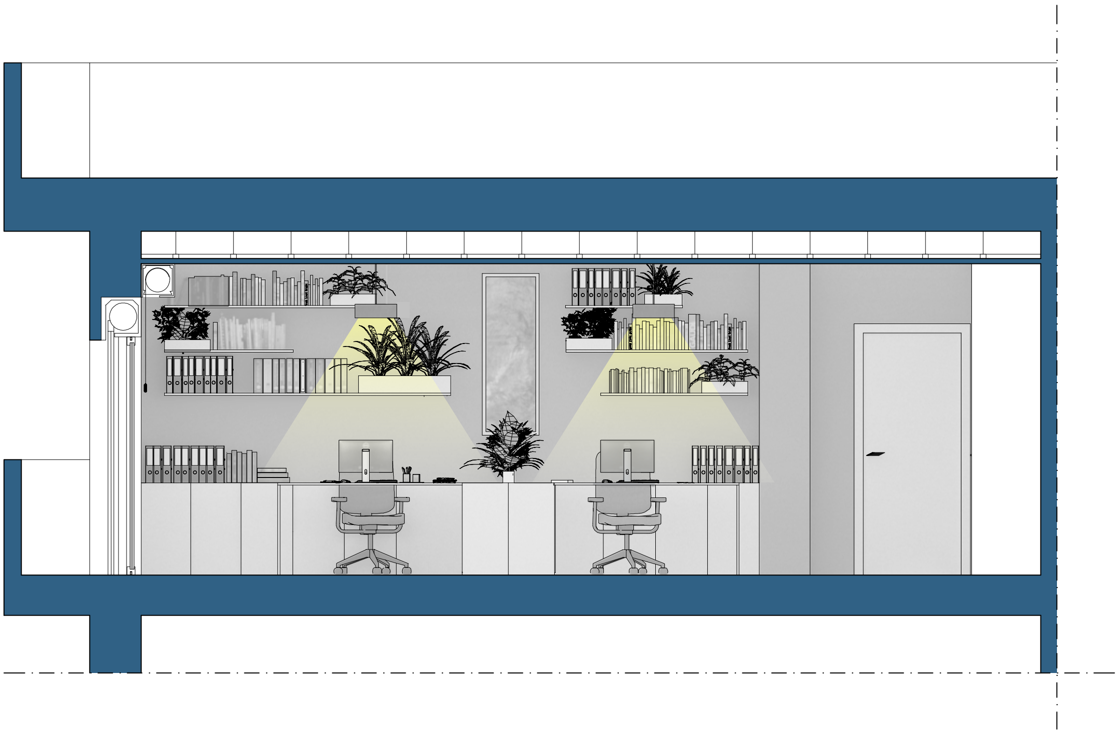


*Figure 25: only suspended luminaires are switched on.*

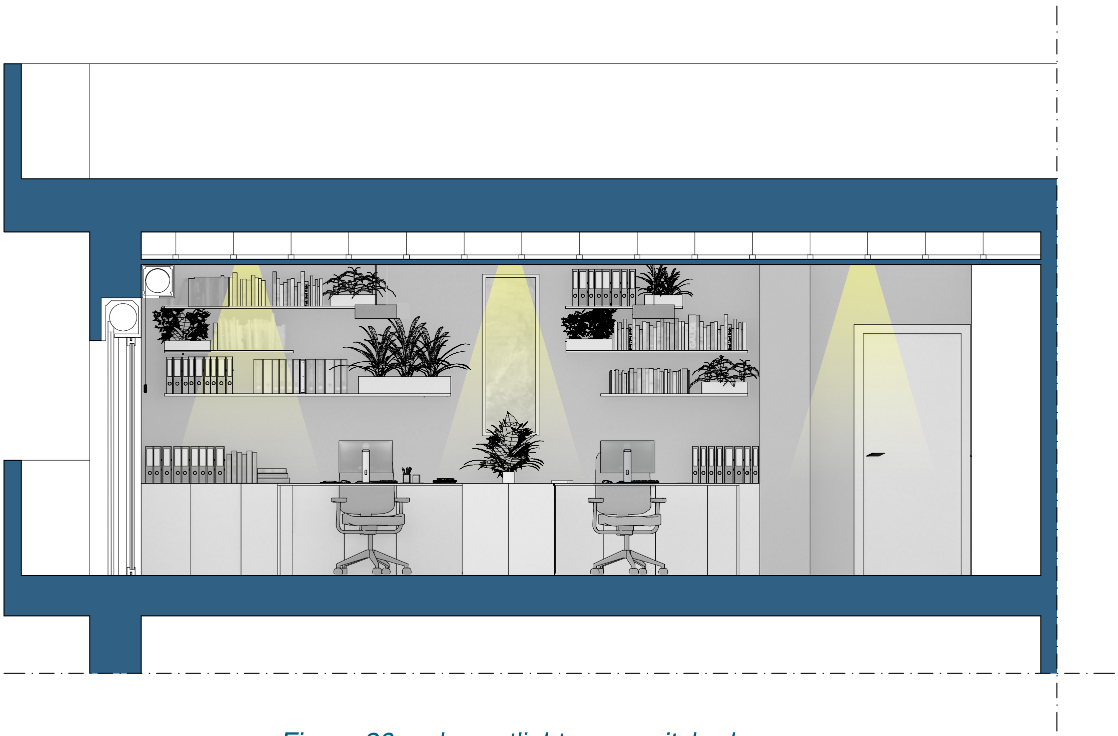


*Figure 26: only spotlights are switched on.*

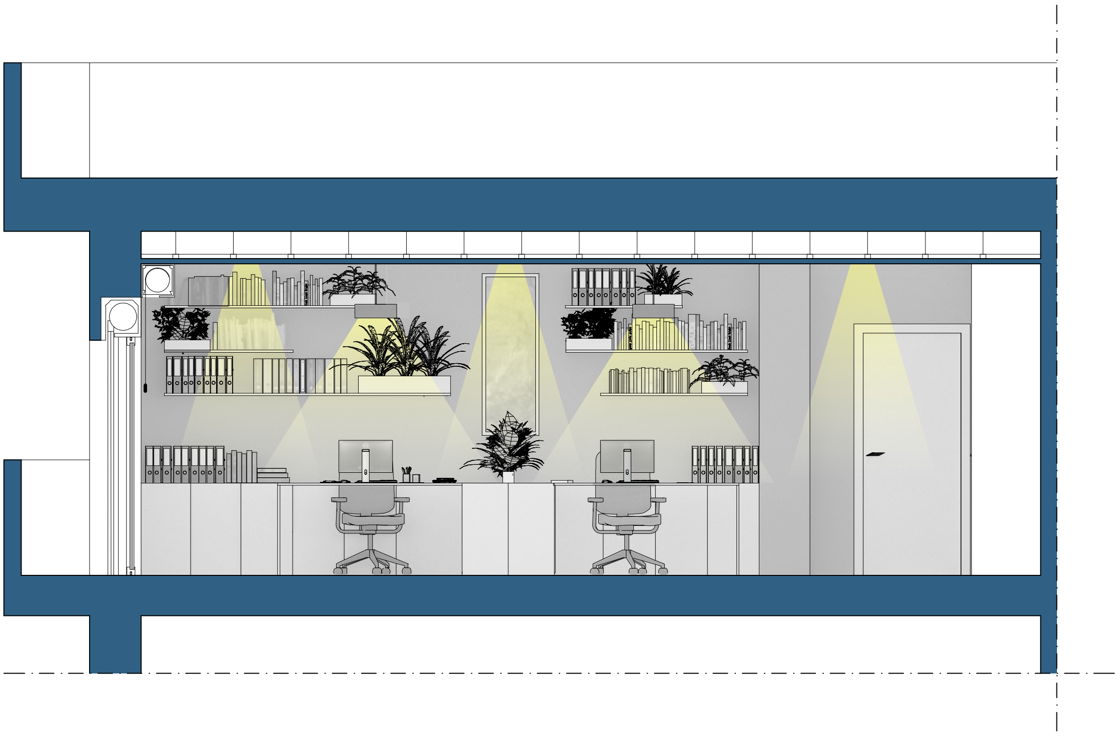


*Figure 27: both suspended luminaires and spotlights are switched on.*


## 4.4 Thermal comfort

The simulation of the thermal domain has been done with the software IDA Indoor Climate and Energy (IDA ICE) version 5.0. This software was developed by EQUA Simulation AB, a Swedish company. It is a dynamic multi-zone simulation software to assess indoor climate of individual zone and energy consumption of the entire building.

### 4.4.1 Workflow of the current state simulation

#### 4.4.1.1 Model creation in IDA ICE

The model can be done creating a new zone directly in the floor plan tab (in

which all main geometrical modelling is done) or starting from an imported CAD file or IFC file. In this case it has been done by importing the CAD file of the office. After the plan has been imported it is necessary to define the building body, that is the limit between indoor and outdoor space and thus represents the dispersing surface towards the outdoor environment. The height, floor area and volume of the building are set. At this point the zone of the office, that must be inside the building body, is defined.
IDA ICE doesn't allow to insert trees in the model, thus in the 3D panel were inserted two rectangular object that should represents the trees at 5 meters distance from south façade of the office, with transparency factor of 0.5.

#### 4.4.1.2 Model settings

In the general tab the climate conditions can be set by defining the location, the climate file and the wind profile. For this case study has been used the EPW (EnergyPlus weather format) climate file from the TMYx of Aosta. that the software transforms directly into a PRN, the weather file supported by IDA ICE.
The TMYx was taken from Climate.OneBuilding.org where is declared that the weather data used are derived from a number of public sources and that the EPW was produced by translating the source data into the EPW format. The TMYx full dataset includes years from 1957 to 2018.
Data from the climate file are:

- Dry-bulb temperature [°C]
- Relative humidity of air [%]
- Direct normal radiance [W/m$^2$]
- Wind speed [m/s]
- Cloudiness [%]

The software allows also to define the wind profile and, due to the location of ARPA headquarters, the suburban (ASHRAE 1993) has been selected.
Furthermore, it is possible to set the geographic north and to draw buildings and obstruction that stand near the simulated one in the site shading and orientation panel.
In defaults panel is possible to create the opaque envelope of the building.

Stratigraphy layers have been created in the software, attributing to each material:

- Thickness (s) [m]
- Thermal conductivity (λ) [W/(mK)]
- Density (ρ) [kg/m$^3$]
- Specific heat (c) [J/(kgK)]

The program then automatically calculates the thermal transmittance (U-value) [W/(m$^2$K)].
In the defaults panel is necessary to set also the model fidelity. For this simulation climate model fidelity has been chosen, because allows to simulate a more detailed physical model if compared to the energy model.
The model calibration has been done in free-running condition, that means without building systems working.
For this reason, controller setpoints have been set in order to don't make building systems activate (Tmin = 16 °C and Tmax = 32 °C). An ideal heater and an ideal cooler are inserted by default in each new zone, when no detailed information are available about room units. They have fixed performance parameters and don't have a specific location inside the room. For the calibration of the model, they have been considered non active.
The model has been considered only naturally ventilated because data monitoring was carried out during the Covid-19 pandemic period, thus systems for mechanical ventilation were switched off for safety reasons.
Furthermore, windows settings have been set, following the information provided by the survey. Nevertheless, it was not known the control strategy (related to the opening of the windows and to the use of both internal and external shadings), thus for shadings it has been set the sun control strategy available in the software (it means that shading is drawn when the incident solar radiation exceeds 100 W/m$^2$ on the outside of the glazing).
For windows opening has been created a control schedule that foresees the opening for half an hour at every hour in the occupation period (from 9:00 to 17:00). This schedule has been created based on $CO_2$ levels measured inside the office (see paragraph 4.5.1).
Additionally, occupants, equipment and lights can be defined for the zone.
Occupants' activity and clothes influence their thermal perception, therefore in standard ISO 7730 are defined values for both. To sedentary activity,

typical of offices, is attributed 1.2 met value. Considered the period in which the measures used for the calibration of the model have been taken (18/08/2020-03/09/2020) the clo value set is 0.7 ± 0.25, associated to workers with light dress. Occupancy schedule also has been defined following indications of real working hours in that office: from 9:00 to 17:00 from Monday to Friday. The same schedule has been used for equipment (three standard PC) and electric lights (fluorescent lights).

#### 4.4.1.3 Model calibration and simulation results

The parameters used for the calibration of the model in IDA ICE are indoor air temperature and $CO_2$ concentration, that have been measured on-site for the thesis work of Niccolò Oggiani. Subsequently PMV-PPD indexes and adaptive comfort model he calculated have been compared with the ones provided by the software. In Figure 28 are presented indoor air temperature and outdoor air temperature measured on-site and given by the software.

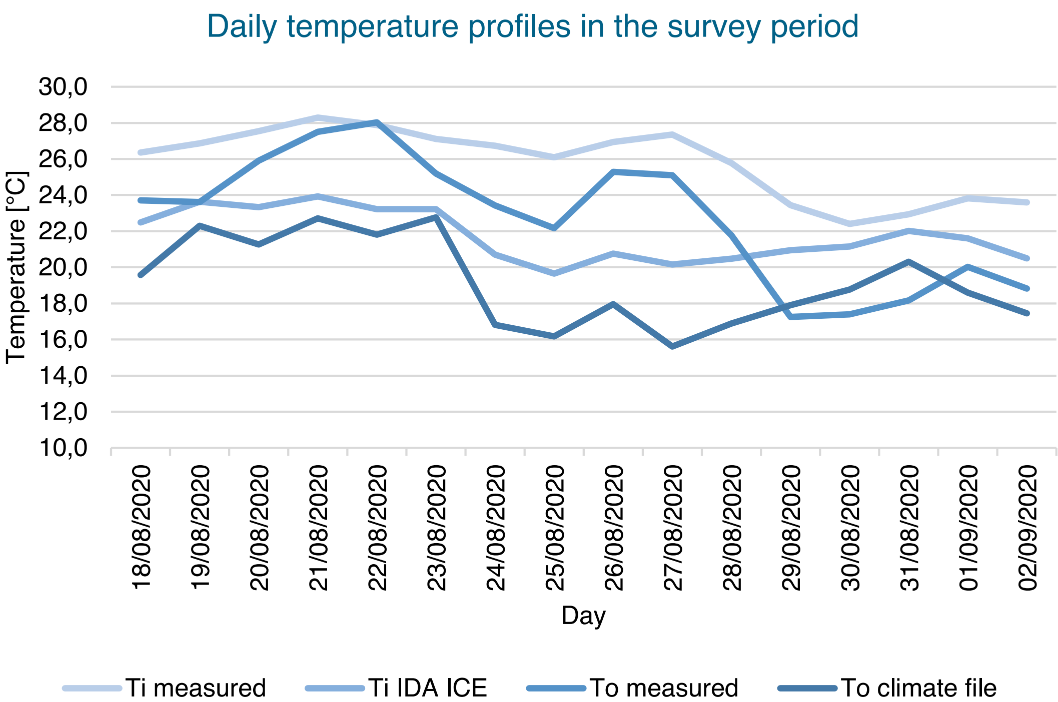



*Figure 28: daily temperature profiles in the survey period: indoor air temperature measured, outdoor air temperature measured, indoor air temperature simulated and outdoor air temperature of the climate file.*

The outdoor air temperature in IDA ICE is determined through the use of the climate file and it can be noticed the difference between it and the outdoor air temperature measured during the survey period. To overcome this drawback the aim has been to normalise indoor air temperature measured and indoor air temperature simulated respect to the corresponding outdoor air temperature. It has been verified whether the difference in percentage between the measured temperatures normalized and the simulated temperatures normalized was less than 20%. This process has been done for three days, the ones in which daily punctual measures where performed: 18/08/2020, 24/08/2020 and 02/09/2020.

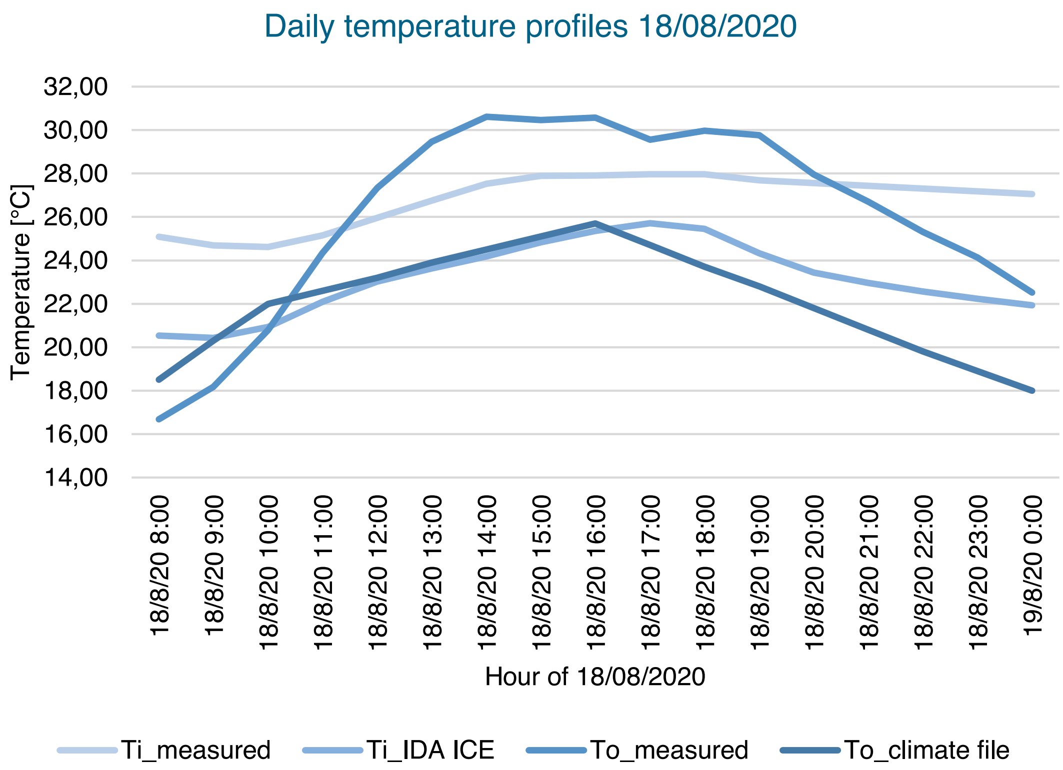



*Figure 29: hourly temperature profiles for 18/08/2020: indoor air temperature measured, outdoor air temperature measured, indoor air temperature simulated, outdoor air temperature of the climate file.*

In the following table (Table 15) are shown hourly values (from 8:00 to 0:00) of the ratio between indoor air temperature measured and outdoor air temperature measured, and between indoor air temperature simulated and outdoor air temperature of the climate file.

