Africa-Europe BioClimatic buildings for XXI century

REPORT ON COMFORT INDICATORS AND SCENARIOS

www.abc21.eu

ABC 21 project

This document has been developed as part of the project titled "**ABC 21 – Africa-Europe BioClimatic buildings for XXI century**".

The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 894712.

Document information

Name:	D3.2 Report on comfort indicators and scenarios
Date:	31.08.2021
Work Package:	WP3 - Performance indicators and guidelines for XXI century bioclimatic buildings and districts
Task:	T3.1 - Review and choice of performance indicators for energy, demand flexibility and comfort

Authors

Name	Email	Institution
Silvia Erba	silvia.erba@polimi.it	PoliMi
Alessandra Barbieri	alessandra.barbieri@polimi.it	PoliMi
Lorenzo Pagliano	lorenzo.pagliano@polimi.it	PoliMi

Revision

Version	Date	Author	Institution	Description of changes
v1.0	27.01.2021	Silvia Erba	PoliMi	Document creation
v2.0	18.04.2021	Silvia Erba, Alessandra Barbieri	PoliMi	Review and completion
v2.1	28.04.2021	Silvia Erba	PoliMi	Minor review
v2.2	03.05.2021	Virginie Grosdemouge	UR	Minor review
v2.3	04.05.2021	Lorenzo Pagliano	PoliMi	Minor review
v2.4	07.05.2021	Francois Garde	UR	Review and inputs
v3.0	08.05.2021	Silvia Erba	PoliMi	Updates according to reviews
v4.0	31.08.2021	Silvia Erba, Alessandra Barbieri	PoliMi	Revision of executive summary, revision of deliverable layout

Executive summary

The aim of this report is to provide a clear framework about the available methodologies, standards, tools and indicators to assess the **Indoor Environmental Quality** (i.e. **thermal, acoustic, visual comfort** and **air quality**) targeted for bioclimatic architecture. To pursue this object a critical review regarding performance indicators available in literature and international standards was carried out. The main concepts and their operative definitions have been clearly presented for effective design work and communication.

The main findings are summarized as follows:

- Thermal comfort is defined as: "that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation". It is the parameter of IEQ which has been more widely investigated and extensive documentation is available in literature. A detailed analysis of the most appropriate methods to **assess thermal comfort** in buildings located **in warm climates,** with a focus on Africa and Europe, has been carried out. The European models analysed to assess thermal comfort are the Fanger Comfort Model (PMV/PPD) and the the Adaptive Comfort Model. For the African context, the bioclimatic chart tools are described in detail.
- Acoustic comfort is defined as "a state of contentment with acoustic conditions". However, the evaluation of indoor acoustic comfort is usually done in terms of prevention of the occurrence of discomfort. Building location, city design, building design, vegetation, construction type, right choice of openings, materials and construction elements can help reducing the annoyance given by neighbours, traffic, outdoor noise, etc.
- Visual comfort is defined as "a subjective condition of visual well-being induced by the visual environment". It depends on the physiology of the human eye, on the physical quantities describing the amount of light and its distribution in space, and on the spectral emission of the light source.
- Indoor Air quality (IAQ) is the quality of air inside **enclosed spaces** and refers to the **types** and **concentrations** of airborne contaminants found in buildings that are known or suspected to affect people's comfort, well-being, health, learning outcomes and work performance. Health effects from indoor air pollutants may be experienced soon after exposure or years later. These include irritation of the eyes, nose, and throat, headaches, dizziness, and fatigue. Such immediate effects are usually short-term and treatable. Other health effects may show up years after exposure has occurred or only after long or repeated periods of exposure. These effects, which include some respiratory diseases, heart disease and cancer, can be severely debilitating or fatal. It is prudent to try to improve the indoor air quality even if symptoms are not noticeable.
- A list of **Key Performance Indicators (KPIs)** has been proposed in order to determine thermal comfort, visual comfort, acoustic comfort and indoor air quality. They will be used to monitor and verify the conditions of the indoor environment in the ABC 21 case studies, offer a comparison between them and provide guidelines for bioclimatic design in warm climates. For each specific case study, the most appropriate indicators will be selected from these lists in relation to the available measured or simulated data.
    - **Thermal comfort indicators**
        1. Percentage of time outside an operative temperature range (Adaptive)

2. Percentage of time outside an operative temperature range (Fanger)
3. Degree-hours (Adaptive)
4. Degree-hours (Fanger)
5. Percentage of time inside the Givoni comfort zone (1 m/s)
6. Percentage of time inside the Givoni comfort zone (0 m/s)
7. Number of hours within a certain temperature range

- **Acoustic comfort indicators**
  1. Airborne sound insulation
  2. Equivalent continuous sound Level
  3. HVAC noise level
  4. Reverberation time
  5. Masking/barriers
- **Visual comfort indicator**
  1. Light level (illuminance)
  2. Useful Daylight Illuminance (UDI)
  3. Glare control
  4. Quality view
  5. Zoning control
- **Indoor Air Quality indicators**
  1. Organic compound
  2. VOCs
  3. Inorganic gases
  4. Particulates (filtration)
  5. Minimum outdoor air provision
  6. Moisture (humidity, leaks)
  7. Hazard material

- A review of global indexes available in literature has been performed. This type of index combines all categories (thermal, acoustic, visual and indoor air quality) and weighs their values according to different methodologies which involve monitored data and subjective surveys.

Abbreviations

Term	Name
ASE	Annual Sunlight Exposure
CDPH	California Department of Public Health
CIBSE	Chartered Institution of Building Services Engineers
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CRI	Color Rendering Index
DA	Daylight Autonomy
DF	Daylight Factor
DGI	Daylight Glare Index
DGP	Daylight Glare Probability index
EPBD	Energy Performance Building Directive
EPW	EnergyPlus Weather File
Ev	Vertical illuminance at the eye level
GI	Glare Impact
HVAC	Heating, Ventilating, and Air Conditioning systems
IAQ	Indoor Air Quality
I_{cl}	clothing insulation
IEQ	Indoor Environmental Quality
KPI	Key Performance Indicator
L_{eq}	equivalent continuous sound level
MET	Metabolic rate
NO_2	Nitrogen dioxide
NVB	Naturally Ventilated Buildings
PM	Particulate Matter
RC	RC: Relative Contrast
RCpi	Relative Contrast on pixel illuminance
Rn	Radon
sDA	spatial Daylight Autonomy
SET	Standard Effective Temperature
SO_2	sulphur dioxide
SRI	Smart Readiness Indicator
STCc	composite Sound Transmission Class
STI	Speech Transmission Index
t_a	average air temperature
t_o	operative temperature
TVOC	Total Volatile Organic Compounds

UDI	Usedul Daylighting Index
UGR	Unified Glare Rating
V_a	Average air speed
VLT	Visible Light Transmittance
VOC	Volatile Organic Compounds
WHO	World Health Organization

Contents

1 Introduction ... 9
2 Indoor thermal comfort ... 9
2.1 Methods for the evaluation of thermal comfort ... 10
2.1.1 Definitions ... 11
2.1.2 The Fanger Comfort Model (PMV/PPD) ... 13
2.1.3 The Elevated Air Speed Comfort Zone Method ... 18
2.1.4 The Adaptive Comfort Model ... 19
2.1.5 Bio-climatic charts ... 22
2.1.6 Highlights ... 25
2.2 Indicators for the evaluation of thermal comfort conditions ... 25
2.2.1 Long-term thermal comfort indices according to EN-ISO standards ... 26
2.2.2 Long-term thermal comfort indices applied to Givoni comfort zones ... 29
2.3 Comfort models in literature ... 29
3 Indoor acoustic comfort ... 34
4 Indoor visual comfort ... 36
5 Indoor air quality ... 41
6 Comfort indicator overview ... 49
6.1 Key Performance Indicators for ABC 21 ... 50
6.2 Indoor Environmental Quality monitoring ... 53
6.3 Standards for quantification and measurements ... 55
6.4 Global IEQ index ... 58
7 Conclusions: KPIs for ABC 21 ... 61
ANNEX A: Example of bioclimatic tool ... 63
ANNEX B: Measurement and Verification protocol for Net Zero Energy Buildings – Levels of monitoring [86] ... 68
8 References ... 70

Figures

Figure 1: Example of the effect of changes in the met value according to the ASHRAE Analytical Comfort Zone Method [5]........ 15
Figure 2: Example of effect of different *clo values* according to the ASHRAE Analytical Comfort Zone Method [5]........ 17
Figure 3: Acceptable ranges of operative temperature t_o and average air speed V_a for 1.0 and 0.5 clo comfort zones at humidity ratio 0.010, according to the ASHRAE Elevated Air Speed Comfort Zone Method [5] 18
Figure 4: Elevated Air Speed Comfort Zone Method example (lightly shaded zone) compared to the Analytical Comfort Zone Method example (darkly shaded zone) [5]........ 19
Figure 5: Comfort temperature ranges according to the three categories defined in [9]. 20
Figure 6: Acceptable operative temperature ranges for naturally conditioned spaces according to [5]........ 21
Figure 7: Summary of climatic analysis tools for building design purposes [38] 23
Figure 8: Comfort zones defined by Givoni [15,41] for an air speed of 2 m/s 24
Figure 9: Assessment of thermal comfort in an office building in La Reunion 24
Figure 10: Human comfort aspects and their relations [83] 49
Figure 11: Indoor Environment Quality indicators for ABC 21 61
Figure 12: Examples of psychrometric chart........ 64

Tables

Table 1: Metabolic rates for typical tasks [5] 16
Table 2: Clothing insulation values for typical ensembles [5] 17
Table 3: Increases in acceptable operative temperature limits (Δt_0) in occupant-controlled naturally conditioned spaces according to [5] 22
Table 4: Overview of the most common thermal comfort index in literature [52] 26
Table 5: PMV ranges – standards comparison 27
Table 6: Operative temperature ranges based on PMV model (EN 7730:2005)........ 27
Table 7: Operative temperature ranges for buildings with mechanical cooling systems (EN 16798-2:2019)........ 28
Table 8: Operative temperature ranges based on adaptive model (ASHRAE 55:2020) 28
Table 9: Operative temperature ranges based on adaptive model (EN 16798-1)........ 28
Table 10: Synthesis of the comfort models used with bioclimatic architecture 29
Table 11: Additional thermal comfort parameters and indexes reviewed in literature........ 31
Table 12: Indoor acoustic comfort indicators literature review........ 34
Table 13: Visual comfort indicators literature overview 36
Table 14: List of contaminants and major sources in buildings [80] 42
Table 15: list of IAQ indicators reviewed in literature 42
Table 16: Long-term thermal comfort indicators 50
Table 17: Visual comfort indicators........ 50
Table 18: Acoustic comfort indicators 52
Table 19: Indoor Air Quality indicators........ 52
Table 20: List of parameters necessary to assess thermal comfort, acoustic comfort, visual comfort and air quality for the indoor environment 54
Table 21: Levels of IEQ monitoring (extract from Annex B [86]) 55
Table 22: Overview of standards relevant to Indoor Environment Quality........ 55
Table 23: List of existing IEQ assessment: 58
Table 24: Quantification IEQ indexes reviewed in Table 23 59
Table 25: Main comfort models available in Climate Consultant 6.0 software........ 64

1 Introduction

ABC 21 aims to increase the energy performance, the quality of life and sustainability of African and European buildings through the identification, strengthening and effective deployment of affordable bioclimatic designs and local materials under the XXI century conditions of warming climate, accelerated urbanisation in Africa and ageing building stock in Europe. The cooperation and the exchanges between African and European partners and Allies aim to provide a larger view on bioclimatic buildings with examples and experiences from different contexts to identify effective technical guidelines and tools for future-proof passive design.

In task *3.1 - Review and choice of performance indicators for energy, demand flexibility and comfort*, the main concepts/variables and their operative definitions are consolidated to provide a basis for effective design work and its communication. The task analyses literature and international standards to produce a critical review on energy (D3.1), indoor environmental quality (D3.2) and energy flexibility (D3.3) indicators. The present deliverable deals with Indoor Environmental Quality (IEQ) and shows how this is related to the energy performance of a building.

The Directive (EU) 2018/844 [1] emphasizes the need to improve the indoor comfort and wellbeing of occupants in parallel to the energy performance. IEQ, which includes thermal comfort, acoustic comfort, visual comfort and indoor air quality, has in fact a major impact on building occupant health, comfort and work performance [2,3].

This deliverable aims to be a reference document on the topic of IEQ for the Consortium and the Allies. It reviews the main approaches, models, definitions and tools available in literature and international standards but not easily accessible and familiar to those outside academia, in spite of their relevance for effective application. It provides information about methods to assess comfort, applicable for buildings located both in Europe and Africa. In bioclimatic architecture a special focus is on thermal comfort, which is achieved by interacting with the exterior climate [4] providing protection of the indoor environment from the outdoor warm or cold conditions, exploiting sources and sinks from the environment and making use of thermal inertia. See D3.1 for an insight on the definition of bioclimatic building.

After this overview, the report provides a complete list of Key Performance Indicators (KPIs) to determine thermal comfort, visual comfort, acoustic comfort and indoor air quality which can be used from the design until the monitoring and verification phase of a bioclimatic building.

A careful choice of these indicators based on the climate type will be done in the next phase of the project in order to assess and compare the case studies examined in *Task 3.4 – Case studies of European and African Bioclimatic buildings*, which will be evaluated using measured data from previous measurement and assessment campaigns or - in a selection of cases - with measurement or simulations performed within ABC 21.

2 Indoor thermal comfort

Thermal comfort is defined as: ‘that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation’ [5]. It is the parameter of IEQ which has been more widely investigated and extensive documentation is available in literature [6–8]. To evaluate the indoor thermal comfort conditions, a large number of surveys about thermal sensations have been as a base for the development of various comfort models aiming at predicting the average comfort perception of groups of people exposed to a certain environment. The assessment of thermal comfort presented in the Standards EN 16798-1:2019 [9] and ASHRAE 55:2020 [5] indicates two main typologies of comfort model: the "Fanger (PMV/PPD) model" (EN ISO 7730 [10]), proposed for actively conditioned buildings and the "Adaptive Model", proposed for naturally conditioned spaces.

In tropical climates and naturally conditioned spaces, field studies have found that the International standard for indoor climate, ISO 7730 [10] based on Fanger's predicted mean vote equations, does not adequately describe comfortable conditions [11–13]. In warm climate conditions, PMV predicts that people will feel hotter than they actually do and therefore tends to encourage the use of more air conditioning than necessary. Fanger himself did recognise that "in non-air-conditioned buildings in warm climates, occupants may sense the warmth as being less severe than the PMV predicts" [14].

In ASHRAE 55:2020 [5], compared to previous versions: "applicability was expanded of the Adaptive Model used for naturally conditioned spaces. The model is now applicable to buildings that have a mechanical cooling system installed, as long as the system is not running". Also an updated method to consider the comfort benefits of enhanced air speed provided e.g. by natural ventilation or ceiling fans and applicable "to all spaces within the scope of this standard" has been inserted in ASHRAE 55:2020.

In the last decades a number of design activities and successful construction activities have taken place based on the Givoni's comfort zone [15,16] or the Standard Effective Temperature (SET*) model developed by Gagge [17–19] and growing evidence of comfort acceptance by occupants of those buildings has been found [20,21].

Studies and tools are available in literature to compare different thermal comfort models (e.g. Attia et al. [22] developed an analysis application for bioclimatic design strategies in hot humid climates and showed the comfort models comparison for the two major cities of Madagascar, situated off the southeast coast of Africa).

In the following sections we present an overview of the above cited methods.

2.1 Methods for the evaluation of thermal comfort

Two main types of models for assessing thermal comfort are often used: the static model (PMV/PPD) and the adaptive model. Fanger's thermal comfort model, often referred as the PMV/PPD model, was built on experiments involving exposure of subjects to steady-state conditions in climate chambers and considers the occupants to be passive receptors detecting the surrounding environmental conditions [23].

On the other hand, the adaptive comfort theory has been developed from field studies and considers the building occupants as active agents interacting with their built environment [8]. This model relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological or climatological parameters.

In addition to those two main models ASHRAE 55:2020 proposes also the Standard Effective Temperature (SET) model which is applicable to dynamic conditions and is recommended to include the effects of the relative humidity and air velocity on thermal comfort [24]. ASHRAE 55 [5] adopts the SET model combined with the "Analytical Comfort Zone Method" in case of the "Elevated Air Speed Comfort Zone Method".

These models have already been integrated into several international standards such as ISO 7730 [10], ASHRAE 55 [5] and EN 15251 [25] (now EN 16798 [9]), which have also undergone several revisions [26]. A complete list of the standards related to thermal comfort and its evaluation can be found in Table 22.
Regarding subjective expression of thermal comfort sensation and preference, the recently updated standard [27] contains commonly used scales and standard questions for interviewing building occupants in view of assessing the quality of thermal environments. To this end, within the EU project AZEB, guidelines for interviewing end-user and examples of application have been developed [28].
When designing bioclimatic buildings, it is common to use bioclimatic charts which are simple tools to analyze climate conditions and investigate appropriate design recommendations for different climates. The charts most widely used by researchers and building planners are: the Olgyay Bioclimatic chart, the Szokolay Bioclimatic chart, the Givoni-Milne Bioclimatic chart and the Mahoney Table and they can be used also for comfort assessment.

2.1.1 Definitions

It is important to use in a consistent and precise manner concepts and terminology for effective exchange of experiences, comparability and ultimately also to reduce time and costs of planning, construction, drafting and communication of legislation and regulations.
The following is a list of the main definitions related to thermal comfort assessment according to the above mentioned reference standards [5,9,10].

Air speed: the rate of air movement at a point, without regard to direction.

Air temperature: the temperature of the air at a point.

Average air speed (V_a): the average air speed surrounding a representative occupant. The average is with respect to location and time. The spatial average is for three heights as defined for average air temperature t_a. The air speed is averaged over an interval not less than one and not greater than three minutes. Variations that occur over a period greater than three minutes shall be treated as multiple different air speeds.

Average air temperature (t_a): the average air temperature surrounding a representative occupant. The average is with respect to location and time. The spatial average is the numerical average of the air temperature at the ankle level, the waist level, and the head level. These levels are 0.1, 0.6, and 1.1 m for seated occupants and 0.1, 1.1, and 1.7 m for standing occupants. Time averaging is over a period not less than three and not more than 15 minutes.

Clothing insulation (I_{cl}): the resistance to sensible heat transfer provided by a clothing ensemble, expressed in units of clo. (Informative Note: The definition of clothing insulation relates to heat transfer from the whole body and, thus, also includes the uncovered parts of the body, such as head and hands).

Humidity: a general reference to the moisture content of the air. It is expressed in terms of several thermodynamic variables, including vapor pressure, dew-point temperature, wet-bulb temperature, humidity ratio, and relative humidity. It is spatially and temporally averaged in the same manner as air temperature. (Informative Note: Any one of these humidity variables must be used in conjunction with dry-bulb temperature in order to describe a specific air condition).

Mean daily outdoor air temperature ($t_{mda(out)}$): any arithmetic mean for a 24-hour period permitted in Section 5.4 of the standard [5]. Mean daily outdoor air temperature is used to calculate prevailing mean outdoor air temperature.

Mean radiant temperature: the temperature of a uniform, black enclosure that exchanges the same amount of heat by radiation with the occupant as the actual surroundings. It is a single value for the entire body and accounts for both long-wave mean radiant temperature and short-wave mean radiant temperature.

Mechanical cooling: cooling of the indoor environment by mechanical means used to provide cooling of supply air

- Note 1: This includes fan coil units, chilled ceilings and beams cooled surfaces, etc.
- Note 2: Opening of windows during night and day time or mechanical supply of cold outdoor air is not regarded as mechanical cooling

Mechanical ventilation: ventilation system where air is supplied or extracted from the building or both by a fan using air terminal devices, ducts and roof/wall devices

Metabolic rate (met): the rate of transformation of chemical energy into heat and mechanical work by metabolic activities of an individual, per unit of skin surface area (expressed in units of met) equal to 58.2 W/m^2 (18.4 Btu/h•ft^2), which is the energy produced per unit skin surface area of an average person seated at rest.

Natural ventilation: ventilation provided by thermal, wind, or diffusion effects through doors, windows, or other intentional devices in the building designed for ventilation

- Note 1: Natural ventilation systems may be either manually or automatically controlled.

Operative temperature (t_o): the uniform temperature of an imaginary black enclosure, and the air within it, in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment.

Operative temperature is calculated according to [29] as:

$$t_0 = \frac{h_c \cdot t_a + h_r \cdot t_r}{h_c + h_r} \qquad (1)$$

t_a is the air temperature;
t_r is the mean radiant temperature;
h_c is the heat-transfer coefficient by convection;
h_r is the heat-transfer coefficient by radiation.

In most practical cases where the relative velocity is small (< 0,2 m/s) or where the difference between mean radiant and air temperature is small (< 4 °C), the operative temperature can be calculated with sufficient approximation as the mean value of air and mean radiant temperature.
Mean radiant temperature:

1) can be calculated using the measurement by instruments such as the globe thermometer, which allows the generally heterogeneous radiation from the walls of an actual enclosure to be "integrated" into a mean value (see Table 11 for further details).
2) can be calculated from measured values of the temperature of the surrounding walls and the size of these walls and their position in relation to a person (calculation of geometrical shape factors).

Optimal operative temperature: operative temperature that satisfies the greatest percentage of occupants at a given clothing and activity level in the current thermal environment

Outdoor running mean temperature (T_{rm-i}): exponentially weighted running mean of the daily mean outdoor air temperature

Prevailing mean outdoor air temperature ($t_{pma(out)}$): when used as an input variable for the adaptive model, this temperature is based on the arithmetic average of the mean daily outdoor temperatures over some period of days in accordance with the following:

A. It shall be based on no fewer than seven and no more than 30 sequential days prior to the day in question.
B. It shall be a simple arithmetic mean of all of the mean daily outdoor air temperatures $t_{mda(out)}$ of all the sequential days in section A.

2.1.2 The Fanger Comfort Model (PMV/PPD)

Based on a steady-state approach, the model developed by Fanger in the 1970s aims at predicting the mean thermal sensation of a group of people and their respective percentage of dissatisfaction with the thermal environments. According to the PMV model, there are six primary factors that affect thermal comfort:

1. Metabolic rate
2. Clothing insulation
3. Air temperature
4. Radiant temperature
5. Air speed
6. Humidity

The first two factors are characteristics of the occupants, and the remaining four factors are conditions of the thermal environment.
The model uses an analytical heat balance of the body and two linear approximations of the relationships between respectively the mean value of skin temperature and sweat secretions, as function of the activity level of the subjects, to construct two indices, proposing them for application in heated and/or mechanical cooled buildings [9]:

- the **Predicted Mean Vote (PMV)**, which estimates the mean value of the sensation votes that would be expressed on the standard thermal sensation scale (-3 cold, -2 cool, -1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot) by a large group of people exposed to a given combination of the personal and environmental variables, and

- the **Predicted Percentage of Dissatisfied (PPD)**, where "decidedly dissatisfied people" are defined by Fanger as those voting ≥ 2 or ≤ -2 on the thermal sensation scale under the same given combination of the personal and environmental variables [23].