*Table 15: hourly values of normalisation of measured and simulated temperature.*

| Hour | Normalisation of the simulated temperature | Normalisation of the measured temperature | Percentage difference of normalization values |
|---|---|---|---|
| 08:00:00 | 1.50 | 1.11 | 35% |
| 09:00:00 | 1.36 | 1.01 | 35% |
| 10:00:00 | 1.18 | 0.95 | 24% |
| 11:00:00 | 1.03 | 0.98 | 6% |
| 12:00:00 | 0.95 | 0.99 | 4% |
| 13:00:00 | 0.91 | 0.99 | 8% |
| 14:00:00 | 0.90 | 0.99 | 9% |
| 15:00:00 | 0.92 | 0.99 | 7% |
| 16:00:00 | 0.91 | 0.99 | 7% |
| 17:00:00 | 0.95 | 1.04 | 9% |
| 18:00:00 | 0.93 | 1.07 | 13% |
| 19:00:00 | 0.93 | 1.07 | 13% |
| 20:00:00 | 0.99 | 1.07 | 8% |
| 21:00:00 | 1.03 | 1.10 | 7% |
| 22:00:00 | 1.08 | 1.14 | 5% |
| 23:00:00 | 1.13 | 1.18 | 4% |
| 00:00:00 | 1.20 | 1.22 | 1% |

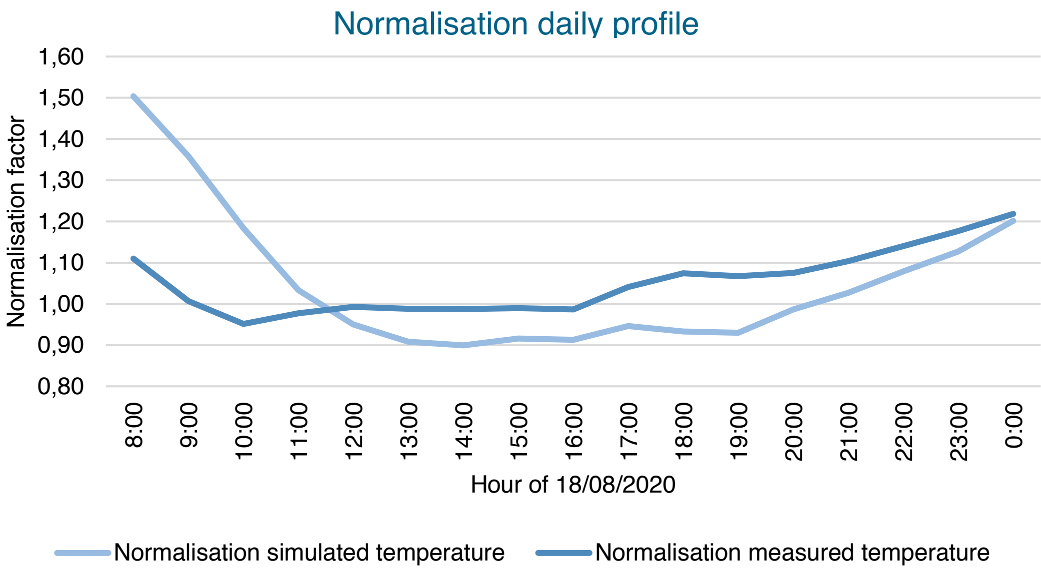



*Figure 30: normalization of temperatures hourly profile.*

The mean daily normalization of measured temperature is equal to 1.05 and the mean daily normalization of simulated temperature is equal to 1.05, thus the daily difference in percentage of the normalisation of temperature for 18/08/2020 is of 0%.
The same operation has been done for 24/08/2020 and for 02/09/2020. Results are presented in Table 16.

*Table 16: percentage difference of normalization values for 24/08/2020 and for 02/09/2020.*

| | **24/08/2020** | **02/09/2020** |
|---|---|---|
| Mean daily normalization of measured temperature | 1.10 | 1.23 |
| Mean daily normalization of simulated temperature | 1.30 | 1.16 |
| Percentage difference of normalization values | 15.96% | 6.29% |

Since normalisation daily mean values have a difference in percentage lower that 20% in all the three days, it can be said that the model is calibrated.
Subsequently, values of PMV and PPD presented in the thesis work “Qualità dell’ambiente interno e comfort globale: misure in campo ed analisi nella sede dell’ARPA della Valle d’Aosta” have been compared to values given by IDA ICE software.
It can be highlighted how the differences between indoor air temperature measured and indoor air temperature simulated, caused by the difference between outdoor air temperature measured and outdoor air temperature of the climate file determine differences in PMV and PPD measured and simulated values.

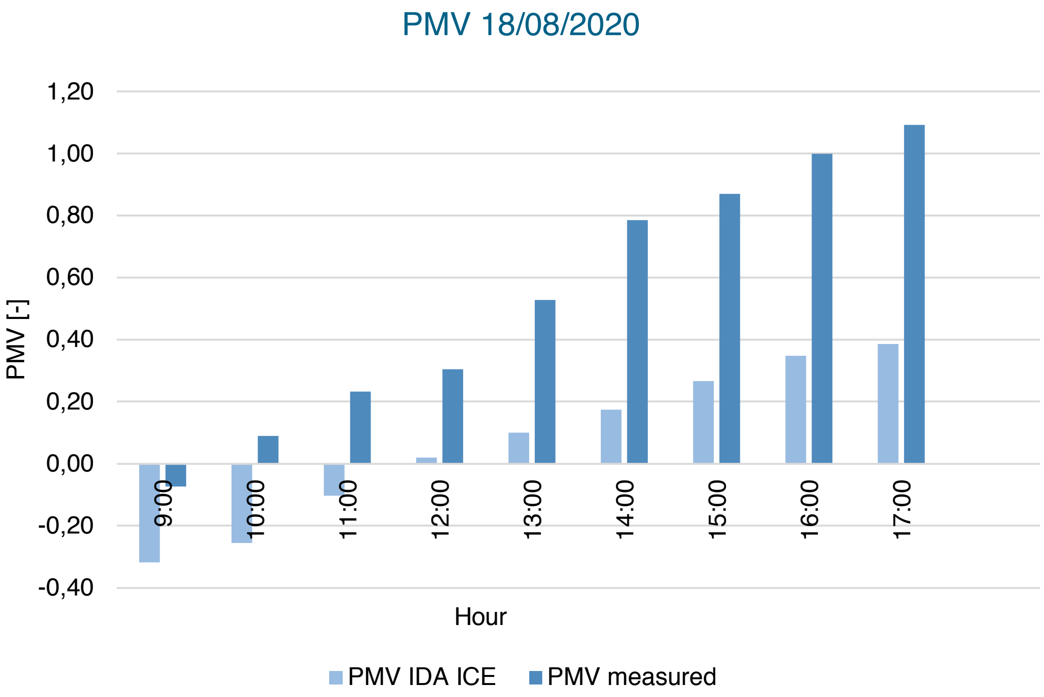



*Figure 31: PMV values from IDA ICE software and from measured data for 18/08/2020.*

The mean daily percentage difference between PMV from IDA ICE and PMV from measured values is of 6.83%.

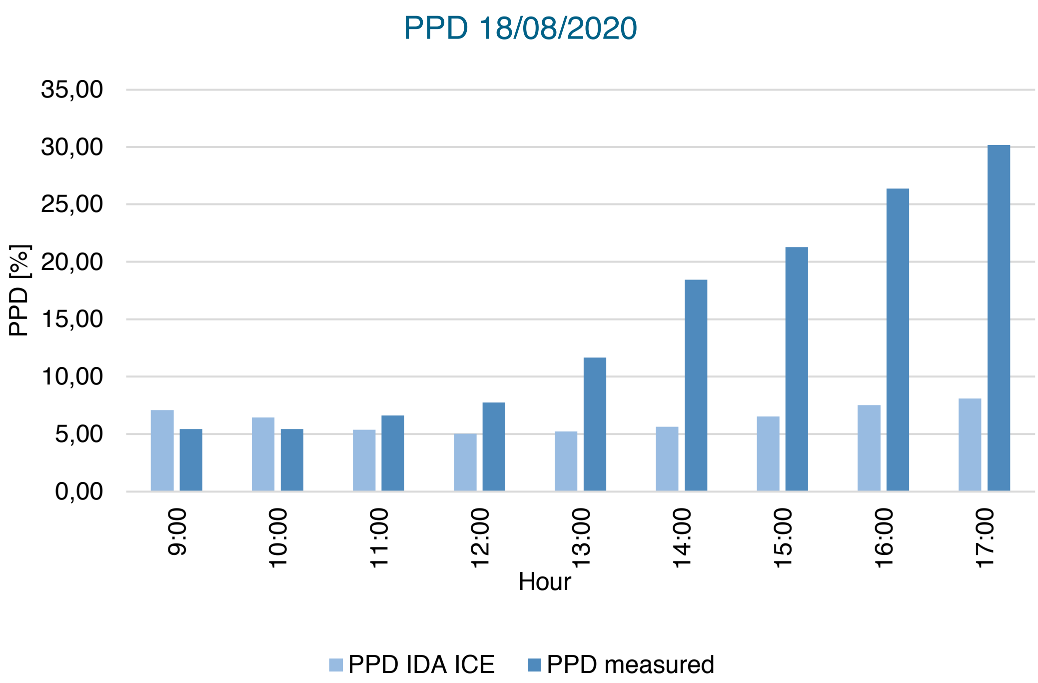



*Figure 32: PPD values from IDA ICE software and from measured data for 18/08/2020.*

The mean daily percentage difference between PPD from IDA ICE and PPD from measured values is of 1.34%.

Adaptive comfort model, obtained from values measured of indoor operative temperature and outdoor air temperature made by N. Oggiani, has been compared to the one obtained with the same procedures but starting from indoor operative temperature and outdoor air temperature given by the software.

As standard EN 16798 specifies, this method can be used to assess conditions in office buildings and other buildings of similar type, without mechanical cooling systems, where mainly sedentary activities are performed, there is easy access to operable windows and occupants can adapt their clothing to the indoor thermal conditions.

For its evaluation it has been calculated (by means of the formula present in EN 16798) the value of the running mean outdoor temperature [°C] based on the mean temperatures of the days preceding the measurement day and the operative air temperature of the office. It has been done for 18/08/2020, one out of the three days of punctual measurements.

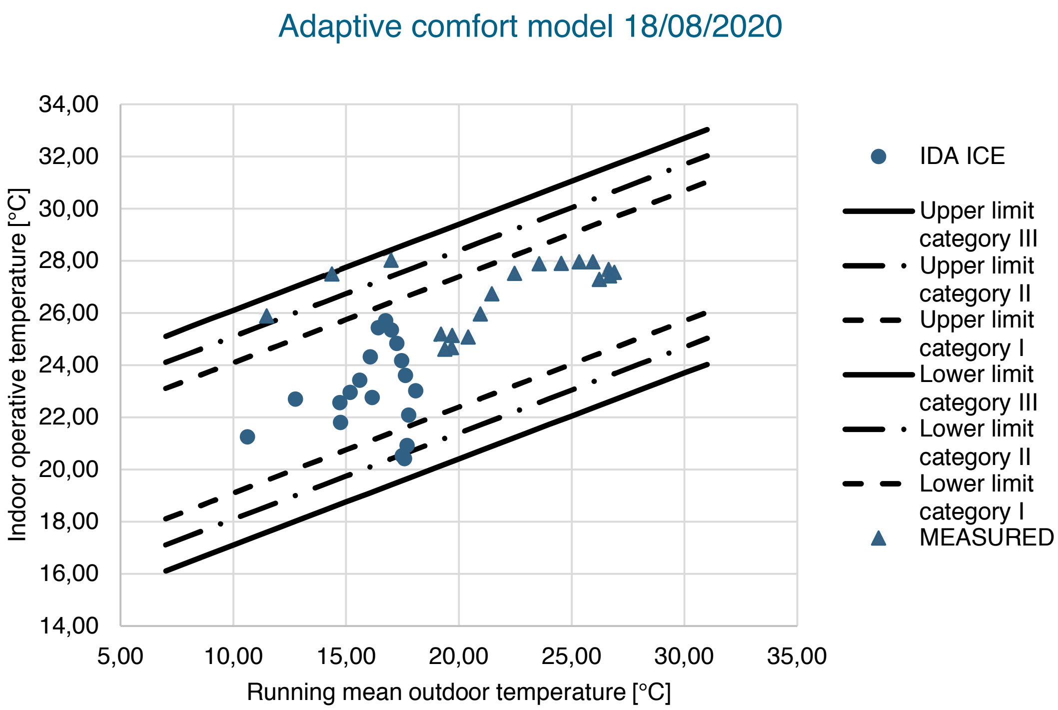



*Figure 33: comparison of adaptive comfort model of day 18/08/2020 from measured values and from simulated value.*

In the following table are presented the percentages of hours of day 18/08/2020 that fall into the three different categories of the model. It can be noticed that for both the cases, measured and simulated, for most of the time the environment is assessed belonging to the higher acceptability category.

*Table 17: percentages of hours of day 18/08/2020 that fall into the three categories of adaptive comfort model.*

| | **Category 1** | **Category 2** | **Category 3** |
|---|---|---|---|
| Measured | 84.21% | 0.00% | 15.79% |
| Simulated | 84.21% | 10.53% | 5.26% |

### 4.4.2 Workflow of the project simulation

From thermal point of view, it has been necessary to improve opaque and transparent envelope performance to meet the requirements of DM 26/06/2015 (Decreto interministeriale 26 giugno 2015 - Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifice) appendix B (requisiti specifici per gli edifici esistenti soggetti a riqualificazione energetica). In particular, thermal transmittance (U-value) must respect specific thresholds required. For this reason, it has been necessary to create an outer coat of the opaque external envelope and new windows have been chosen. Starting from the existing envelope, stratigraphy layers have been modified.

*Table 18: U-value required by DM 26/06/2015-Appendix B and reached with the project.*

| CLIMATE ZONE E | U-value [W/(m$^2$K)] (DM 26/06/2015) | U-value [W/(m$^2$K)] project |
|---|---|---|
| External wall | 0.28 | 0.24 |
| Roof | 0.24 | 0.19 |
| Window | 1.4 | 1.3 |

The choice for the new glazed components, as well as for the intervention on the opaque envelope, was dictated by the need to determine a balance between the needs of each single domain.
Glaze and frame parameters, internal shading and external shading have been set. The control strategy used for internal and external shadings is the sun control strategy, as was for the current state.
In this case, the simulation has been done for an entire year, therefore the schedule of opening of the windows for natural ventilation has been done following the indications provided by IBN (Institut Für Baubiologie), that foresees 4-6 minutes per day in winter and 25-30 minutes per day in summer of opening.
Furthermore, the simulation has been performed in “ideal loads” to calculate heating and cooling loads and to understand the “ideal” thermal needs of the office. To do so, the controller setpoints have been set in order to make ideal heater and ideal cooler activate, based on indications “parameters and setpoints” present in Annex C of standard EN 16798.

- $T_{min}$ = 20 °C
- $T_{max}$ = 26 °C
- Max. $CO_2$ concentration = 500 ppm
- Min. relative humidity = 25%
- Max. relative humidity = 60%

Air Handling Unit has been inserted in the office and supply air and return air have been set at 0.8 $l/(sm^2)$, as foreseen in EN 16798.
The presence of building systems allows to maintain along the whole year comfort conditions.
The project foresees the presence of four people in the office, with an occupancy schedule that follows the real working hours: from 9:00 to 17:00. The same schedule has been attributed to equipment (four PC) and lights. To make occupants have the correct clothing thermal insulation in relation to the season, a schedule that determines the value of clo along the entire year has been created.

#### 4.4.2.1 Simulation results

A first simulation in free running has been run both for the current state and the project for an entire year, and indoor air temperature have been compared. As it could be expected, the improvement of the performance of the opaque and transparent envelope can be noticed, because temperature for the project are higher along the whole year. Are higher also in summer due to the higher level of insulation.

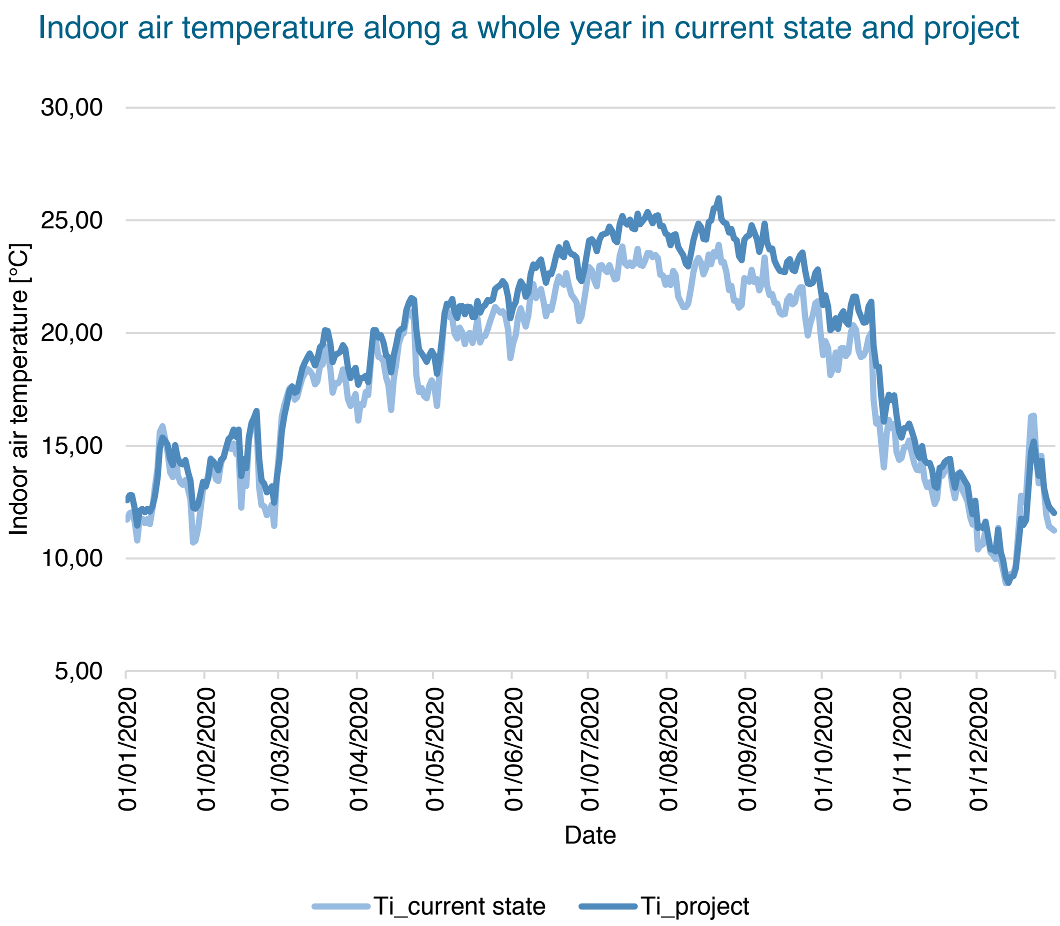



*Figure 34: comparison between indoor air temperature in the current state and indoor air temperature in the project, along a whole year.*

Subsequently, to assess the improvement of the performance of transparent and opaque envelope it has been necessary to run an "ideal loads" simulation, both for the current state and for the project. In this way it has been possible to make a comparison between heating load and cooling load of the current state and of the project. As it could be expected there has been a proper improvement in wintertime: heating load is lower of 52%. On the other side, due to the high level of insulation performed by the envelope, the cooling load has had a little reduction, of 1.24%.

*Table 19: comparison of the thermal loads between current state and project.*

| | Heating load (kWh/m²) | Cooling load (kWh/m²) |
|---|---|---|
| Current state | 155.5 | 24.27 |
| Project | 74.85 | 23.97 |

## 4.5 Indoor air quality

The simulation of IAQ has been done with the software IDA Indoor Climate and Energy (IDA ICE) version 5.0, too.

### 4.5.1 Workflow of the current state simulation

The model is the same done for thermal and visual domains, therefore settings are the same. It should be reminded that during the survey period the air conditioning system was switched off for safety reasons, due to Covid-19 virus. It is important to remember also that the window opening schedule has been determined through the calibration of the model.

#### 4.5.1.1 Model calibration and simulation results

The calibration of the model for what concerns the indoor air quality parameters has been based on $CO_2$ concentration levels. This kind of operation implies the knowledge of occupant behaviour in relation to the windows opening. Unfortunately, this information was not owned, therefore it

has been necessary to start from the values of $CO_2$ concentration measured on-site to determine the windows opening strategy necessary to reach, through the software simulation, the $CO_2$ concentration levels measured. In this way it has been determined the schedule regarding the windows opening that must be inserted in the software. To reach the levels of $CO_2$ measured it has been necessary to set windows opening for half an hour for every hour of the occupied time lapse (9:00-17:00).
Although the simulated $CO_2$ levels are of an order of magnitude similar to those measured, it can be seen from the graph that the profiles reflecting the trend of $CO_2$ levels in the environment are not exactly superimposable. This result is due to the uncertainty regarding the behaviour of the occupants in relation to windows management.
The calibration operation has been done for the three days of punctual measurement held: 18/08/2020, 24/08/2020 and 02/09/2020.