The PMV is calculated using the following equations (2)(3)(4)(5):

$$PMV = [0.303 \cdot exp(-0.036 \cdot M) + 0.028] \cdot \begin{Bmatrix} (M-W) - 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M-W) - p_a] - 0.42 \cdot [(M-W) - 58.15] \\ -1.7 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) - 0.0014 \cdot M \cdot (34 - t_a) \\ -3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl}+273)^4 - (\bar{t_r}+273)^4] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \end{Bmatrix} \quad (2)$$

$$t_{cl} = 35.7 - 0.028 \cdot (M-W) - I_{cl} \cdot \{3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl}+273)^4 - (\bar{t_r}+273)^4] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\} \quad (3)$$

$$h_c = \begin{cases} 2.38 \cdot |t_{cl} - t_a|^{0.25} & for \quad 2.38 \cdot |t_{cl} - t_a|^{0.25} > 12.1 \cdot \sqrt{v_{ar}} \\ 12.1 \cdot \sqrt{v_{ar}} & for \quad 2.38 \cdot |t_{cl} - t_a|^{0.25} < 12.1 \cdot \sqrt{v_{ar}} \end{cases} \quad (4)$$

$$f_{cl} = \begin{cases} 1.00 + 1.290 l_{cl} & for \quad l_{cl} \leq 0.078 \cdot m^2 \cdot K/W \\ 1.05 + 0.645 l_{cl} & for \quad l_{cl} > 0.078 \cdot m^2 \cdot K/W \end{cases} \quad (5)$$

Where:

- M is the metabolic rate, in watts per square metre (W/m^2);
- W is the effective mechanical power, in watts per square metre (W/m^2);
- I_{cl} is the clothing insulation, in square metres kelvin per watt (m^2 · K/W);
- f_{cl} is the clothing surface area factor;
- t_a is the air temperature, in degrees Celsius (°C);
- t_r is the mean radiant temperature, in degrees Celsius (°C);
- v_{ar} is the relative air velocity, in metres per second (m/s);
- p_a is the water vapour partial pressure, in pascals (Pa);
- h_c is the convective heat transfer coefficient, in watts per square metre kelvin [W/(m^2 · K)];
- t_{cl} is the clothing surface temperature, in degrees Celsius (°C).
- *NOTE 1 metabolic unit = 1 met = 58,2 W/m^2; 1 clothing unit = 1 clo = 0,155 m^2 · °C/W.*

PMV may be calculated for different combinations of clothing insulation, metabolic rate, air temperature, mean radiant temperature, air velocity and air humidity.

Metabolic rate can be estimated using tabulated values (e.g. Table 1), taking into account the type of work. An example of the effect of increased met value on the comfort zone is shown in Figure 1.

The thermal resistance of clothing and chair can be estimated using tabulated values (e.g.

Table 2), taking into account the time of the year. An example of the effect of increased clo value on the comfort zone is reported in Figure 2.

The model expresses PPD as a function of PMV through the equation (6):

$$PPD_{Fanger}^{ISO}(PMV) = 100 - 95e^{-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2} \in (5, 100). \quad (6)$$

symmetrically distributed around the neutral vote at PMV = 0.

In ASHRAE 55:2020 part of Fanger model is incorporated in the Analytical Comfort Zone Method. Examples in graphical form of this method are presented in Figure 1 and Figure 2.

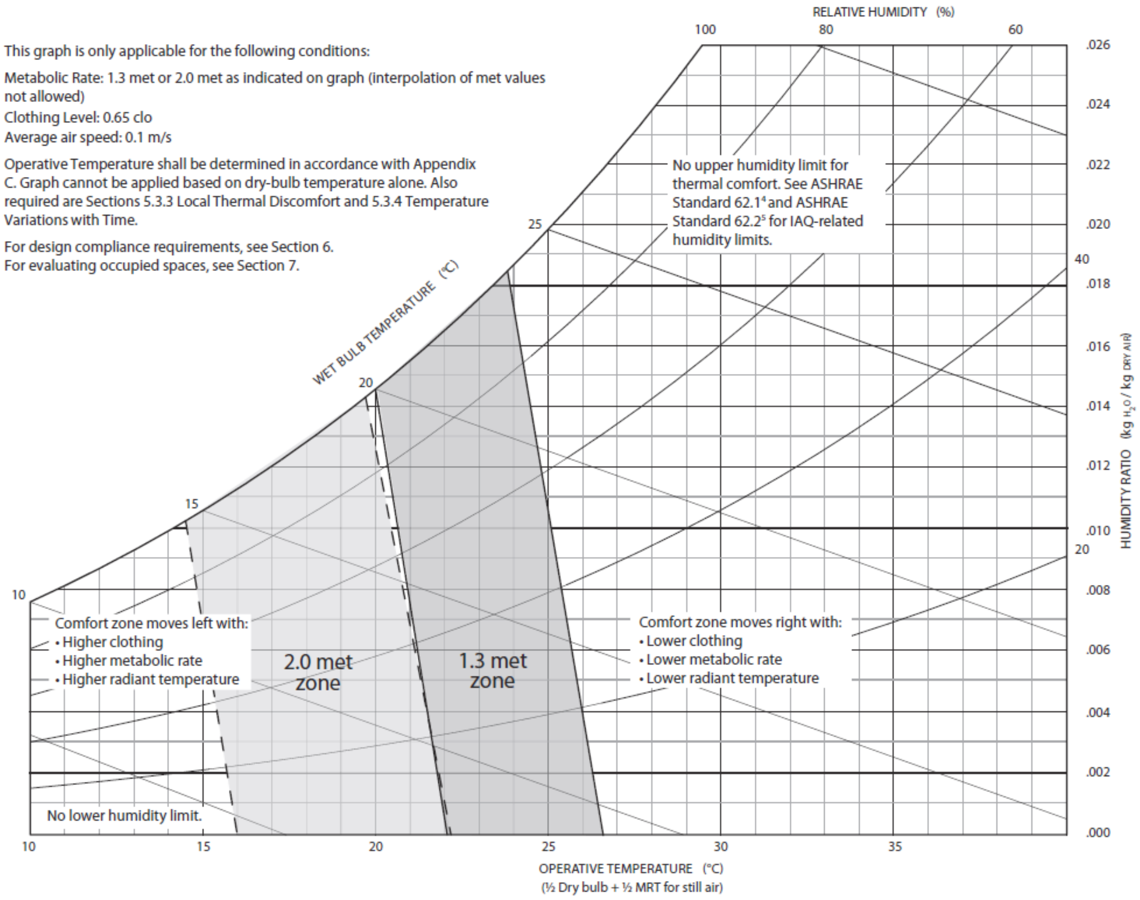

Figure 1: Example of the effect of changes in the met value according to the ASHRAE Analytical Comfort Zone Method [5]

Table 1: Metabolic rates for typical tasks [5]

Activity	Metabolic Rate met	W/m²	Btu/h·ft²
Resting			
Sleeping	0.7	40	13
Reclining	0.8	45	15
Seated, quiet	1.0	60	18
Standing, relaxed	1.2	70	22
Walking (on level surface)			
0.9 m/s, 3.2 km/h, 2.0 mph	2.0	115	37
1.2 m/s, 4.3 km/h, 2.7 mph	2.6	150	48
1.8 m/s, 6.8 km/h, 4.2 mph	3.8	220	70
Office Activities			
Reading, seated	1.0	55	18
Writing	1.0	60	18
Typing	1.1	65	20
Filing, seated	1.2	70	22
Filing, standing	1.4	80	26
Walking about	1.7	100	31
Lifting/packing	2.1	120	39
Driving/Flying			
Automobile	1.0 to 2.0	60 to 115	18 to 37
Aircraft, routine	1.2	70	22
Aircraft, instrument landing	1.8	105	33
Aircraft, combat	2.4	140	44
Heavy vehicle	3.2	185	59
Miscellaneous Occupational Activities			
Cooking	1.6 to 2.0	95 to 115	29 to 37
House cleaning	2.0 to 3.4	115 to 200	37 to 63
Seated, heavy limb movement	2.2	130	41
Machine work			
Sawing (table saw)	1.8	105	33
Light (electrical industry)	2.0 to 2.4	115 to 140	37 to 44
Heavy	4.0	235	74
Handling 50 kg (100 lb) bags	4.0	235	74
Pick and shovel work	4.0 to 4.8	235 to 280	74 to 88
Miscellaneous Leisure Activities			
Dancing, social	2.4 to 4.4	140 to 255	44 to 81
Calisthenics/exercise	3.0 to 4.0	175 to 235	55 to 74
Tennis, single	3.6 to 4.0	210 to 270	66 to 74
Basketball	5.0 to 7.6	290 to 440	90 to 140
Wrestling, competitive	7.0 to 8.7	410 to 505	130 to 160

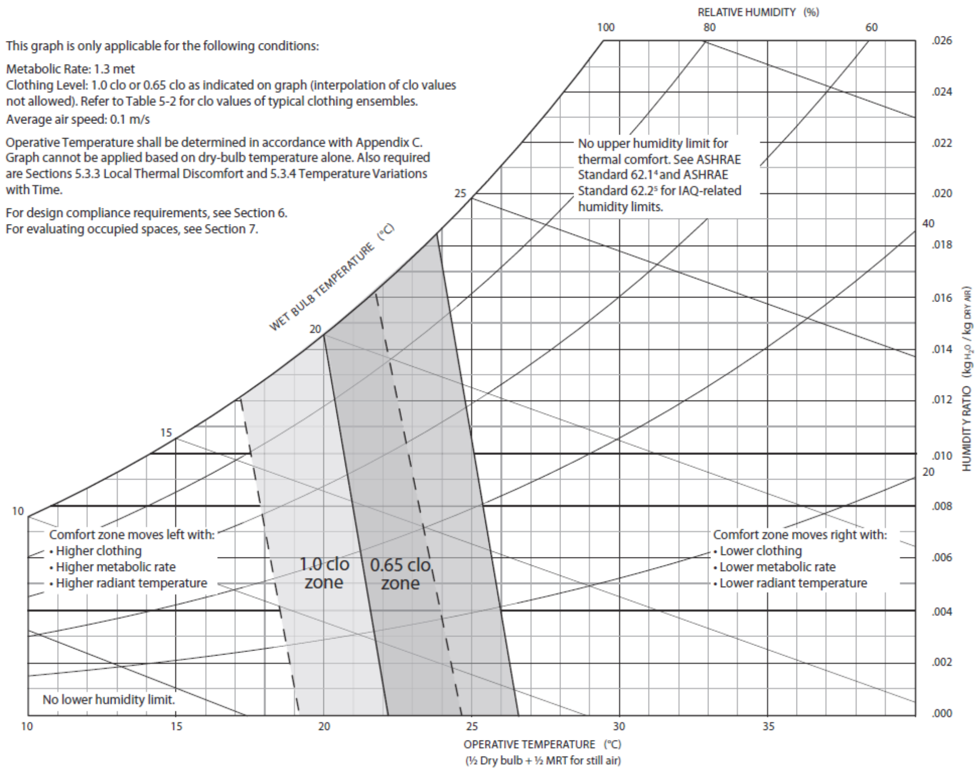

Figure 2: Example of effect of different *clo values* according to the ASHRAE Analytical Comfort Zone Method [5]

Table 2: Clothing insulation values for typical ensembles [5]

Clothing Description	Garments Included [a]	I_{cl}, clo
Trousers	(1) Trousers, short-sleeve shirt	0.57
	(2) Trousers, long-sleeve shirt	0.61
	(3) #2 plus suit jacket	0.96
	(4) #2 plus suit jacket, vest, t-shirt	1.14
	(5) #2 plus long-sleeve sweater, t-shirt	1.01
	(6) #5 plus suit jacket, long underwear bottoms	1.30
Skirts/dresses	(7) Knee-length skirt, short-sleeve shirt (sandals)	0.54
	(8) Knee-length skirt, long-sleeve shirt, full slip	0.67
	(9) Knee-length skirt, long-sleeve shirt, half slip, long-sleeve sweater	1.10
	(10) Knee-length skirt, long-sleeve shirt, half slip, suit jacket	1.04
	(11) Ankle-length skirt, long-sleeve shirt, suit jacket	1.10
Shorts	(12) Walking shorts, short-sleeve shirt	0.36
Overalls/coveralls	(13) Long-sleeve coveralls, t-shirt	0.72
	(14) Overalls, long-sleeve shirt, t-shirt	0.89
	(15) Insulated coveralls, long-sleeve thermal underwear tops and bottoms	1.37
Athletic	(16) Sweat pants, long-sleeve sweatshirt	0.74
Sleepwear	(17) Long-sleeve pajama tops, long pajama trousers, short 3/4 length robe (slippers, no socks)	0.96

a. All clothing ensembles, except where otherwise indicated in parentheses, include shoes, socks, and briefs or panties. All skirt/dress clothing ensembles include pantyhose and no additional socks.

2.1.3 The Elevated Air Speed Comfort Zone Method

The Elevated Air Speed Comfort Zone method uses the Analytical Comfort Zone Method combined with the Standard Effective Temperature (SET).

It is permissible to apply the method to all spaces within the scope of the ASHRAE 55:2020 standard where the occupants have activity levels that result in average metabolic rates between 1.0 and 2.0 met, clothing insulation I_{cl} between 0.0 and 1.5 clo, and average air speeds V_a greater than 0.20 m/s.

Figure 3 represents two particular cases (0.5 and 1.0 clo) of the Elevated Air Speed Comfort Zone Method and it is applicable as a method of compliance for the conditions specified in the figure. The figure also defines comfort zones for air movement with occupant control (darkly shaded) versus without occupant control (lightly shaded).

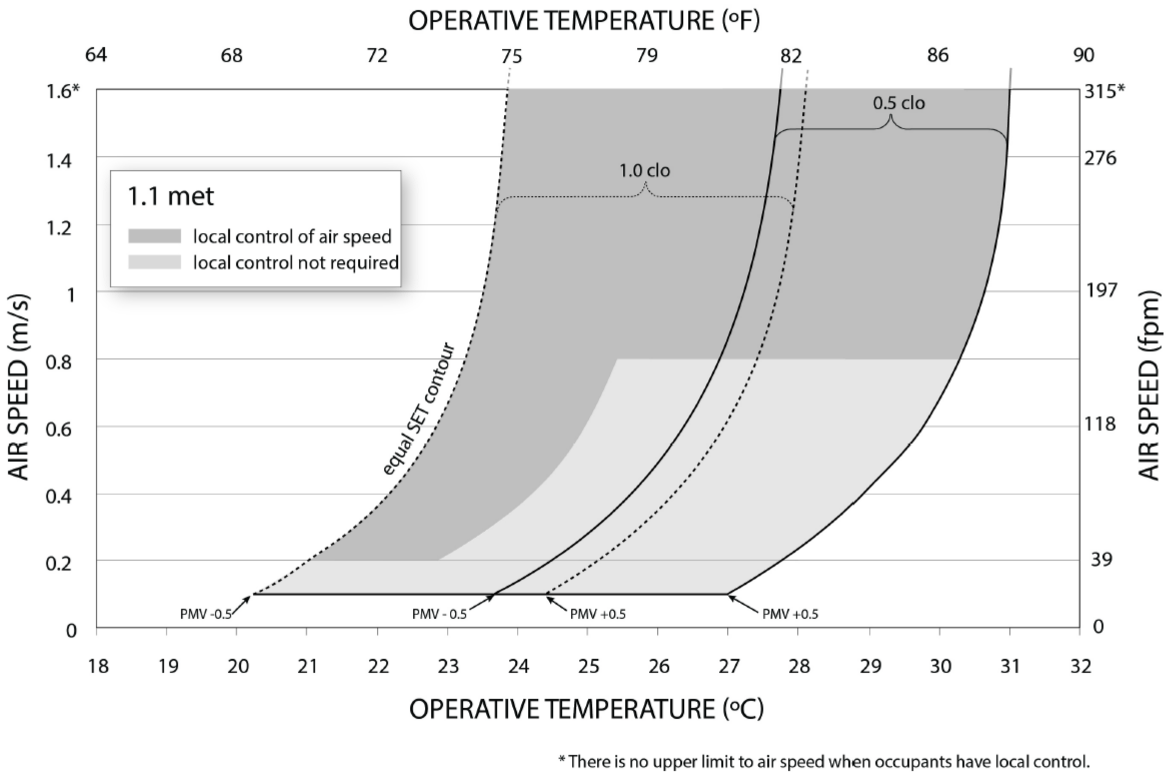

Figure 3: Acceptable ranges of operative temperature t_o and average air speed V_a for 1.0 and 0.5 clo comfort zones at humidity ratio 0.010, according to the ASHRAE Elevated Air Speed Comfort Zone Method [5]

Figure 4 provides a graphical example of a comfort zone using the Elevated Air Speed Comfort Zone Method (lighter shade zone) compared to one using the Analytical Comfort Zone Method (darker shade zone). Direct use of this chart to comply with the Elevated Air Speed Comfort Zone Method using the lighter shade zone is allowable for the specific input conditions described on the chart.

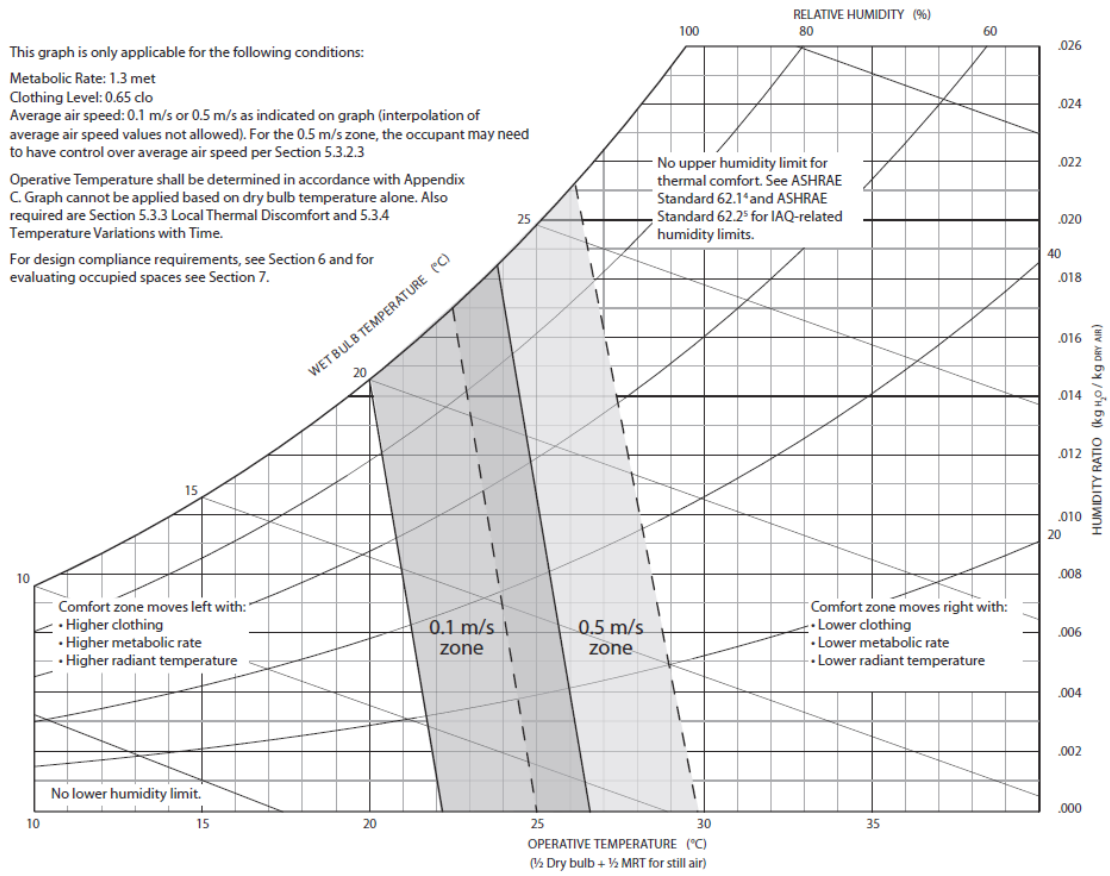

Figure 4: Elevated Air Speed Comfort Zone Method example (lightly shaded zone) compared to the Analytical Comfort Zone Method example (darkly shaded zone) [5]

2.1.4 The Adaptive Comfort Model

The adaptive model is based on the different expectation of the users and the strong link between their adaptation and the outdoor climatic conditions [30]. There are currently two main standards related to indoor thermal comfort assessment which propose the adaptive model in buildings without mechanical cooling or heating systems in operation: the European EN 16798-1 [9] and the American ASHRAE 55 [5].

The European adaptive comfort model

According to the European model [9] the acceptable indoor operative temperature is evaluated through the running mean external temperature that is "the exponentially weighted running mean of the daily mean outdoor air temperature" and is calculated by means of formula (7):

$$\mathrm{T}_{rm} = (1-\alpha)\cdot\{\mathrm{T}_{ed-1} + \alpha\mathrm{T}_{ed-2} + \alpha^2\mathrm{T}_{ed-3}\} \tag{7}$$

Where:

- T_{rm} = Outdoor Running mean temperature for the considered day (°C).
- T_{ed-1} = daily mean outdoor air temperature for previous day
- α= constant between 0 and 1 (recommended value is 0,8)
- T_{ed-i}= daily mean outdoor air temperature for the *i-th* previous day

The following approximate formula (8) shall be used where records of daily running mean outdoor temperature are not available:

$$\mathrm{T}_m = (\mathrm{T}_{ed-1} + 0.8\mathrm{T}_{ed-2} + 0.6\mathrm{T}_{ed-3} + 0.5\mathrm{T}_{ed-4} + 0.4\mathrm{T}_{ed-5} + 0.3\mathrm{T}_{ed-6} + 0.2\mathrm{T}_{ed-7})/3.8 \qquad (8)$$

Once the running mean temperature is calculated, it is possible to estimate the indoor comfort range as shown in Figure 5. The comfort boundaries are related to the running mean through a linear equation and are differentiated between the following categories:

Category I	upper limit:	T_o = 0.33 T_{rm}+ 18,8 + 2	(9)
	lower limit:	T_o = 0.33 T_{rm}+ 18.8 - 3	(10)
Category II	upper limit:	T_o = 0.33 T_{rm}+ 18,8 + 3	(11)
	lower limit:	T_o = 0.33 T_{rm}+ 18,8 - 4	(12)
Category III	upper limit:	T_o = 0.33 T_{rm}+ 18,8 + 4	(13)
	lower limit:	T_o = 0.33 T_{rm}+ 18,8 – 5	(14)

The limits only apply when 10 < T_{rm} < 30 °C.