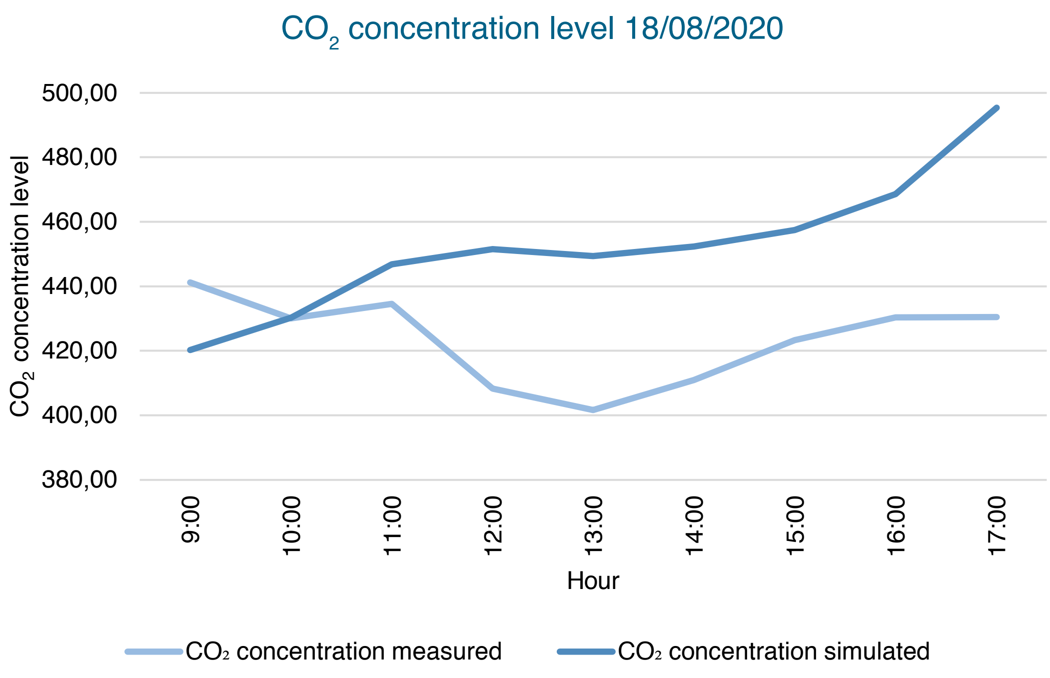



*Figure 35: $CO_2$ concentration level trend from 9:00 to 17:00 of 18/08/202.*

Table 20 presents the values of difference in percentage between the mean daily $CO_2$ concentration level monitored on-site and mean daily $CO_2$ concentration level taken from IDA ICE software.

*Table 20: percentage difference between CO2 mean daily concentration levels monitored and taken from IDA ICE software.*

| | **18/08/2020** | **24/08/2020** | **02/09/2020** |
|---|---|---|---|
| Mean daily $CO_2$ concentration level monitored on-site | 423.42 | 434.88 | 459.48 |
| Mean daily $CO_2$ concentration level from IDA ICE | 452.46 | 423.36 | 428.62 |
| Percentage difference | 7% | 3% | 7% |

### 4.5.2 Workflow of the project simulation

Also for the project, the model is the same used for thermal and visual domain simulations. It should be reminded that the simulation has been performed in "ideal loads", the controller setpoints have been set based on indications "parameters and setpoints" present in Annex C of standard EN 16798 and the schedule attributed to the opening of windows has been done following the indications provided by IBN (Institut Für Baubiologie) (see paragraph 4.4.2).

#### 4.5.2.1 Simulation results

The simulation of the project has been carried out for an entire year in "ideal loads", as previously mentioned. The presence of building systems (ideal heater, ideal cooler, air handling unit), with the aforementioned settings, allows to maintain along the whole year comfort conditions. $CO_2$ concentration level is always kept under 500 ppm.

## 4.6 Acoustic comfort

The simulation of the acoustic domain has been done with the software Odeon version 16 and ECHO version 8.1.
The first one, Odeon, has been used for simulating and measuring the interior acoustics of buildings, while ECHO was developed by ANIT for the calculation of passive acoustic requirements (DPCM 5-12-1997), the acoustic class of real estate units (UNI 11367) and the verification of the internal acoustic characteristics of the rooms (UNI 11532).
These software have been used to evaluate acoustical properties in offices and to compare alternative design solutions. In this case study, Odeon has been useful to simulate reverberation time, while Echo to study noise insulating.

### 4.6.1 Workflow of the current state simulation

The choice to use Odeon for the simulation of reverberation time was made for the possibility to set specific absorption and scattering coefficients, defining in a more detailed way the space.

#### 4.6.1.1 Model creation in ODEON

For the acoustic simulation the first step was the creation of a 3D model with furniture, thus the room model must include tables, chairs, bookshelves, but with no people present. The model can be done using a software as SketchUp and imported in Odeon. It has to be simple in order to reduce the number of surfaces, resulting to cleaner models and faster computation.

#### 4.6.1.2 Model settings

After the model has been imported, it is necessary to assign to each layer, referred to the materials, absorption coefficients. Table 21 shows the absorption coefficients, they control the amount of sound energy that is absorbed by a surface. Another element that has been defined is the scattering coefficient of each surface that determines the way in which sound energy is reflected.

*Table 21: the first column shows the material assigned for each surface, the second one the source from which derive absorption coefficients for each frequency.*

| Material | Source | Absorption coefficients [Hz] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 63 | 125 | 250 | 500 | 1k | 2k | 4k | 8k |
| Light upholstered chairs | UNI 11531-1 | 0.09 | 0.09 | 0.09 | 0.14 | 0.26 | 0.42 | 0.5 | 0.55 |
| Desk | S. Calabrese's thesis | 0.44 | 0.44 | 0.33 | 0.22 | 0.34 | 0.33 | 0.33 | 0.32 |
| Double-glazed windows and aluminium window | UNI EN 12354-6 | 0.15 | 0.15 | 0.15 | 0.1 | 0.03 | 0.02 | 0.02 | 0.01 |
| Sound-absorbing counter-offer | Knauf Micro M1 panel | 0.7 | 0.7 | 0.95 | 1 | 1 | 1 | 1 | 1 |
| Wood doors | UNI EN 12354-6 | 0.14 | 0.14 | 0.14 | 0.12 | 0.08 | 0.08 | 0.08 | 0.07 |
| Gypsum | BB93_2 x 13mm plasterboard on steel frame, 50mm mineral wool in cavity, surface painted | 0.15 | 0.18 | 0.2 | 0.25 | 0.1 | 0.04 | 0.05 | 0.05 |
| Tiles floor | UNI 11531-1 | 0.01 | 0.03 | 0.07 | 0.1 | 0.04 | 0.02 | 0.02 | 0.02 |
| Wood shelves | UNI EN 12354-6 | 0.14 | 0.14 | 0.14 | 0.12 | 0.08 | 0.08 | 0.08 | 0.07 |

*Table 22: scattering coefficient of the surfaces.*

| Surface | Scattering value |
|---|---|
| Light upholstered chairs | 0.3 |
| Desk | 0.5 |
| Double-glazed windows and aluminum window | 0.3 |
| Sound-absorbing counter-offer | 0.05 |
| Wood doors | 0.05 |
| Gypsum | 0.05 |
| Tiles floor | 0.05 |

#### 4.6.1.3 Calibration of the model

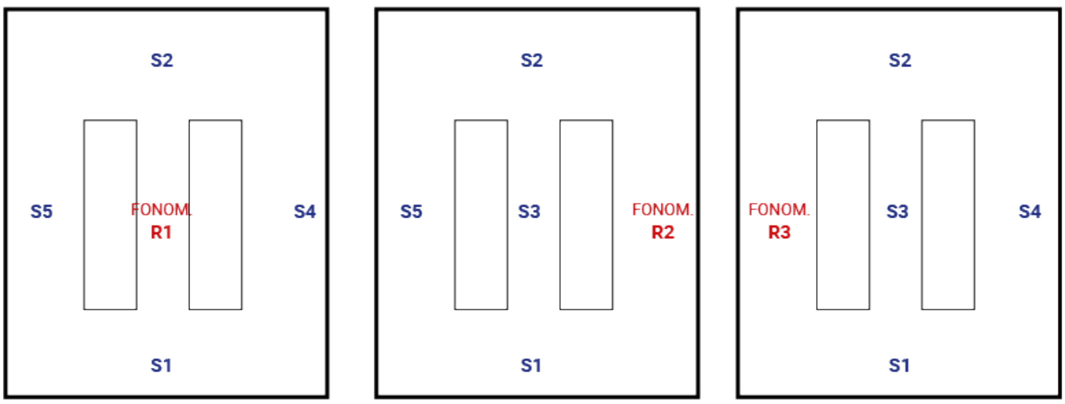
The calibration of the model has been useful for attributing to the materials of the model characteristics similar to those of real surfaces, changing absorption coefficients if necessary. The parameter used to calibrate the model has been the reverberation time, because it depends on the size of the room and the ability of the surfaces inside of it to reflect or absorb sound waves.
For an accurate calibration has been set the sound power spectrum of the source that represents the same kind of clapper with rubber surfaces used during measurement step.

*Table 23: sound power spectrum of clapper source.*

| Frequency [Hz] | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|---|
| Sound pressure level [dB] | 78 | 78 | 81 | 95 | 102 | 104 | 102 | 98 |

#### 4.6.1.4 Reverberation time measurement

Reverberation time $T_{30}$ has been measured through a sound meter in the following measurement positions, thus the simulation for the calibration was done in the same points. Subsequently, the measured values of each position have been averaged. $T_{30}$ indicates a decay of 30 dB, easier to be appreciate during the measurement than a decay of 60 dB.




R1: Measure 1 R2: Measure 2 R3: Measure 3

#### 4.6.1.5 Simulation

The same procedure (three different measurements averaged) has been used during the simulation phase. Five different sources with the sound power spectrum of the clapper have been allocated in the correct positions, after that the three receivers. In the section "Auralisation setup" the receiver type set was "unity_SRate44100_Apass0,50_Astop40,00_BOvrLap100%_PPrHRTF", more similar to a phonometer.
Before starting the simulation, when materials and source have been set, a quick calculation of the reverberation time has been launched, to understand room setup value of the maximum reflection order, that usually have to be 2/3 of the time resulted.
To each receiver have been associated 4 sources, obtaining three different combinations, like during the measurements.
The result of the simulation has been compared, for each frequency, with the measured value, excluding the values with a difference of more than 20% of the measured value for each frequency. In this case the absorption coefficient of that particular frequency was slightly corrected for materials with a larger surface area, because they affect widely the result.

*Table 24: comparison between simulated and measured reverberation time for each frequency.*

| Frequency [Hz] | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|---|
| $T_{30}$ measured [s] | 0.41 | 0.41 | 0.28 | 0.29 | 0.46 | 0.5 | 0.5 | 0.41 |
| $T_{30}$ simulated [s] | 0.39 | 0.37 | 0.35 | 0.35 | 0.40 | 0.51 | 0.50 | 0.36 |

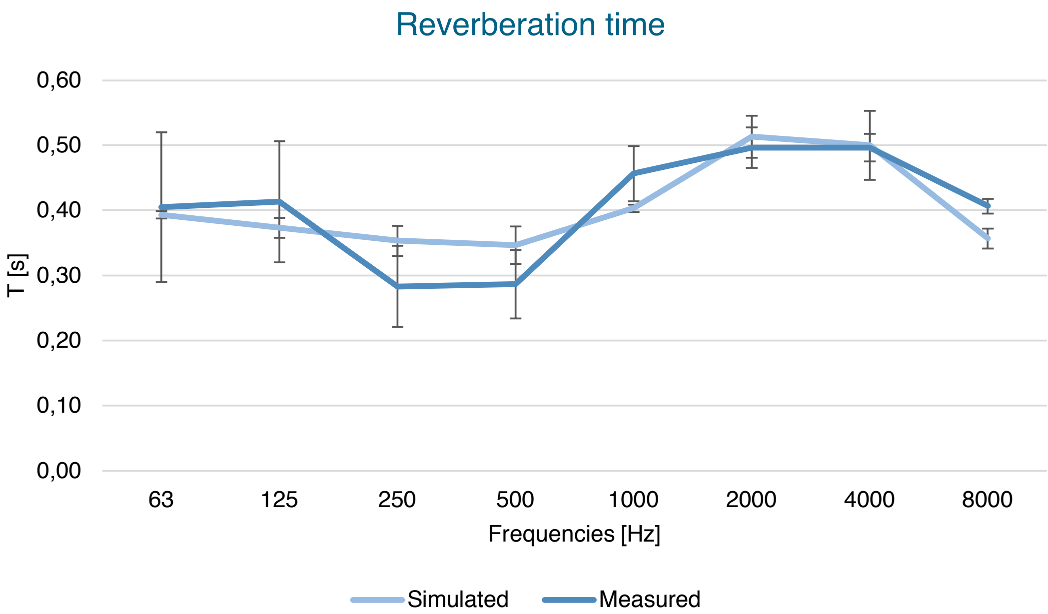



*Figure 36: the graphic shows the comparison of simulated and measured reverberation time.*

The reverberation time values have a peak at the frequencies of 250 and 500 Hz.
The calculation of reverberation time allowed to evaluate STI (speech transmission index), that represents speech intelligibility. The value reached is 0.8, that represents an excellent condition.

### 4.6.2 Workflow of the project simulation

The project foresees a new layout with new surfaces, thus it was necessary to recalculate the reverberation time.
Measured value represented the highly efficient level of the reverberation time of comfort protocol, thus was important to ensure the same acoustic condition, changing the layout.
The different distribution of furniture brought to the necessity to improve the acoustic performance, working on the suspended ceiling, because it is one of the most diffuse surface and there are a lot of commercial solutions with high acoustic performances. Absorption coefficients of the project state are listed below.

Table 25: absorption coefficients of materials in the project state.

| Material | Source | Absorption coefficients [Hz] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 63 | 125 | 250 | 500 | 1k | 2k | 4k | 8k |
| Light upholstered chairs | UNI 11531-1 | 0.09 | 0.09 | 0.09 | 0.14 | 0.26 | 0.42 | 0.5 | 0.55 |
| Desk | S. Calabrese's thesis | 0.44 | 0.44 | 0.33 | 0.22 | 0.34 | 0.33 | 0.33 | 0.32 |
| Double-glazed windows and aluminium window | UNI EN 12354-6 | 0.15 | 0.15 | 0.15 | 0.1 | 0.03 | 0.02 | 0.02 | 0.01 |
| Sound-absorbing counter-offer | Rockfon Monoacoustic | 0.25 | 0.25 | 0.75 | 1 | 1 | 1 | 1 | 1 |
| Wood doors | UNI EN 12354-6 | 0.14 | 0.14 | 0.14 | 0.12 | 0.08 | 0.08 | 0.08 | 0.07 |
| Gypsum | BB93_2 x 13mm plasterboard on steel frame, 50mm mineral wool in cavity, surface painted | 0.15 | 0.18 | 0.2 | 0.25 | 0.1 | 0.04 | 0.05 | 0.05 |
| Parquet | UNI 11531-1 | 0.04 | 0.04 | 0.05 | 0.6 | 0.07 | 0.07 | 0.06 | 0.06 |
| Wood shelves | UNI EN 12354-6 | 0.14 | 0.14 | 0.14 | 0.12 | 0.08 | 0.08 | 0.08 | 0.07 |

The calculation was done simultaneously for all the receivers, placed in the position of three chairs, combined with a source, with the same sound power spectrum used for the simulation. It was not possible to place source and receivers in the same position of the first simulation, due to the change in the layout of the office. The results of the reverberation time of the project are compared to the current state values in Table 26.

Table 26: reverberation time of the current state, compared to the project values.

| Frequency [Hz] | 63 | 125 | 250 | 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|---|---|
| $T_{30}$ current state [s] | 0.39 | 0.37 | 0.35 | 0.35 | 0.40 | 0.51 | 0.50 | 0.36 |
| $T_{30}$ project [s] | 0.44 | 0.45 | 0.46 | 0.48 | 0.48 | 0.51 | 0.49 | 0.38 |

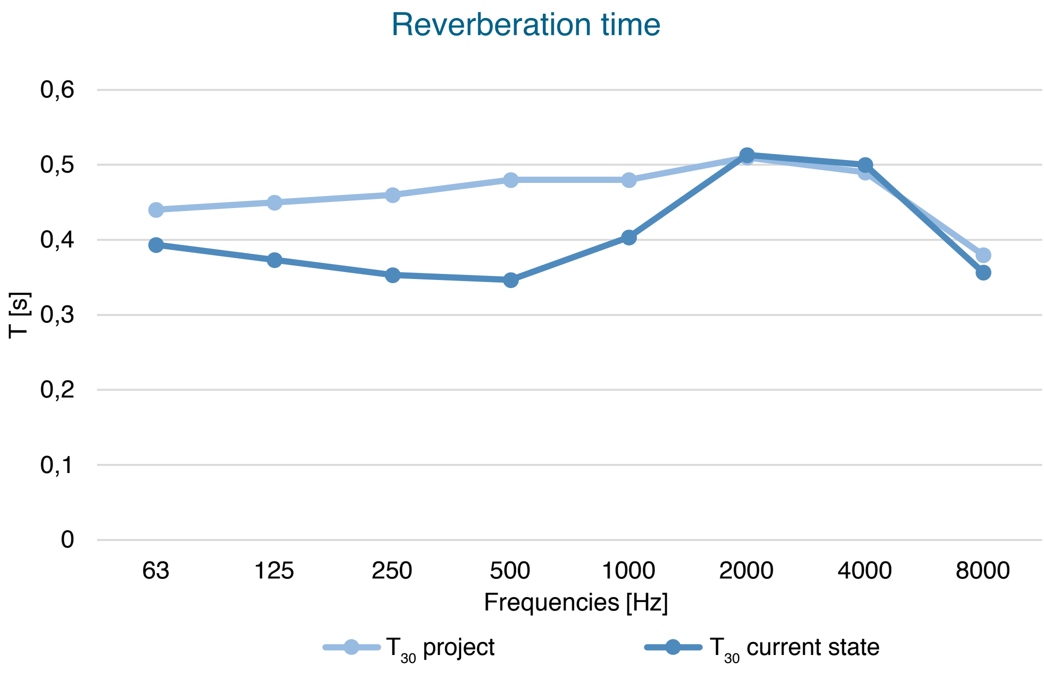



*Figure 37: $T_{30}$ profile for current state and project state.*

The values from project are slightly higher because changing the layout increase the reflective surfaces, but it is still an optimal value for reverberation time in this type of office.

### 4.6.3 Simulation with ECHO 8.1

The software ECHO 8.1 has been used to simulate and analyse the soundproofing power of internal and external walls, for current state and project.

The software does not require the creation of a model, but the definition of the characteristics of the materials (such as density) and stratigraphy (thickness, layers). When all the stratigraphies and their properties have been defined, weighted sound reduction index ($R_w$) has been calculated, for each stratigraphy. This index specifies the acoustic performance of a building component. Subsequently, combining the different stratigraphies and analysing the joint points, it has been possible to assess the weighted standardized level difference ($D_{nTw}$), that describes the acoustic performance of a completed part of a building. Connection points cause the passage of

the noise.
$D_{2m,nTw}$ indicates the sound insulation power of the façade, important to reduce the external noise. For calculating this index are considered the presence of windows, their weighted sound reduction and the façade profile. Due to the position of this office, facing the garden and not a road, for the analysis of $D_{2m,nTw}$ it has not been necessary to consider the road as a noise source. Table 27 shows the improvement of the insulating performance, thanks to the external insulation.

*Table 27: comparison between insulation from internal noise ($D_{nTw}$) and soundproofing of the façade ($D_{2m,nTw}$).*

| | Current state | Project |
|---|---|---|
| **$D_{nTw}$ [dB]** | 42.4 | 45 |
| **$D_{2m,nTw}$ [dB]** | 39.9 | 49.9 |

The results show an increase of the insulating performance due to the density of the cellulose panels, because acoustic performance of the materials is strongly related to their density.