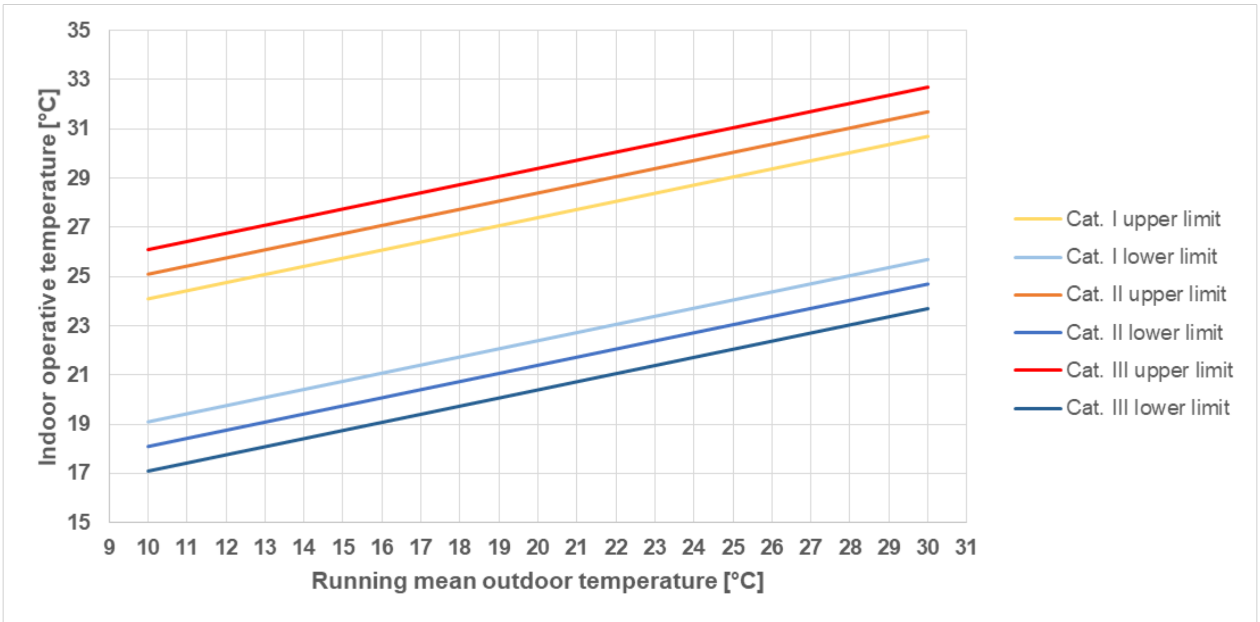

Figure 5: Comfort temperature ranges according to the three categories defined in [9].

Based on the EN adaptive thermal comfort model [6] it has been developed the Nicol et al.'s Overheating risk (NaOR) indicator [31]. It proposes that thermal dissatisfaction is not anchored to a fixed indoor temperature value, but rather to the difference, ΔT, between the actual operative temperature in a space at a given time and the EN 15251 (revised by EN 16798) adaptive optimal operative temperature T_c, the latter being a function of outdoor running mean temperature T_{rm}. The NaOR index is asymmetric and predicts the percentage of individuals, P(ΔT), voting +2 (warm) or +3 (hot) on the ASHRAE thermal sensation scale, as described in equation (15):

$$P(\Delta T) \equiv \frac{\exp(0.4734 \cdot \Delta T - 2.607)}{1 + \exp(0.4734 \cdot \Delta T - 2.607)} \in [0.069; 1] \qquad (15)$$

Where the optimal operative temperature $T_{c,EN}$ [°C] is calculated using the formula (16):

$$T_{c,EN} = 0.33 \cdot T_{rm} + 18.8 \qquad (16)$$

The ASHRAE adaptive comfort model

The ASHRAE adaptive thermal comfort model instead, provides 80% and 90% acceptability threshold temperatures on either side of the adaptive comfort temperature optimum, which is calculated as a function of the prevailing mean outdoor air temperature $t_{pma(out)}$ as eq. (17):

$$T_{c,ASHRAE} = 0.31 \cdot t_{pma(out)} + 17.8 \quad (17)$$

The limits are calculated according to the following equations (18)(19)(20)(21) and are reported in Figure 6:

Upper 90% acceptability limit (°C) = 0.31 $t_{pma(out)}$ + 20.3 (18)
Lower 90% acceptability limit (°C) = 0.31 $t_{pma(out)}$ + 15.3 (19)
Upper 80% acceptability limit (°C) = 0.31 $t_{pma(out)}$ + 21.3 (20)
Lower 80% acceptability limit (°C) = 0.31 $t_{pma(out)}$ + 14.3 (21)

According to the ANSI/ASHRAE Standard 55:2020 [5], this method defines acceptable thermal environments only for occupant controlled naturally conditioned spaces that meet all of the following criteria:

a. There is no mechanical cooling system or heating system **in operation**.
b. Representative occupants have metabolic rates ranging from 1.0 to 1.5 met.
c. Representative occupants are free to adapt their clothing to the indoor and/or outdoor thermal conditions within a range at least as wide as 0.5 to 1.0 clo.
d. The prevailing mean outdoor temperature is greater than 10°C and less than 33.5°C.

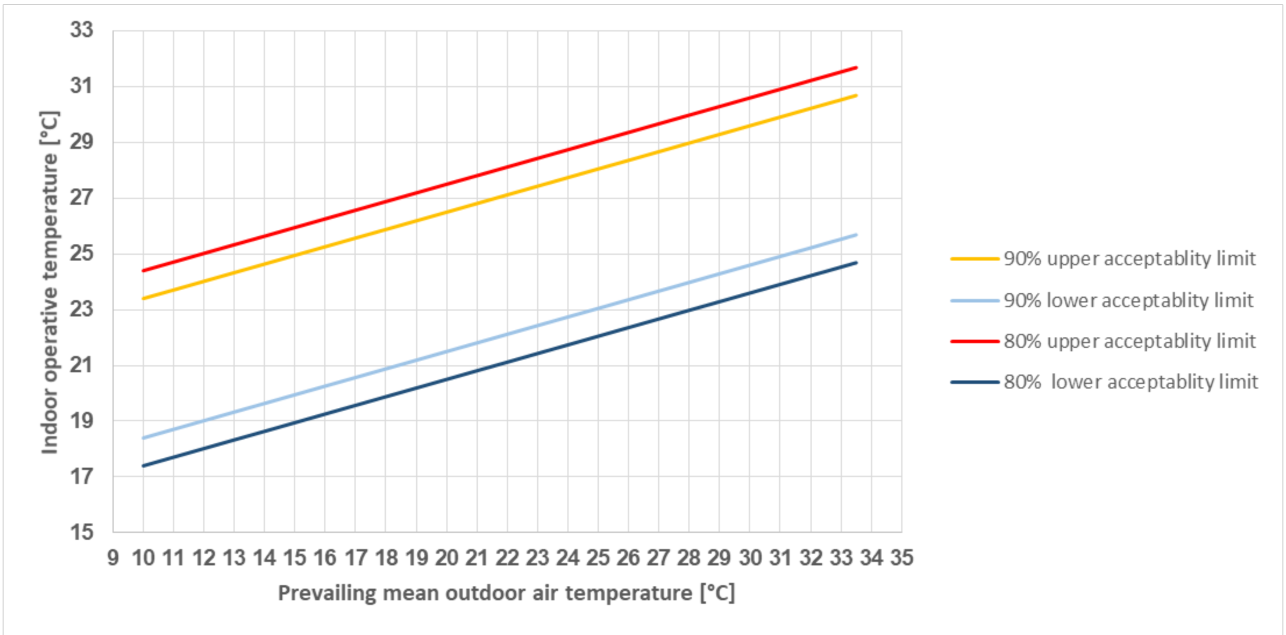

Figure 6: Acceptable operative temperature ranges for naturally conditioned spaces according to [5]

The adaptive model is based on statistical analyses of the two official ASHRAE databases; the second one [32] has recently been published and contains a large set of worldwide data from comfort surveys in real buildings.

Increase in acceptable operative temperature limits in occupant-controlled naturally conditioned spaces resulting from increasing air speed above 0.3 m/s

Both the European and the American Standard indicates that under summer comfort conditions with indoor operative temperatures > 25 °C, increased air velocity can be used to reduce the adverse effects of increased air temperatures.

Where there are fans (that can be controlled directly by occupants) or other means for personal air speed adjustment (e.g. personal ventilation systems, or personally operable windows) it is permitted to consider an increase of the upper acceptability temperature limits, shown in Figure 5 and Figure 6 and described respectively by the equations (9)(11)(13) and (18)(20), by the corresponding Δt_0 reported in Table 3:

Table 3: Increases in acceptable operative temperature limits (Δt_0) in occupant-controlled naturally conditioned spaces according to [5]

Average Air Speed V_a [m/s]	Δt_0 [°C]
0.6	1.2
0.9	1.8
1.2	2.2

Examples of the effect of the increase in air velocity on the comfort ranges are shown in the *Best Practices Manual for Users* [33], developed within the EU project AZEB (Affordable Zero Energy Buildings).

Different studies show the benefits of using ceiling fans to improve summer thermal comfort conditions. However, nowadays designers still lack guidance for designing rooms with fans (spacing, sizing and cooling effect) [34].

A new design and sizing tool to quickly select and layout ceiling fans in a given room to meet their airspeed requirements and other constraints has been created and made available by the Center for the Built Environment, CBE, UC Berkeley [35] which also provided results and analysis from the largest study to date of air speeds generated by ceiling fans [36].

2.1.5 Bio-climatic charts

When designing bioclimatic buildings, it is common to use bioclimatic charts, which are simple tools to analyze climate conditions and investigate appropriate design recommendations for different climates. The charts most widely used by researchers are: the Olgyay Bioclimatic chart, the Szokolay Bioclimatic chart, the Givoni-Milne Bioclimatic chart and the Mahoney Table. The use of these diagrams allows quantifying the climate severity and the thermal comfort levels inside the building, helping to understand the way the building has to be designed to obtain a comfortable thermal sensation for the users [37]. Figure 7 presents a comparison between the main tools available in literature as provided by [38]: it offers the list of the monitored ambient variables, the design recommendations, advantages and limitations. In section 2.2.1 we present a focus on the Givoni bioclimatic chart, which is specific for hot climates.

	Olgyay Bioclimatic Chart	Szokolay Bioclimatic Chart	Givoni–Milne Bioclimatic Chart	Mahoney Table
Monitored ambient variables	1. Dry bulb temperature 2. Relative humidity	1. Dry bulb temperature 2. Wet bulb temperature 3. Relative humidity 4. Absolute humidity	1. Dry bulb temperature 2. Wet bulb temperature 3. Relative humidity 4. Absolute humidity 5. Vapor pressure	1. Monthly mean min, max and average temperature 2. Monthly mean min, max and average relative humidity 3. Precipitation
Strategy proposed/ Design recommendation	1. Solar radiation 2. Air movement 3. Shading	1. Natural ventilation 2. Passive heating 3. Evaporative cooling 4. Indirect evaporative cooling 5. Thermal mass 6. Thermal mass with nigh ventilation	1. Natural ventilation 2. Passive heating 3. Active heating 4. Humidification 5. Conventional dehumidification 6. High thermal mass 7. High thermal mass with night ventilation 8. Evaporative cooling 9. Conventional/mechanical air conditioning	1. Layout 2. Spacing 3. Air movement 4. Openings 5. Walls 6. Roofs 7. Outdoor space 8. Rain protection
Advantage	1. The chart is applicable in hot humid areas 2. Suitable for residential building	1. Define two comfort zones	1. Mainly used for residential buildings	1. Provide much more and different points of view for design recommendation than the bioclimatic chart
Limitation	1. Only provides limited design recommendation	1. The relative humidity should not exceed 90%	1. Windows are closed during the daytime for thermal mass	2. The thermal comfort limit assumes no heat gain or loss due to ventilation or insulation

Figure 7: Summary of climatic analysis tools for building design purposes [38]

Different software and web app offer the possibility to evaluate appropriate strategies according to the analysed weather file; see e.g. the Psychrometric Chart by A. Marsh [39] or the example reported in the Annex A. Besides, Attia et al. [22] developed an analysis application for bioclimatic design strategies in hot humid climates which can be used to compare different thermal comfort models [40]. They showed the comfort models comparison for the two major cities of Madagascar, situated off the southeast coast of Africa.

The Givoni comfort zones

A simple way of assessing thermal comfort is to use the Givoni comfort zones. The original boundaries of these comfort zones are based on research conducted by Givoni [41,42]. The originality of the work proposed by Givoni is to use the psychrometric chart as the base layer to characterise comfort zones.

Givoni has developed several comfort zones depending on:
- the level of air velocities on the users (0 to 2 m/s);
- the level of development of countries (developed countries and developing countries).

For developing countries, the upper limits of accepted temperature and humidity are higher than in developed countries, assuming that people are acclimatised to hot and humid conditions .

<u>Comfort zone for still air conditions (v = 0 m/s)</u>

In the conditions defined for this zone, it is assumed that a person wearing light clothes – i.e. 0,5 clo is in thermal comfort conditions in the indoor space. According to Givoni, it can be noted that people can be in thermal comfort conditions in different boundaries of relative humidity (between 20% and 80%) and air temperature (between 20°C and 26°C).

<u>Comfort zone for air velocity around 1-2 m/s</u>

If the temperature in the indoor space exceeds 26°C or relative humidity is quite high, natural cross ventilation can improve the thermal comfort. In hot and humid climates, natural cross ventilation (or the use of ceiling fans) is the simplest strategy to adopt if the indoor temperature is almost the same as the outdoor temperature. Givoni assumes that the maximum allowed indoor air speed is about 1-2 m/s (which is a range considered now in ASHRAE 55:2020), thus ventilation on the users maintains comfort up to an outdoor temperature limit of 30°C (for developed countries) and of 32°C (for hot-developing countries), as shown in Figure 8.

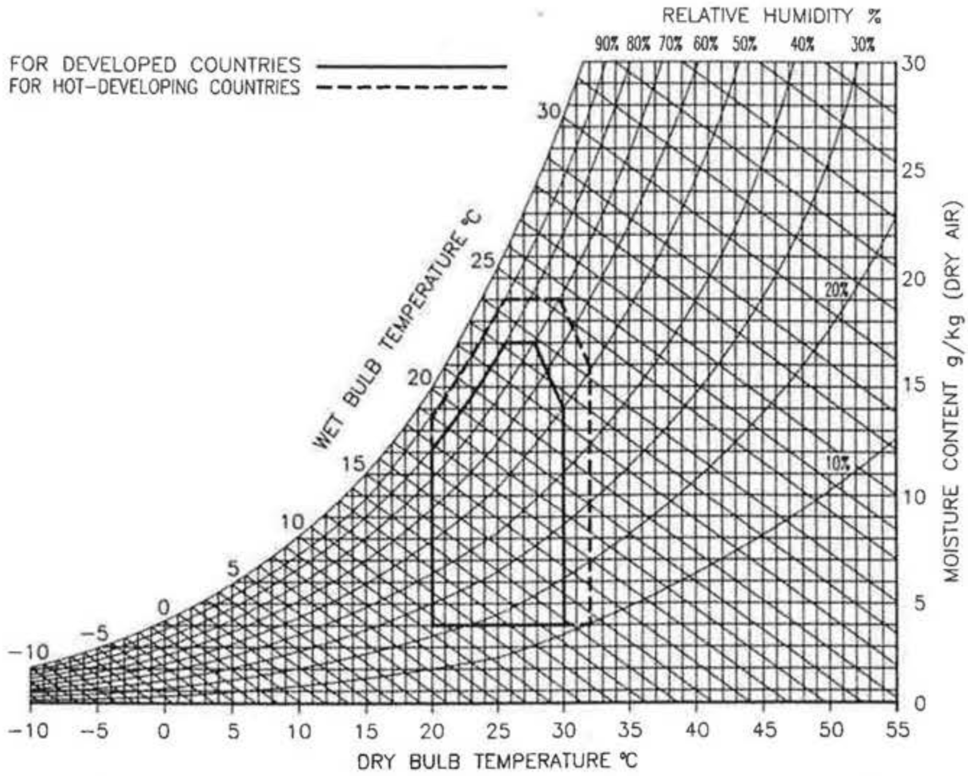

Figure 8: Comfort zones defined by Givoni [15,41] for an air speed of 2 m/s

The Givoni bioclimatic chart is a useful tool to assess thermal comfort at the design stage or during the post occupancy evaluation process. Figure 9 shows the results of measured data in an office space during the hot and humid season in La Reunion. One can notice that the comfort conditions are reached 96% of time in the comfort zone of 1m/s. The percentage of time inside one specific zone can be set as a clear performance indicator of thermal comfort in hot countries.

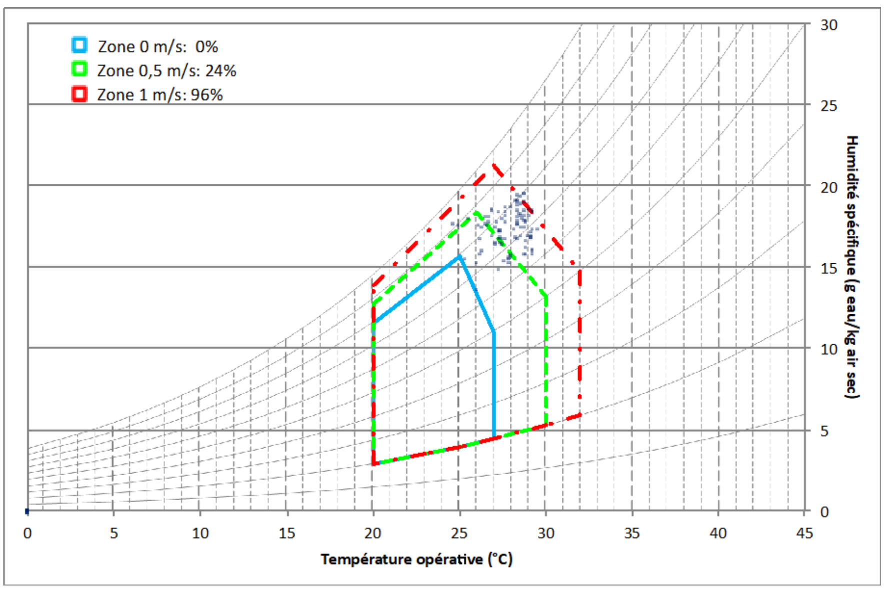

Figure 9: Assessment of thermal comfort in an office building in La Reunion

2.1.6 Highlights

The possibility to apply (as a user of a building as much as a designer or manager of a building) measures such as **night ventilation** in summer nights and use **ceiling fans** during the day instead of (or to reduce use of) air-conditioning depends on explicit recognition at the regulation level of the following issues:

- **the same level of thermal comfort**, as measured e.g. via the index Predicted Mean Vote (PMV), **can be achieved via various combinations of the physical parameters** (operative temperature, relative humidity and air velocity), each with different values of energy need for cooling and energy need for dehumidification [7,43]. With a correct choice of these parameters the user can therefore achieve the same or better comfort level with lower energy and power demand than other scenarios, implying a strong cost reduction. A tool for analyzing the influence of those parameters according to the EN and ASHRAE standards is available from Berkeley University [44]. Examples of the effect of the different parameters on the comfort temperature ranges are shown in the *Best Practices Manual for Users* [39], developed within the EU project AZEB (Affordable Zero Energy Buildings).
- The **choice of the comfort category** (I, II or III according to EN 16798-1, formerly known as EN 15251, or A, B, C according to ASHRAE 55) which is aimed at by the building design and/or controls strongly affects energy use [45].
- A number of research works show that **Comfort category I** (A), which is the more energy demanding, **cannot be perceived subjectively** [46] **and it is below the accuracy of measurements** [47]. In the EU standard (EN 16798) category I (A) is reserved to buildings occupied by fragile people (children, elderly, persons with disabilities, etc.), but it may nevertheless be perceived by designers and presented to clients/operators as the "best" condition.

  An important parameter affecting comfort in the warm season is the **insulation level of clothing and of furniture**, as e.g. office chairs (both measured in the unit clo and with indicative values reported e.g. in ISO 7730 [48]). Regulation and cultural norms may actively and explicitly promote the adoption of dressing codes where light clothing in summer is the norm rather than the exception (see e.g. the Cool Biz Programme in Japan [49]) and office furniture is chosen with low thermal insulation. Generally, the amount of clothing that can be worn in hot climates to allow the cooling effects of air movement to be felt is, for Western outfits, equal to about 0.3 clo units. However, for a loose traditional dress fashioned from a fabric of natural fibre with an open weave and in bright colours, clo units of up to 0.5 will also allow the cooling effect of air movement. A long open dress may even create some chimney-stack effect, i.e. ventilation between the body and the dress due to air rising from the feet to the neckline [50].

2.2 Indicators for the evaluation of thermal comfort conditions

A number of metrics to assess indoor thermal comfort has been proposed over the last decades. Two main categories can be identified:

- indices that focus on comfort conditions at a certain time and position in space (e.g. PMV, PPD, NaOR, described in sections 2.1.2 and 2.1.3)
- long-term comfort indices that aim at assessing thermal comfort quality of a building over a span of time and considering all the building zones [51].

2.2.1 Long-term thermal comfort indices according to EN-ISO standards

An overview of long-term thermal comfort indices according to EN-ISO standards (ISO 7730 [48] and EN 16798 [9]) is shown in Table 4. Afterwards, these are described in detail and targeted information regarding the types of building currently selected in Task 3.4 is provided. To evaluate the comfort conditions over time (season, year) a summation of parameters can be made based on data measured in real buildings or dynamic computer simulations.

Table 4: Overview of the most common thermal comfort index in literature [52]

Long-term thermal comfort index	ISO 7730:2005	EN 16798-2:2019
Percentage of time outside a PMV range	•	•
Percentage of time outside an operative temperature range	•	•
Degree-hours	•	•
PPD-weighted criterion	•	•
Average PPD	•	
Sum PPD	•	

The long-term thermal comfort indices are described as follow:

- *Percentage of time outside a PMV range or an operative temperature range:* the number or percentage of hours during the hours the building is occupied, the PMV or the operative temperature is outside a specified range (definition from EN ISO 7730:2005 – method A [48]). When considering the operative temperature ranges, it is possible to apply the Fanger method or the adaptive one, as explained in section 2.1.