## 4.7 Visual comfort, natural lighting

The simulation of the visual domain, for what concerns the natural lighting, has been done with the software IDA Indoor Climate and Energy (IDA ICE) version 5.0, too.

### 4.7.1 Workflow of the current state simulation

The model is the same done for thermal domain and indoor air quality, therefore settings are the same.
Important for what concerns the natural lighting is the control strategy of internal and external shading, that, as previously mentioned (see paragraph 4.4.1), has been set as sun control strategy.

#### 4.7.1.1 Simulation results

For this domain it has not been possible to carry out a calibration of the model, due to the absence of information related to external natural lighting conditions.
For this reason, the model has been calibrated by means of thermal and IAQ domains and subsequently it has been possible to simulate the indoor lighting conditions.
Simulation is set in the Daylight tab, where it is possible to carry out three different kinds of simulations:

- Daylight factor [%]
- Illuminance [lx]
- Whole year illuminance [lx]

To perform these simulations the measuring plane has been set at 0.85 m height above floor and 0.5 m distance from walls, as recommended by standard EN 17037.
Factors of reflectance, transmittance, diffusion, specularity and roughness are associated to each surface in the room, in relation to the typology of material and the colour.
The daylight factor has been calculated with CIE overcast sky conditions and without shadings drawn. It resulted equal to 2.8%.
The whole year illuminance calculation allows to obtain yearly dynamic simulation of illuminance, spatial daylight autonomy ($sDA_{300,\ 50\%}$) and annual sunlight exposure ($ASE_{1000,250h}$). It has been performed with climate-based sky (Perez). To obtain these values the model has been done following specific indications of standard IES Lighting Measurements (LM) 83-12, Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE).
$sDA_{300,\ 50\%}$ is equal to 72%, $ASE_{1000,250h}$ is equal to 0%.
Values of illuminance for the two equinoxes (21/03/2020 and 23/09/2020) at 9:00, 12:00 and 15:00 are then reported.

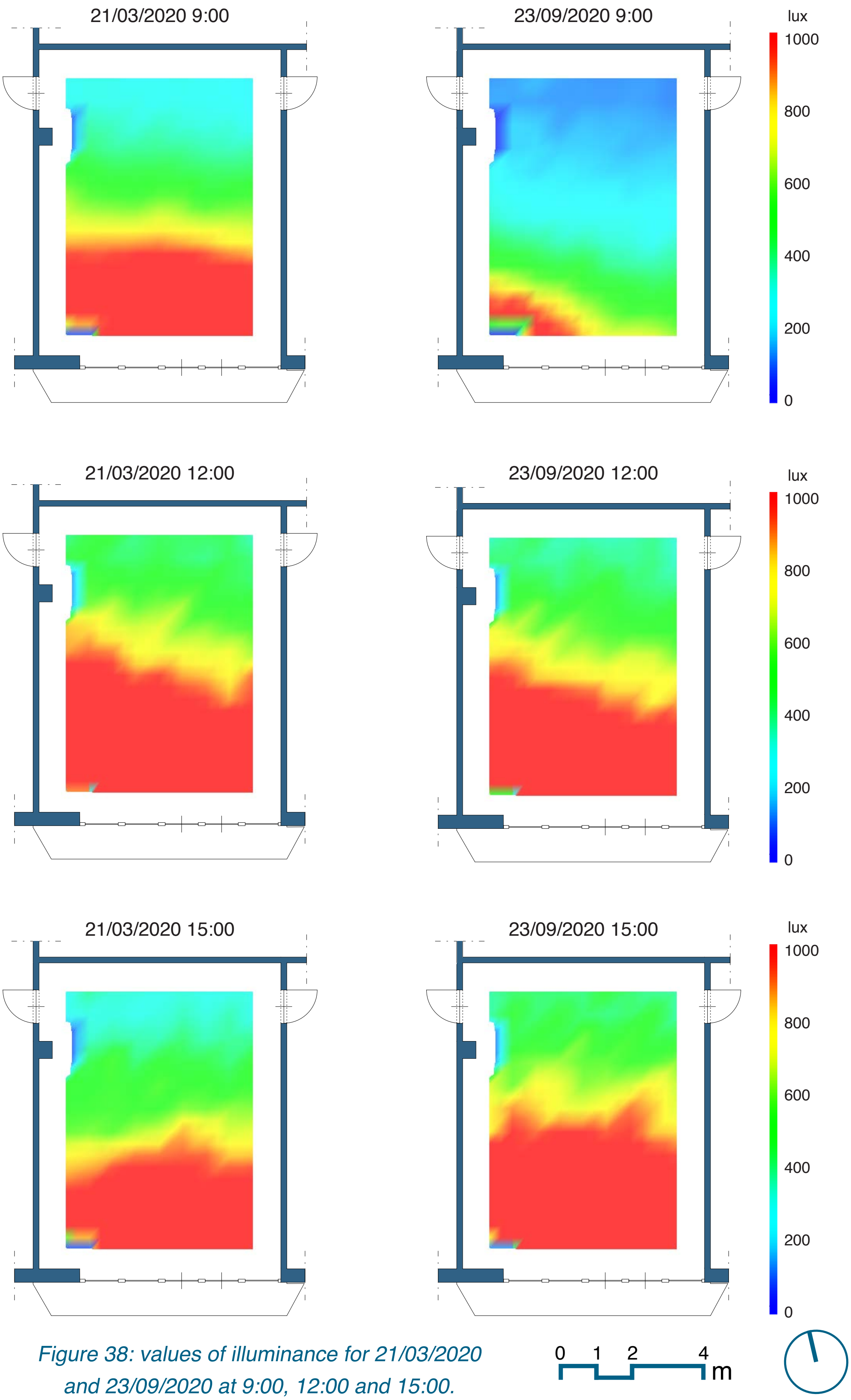


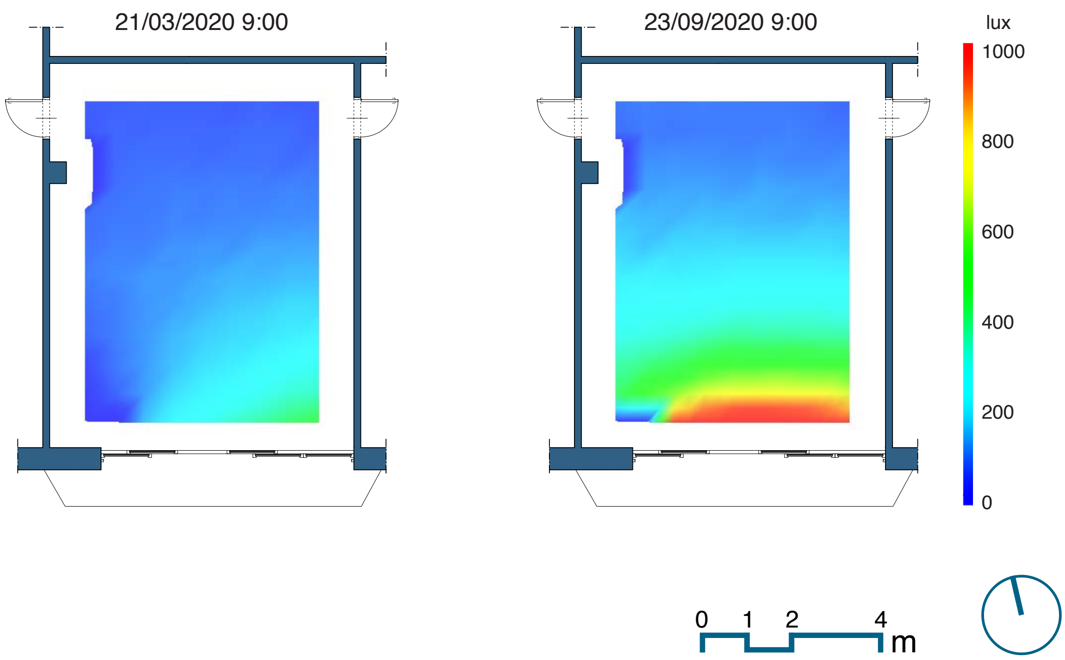

Figure 38: values of illuminance for 21/03/2020 and 23/09/2020 at 9:00, 12:00 and 15:00.

### 4.7.2 Workflow of the project simulation

As previously mentioned, the choice for the new glazed components was dictated by the need to determine a balance between the needs of each single domain. Also for the project simulation windows, internal shading (interior roller shade) and external shading (exterior roller shade) parameters have been set. The control strategy used for internal and external shadings is the sun control strategy, as was for the current state.

#### 4.7.2.1 Simulation results

For the project, daylight factor and whole year illuminance simulation have been run too. Measuring plane has been set as for the current state simulation (as recommended by standard EN 17037) at 0.85 m height above floor and 0.5 m distance from walls. Surfaces properties have been modified in relation to the project solutions adopted.
The daylight factor is equal to 3.8%, whereas $sDA_{300,\,50\%}$ is equal to 75% and $ASE_{1000,250h}$ is equal to 0%.
Values of illuminance for the two equinoxes (21/03/2020 and 23/09/2020) at 9:00, 12:00 and 15:00 are then reported.



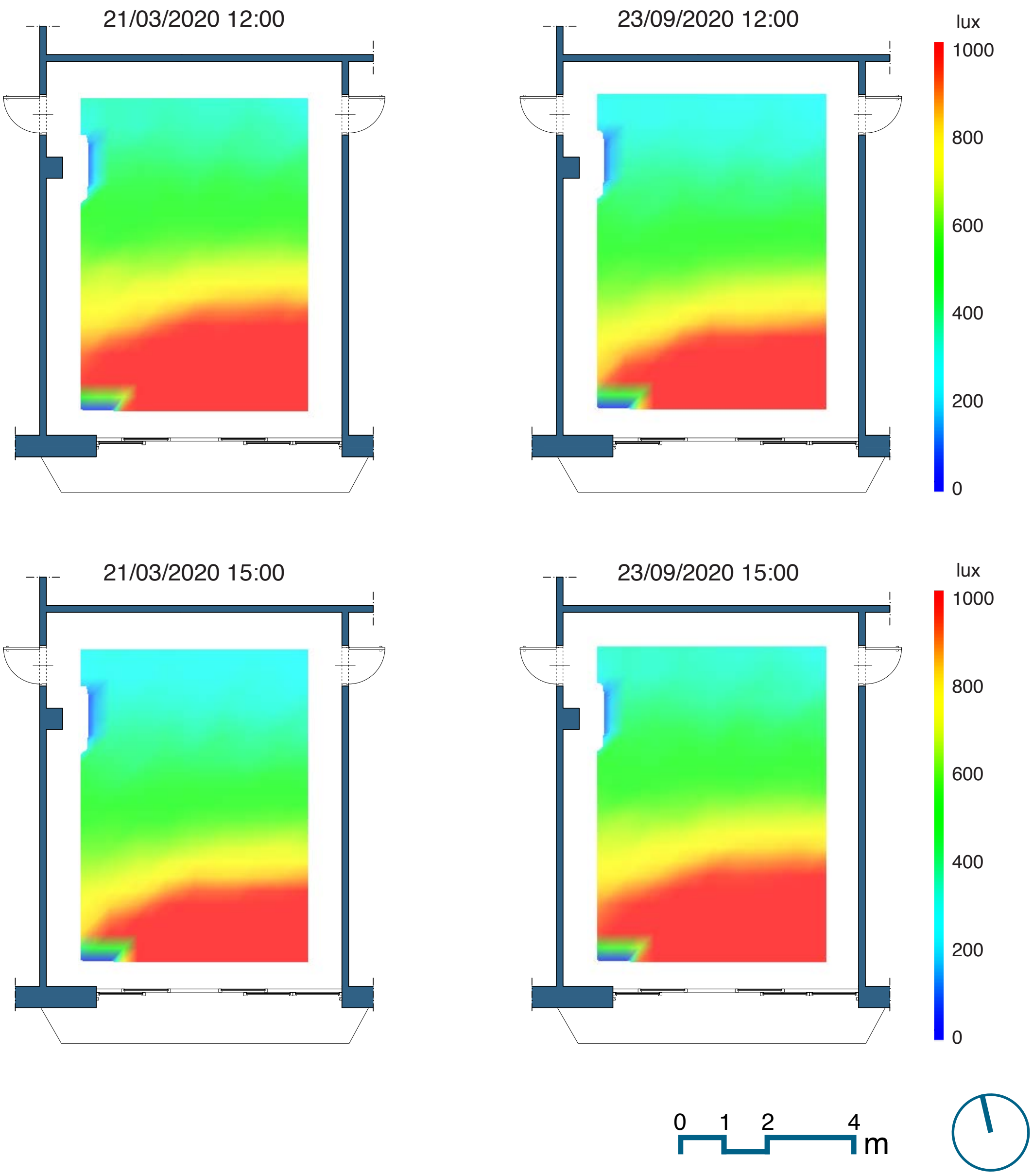



*Figure 39: values of illuminance for 21/03/2020 and 23/09/2020 at 9:00, 12:00 and 15:00.*

## 4.8 Visual comfort, electric lighting

The simulation of the visual domain, for what concerns the electric lighting, has been done with the software DIALux evo, developed by the DIAL company, founded in 1989. It allows to plan, calculate and visualize light for indoor areas (entire buildings or single rooms) and outdoor areas (parking spaces or street lighting).

### 4.8.1 Workflow of the current state simulation

#### 4.8.1.1 Model creation in DIALux evo

The model has been created importing the CAD file with office planimetry and then modelling it in the simulation program. Through the construction tab, the geometry can be defined and doors, windows and furniture can be inserted.

#### 4.8.1.2 Model settings

For this simulation it is important to define the material properties of the surfaces inside the room: to each material have been attributed the typology of material, the colour and the reflection coefficient.
To run the calculation, it is necessary to insert one or more measuring plan (defined in its dimensions, position, height above floor and rotation) and select the indexes to be assessed in relation to the plan. In this case have been evaluated the indexes listed below:

- Mean perpendicular illuminance [lx]
- Illuminance uniformity [-]
- Unified glare rating [-]

The grid of the measuring plan can be set and the typology of output of results can be chosen: false colour, isolines, numeric grid.
As shown in Figure 40, two measuring planes have been put over the desks, at 0.85 m height above floor, to assess the aforementioned indexes.

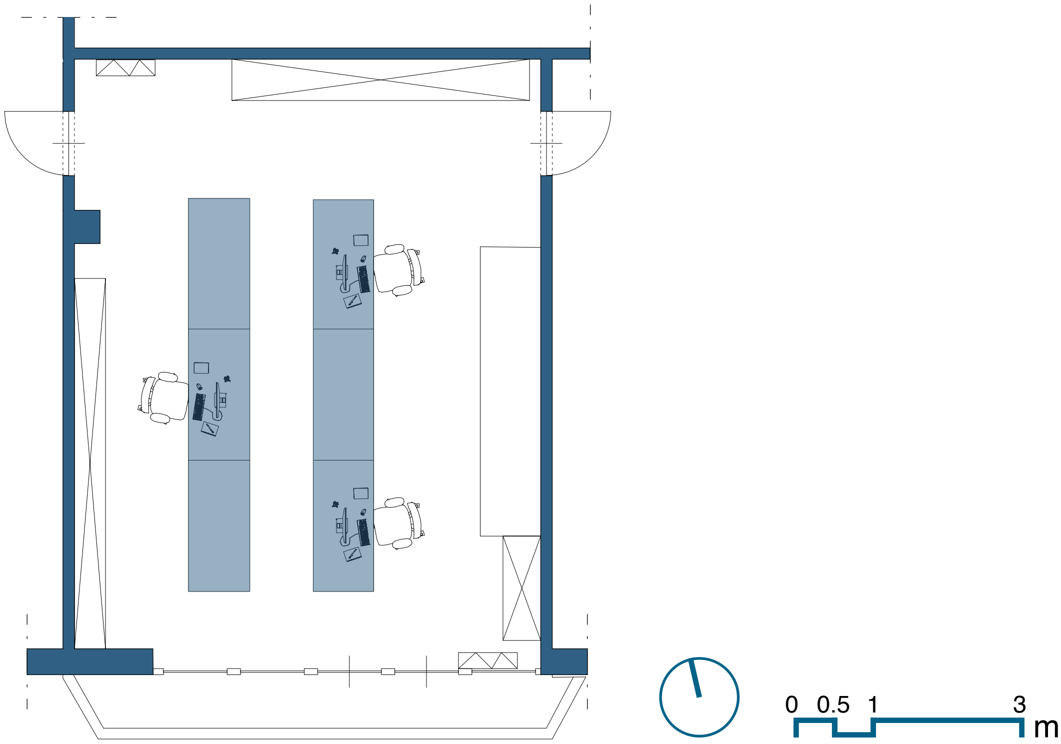



*Figure 40: measuring plans positioned inside the room, at 0.85 m height above floor. Office plan, scale 1:100*

For the electric light simulation one or more light scenes can be created. Each of them can encompass one or more groups of luminaires. Subsequently, when the simulation is run, the light scenes can be simulated one by one or all together. When importing the luminaire, it is possible to set the position and height above floor, and although all the lighting properties are already defined because of the file imported, it is possible to modify the dimensions, the luminous flux, the nominal wattage and the luminous efficacy.
Light bulb properties are still defined too, but also in this case is possible to modify luminous flux, nominal wattage, type of light source, colour temperature and colour rendering Index.
In the thesis work "Qualità dell'ambiente interno e comfort globale: misure in campo ed analisi nella sede dell'ARPA della Valle d'Aosta" it is stated that with electric lighting switched on, an illuminance of 300 lx is granted on desks and that there are six fluorescent lamps in the room. Starting from this knowledge and from photos of the room, the position of luminaires has been determined.