- *Degree-hours*:
  time during which actual operative temperature exceeds the specified comfort range during occupied hours is weighted by a factor, wf, which is a function of how many degrees the range has been exceeded (definition from EN ISO 7730:2005 – method B [48]).

  The weighting factor, wf_i, has two different formulations according to the two above-mentioned standards:

  $$wf_i|_{ISO7730} = 1 + \frac{|T_{op,i} - T_{op,limit}|}{|T_{op,comfort} - T_{op,limit}|}$$

  $$wf_i|_{EN16798} = T_{op,i} - T_{op,limit}$$

  For a characteristic period during a year (warm period/cold period), the product of the weighting factor and time is summed. The summation of the product has the unit of *hours* according to the ISO 7730 and of *degree* · *hours* following the EN16798-2, in spite of an error in the technical report. The degree-hour criterion can be evaluated applying the Fanger or the Adaptive comfort method.

- *PPD-weighted criterion*:

  The time during which PMV exceeds the comfort boundaries is weighted with a weighting factor, wf_i. which is a function of the PPD (definition from EN ISO 7730:2005 – method C [48]). The weighting factor, wf_i, is defined as follow:

$$PPDwC|_{ISO7730} = f(wf_i): \begin{cases} wf_i = \dfrac{PPD_{actualPMV,i}}{PPD_{PMV\ limit}} \Leftarrow (|PMV| > |PMV_{limit}|) \\ wf_i = 1 \Leftarrow (PMV = PMV_{limit}) \end{cases}$$

$$PPDwC|_{EN16798-2} = f(wf_i): \begin{cases} wf_i = \dfrac{PPD_{actualPMV,i}}{PPD_{PMV\ limit}} \Leftarrow (PMV > PMV_{upper\ limit}) \\ wf_i = 0 \Leftarrow (PMV_{lower\ limit} \leq PMV \leq PMV_{upper\ limit}) \\ wf_i = \dfrac{PPD_{actualPMV,i}}{PPD_{PMV\ limit}} \Leftarrow (PMV < PMV_{lower\ limit}) \end{cases}$$

For a characteristic period during a year (warm period/cold period), the product of the weighting factor, wf, and the time, t, is summed and the result expressed in hours.

- *average PPD:*
  The average PPD over time during the occupied hours is calculated (definition from EN ISO 7730:2005 – method D [48]).
- *sum PPD:*
  The PPD over time during the occupied hours is summed (definition from EN ISO 7730:2005 – method E [48]).

The recommended PMV ranges are presented in Table 5. The ranges of operative temperature according to Fanger comfort model are reported in Table 6 and Table 7. The operative temperature ranges based on the adaptive comfort model can be calculated according to the equations reported in Table 8 and Table 9.

Table 5: PMV ranges – standards comparison

Standard	Category	Thermal state of the body as a whole	
		PPD %	PMV
ISO 7730:2015	A	< 6	- 0.2 < PMV < + 0.2
	B	< 10	- 0.5 < PMV < + 0.5
	C	< 15	- 0.7 < PMV < + 0.7
EN 16798-2:2019	I	< 6	- 0.2 < PMV < + 0.2
	II	< 10	- 0.5 < PMV < + 0.5
	III	< 15	- 0.7 < PMV < + 0.7
	IV	< 25	- 1.0 < PMV < + 1.0

Table 6: Operative temperature ranges based on PMV model (EN 7730:2005)

Type of building/space	Cat	Operative temperature [°C]	
		Summer (cooling season)_ 0.5 clo_60% RH	Winter (heating season)_ 1.0 clo_40% RH
	A	24.5 ± 1.0	22.0 ± 1.0

[a] Single office, Landscape office, Conference room, Auditorium, Cafeteria, restaurant, Classroom	B	24.5 ± 1.5	22.0 ± 2.0
	C	24.5 ± 2.5	22.0 ± 3.0
[b] Kindergarten	A	23.5 ± 1.0	20.0 ± 1.0
	B	23.5 ± 2.0	22.0 ± 2.5
	C	23.5 ± 2.5	22.0 ± 3.5
[c] Department store	A	23.0 ± 1.0	19.0 ± 1.5
	B	23.0 ± 2.0	19.0 ± 3.0
	C	23.0 ± 3.0	19.0 ± 4.0

Table 7: Operative temperature ranges for buildings with mechanical cooling systems (EN 16798-2:2019)

Type of building/space	Cat	Operative temperature [°C]		Ranges for energy calculations	
		Max for cooling (summer season)	Min for heating (winter season)	T range for cooling (0.5 clo)	T range for heating (1 clo)
[a] Residential buildings, living spaces (bed room's, living rooms, kitchens, etc.)	I	25.5	21	23.5 - 25.5	21 - 25
	II	26	20	23 - 26	20 - 25
	III	27	18	22 - 27	19 - 25
	IV	28	16	21 - 28	17 - 25
[b] Residential buildings, other spaces (utility rooms, storages, etc.)	I	-	18	-	18 - 25
	II	-	16	-	16 - 25
	III	-	14	-	14 - 25
[c] Single offices, open plan offices, conference rooms, auditorium, cafeteria, restaurants, classrooms	I	25.5	21	23.5 - 25.5	21 - 23
	II	26	20	23 - 26	20 - 24
	III	27	19	22 - 27	19 - 25
	IV	28	18	21 - 28	17 - 25
[d] Kindergarten	I	25.0	21	23.5 - 25.5	21 - 23
	II	26	20	23 - 26	20 - 24
	III	27	19	22 - 27	19 - 25
	IV	Not recommended		Not recommended	

Table 8: Operative temperature ranges based on adaptive model (ASHRAE 55:2020)

Class	Limit	Operative Temperature
90%	Upper	$T_o = 0.31*t_{pma(out)} + 17.8 + 2.5$
	Lower	$T_o = 0.31*t_{pma(out)} + 17.8 - 2.5$
80%	Upper	$T_o = 0.31*t_{pma(out)} + 17.8 + 3.5$
	Lower	$T_o = 0.31*t_{pma(out)} + 17.8 - 3.5$

Table 9: Operative temperature ranges based on adaptive model (EN 16798-1)

Class	Limit	Operative Temperature
I	Upper	To= 0.33*T_{rm} + 18.8 + 2
	Lower	To= 0.33*T_{rm} + 18.8 - 3
II	Upper	To= 0.33*T_{rm} + 18.8 + 3
	Lower	To= 0.33*T_{rm} + 18.8 - 4
III	Upper	To= 0.33*T_{rm} + 18.8 + 4
	Lower	To= 0.33*T_{rm} + 18.8 - 5

2.2.2 Long-term thermal comfort indices applied to Givoni comfort zones

When using the Givoni bioclimatic chart it is common [21] to determine the:

- Percentage of time inside the different Givoni comfort zone as the number or percentage of hours during the hours the building is occupied, when the operative temperature is inside a specified zone (comfort zone for still air conditions, i.e. v = 0 m/s or comfort zone for air velocity at 1 m/s, as described in section 2.2.1)
- Number of hours during which the operative temperature is within a certain range.

2.3 Comfort models in literature

In the previous sections, we have defined the most significant thermal comfort models and indices for European and African countries.

However, literature shows several studies dealing with thermal comfort in bioclimatic architecture and different other parameters and metrics have been investigated over the last decades. Table 10 provides a summary of these analyses and Table 11 shows newly proposed thermal comfort indexes found in literature.

Table 10: Synthesis of the comfort models used with bioclimatic architecture

Ref	Comfort Model / Standards	Additional formulas / definitions
[4]	- Olgyay - Givoni - ASHRAE, 2013 ASHRAE handbook fundamental	No additional information
[53]	The static model (PMV/PPD) and the adaptive model	• Metabolic rate: The rate of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism usually expressed in terms of unit area of the total body surface. In this standard, the metabolic rate is expressed in met units. • Clothing insulation: The resistance to sensible heat transfer provided by a clothing ensemble. Expressed in clo units. Note: the definition of clothing insulation relates to heat transfer from the whole body and, thus, also includes the uncovered parts of the body, such as head and hands. • Air temperature: Air temperature is a measure of how hot or cold the air is. It is the most commonly measured weather parameter. • Radiant temperature: Is defined as the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-

		uniform enclosure. • Airspeed: The rate of air movement at a point, without regard to direction • Relative humidity: The ratio of the partial pressure (or density) of the water vapor in the air to the saturation pressure (or density) of water vapor at • PET (Physiological Equivalent Temperature): Is defined as the equivalent air temperature at which, in a typical indoor condition heat balance of the human body exists. • SET (Temperature, Standard Effective): The temperature of an imaginary environment at 50% RH, <0.1 m/s airspeed, Moreover, Tr=Ta, in which the total heat loss from the skin of an imaginary occupant with an activity level of 1.0 met and a clothing level of 0.6 clo is the same as that from a person in the actual environment, with real clothing and activity level. • PMV (Predicted Mean Vote): An index that predicts the mean value of the votes of a large group of persons on the seven-point thermal sensation scale. • PPD (Predicted percentage dissatisfied): An index that establishes a quantitative prediction of the percentage of thermally dissatisfied people determined from PMV. • WBGT (Wet-bulb Globe Temperature): A type of apparent temperature used to estimate the effect of temperature, humidity, wind speed (wind chill), and visible and infrared radiation (usually sunlight) on humans. • UTCI (Universal Thermal Climate Index): The UTCI is defined as the air temperature (T_a) of the reference condition causing the same model response as actual conditions.
[54]	- Milne and Givoni - ASHRAE standard 55 -2013 - Szokolay - Tropical Summer Index - India Model for Adaptive Comfort (IMAC)	3. Defining comfort zone and boundaries of passive strategies: *3.1. Comfort zone* For naturally ventilated office buildings, optimum comfort temperature (T_n) can be calculated based on mean monthly outdoor temperature (T_{avg}): $Tn = 12.83 + 0.54\ x\ Tavg$ $Upper\ comfort\ temperature = Tn + 2.5$ $Lower\ comfort\ temperature = Tn + 2.5$ 3.2. Comfort potential zone using passive cooling strategies 3.2.1. Natural ventilation: $Upper\ limit = Upper\ comfort\ temperature + 3$ 3.2.2. Evaporative cooling ⤏ $Upper\ limit = Tn + 11$ 3.2.3. Thermal mass: $Upper\ limit = Upper\ comfort\ temperature + 0.3\ x\ (Tmax - Tmin)$ 3.2.4. Thermal mass with night ventilation: $Upper\ limit = Upper\ comfort\ temperature + 0.6\ x\ (Tmax - Tmin)$
[55]	Adaptive approaches (see the attached table 1 on the right) - ASHRAE Standard 55-2004 - EN 15251:2008 - Indraganti's equation - Nguyen's equation	3. Thermal comfort models for Naturally Ventilated Buildings (NVB) under hot-humid climates 3.1. Other extensions of the PMV approach $MET_{(e)} = MET\left(1 - \frac{6.7 \cdot PMV}{100}\right)$ $aPMV = \frac{PMV}{1 + \lambda \cdot PMV}$ $POR = \frac{\sum_{i=1}^{Oh}(wf_i \cdot h_i)}{\sum_{i=1}^{Oh} \cdot h_i} \in [0;\ 1]$ $POR_{Fanger,PMV} = f(wf_i)$: $\left\{\begin{matrix} wf_i = 1 \Leftarrow (PMV < PMV_{lower\ \lim it}) \vee (PMV > PMV_{upper\ \lim it}) \\ wf_i = 0 \Leftarrow (PMV \leq PMV_{lower\ \lim it} \leq PMV \leq PMV_{upper\ \lim it}) \end{matrix}\right\}$

<table>
<tr>
<td></td>
<td>- Humphreys's equation
- Ye's equation
- Nicol's equation</td>
<td>

3.2. Adaptive approach

$T_{comf} = A \cdot T_{a,out} + B$

Table 1
Adaptive thermal comfort equations for hot-humid climates.