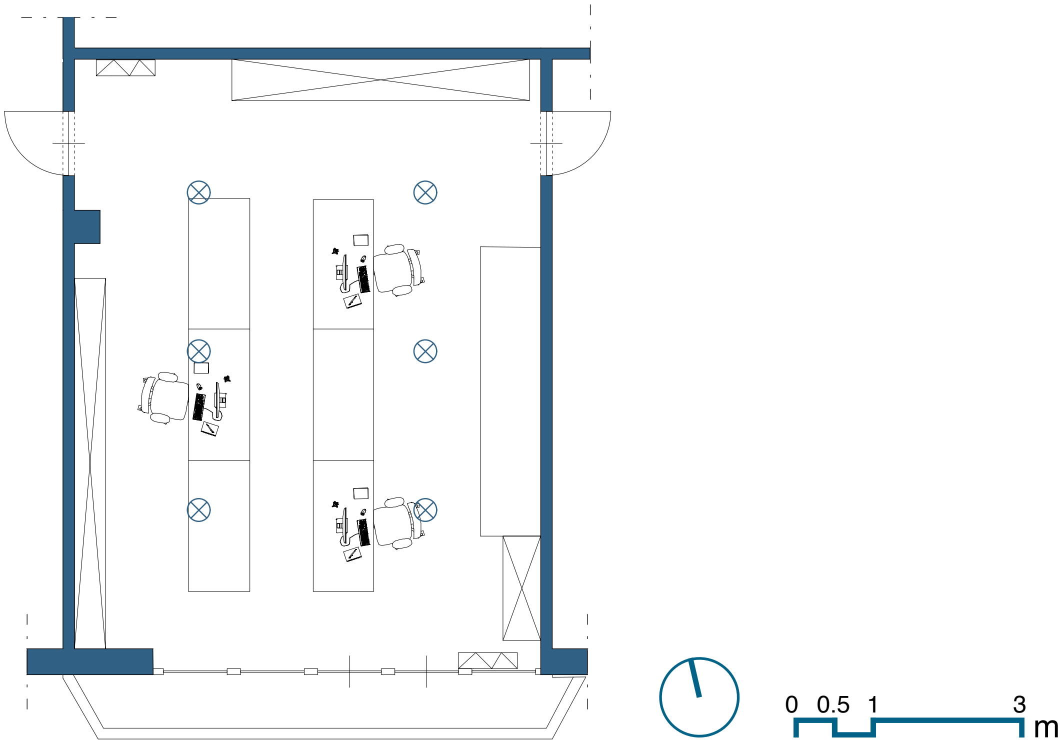
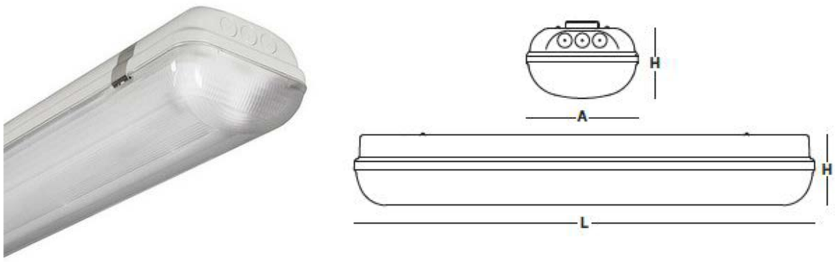
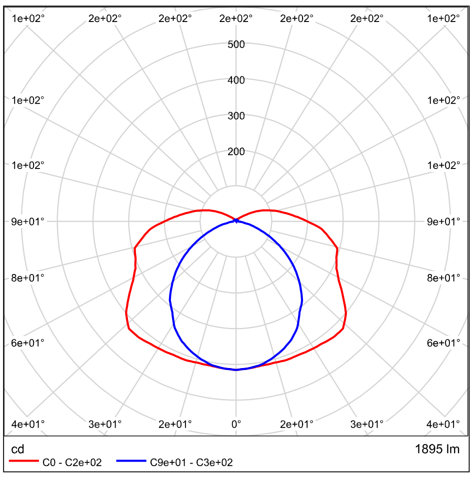


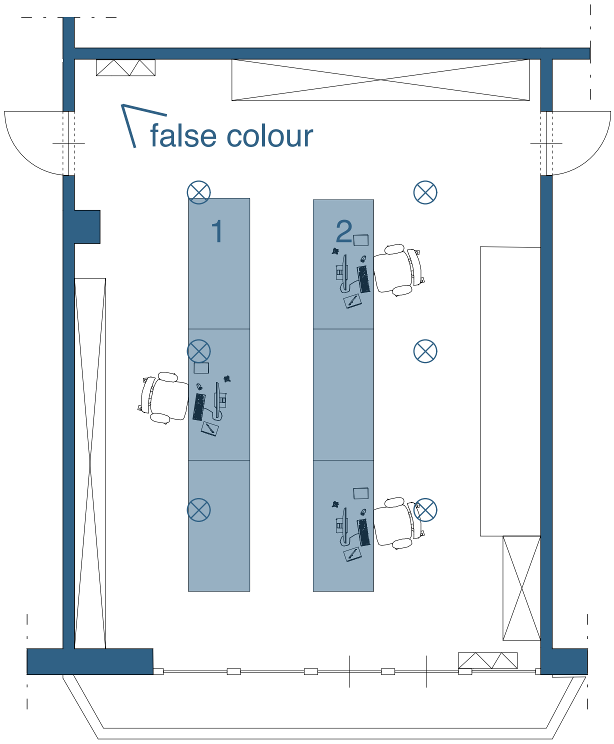

*Figure 41: scheme of luminaires position in the office.*
*Office plan, scale 1:100*

Subsequently, it has been identified the luminaire with the light source able to answer to those requirements.

*Table 28: luminaire datasheet*

| **3F Linda Inox 2x18 HF** | |
|---|---|
|  *3F Linda Inox photo and section* | |
| Manufacturing company | 3F Filippi |
| Dimensions | A: 160 mm<br>H: 100 mm<br>L: 660 mm |
| Light source characteristics | |
| Light source typology | fluorescent |
| Nominal wattage | 35 W |
| Luminous flux | 1895 lm |
| Colour temperature | 3000 K |
| Colour rendering Index | 80 |
| Nominal average life | 10000 h |
| Luminous efficacy light source-luminaire system | 54.1 lm/W |
| Luminaire characteristics | |
|  *3F Linda Inox photometric curve* | |

### 4.8.1.3 Simulation results



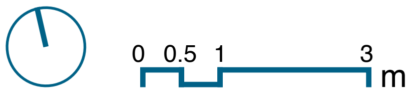
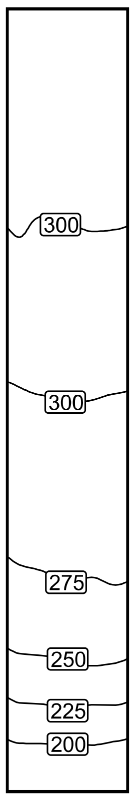
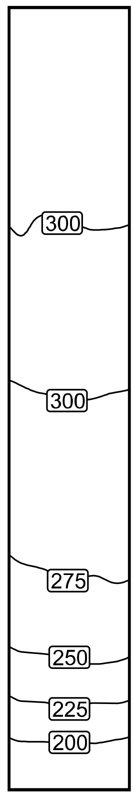




*Figure 42: plan with indications regarding the simulation (measuring planes and false colour view). Office plan scale 1:100*

| Calculation surface 1 | | Calculation surface 2 | |
|---|---|---|---|
| Illuminance Isolines [lx] Scale 1:50 |  | Illuminance Isolines [lx] Scale 1:50 |  |

| | | | |
|---|---|---|---|
| Average illuminance | 276 lx | Average illuminance | 277 lx |
| Illuminance uniformity | 0.65 | Illuminance uniformity | 0.63 |
| Unified Glare Rating | 15.9 | Unified Glare Rating | 15.4 |

False colour view

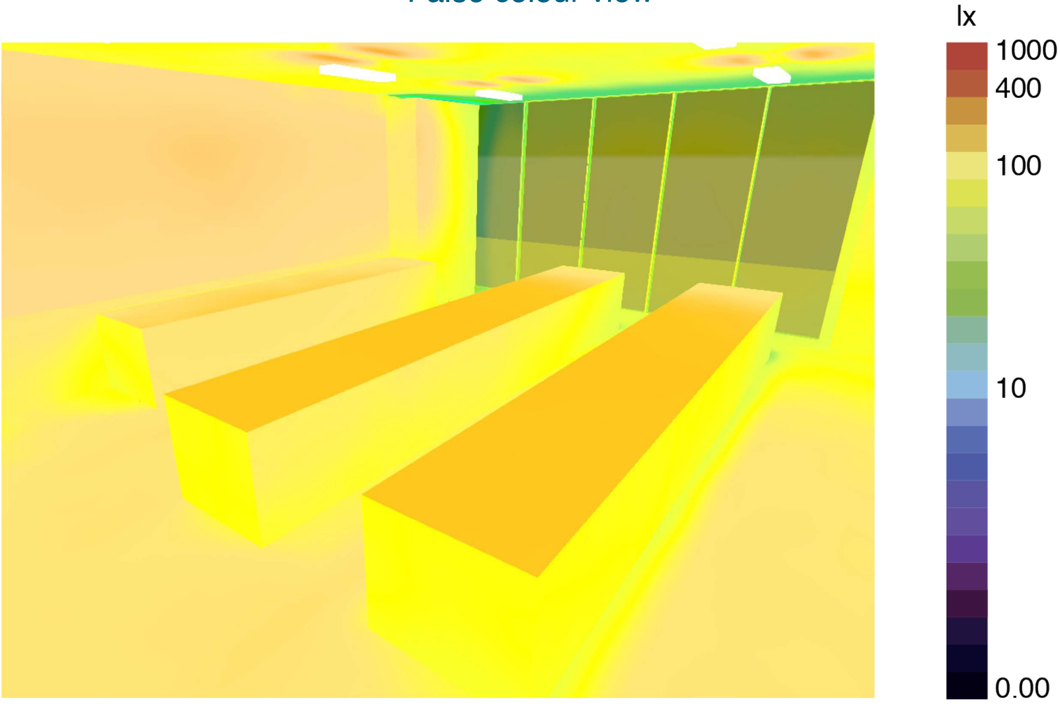



*Figure 43: false colour view of the office.*

### 4.8.2 Workflow of the project simulation

The model has been modified in its layout and surfaces materials following the project indications, and then the same indexes of the current state have been assessed.
As shown in Figure 46, four measuring planes over the desks and one measuring plane covering the floor surface with an offset of 0.5 m from walls, have been put at 0.85 m height above floor and for each of them have been assessed the previously mentioned indexes.

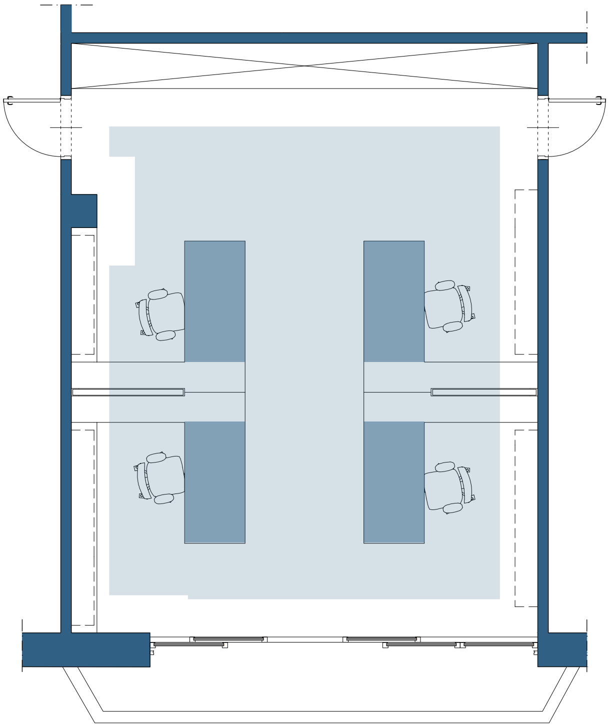


*Figure 44: measuring plans positioned inside the room, at 0,85 m height above floor.*

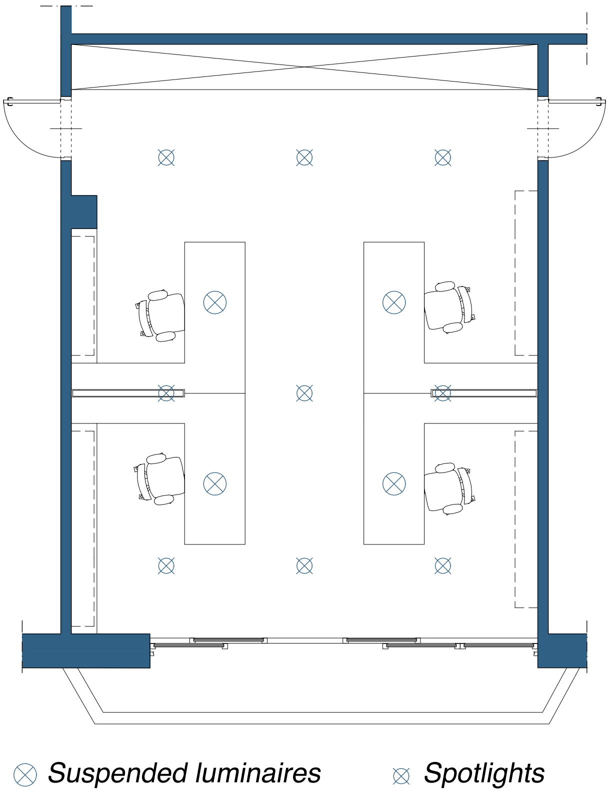



*Figure 45: scheme of luminaires position in the office.*

Two different kinds of luminaires have been chosen to answer different needs. Over each desk a suspension lamp has been placed at 1.45 m height above the desk, to guarantee 500 lx as requested in standard EN 16798. Furthermore, six spotlights have been placed embedded in the false ceiling, as shown in Figure 47. Spotlights are thought to create ambient lighting when occupants are not working on the desk and so is not needed to have 500 lx on it. The choice of inserting two different kinds of luminaires is due to the will to provide occupants with the possibility to control the lighting of their workstation, reaching the personal comfort level without compromising the comfort perception of the other occupants. For the electric light simulation two scenes have been created: one for the evaluation of suspended lamps performance necessary to meet standard requirements for the visual task of occupants in the office; the other one to assess lighting performance of spotlights.

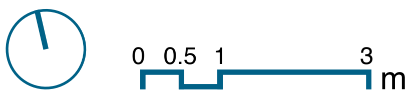
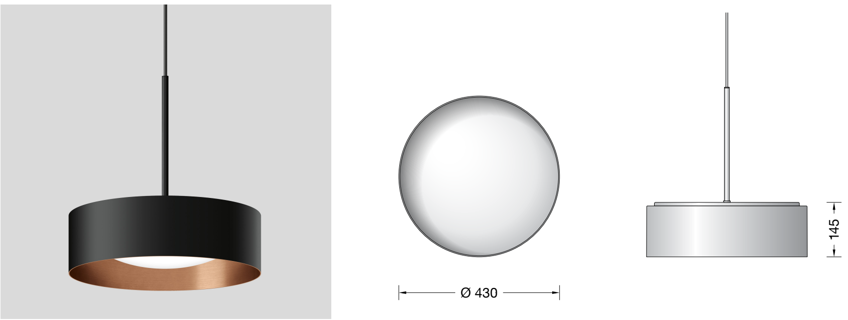


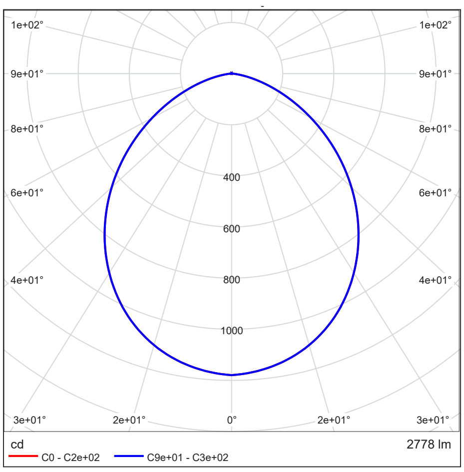
*Table 29: luminaire datasheet*

| Studio line | |
|---|---|



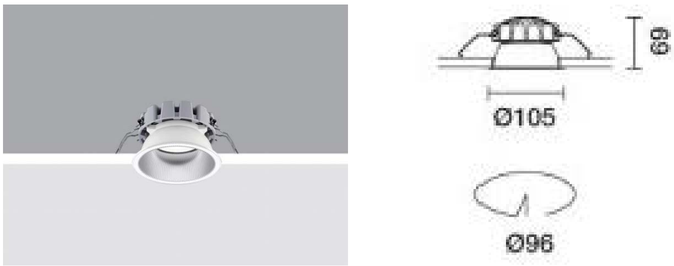
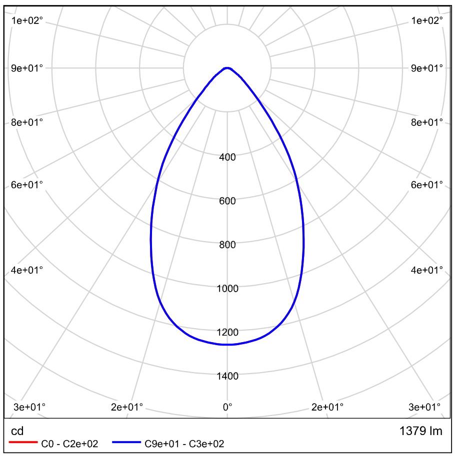

*Studio line photo and section*

| | |
|---|---|
| Manufacturing company | BEGA |
| Dimensions | A: 120 mm<br>ϕ: 360 mm |
| Light source characteristics | |
| Light source typology | LED |
| Nominal wattage | 26.9 W |
| Luminous flux | 3385 lm |
| Colour temperature | 3000 K |
| Colour rendering Index | 90 |
| Nominal average life | 50000 h |
| Luminous efficacy light source-luminaire system | 68 lm/W |
| Luminaire characteristics | |



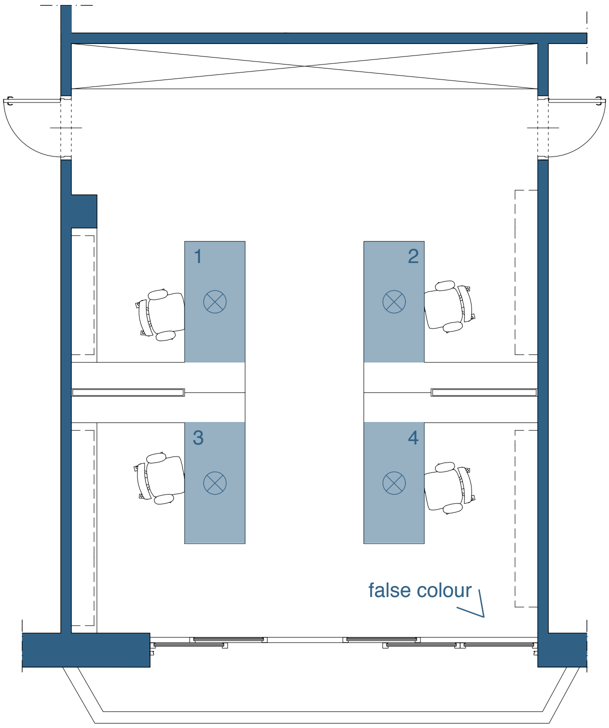

*Studio line photometric curve*

*Table 30: luminaire datasheet*

| Easy Space QV79.D8 | |
|---|---|
|   *Easy Space QV79.D8 photo and section* | |
| Manufacturing company | iGuzzini |
| Dimensions | A: 69 mm<br>ϕ: 105 mm |
| Light source characteristics | |
| Light source typology | LED |
| Nominal wattage | 11 W |
| Luminous flux | 1550 lm |
| Colour temperature | 3000 K |
| Colour rendering Index | 90 |
| Nominal average life | 50000 h |
| Luminous efficacy light source-luminaire system | 89 lm/W |
| Luminaire characteristics | |
|   *Easy Space QV79.D8 photometric curve* | |

#### 4.8.2.1 Simulation results

Scene 1: luminaires: Studio line



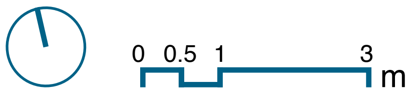
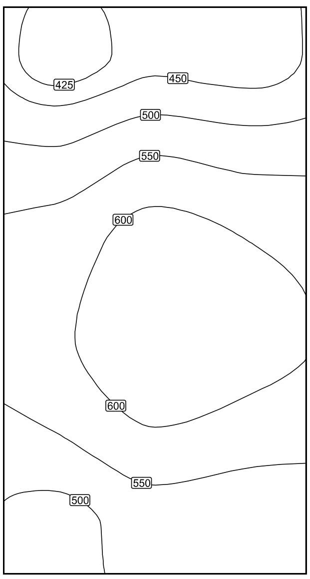
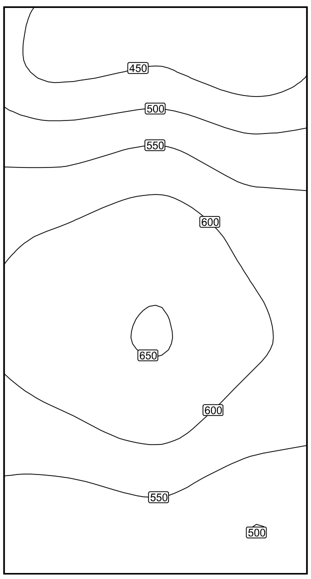
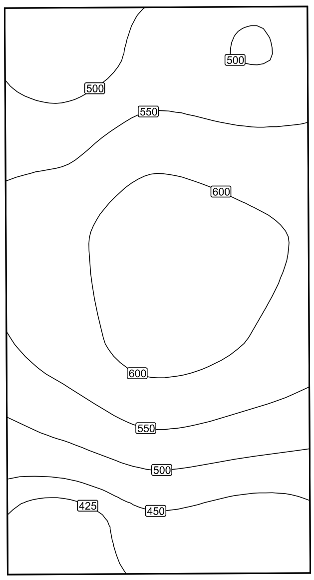
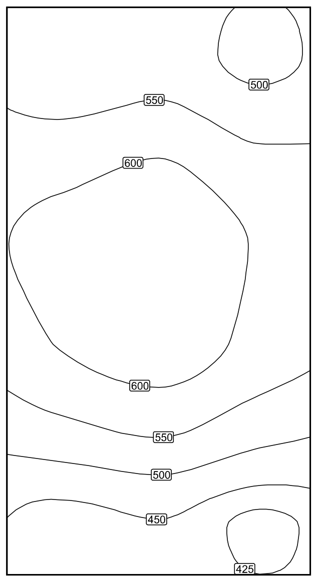




*Figure 46: plan with indications regarding the simulation (measuring planes and false colour view).*

| Calculation surface 1 | Calculation surface 2 |
|---|---|
| Illuminance Isolines [lx]<br>Scale 1:20 | Illuminance Isolines [lx]<br>Scale 1:20 |
|   |   |

| | | | |
|---|---|---|---|
| Average illuminance | 546 lx | Average illuminance | 555 lx |
| Illuminance uniformity | 0.75 | Illuminance uniformity | 0.76 |
| Unified Glare Rating | 17.3 | Unified Glare Rating | 17.4 |

<table>
<tr><th colspan="2">Calculation surface 3</th><th colspan="2">Calculation surface 4</th></tr>
<tr><td colspan="2">Illuminance Isolines [lx]<br>Scale 1:20</td><td colspan="2">Illuminance Isolines [lx]<br>Scale 1:20</td></tr>
<tr><td colspan="2">


</td><td colspan="2">


</td></tr>
<tr><td>Average illuminance</td><td>541 lx</td><td>Average illuminance</td><td>548 lx</td></tr>
<tr><td>Illuminance uniformity</td><td>0.77</td><td>Illuminance uniformity</td><td>0.77</td></tr>
<tr><td>Unified Glare Rating</td><td>17.1</td><td>Unified Glare Rating</td><td>17.2</td></tr>
</table>

## False colour view

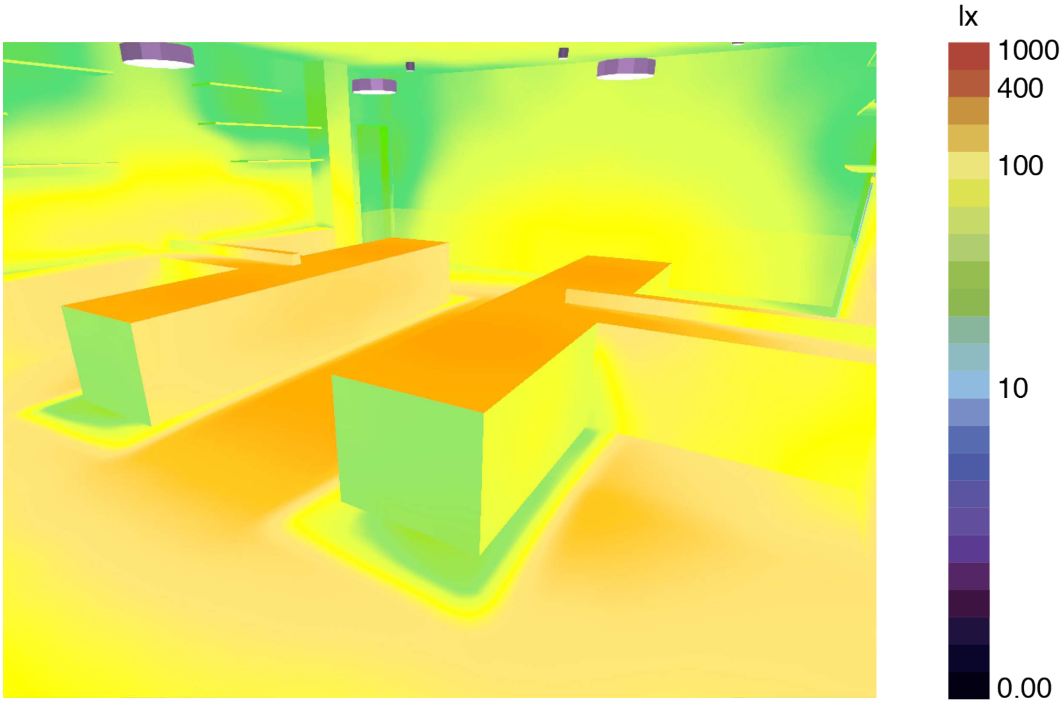



*Figure 47: false colour view of the office.*

## Scene 2: luminaires: Easy Space QV79.D8

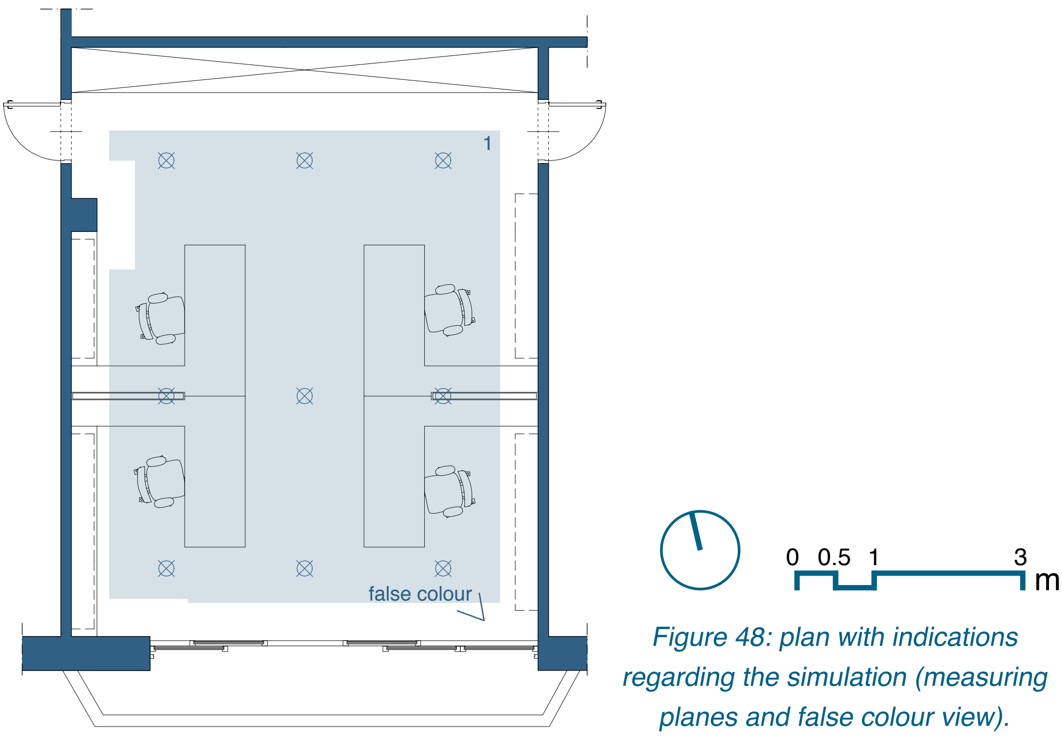
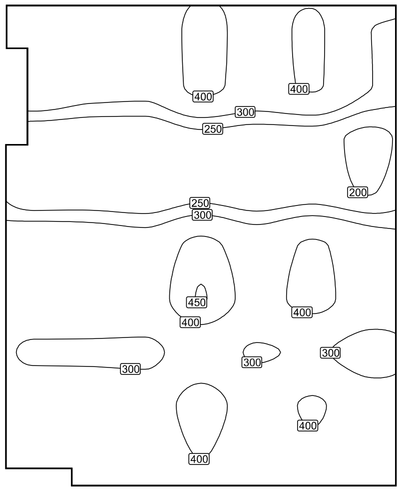



*Figure 48: plan with indications regarding the simulation (measuring planes and false colour view).*

| Calculation surface 1 | |
|---|---|
| Illuminance Isolines [lx]<br>Scale 1:25 | |




| | |
|---|---|
| Average illuminance | 347 lx |
| Illuminance uniformity | 0.62 |
| Unified Glare Rating | 19 |

False colour view

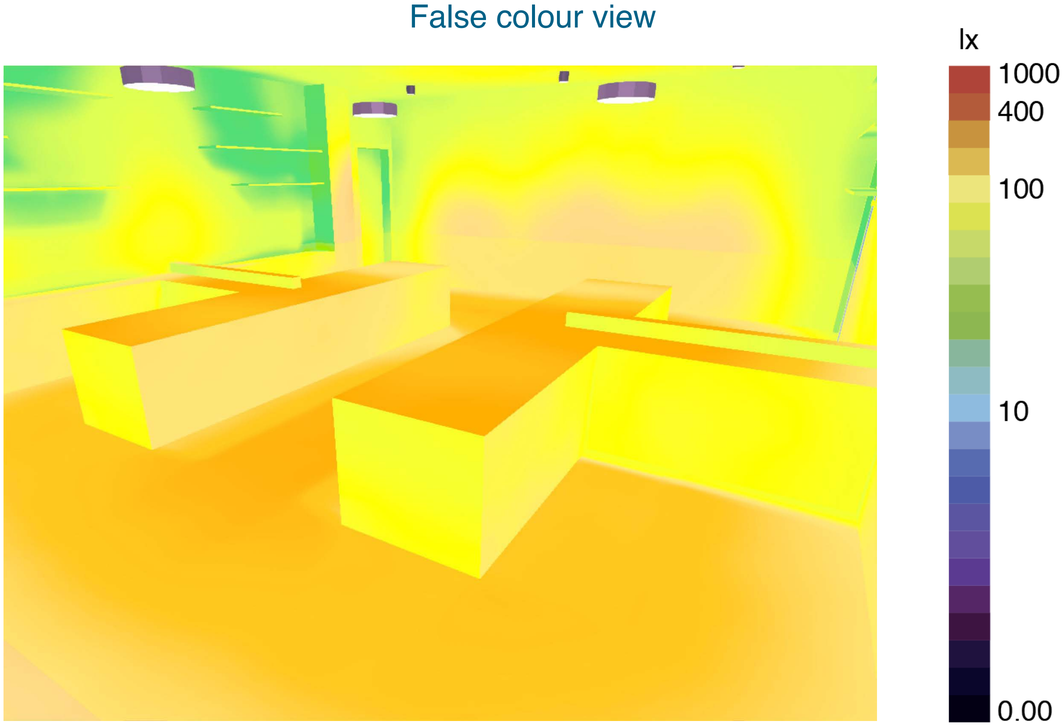



*Figure 49: false colour view of the office.*

## 4.9 References

1. Oggiani, N. (2020). Qualità dell'ambiente interno e comfort globale: misure in campo ed analisi nella sede dell'ARPA della Valle d'Aosta. = Indoor environment quality and global comfort: field measurements and analysis at the ARPA headquarters in the Aosta Valley. Retrieved from http://webthesis.biblio.polito.it/16368/

# 5 Assessment and representation of global comfort

In this chapter will be explained the protocol developed to evaluate global comfort and to compare monitored and project related results with perceived comfort. Subsequently, these results will be represented with different graphic proposals.

## 5.1 Assessment of global comfort

A strategy for the assessment of global comfort will be presented in this chapter. As highlighted in the previous chapters, global comfort depends not only on physical environmental conditions, but also on occupants' perception and thus personal characteristics. The aim of this section is to show a strategy of how both objective and subjective evaluations can be taken into account and combined together.
Another important aspect is the will of showing that the global comfort can be assessed in the current state and can also be forecasted for the project aimed to the improvement of indoor environmental conditions.
For this reason, the assessment and the representation of global comfort deal with and combine three different evaluations: perceived global comfort, monitored global comfort and project related global comfort.

### 5.1.1 Perceived global comfort assessment

Perceived global comfort assessment is based on personal feedback given by office occupants, through the filling in of a questionnaire with specific questions. Its evaluation is expressed in percentage of satisfaction, and to each of the comfort categories presented in the previous chapters (see chapter 3, paragraph 3.8.4) a specific percentage range is attributed.

*Table 31: comfort categories and percentage range*

| Comfort category | Percentage range |
|---|---|
| Discomfort | 0-40% |
| Standard | 41-60% |
| Comfort - Good (Threshold: 80% satisfaction) | 61-80% |
| Comfort - Optimal (High acceptability and well-being) | 81-100% |

For the application of this strategy of global comfort representation, the perceived global comfort assessment has been done taking the results of subjective evaluation presented in the thesis work “Qualità dell’ambiente interno e comfort globale: misure in campo ed analisi nella sede dell’ARPA della Valle d’Aosta”. In this thesis work a scale composed by five different ratings in relation to subjective perception has been created. For the assessment of perceived global comfort, a percentage of satisfaction has been attributed to each of these ratings.

| | | |
|---|---|---|
|  | Very bad | 0-20% |
|  | Scarce | 21-40% |
|  | Discrete | 41-60% |
|  | Good | 61-80% |
|  | Great | 81-100% |

5.1.1.1 Results of perceived global comfort in the office

Results from subjective feedback of 18/08/2020 afternoon, shown in the thesis work of N. Oggiani are then presented.

THERMAL COMFORT | ACOUSTIC COMFORT | VISUAL COMFORT (natural lighting) | INDOOR AIR QUALITY

INDOOR ENVIRONMENTAL QUALITY

41-60 % -> Standard

### 5.1.2 Monitored and project related global comfort assessment: a new protocol

The necessity to evaluate global comfort in existing office buildings and to define guidelines for new construction, brings to the definition of a protocol. The structure derives from the study of Building Performance Certification Programs, while indexes values from standards analysis.
It is organised according to the four domains and to office typologies: single, shared and open plan office.
The first one is a space designed to allocate only one person for individual tasks (such as administrative work, telephone calls, reading and writing) or two or three people to hold conversations.
The second one, the shared office, is a typology thought for a number of people from two to five, that carry out separate individual tasks in a common

space, sometimes with partial separations.
The open plan office is designed to accommodate more than five people without full separation between the different workstations. It is a flexible space where many activities are carried out simultaneously. According to the type of office, the dimensions and the threshold to reach comfort change. Open plan offices present many drawbacks: lack of privacy, noise, differences in temperature, differences in illuminance.
The scope of this protocol is to define a baseline with the aim to represent global comfort, analysing the contribution in percentage of each domain on the result of global comfort.
Indexes values derive from an accurate analysis of standards, they are organised in categories, levels and optimal values. These differences are related to the discrepancies between the organisation of standards: in fact, not all of them define performance categories or range. Scores are assigned for each index, as explained in the following tables.
Since each domain has a different number of indexes, this makes difficult the evaluation of global comfort. Nevertheless, it is overcome converting the numerical results in percentages. In this way is possible to compare the result of different domains and evaluate their contribution to the final result, expressed in percentage too. Monitored and project related comfort are comparable also through the score because they are quantified with the same protocol. To compare these results with perceived comfort is necessary to express monitored and projected comfort as percentage.
In the following paragraphs are presented the sections of the protocol related to the four IEQ domains.

### Thermal comfort

For the definition of thermal comfort indexes in this protocol, standard EN 16798 was used. It is organised in categories that provide different comfort ranges. This section is divided into four main indexes:
- PMV
- PPD
- Operative temperature
- Relative humidity

PMV is divided into categories and the score is assigned in relation to the one reached.

| Predicted Mean Vote (PMV) | | |
|---|---|---|
| Category I | -0.2< PMV <+0.2 | 1 |
| Category II | -0.5< PMV <+0.5 | 0.75 |
| Category III | -0.7< PMV <+0.7 | 0.5 |
| Category IV | PMV <-0.7, PMV > +0.7 | 0.25 |

PPD is organised in the same way, thus the score is assigned in relation to the value reached.

| Predicted Percentage of Dissatisfied (PPD) | | |
|---|---|---|
| Category I | PPD < 6% | 1 |
| Category II | PPD < 10% | 0.75 |
| Category III | PPD < 15% | 0.5 |
| Category IV | PPD > 15% | 0.25 |

To obtain score 1 for operative temperature, summer condition and winter condition must be verified.

| Operative temperature ($T_{op}$) | | |
|---|---|---|
| Winter | 20< $T_{op}$ <24°C | 0.5 |
| Summer | 23< $T_{op}$ <26°C | 0.5 |

Relative humidity value must be within the defined range to have score 1.

| Relative humidity (RH) | | |
|---|---|---|
| | 30%< RH <70% | 1 |

## Acoustic comfort

Acoustic comfort indexes values derive from standard NF S 31-080.

The indexes are:

- Reverberation time
- Equipment noise
- Insulation from external noise
- Sound insulation
- Impact noise

Scores between 0.5 and 1 will be assigned according to the compliance of the value reached.
There are different values for reverberation time according to the office typologies, due to the relation between this index and the dimension of the office.

Single office

| Reverberation time | | |
|---|---|---|
| Standard level | - | - |
| Efficient level | $T_r \leq 0.7$ s | 0.75 |
| Highly efficient level | $T_r \leq 0.6$ s | 1 |

Shared office

| Reverberation time | | |
|---|---|---|
| Standard level | $T_r \leq 0.6$ s | 0.5 |
| Efficient level | $T_r \leq 0.6$ s | 0.75 |
| Highly efficient level | $T_r \leq 0.5$ s | 1 |

Open plan office

| Reverberation time | | |
|---|---|---|
| Standard level | $T_r \leq 0.8$ s | 0.5 |
| Efficient level | $0.6 < T_r < 0.8$ s | 0.75 |
| Highly efficient level | $T_r \leq 0.6$ s | 1 |

Equipment noise can be permanent (e.g. ventilation, air conditioning, water supercharger), thus emitted by technical equipment for a period greater or equal to 50% of the normal occupation time of the rooms. $L_p$ equipment is the same for single and shared office.

Single and shared office

| **$L_p$ equipement** | | |
|---|---|---|
| Standard level | $L_{Aeq} \leq 45$ dB(A) | 0.5 |
| Efficient level | $L_p \leq$ NR 33 | 0.75 |
| Highly efficient level | $L_p \leq$ NR 30 (permanent)<br>$L_{max} \leq 35$ dB(A) (intermittent) | 1 |

Open plan office

| **$L_p$ equipement** | | |
|---|---|---|
| Standard level | $L_{Aeq} \leq 45$ dB(A) | 0.5 |
| Efficient level | NR35 $\leq L_p \leq$ NR40 | 0.75 |
| Highly efficient level | $L_p \leq$ NR 33 (permanent)<br>$L_{max} \leq 35$ dB(A) (intermittent) | 1 |

Insulation of the external noise ($D_{nT,A,tr}$) is organised in levels.

Single, shared and open plan office

| **Lp external** | | |
|---|---|---|
| Standard level | $D_{nT,A,tr} \geq 30$ dB | 0.5 |
| Efficient level | $D_{nT,A,tr} \geq 30$ dB<br>$L_{50} \leq 35$dB | 0.75 |
| Highly efficient level | $D_{nT,A,tr} \geq 30$ dB<br>$L_{50} \leq 30$ dB | 1 |

Sound insulation is necessary to reduce noise between indoor spaces. It is divided in levels and differentiated according to office typology.

Single and shared office

| **Insulation from internal airborne noise** | | |
|---|---|---|
| Standard level | $D_{nT,A} \geq 35$ dB | 0.5 |
| Efficient level | $D_{nT,A} \geq 40$ dB | 0.75 |
| Highly efficient level | $D_{nT,A} \geq 45$ dB | 1 |

Open plan office

| Insulation from internal airborne noise | | |
|---|---|---|
| Standard level | $D_{nT,A} \geq 30$ dB | 0.5 |
| Efficient level | $D_{nT,A} \geq 35$ dB | 0.75 |
| Highly efficient level | $D_{nT,A} \geq 40$ dB | 1 |

If there is a walkable floor on the upper floor, the impact noise must be verified. It does not change according to office typology.

Single, shared and open plan office

| Impact noise | | |
|---|---|---|
| Standard level | $L'_{nTw} \leq 62$ dB | 0.5 |
| Efficient level | $L'_{nTw} \leq 60$ dB | 0.75 |
| Highly efficient level | $L'_{nTw} \leq 58$ dB | 1 |

Spatial decay represents the slope of the spatial sound decay curve within a given distance range, when the distance from the source doubles. For dimensional reasons it is assessed in open plan offices with a volume greater than 250 $m^3$.

| Spatial decay | | |
|---|---|---|
| Standard level | 2 dB or Tr ≤ 1.2 s | 0.5 |
| Efficient level | 3 dB or Tr ≤ 1 s | 0.75 |
| Highly efficient level | 4 dB or Tr ≤ 0.8 s | 1 |

## Visual comfort

Visual comfort must be divided in electric and natural lighting, because they affect differently the comfort perception.

### Natural lighting

The main indexes for the assessment of natural lighting are:

- Spatial daylight autonomy
- Annual sunlight exposure

- Daylight factor
- Daylight glare probability

Spatial daylight autonomy is codified, as in standard IES_LM-83-12, in two categories: nominally accepted or preferred value.

| Spatial daylight autonomy (sDA) | | |
|---|---|---|
| Nominally accepted | sDA > 55% | 0.5 |
| Preferred | sDA > 75% | 1 |

Annual sunlight exposure is codified, as in standard IES_LM-83-12, in two categories: nominally acceptable or clearly acceptable.

| Annual sunlight exposure (ASE) | | |
|---|---|---|
| Nominally acceptable | < 7% | 0.5 |
| Clearly acceptable | < 3% | 1 |

The value of daylight factor derives from EN 17037.

| Daylight factor (DF) | | |
|---|---|---|
| Highly efficient level | > 2% | 1 |

Daylight glare probability is organized in four main levels, according standard EN 17037.

| Daylight glare probability (DGP) | | |
|---|---|---|
| DG mostly not perceived | DGP ≤ 0.35 | 1 |
| DG perceived not disturbing | 0.35 < DGP ≤ 0.4 | 0.75 |
| DG often disturbing | 0.4 < DGP ≤ 0.45 | 0.5 |
| DG intolerable | DGP ≥ 0.45 | 0.25 |

### Electric lighting

Indexes for the assessment of electric lighting are:

- Illuminance on the task area
- Illuminance uniformity
- Unified glare rating

All these indexes are codified and differentiated, in relation to the visual task to be performed, in standard EN 12464. For single office task 4 (conference and meeting rooms) must not be considered, whereas for open plan office task 6 (archives) must not be considered.

Illuminance on the task area that has to be maintained. Score of 1 will be assigned in correspondence of the task, if it complies with the optimal value.

| **Illuminance on the task area (E)** | |
|---|---|
| Filing, copying, etc. | 300 lx |
| Writing, typing, reading, data processing, CAD workstations. | 500 lx |
| Technical drawing. | 750 lx |
| Conference and meeting rooms. | 300 lx |
| Reception desk. | 200 lx |
| Archives. | 500 lx |

Illuminance uniformity. Score of 1 will be assigned in correspondence of the task, if it complies with the required range.

| **Illuminance uniformity (U)** | |
|---|---|
| Filing, copying, etc. | $U \geq 0.4$ |
| Writing, typing, reading, data processing, CAD workstations. | $U \geq 0.6$ |
| Technical drawing. | $U \geq 0.7$ |
| Conference and meeting rooms. | $U \geq 0.6$ |
| Reception desk. | $U \geq 0.4$ |
| Archives. | $U \geq 0.6$ |

Unified glare rating. Score of 1 will be assigned in correspondence of the task, if it complies with the required range.

| Unified Glare Rating (UGR) | |
|---|---|
| Filing, copying, etc. | UGR ≤ 19 |
| Writing, typing, reading, data processing, CAD workstations. | UGR ≤ 19 |
| Technical drawing. | UGR ≤ 16 |
| Conference and meeting rooms. | UGR ≤ 22 |
| Reception desk. | UGR ≤ 35 |
| Archives. | UGR ≤ 19 |

## Indoor air quality

IAQ indexes derive from standard EN16798 values.

The main indexes are:

- $CO_2$ concentration
- Formaldehyde
- $PM_{2.5}$
- $PM_{10}$

Score for $CO_2$ concentration will be assigned in correspondence of the value reached.

| $CO_2$ concentration | | |
|---|---|---|
| Category I | 550 ppm | 1 |
| Category II | 800 ppm | 0.75 |
| Category III | 1350 ppm | 0.5 |
| Category IV | 1350 ppm | 0.25 |

Formaldehyde must be less than the limit indicated to obtain the point.

| Formaldehyde | | |
|---|---|---|
| | $< 30 \mu g/m^3$ | 1 |

$PM_{2.5}$ must be less than the limit indicated to obtain the point.

| PM$_{2.5}$ | | |
|---|---|---|
| | PM$_{2.5}$ ≤ 25 µg/m$^3$ | 1 |

PM$_{10}$ must be less than the limit indicated to obtain the point.

| PM$_{10}$ | | |
|---|---|---|
| | PM$_{10}$ ≤ 50 µg/m$^3$ | 1 |

Before the application of the protocol, it is necessary to perform a preliminary analysis to understand which indexes may be evaluated and what is the maximum achievable score, considering office and building characteristics. This protocol can be applied both for point-in-time evaluations and for annual-based evaluations, thus indexes to be assessed must be correctly selected.

The following case study is an example of application. Due to the morphology of the building, the lack of some on-site measurements and limitations related to the software, some indexes were not assessed. Furthermore, to best compare perceived global comfort with monitored global comfort, also the latter has been assessed on 18/08/2020 afternoon. For what concerns the project, annual-based evaluation has been performed.

#### 5.1.2.1 Results of monitored global comfort

##### Thermal comfort

For thermal comfort it was possible to analyse all the indexes, obtaining a score of 3 out of 4.

| Preliminary analysis | Indexes | | | |
|---|---|---|---|---|
| YES | **Predicted Mean Vote (PMV)** | | | |
| | Category I | -0.2<PMV<+0.2 | | 1 |
| | Category II | -0.5<PMV<+0.5 | 0.25 | 0.75 |
| | Category III | -0.7<PMV<+0.7 | | 0.5 |
| | Category IV | PMV <-0.7, PMV > +0.7 | | 0.25 |
| YES | **Predicted Percentage of Dissatisfied (PPD)** | | | |
| | Category I | PPD < 6% | | 1 |
| | Category II | PPD < 10% | 6.6% | 0.75 |
| | Category III | PPD < 15% | | 0.5 |
| | Category IV | PPD > 15% | | 0.25 |
| YES | **Operative temperature ($T_{op}$)** | | | |
| | Winter | $20 < T_{op} < 24°C$ | | 0.5 |
| | Summer | $23 < T_{op} < 26°C$ | 24.9 °C | 0.5 |
| YES | **Relative humidity (RH)** | | | |
| | | 30% < RH <70% | 69% | 1 |
| | | | **TOT.** | **3/4** |

## Acoustic comfort

For acoustic comfort evaluation, were excluded indexes related to equipment noise, because building systems are not object of this thesis.
Impact noise was not assessed due to the morphology of the building, there is not a walkable floor on the office object of study.
Regarding the insulation from external noise, office is placed on the façade exposed to the internal gardern, thus there is not a source such as noise releted to the traffic. However, sound insulating power of the façade was calculated, as shown in the previous chapter.
The score reached is 1.75 out of 2.

| Preliminary analysis | Indexes | | | |
|---|---|---|---|---|
| | **Reverberation time** | | | |
| YES | Standard level | $T_r \leq 0.6$ s | | 0.5 |
| | Efficient level | $T_r \leq 0.6$ s | | 0.75 |
| | Highly efficient level | $T_r \leq 0.5$ s | 0.38 s | 1 |
| | **Lp equipement** | | | |
| NO | Standard level | $L_{Aeq} \leq 45$ dB(A) | | 0.5 |
| | Efficient level | $L_p \leq$ NR 33 | | 0.75 |
| | Highly efficient level | $L_p \leq$ NR 33 (permanent) $L_{max} \leq 35$ dB(A) (intermittent) | | 1 |
| | **Lp external** | | | |
| NO | Standard level | $D_{nT,A,tr} \geq 30$ dB | | 0.5 |
| | Efficient level | $D_{nT,A,tr} \geq 30$ dB $L_{50} \leq 35$ dB | | 0.75 |
| | Highly efficient level | $D_{nT,A,tr} \geq 30$ dB $L_{50} \leq 30$ dB | | 1 |
| | **Insulation from internal airborne noise** | | | |
| YES | Standard level | $D_{nT,A} \geq 35$ dB | | 0.5 |
| | Efficient level | $D_{nT,A} \geq 40$ dB | 42.4 dB | 0.75 |
| | Highly efficient level | $D_{nT,A} \geq 45$ dB | | 1 |
| | **Impact noise** | | | |
| NO | Standard level | $L'_{nTw} \leq 62$ dB | | 0.5 |
| | Efficient level | $L'_{nTw} \leq 60$ dB | | 0.75 |
| | Highly efficient level | $L'_{nTw} \leq 58$ dB | | 1 |
| | | | **TOT.** | **1.75/2** |

## Visual comfort - electric lighting

For electric lighting it was possible to analyse all the indexes, obtaining a score of 2 out of 3.

| Preliminary analysis | Indexes | | | |
|---|---|---|---|---|
| | **Illuminance on the task area (E)** | | | |
| YES | Filing, copying, etc. | 300 lx | | |
| | Writing, typing, reading, data processing, CAD workstations. | 500 lx | 277 lx | 0 |
| | Technical drawing. | 750 lx | | |
| | Conference and meeting rooms. | 300 lx | | |
| | Reception desk. | 200 lx | | |
| | Archives. | 500 lx | | |
| | **Illuminance Uniformity (U)** | | | |
| YES | Filing, copying, etc. | U ≥ 0.4 | | |
| | Writing, typing, reading, data processing, CAD workstations. | U ≥ 0.6 | 0.6 | 1 |
| | Technical drawing. | U ≥ 0.7 | | |
| | Conference and meeting rooms. | U ≥ 0.6 | | |
| | Reception desk. | U ≥ 0.4 | | |
| | Archives. | U ≥ 0.6 | | |
| | **Unified Glare Rating (UGR)** | | | |
| YES | Filing, copying, etc. | UGR ≤ 19 | | |
| | Writing, typing, reading, data processing, CAD workstations. | UGR ≤ 19 | 15 | 1 |
| | Technical drawing. | UGR ≤ 16 | | |
| | Conference and meeting rooms. | UGR ≤ 22 | | |
| | Reception desk. | UGR ≤ 35 | | |
| | Archives. | UGR ≤ 19 | | |
| | | | **TOT.** | **2/3** |

## Visual comfort – natural lighting

For natural lighting, due to limitations related to the software used, it was not possible to evaluate DGP. Furthermore, it has been possible to assess sDA and ASE, that are annual-based metrics and, although are not strictly referred to 18/08 afternoon, they provide useful information about natural lighting conditions.The score reached is 2.5 out of 3.

| Preliminary analysis | INDEXES | | | |
|---|---|---|---|---|
| YES | **Spatial daylight autonomy (sDA)** | | | |
| | Nominally accepted | sDA > 55% | 72% | 0.5 |
| | Preferred | sDA > 75% | | 1 |
| YES | **Annual sunlight exposure (ASE)** | | | |
| | Nominally acceptable | ASE < 7% | | 0.5 |
| | Clearly acceptable | ASE < 3% | 0% | 1 |
| YES | **Daylight Factor (DF)** | | | |
| | Highly efficient level | DF > 2% | 2.8% | 1 |
| NO | **Daylight glare probability (DGP)** | | | |
| | DG mostly not perceived | DGP ≤ 0.35 | | 1 |
| | DG perceived not disturbing | 0.35 < DGP ≤ 0 .4 | | 0.75 |
| | DG often disturbing | 0.4 < DGP ≤ 0.45 | | 0.5 |
| | DG intolerable | DGP ≥ 0.45 | | 0.25 |
| | | | **TOT.** | **2.5/3** |

## Indoor air quality

For indoor air quality, due to limitations related to the software used, it was not possible to evaluate formaldehyde, $PM_{2.5}$ and $PM_{10}$. The score reached is 1 out of 1.

| Preliminary analysis | Indexes | | | |
|---|---|---|---|---|
| YES | $CO_2$ concentration | | | |
| | Category I | 550 ppm | 464 | 1 |
| | Category II | 800 ppm | | 0.75 |
| | Category III | 1350 ppm | | 0.5 |
| | Category IV | 1350 ppm | | 0.25 |
| NO | Formaldehyde | | | |
| | | $< 30$ µg/m$^3$ | | 1 |
| NO | $PM_{2.5}$ | | | |
| | | $\leq 25$ µg/m$^3$ | | 1 |
| NO | $PM_{10}$ | | | |
| | | $\leq 50$ µg/m$^3$ | | 1 |
| | | | **TOT.** | **1/1** |

5.1.2.2 Results of project related global comfort

### Thermal comfort

For what concerns thermal comfort, the project ensures the highest comfort conditions, with a score of 4 out of 4.

| Preliminary analysis | Indexes | | | |
|---|---|---|---|---|
| YES | Predicted Mean Vote (PMV) | | | |
| | Category I | -0.2<PMV<+0.2 | -0.001 | 1 |
| | Category II | -0.5<PMV<+0.5 | | 0.75 |
| | Category III | -0.7<PMV<+0.7 | | 0.5 |
| | Category IV | PMV <-0.7, PMV > +0.7 | | 0.25 |
| YES | Predicted Percentage of Dissatisfied (PPD) | | | |
| | Category I | PPD < 6% | 0.11% | 1 |
| | Category II | PPD < 10% | | 0.75 |
| | Category III | PPD < 15% | | 0.5 |
| | Category IV | PPD > 15% | | 0.25 |
| YES | Operative temperature ($T_{op}$) | | | |
| | Winter | $20 < T_{op} < 24°C$ | 20.3 | 0.5 |
| | Summer | $23 < T_{op} < 26°C$ | 23.4 | 0.5 |
| YES | Relative humidity (RH) | | | |
| | | 30% < RH <70% | 42% | 1 |
| | | | **TOT.** | **4/4** |

### Acoustic comfort

Regarding acoustic comfort, the addiction of insulating material in the internal wall improves acoustic condition, thus the reached score is 2 out of 2.

| Preliminary analysis | Indexes | | | |
|---|---|---|---|---|
| | **Reverberation time** | | | |
| YES | Standard level | $T_r \leq 0.6$ s | | 0.5 |
| | Efficient level | $T_r \leq 0.6$ s | | 0.75 |
| | Highly efficient level | $T_r \leq 0.5$ s | 0.48 s | 1 |
| | **Lp equipement** | | | |
| NO | Standard level | $L_{Aeq} \leq 45$ dB(A) | | 0.5 |
| | Efficient level | $L_p \leq$ NR 33 | | 0.75 |
| | Highly efficient level | $L_p \leq$ NR 33 (permanent) $L_{max} \leq 35$ dB(A) (intermittent) | | 1 |
| | **Lp external** | | | |
| NO | Standard level | $D_{nT,A,tr} \geq 30$ dB | | 0.5 |
| | Efficient level | $D_{nT,A,tr} \geq 30$ dB $L_{50} \leq 35$ dB | | 0.75 |
| | Highly efficient level | $D_{nT,A,tr} \geq 30$ dB $L_{50} \leq 30$ dB | | 1 |
| | **Insulation from internal airborne noise** | | | |
| YES | Standard level | $D_{nT,A} \geq 35$ dB | | 0.5 |
| | Efficient level | $D_{nT,A} \geq 40$ dB | | 0.75 |
| | Highly efficient level | $D_{nT,A} \geq 45$ dB | 45 dB | 1 |
| | **Impact noise** | | | |
| NO | Standard level | $L'_{nTw} \leq 62$ dB | | 0.5 |
| | Efficient level | $L'_{nTw} \leq 60$ dB | | 0.75 |
| | Highly efficient level | $L'_{nTw} \leq 58$ dB | | 1 |
| | | | **TOT.** | **2/2** |

## Visual comfort - electric lighting

Electric lighting project ensures the maximum score of 3 out of 3.

| Preliminary analysis | Indexes | | | |
|---|---|---|---|---|
| YES | **Illuminance on the task area (E)** | | | |
| | Filing, copying, etc. | 300 lx | | |
| | Writing, typing, reading, data processing, CAD workstations. | 500 lx | 546 lx | 1 |
| | Technical drawing. | 750 lx | | |
| | Conference and meeting rooms. | 300 lx | | |
| | Reception desk. | 200 lx | | |
| | Archives. | 500 lx | | |
| YES | **Illuminance Uniformity (U)** | | | |
| | Filing, copying, etc. | U ≥ 0.4 | | |
| | Writing, typing, reading, data processing, CAD workstations. | U ≥ 0.6 | 0.8 | 1 |
| | Technical drawing. | U ≥ 0.7 | | |
| | Conference and meeting rooms. | U ≥ 0.6 | | |
| | Reception desk. | U ≥ 0.4 | | |
| | Archives. | U ≥ 0.6 | | |
| YES | **Unified Glare Rating (UGR)** | | | |
| | Filing, copying, etc. | UGR ≤ 19 | | |
| | Writing, typing, reading, data processing, CAD workstations. | UGR ≤ 19 | 17 | 1 |
| | Technical drawing. | UGR ≤ 16 | | |
| | Conference and meeting rooms. | UGR ≤ 22 | | |
| | Reception desk. | UGR ≤ 35 | | |
| | Archives. | UGR ≤ 19 | | |
| | | | **TOT.** | **3/3** |

## Visual comfort - natural lighting

For what concerns natural lighting, the project ensures the optimisation of the conditions and allows to reach the maximum score for each index.

| **Preliminary analysis** | **INDEXES** | | | |
|---|---|---|---|---|
| YES | **Spatial daylight autonomy (sDA)** | | | |
| | Nominally accepted | sDA > 55% | | 0.5 |
| | Preferred | sDA > 75% | 75% | 1 |
| YES | **Annual sunlight exposure (ASE)** | | | |
| | Nominally acceptable | ASE < 7% | | 0.5 |
| | Clearly acceptable | ASE < 3% | 0% | 1 |
| YES | **Daylight Factor (DF)** | | | |
| | Highly efficient level | DF > 2% | 3.8% | 1 |
| NO | **Daylight glare probability (DGP)** | | | |
| | DG mostly not perceived | DGP ≤ 0.35 | | 1 |
| | DG perceived not disturbing | 0.35 < DGP ≤ 0 .4 | | 0.75 |
| | DG often disturbing | 0.4 < DGP ≤ 0.45 | | 0.5 |
| | DG intolerable | DGP ≥ 0.45 | | 0.25 |
| | | | **TOT.** | **3/3** |

## Indoor air quality

The project ensures the same optimal conditions of the current state.

| Preliminary analysis | Indexes | | | |
|---|---|---|---|---|
| YES | $CO_2$ concentration | | | |
| | Category I | 550 ppm | 403 | 1 |
| | Category II | 800 ppm | | 0.75 |
| | Category III | 1350 ppm | | 0.5 |
| | Category IV | 1350 ppm | | 0.25 |
| NO | Formaldehyde | | | |
| | | < 30 µg/m³ | | 1 |
| NO | $PM_{2.5}$ | | | |
| | | ≤ 25 µg/m³ | | 1 |
| NO | $PM_{10}$ | | | |
| | | ≤ 50 µg/m³ | | 1 |
| | | | **TOT.** | **1/1** |

## 5.2 Representation of global comfort

The representation of global comfort is functional to the knowledge of indoor environmental conditions in relation to the measured and perceived value. Three proposals with differences in the graphic rendering have been designed for this purpose. All the solutions are based on the need to represent global comfort through three different values: perceived global comfort, monitored global comfort, project related global comfort. These three different values are evaluated for all the four domains (according to the methods presented in the previous paragraph) and subsequently averaged to obtain the global comfort value. This strategy is originated from the result of the analyses and studies carried out and wants to emphasize the importance of occupants'

comfort perception, since although the numerical and objective values indicate the achievement of a certain level of comfort, it does not mean that the personal perception of indoor environmental conditions reflects that.
These solutions designed may be used in an application or a browser, to have a frame of the global comfort in offices, in relation to the answer to the benchmarks. The application may show the results of perceived, monitored and projected. In this case different types of users can have access: the occupants of the monitored environment, the facilities manager, and professionals. Each of them may have access to different information: occupants are interested to give feedback about the perceived comfort for each domain, or global comfort; the facilities manager is interested in knowing the monitored conditions of the environment and the perception of workers, to understand possible problems; professionals are interested in knowing the perception of users, the monitored conditions but also the project value, to do the better choices for improving indoor conditions.
A very important feature of this comfort representation strategy is the possibility of creating a history of the values monitored in the environment: it is in fact possible to consult the application or the browser to find out what the internal conditions are at the present time but also what were the internal conditions in the previous moments.

### 5.2.1 Representation of global comfort solutions: strength and weakness

The score obtained from protocol has been converted in percentage, in order to make it comparable with the percentage of perceived comfort, resulted from the thesis of N. Oggiani.
The following percentage of satisfaction are reached for the current state:

| Comfort domain | Percentage of satisfaction |
|---|---|
| Thermal | 75% |
| Acoustic | 87.5% |
| Visual (electric) | 67% |
| Visual (natural) | 83% |
| IAQ | 100% |
| **IEQ** | **82.5%** |

The project has optimized indoor conditions, obtaining the maximum score:

| Comfort domain | Percentage of satisfaction |
|---|---|
| Thermal | 100% |
| Acoustic | 100% |
| Visual (electric) | 100% |
| Visual (natural) | 100% |
| IAQ | 100% |
| **IEQ** | **100%** |

The results of the application of the protocol to the current state and to the project have been compared and represented through three different proposals of graphic representation of global comfort in space and time.
The representation in space is easy with all types of representations, because is sufficient to select the office. The representation during the time is more complicated, not all the proposals ensure an intuitive time representation.
Each proposal compares perceived, monitored (including measurements on site and simulations) and project related comfort, joining these information with the comfort ranges defined through the literature review.

### First proposal

The first proposal is more technical than the other ones. It permits to represent detailed results, but it may be not easily understandable at a first look. Highlights section informs the user of the reaching of the alert level, thus that there is a situation of not compliance with the expected comfort level.

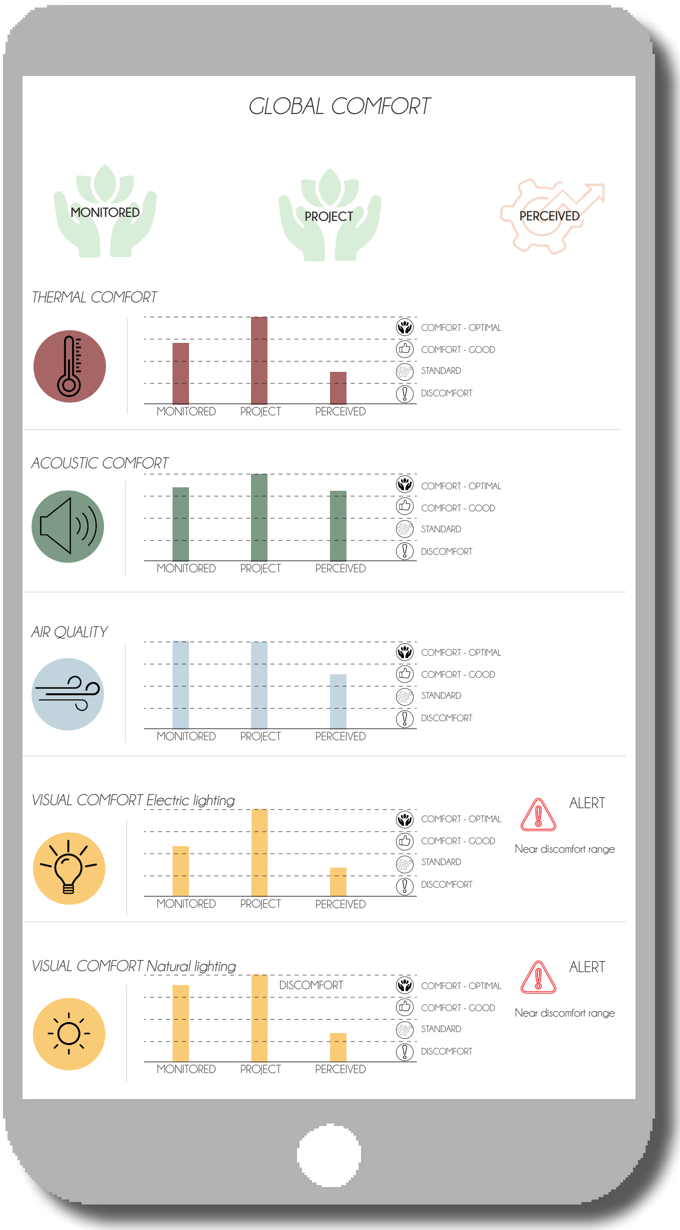



*Figure 50: global comfort representation first proposal.*

### Second proposal

The second proposal is more graphic and combines in the same image all the information. It is less understandable immediately, but through these counters compare the results in only one scheme. The rays divide in sectors in relation to the range. The alert ray is coloured with red to better emphasize the proximity to the discomfort range.

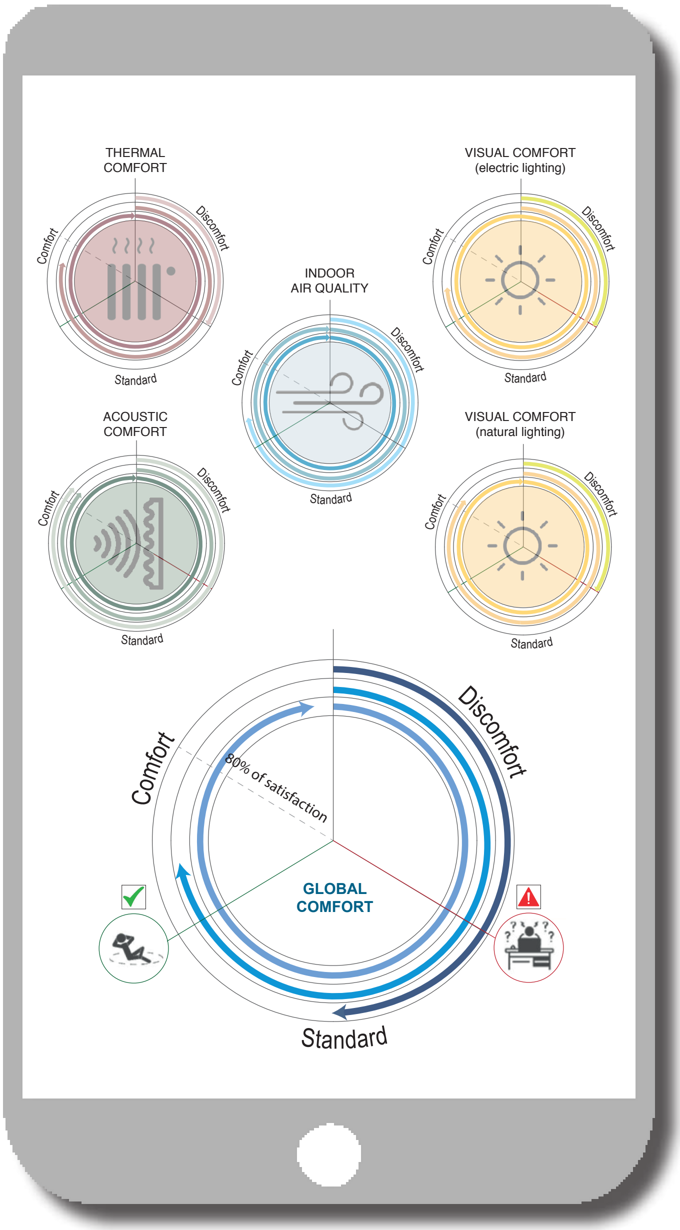



*Figure 51: global comfort representation second proposal.*

## Third proposal

The third proposal combines the graphic representation developed in the thesis work of N. Oggiani to communicate results to office occupants, with the new thresholds defined through this project of thesis. It compares linearly the results, thus is more understandable and useful to communicate immediately the results. Visual comfort is composed by natural and electrical lighting, that may have different results, thus they are represented as single bars.

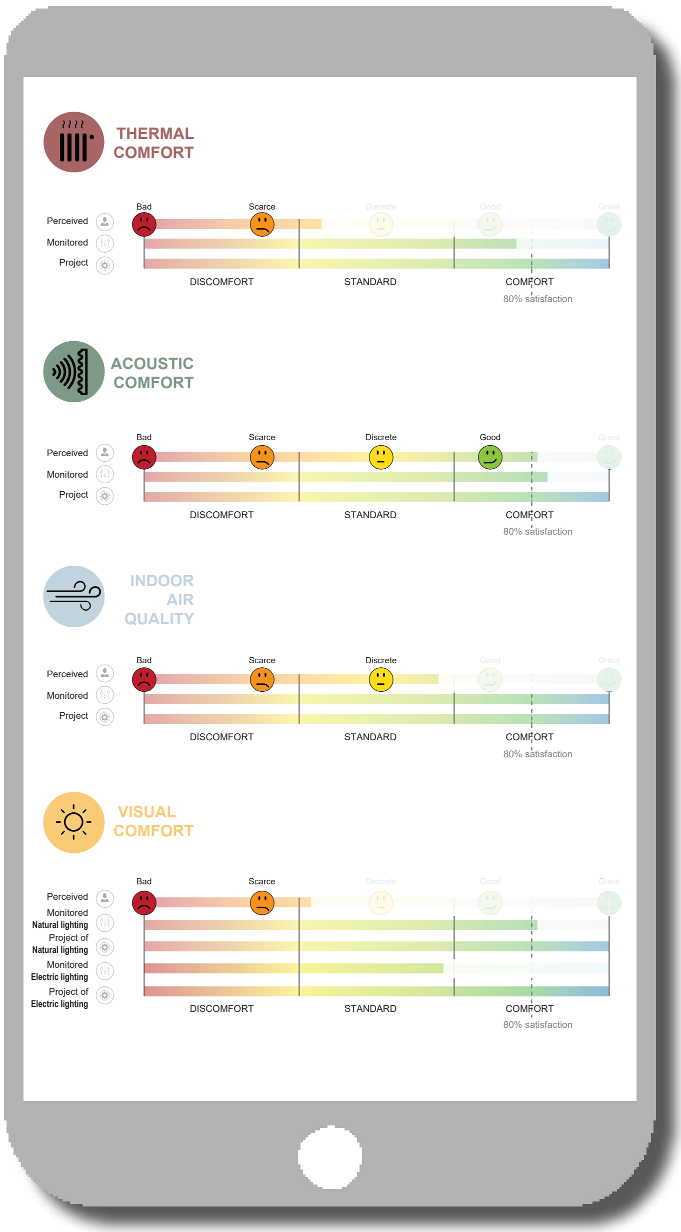



*Figure 52: global comfort representation third proposal.*

With this kind of representation is easy the representation in time of the different categories of comfort, thus it is possible to see the story of the comfort during a specific day, organised in ranges of time (15 minutes, 30 minutes, 1 hour).

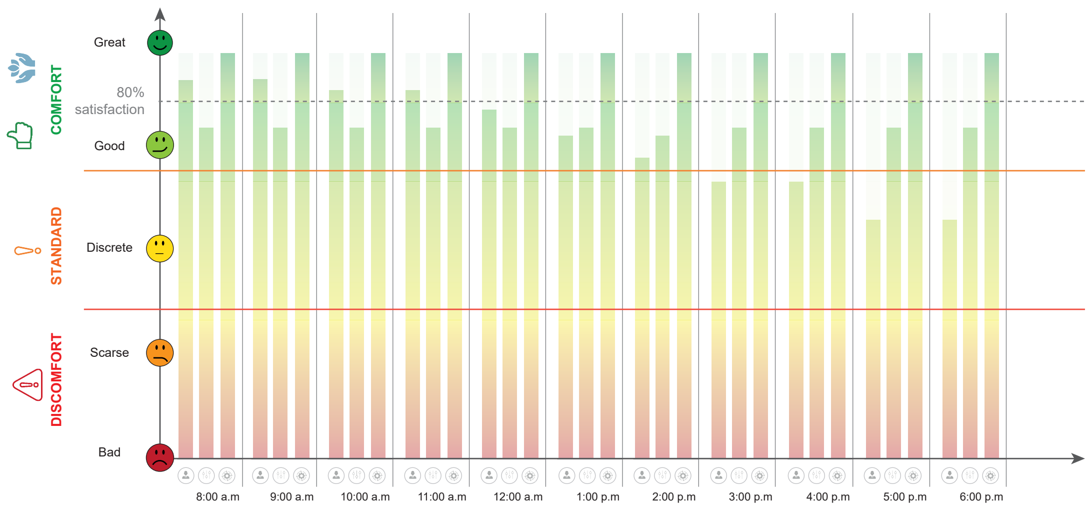



*Figure 53: global comfort representation during time.*

This kind of representation is useful to analyse the discrepancies between comfort perceived, monitored and project related, during the time. In this way it is possible to understand the relation between the objective indoor environmental conditions and how are perceived by occupants.

## 5.3 References


1. Oggiani, N. (2020). Qualità dell’ambiente interno e comfort globale: misure in campo ed analisi nella sede dell’ARPA della Valle d’Aosta. = Indoor environment quality and global comfort: field measurements and analysis at the ARPA headquarters in the Aosta Valley. Retrieved from http://webthesis.biblio.polito.it/16368/

# 6 Thesis results

## 6.1 Discussions

The aim of this work of thesis was to thoroughly study indoor environmental quality and global comfort in offices and find a method for representing global comfort in space and time. Thanks to the study of standards, protocols and the drafting of the literature review, it was possible to identify the strengths and weaknesses relating to this issue, towards which interest has grown a lot in recent years. This preliminary study carried out, allowed to observe that the regulations on thermal comfort, acoustic comfort, visual comfort and indoor air quality often provide threshold values of the indexes that guarantee to avoid a condition of discomfort, but do not ensure the achievement of comfort. Only some standards, such as EN 16798 and NF S 31-080 provide a subdivision into categories, allowing different levels of quality to be achieved in the indoor environment. For this reason, this thesis presents new ranges and thresholds, to identify and achieve different levels of comfort, based on the indoor conditions of the environment analysed. In order to reach the maximum expected level of comfort, it is not sufficient that all the indexes, identified as contributing to the definition of the quality of the internal environment, comply to the highest level of comfort: in fact, there are contextual and personal variables that are not objectively quantifiable, but greatly influence the occupants' comfort perception. The influence of these variables determines an uncertainty that can only find expression with the assessment of the occupants' perceived comfort which, in a practical sense, can be evaluated through a percentage of satisfaction. For this reason, within this thesis, a protocol was created to allow to compare the subjective data, that is the perceived global comfort, and the objective data, that is the evaluation of the physical indexes of comfort. The indexes included in the protocol were selected following the analysis of standards and protocols, and are considered directly capable of providing an assessment of the quality within the environment and therefore of comfort. For each domain,

therefore, the indexes that contribute to the definition of global comfort have been selected.
The protocol, organized as explained in the previous chapter, allows to obtain a percentage value of the global comfort, able to express the environmental conditions and directly comparable with the perceived comfort. In addition, the aim of the implementation of this protocol, is to provide a tool solely focused on the evaluation of IEQ and therefore of global comfort, overcoming the separation of the four domains, a topic widely discussed in literature. In fact, to determine the quality of an environment, it is essential to evaluate the four domains simultaneously giving them the same weight, because dissatisfaction with even a single domain is sufficient to determine the perception of discomfort. Thanks to the rating system of this protocol, it is possible to obtain a single score, in percentage, which gives the same importance to all domains; moreover, it is possible to add over time indexes considered important for the evaluation of comfort for a specific domain and to change the weight of the single domain on the evaluation of global comfort result, after studies that verified the greatest impact of some domains respect the other ones.
Equally important and fulcrum of this thesis is the representation of global comfort in space and time. The aim was to find a way to provide information on the conditions of the internal environment to different types of users. The proposed solutions allow to have information related to individual domains, but also provide a unique data of global comfort. These graphic proposals find concreteness both in a browser and in a mobile application, where a questionnaire is inserted to be submitted to users for the assessment of perceived global comfort. This percentage of perceived global comfort can be compared with a percentage of global comfort obtained by on-site monitoring of the physical indexes entered within the protocol, if existing, with the percentage value of the project related global comfort. Very important within this application is the ability to view data relating to global comfort at the current time, or in a history that keeps in memory the conditions in the previous hours and days.
This thesis also had as its objective the realization of a renovation project for an existing office, within the ARPA Valle d’Aosta building. Thanks to this project it was possible to provide a practical example of application of the protocol and representation of global comfort in space and time.

The protocol has been designed so that, through a preliminary analysis of the project and the tools available, it is possible to identify which indexes will be possible to evaluate, without losing validity in the definition of the conditions of the internal environment, thanks to a simple rating proportion system, as shown in the previous chapter. Within this case study, because of the morphological conditions and the software used, it was not possible to evaluate all the indexes. However, the process was followed in its entirety: thanks to the development of the thesis "Qualità dell'ambiente interno e comfort globale: misure in campo ed analisi nella sede dell'ARPA della Valle d'Aosta" by N. Oggiani, it was possible to obtain the data necessary for the assessment of perceived global comfort, which was transformed into a percentage within this thesis work, and it was possible to have parameters values monitored in the environment. Thanks to these data, within this thesis work, models were created within the various software to simulate the current state and subsequently the project state. In this way it was possible to obtain the values of the indexes and compile the protocol for both cases, thus obtaining values as a percentage of global comfort. These values were then compared with the perceived comfort. It is also possible to see that thanks to the project, the global comfort has been improved.
To evaluate the perceived global comfort within the office taken as a case study, it would be necessary to submit the questionnaire to users, through the developed application, and then compare the result with the global comfort expected by the project.
The result of the comparison shows some discrepancy between perceived and monitored or project related comfort, due to the presence of these non-physical variables, that affect comfort. Therefore, with the project is not possible to reach the maximum level of comfort, without considering and quantifying these variables, as new sections of the protocol.

## 6.2 Conclusions

This project of thesis starts with the necessity to evaluate IEQ and comfort perception. The study carried out defines new thresholds for comfort evaluation: “discomfort”, “standard”, “comfort”, due to the fact that standards avoid the risk of discomfort but are not able to guarantee comfort. Comfort range is divided into two sections: below 80% of satisfaction and above this value. To reach the maximum value of comfort perceived is necessary to consider other variables and elements nowadays not codified in standards and protocols. Some of these variables (contextual and personal), that greater affect comfort, in future may be studied and codified in regulations, defining new levels in relation to the users.

The project of renovation developed shows the importance to find a balance between the requirements of each domain. It is not possible to optimize energy performance and comfort for each domain without considering the needs related to the others. Nevertheless, according to the users and clients’ necessity, an optimal result may be obtained.

The representation of comfort shows the discrepancies between perceived and monitored comfort: usually the monitored data comply with the comfort level, but on the contrary users are not satisfied with indoor conditions. On the other side, in some cases, occupants do not perceived discomfort despite monitored data corresponds to a low or medium level of satisfaction. An example is the perception of visual comfort in the office analysed: occupants were more satisfied with it when the objective measure of illuminance was significantly lower than the value required by standards. This fact introduces the topic of natural and electric lighting: occupants may not perceive discomfort with natural lighting conditions because are balanced with electric lighting.

The perception of global comfort and the combined effect of the four domains is a field still to be studied widely, to understand their weight respect to the global comfort. The use of a device, such as a mobile application, to have a frame of the comfort conditions indoor may be useful to collect all these information related to the occupants’ perception. Usually, mobile applications are used to submit benchmarks, but they can be implemented with the representation of global comfort, with the aim to show perceived, monitored and project related percentage of global comfort.