<table>
<tr><th>Source</th><th>Equation</th><th></th></tr>
<tr><td>ASHRAE 55 [44]</td><td>$t_{comfop} = 0.31\ t_{outmm} + 17.8$</td><td>(8)</td></tr>
<tr><td>EN 15251 [51]</td><td>$t_{comfop} = 0.33\ t_{outmm} + 18.8$</td><td>(9)</td></tr>
<tr><td>Indraganti [53]</td><td>$t_{comfop} = 0.26\ t_{outmm} + 21.4$</td><td>(10)</td></tr>
<tr><td>Nguyen [58]</td><td>$t_{comfop} = 0.341\ t_{outmm} + 18.83$</td><td>(11)</td></tr>
<tr><td>Humphreys [61]</td><td>$t_{comfop} = 0.534\ t_{outmm} + 11.9$</td><td>(12)</td></tr>
<tr><td>Ye [65]</td><td>$t_{comfop} = 0.42\ t_{outmm} + 15.12$</td><td>(13)</td></tr>
<tr><td>Nicol [66]</td><td>$t_{comfop} = 0.54\ t_{outmm} + 13.5$</td><td>(14)</td></tr>
</table>

- T_{comfop} is indoor comfort operative temperature [°C]
- T_{outmm} is monthly mean outdoor air temperature [°C]

$$POR^{Adaptive} \propto \begin{pmatrix} wf_i = 1 \Leftarrow (t_{op} < t_{\text{op,lower limit}}) \vee (t_{op,in} > t_{\text{op,upper limit}}) \\ wf_i = 0 \Leftarrow (t_{\text{op,lower limit}} \leq t_{op,in} \leq t_{\text{op,upper limit}}) \end{pmatrix}$$

</td>
</tr>
<tr>
<td>[56]</td>
<td>- Olgyay
- ASHRAE (1997) ASHRAE Handbook Fundamentals</td>
<td>No additional information</td>
</tr>
<tr>
<td>[38]</td>
<td>Predictive Comfort Temperature (PCT)
(see the attached table 3 on the right):
- ASHRAE standard 55-2004
- Humphreys and Nicol
- Nguyen
- Toe and Kubota
- Indraganti et al.
- Karyono
- Santy</td>
<td>

Table 3. Several adaptive comfort model in the literature. PCT, Predictive Comfort Temperature.

<table>
<tr><th>No.</th><th>Source</th><th>Equation</th><th>Outdoor Temperature Limitation</th></tr>
<tr><td>1</td><td>ASHRAE 55-2004 [20]</td><td>$Tc = 0.31T_o{}^* + 17.8$</td><td>10–33 °C</td></tr>
<tr><td>2</td><td>Humphreys and Nicol [21,22]</td><td>$Tc = 0.54T_o{}^* + 13.5$</td><td>10–34 °C</td></tr>
<tr><td>3</td><td>Nguyen [24]</td><td>$Tc = 0.341T_o{}^* + 18.83$</td><td>26–34 °C</td></tr>
<tr><td>4</td><td>Toe and Kubota [27,28]</td><td>$Tc = 0.57\ T_{outdm}{}^\# + 13.8$</td><td>10–33 °C</td></tr>
<tr><td>5</td><td>Indraganti et al. [29]</td><td>$Tc = 0.26T_{rm} + 21.4$</td><td>24.5–35.5 °C</td></tr>
<tr><td>6</td><td>Karyono [26]</td><td>$PCT = 0.749T_d{}^\# + 5.953$</td><td>24–29 °C</td></tr>
<tr><td>7</td><td>Santy [30]</td><td>$PCTu = 0.61T_d{}^\# + 9.69$</td><td>24–30.8 °C</td></tr>
</table>

Notes: * For ASHRAE, Humphreys and Nicol, Nguyen, T_o is mean monthly outdoor temperature; # for Toe and Kubota, Karyono and Santy, T_{outdm} and T_d are mean daily outdoor temperature; for Indraganti, T_{rm} is running mean outdoor temperature.

</td>
</tr>
<tr>
<td>[37]</td>
<td>- ISO 7730:2005
- UNE-EN 15251:2008
- ASHRAE 55:2017
- Spanish Regulation</td>
<td>Long term comfort indices:
- Prediction Mean Vote (PMV). Fanger Method
- Operative temperature. Percentage of hours outside the valid range
- Spanish Regulation
- Adaptive Model. ASHRAE 55:2017</td>
</tr>
</table>

Table 11: Additional thermal comfort parameters and indexes reviewed in literature

<table>
<tr><th>Ref</th><th>indicators</th><th>Quantification/definition/standards</th></tr>
<tr>
<td>[29,57]</td>
<td>Mean radiation temperature</td>
<td>

$$T_{mrt} = \left[\left(T_g + 273\right)^4 + \frac{1.1 \times 10^8 V_a{}^{0.6}}{\varepsilon D^{0.4}} \left(T_g - T_a\right) \right]^{\frac{1}{4}} - 273$$

Parameters used: black globe temperature, air dry bulb temperature, wind speed, black bulb diameter, black ball emissivity.

</td>
</tr>
</table>

<table>
<tr><td rowspan="4">[52]</td><td>Mean temperature</td><td>$index = \frac{\sum T_a or \sum T_o}{total\ number\ of\ occupied\ hours}$</td></tr>
<tr><td>New temperature ranges for percentage hour and degree-hours</td><td>
<table>
<tr><th>Range name</th><th>Meaning</th><th colspan="2">Operative temperature °C</th><th colspan="2">Air temperature °C</th></tr>
<tr><th></th><th></th><th>Summer</th><th>Winter</th><th>Summer</th><th>Winter</th></tr>
<tr><td>P20</td><td>The 40th to 60th percentile</td><td>23.6 – 24.0</td><td>23.3 – 23.6</td><td>23.3 – 23.7</td><td>23.1 – 23.5</td></tr>
<tr><td>P40</td><td>The 30th to 70th percentile</td><td>23.4 – 24.2</td><td>23.1 – 23.8</td><td>23.1 – 23.9</td><td>22.9 – 23.7</td></tr>
<tr><td>P60</td><td>The 20th to 80th percentile</td><td>23.2 – 24.5</td><td>22.9 – 24.0</td><td>22.9 – 24.2</td><td>22.7 – 23.9</td></tr>
<tr><td>P80</td><td>The 10th to 90th percentile</td><td>22.9 – 25.0</td><td>22.6 – 24.4</td><td>22.6 – 24.8</td><td>22.4 – 24.3</td></tr>
<tr><td>1sd</td><td>Mean ± 1sd</td><td>22.9 – 25.0</td><td>22.7 – 24.2</td><td>22.6 – 24.8</td><td>22.5 – 24.2</td></tr>
</table>
</td></tr>
<tr><td>Temperature variance</td><td>$index = \frac{\sum_{i=1}^{n} (T_{a,i} - \overline{T_a})^2}{n-1}$ or $\frac{\sum_{i=1}^{n} (T_{o,i} - \overline{T_o})^2}{n-1}$</td></tr>
<tr><td>Daily range outlier</td><td>$index = \frac{number\ of\ days\ that\ T_a\ or\ T_o\ daily\ range > a\ threshold}{total\ number\ of\ occupied\ days} \times 100$</td></tr>
<tr><td rowspan="8">[58]</td><td>Predicted mean vote (PMV)</td><td>$\mathrm{PMV} = (0.303e^{-0.036M}) + 0.028) \times \mathrm{L}$</td></tr>
<tr><td>Discomfort Index (DI) (°C)</td><td>$\mathrm{DI} = \mathrm{T_{db}} - (0.55 - 0.005 \times \mathrm{RH\%}) \times (\mathrm{T_{db}} - 14.5)$</td></tr>
<tr><td>Cooling power index (CPI) (mcal/cm²s)</td><td>$\mathrm{CPI} = (0.37 + 0.51 \times \mathrm{V^{0.63}}) \times (36.5 - \mathrm{T_{db}})$</td></tr>
<tr><td>Humidex index (°C)</td><td>$\mathrm{H} = \mathrm{Tdb} + \frac{5}{9} \times (\mathrm{P_v} - 10)$</td></tr>
<tr><td>Wet Bulb Globe Temperature (WBGT) index (°C)</td><td>$\mathrm{P_v} = 6.112 \times \left(\frac{\mathrm{RH}}{100}\right) \cdot \times 10e^{\left(\frac{7.5 \cdot \mathrm{T_{db}}}{237.7 + \mathrm{T_{db}}}\right)}$
$\mathrm{WBGT} = 0.7\mathrm{T_w} + 0.2\mathrm{T_G} + 0.1\mathrm{T_a}$</td></tr>
<tr><td>Standard Effective Temperature (SET) index (°C)</td><td>$\mathrm{H_{sk}} = \mathrm{h_s}(\mathrm{t_{sk}} - \mathrm{SET}) + \mathrm{wh_{s,e}}(\mathrm{p_{s,sk}} - 0.5\mathrm{p_{SET}})$</td></tr>
<tr><td>Thermal Sensation Vote (TSV)</td><td>Using the TSV from the questionnaire answers, the mean thermal sensation vote (mTSV)
$mTSV = \frac{Responses \times TSV}{Total\ Respondents}$</td></tr>
<tr><td>CFD predicted indices</td><td>Is used to obtain the average thermal comfort indices of the corresponding zones for comparison with the results obtained from the questionnaire.</td></tr>
<tr><td>[59]</td><td>Predicted mean vote index IPMV</td><td>The thermo-hygrometric measurements were carried out employing a microclimatic station BABUC - LSI, in compliance with ISO 7726, monitoring the parameters defined in UNI EN ISO 7730/2006, UNI EN ISO 10551/2002, and ASHRAE Standard 55/200.</td></tr>
</table>

<table>
<tr>
<td></td>
<td></td>
<td>
Table 2
Measured indoor and outdoor thermal comfort parameters, operative range, and accuracy.
<table>
<tr><th>Primary indoor parameters</th><th></th><th>Operative Range</th><th>Accuracy</th><th>Measurement/calculation system</th></tr>
<tr><td>forced airy dry bulb air temperature T</td><td>T</td><td>$-50\,^{\circ}C \div 80\,^{\circ}C$</td><td>$\pm 0.17\,^{\circ}C$</td><td>BABUC - LSI</td></tr>
<tr><td>forced airy wet bulb air temperature</td><td>T_u</td><td>$-50\,^{\circ}C \div 80\,^{\circ}C$</td><td>$\pm 0.17\,^{\circ}C$</td><td></td></tr>
<tr><td>dew point temperature</td><td>T_{dp}</td><td>$-50\,^{\circ}C \div 80\,^{\circ}C$</td><td>$\pm 0.17\,^{\circ}C$</td><td></td></tr>
<tr><td>globothermometer temperature</td><td>T_g</td><td>$-50\,^{\circ}C \div 100\,^{\circ}C$</td><td>$\pm 0.17\,^{\circ}C$</td><td></td></tr>
<tr><td>average air flow speed</td><td>v_{air}</td><td>$0\,m/s \div 50\,m/s$</td><td>$\pm$ 0.05 m/s for v_a = 0–0.5 m/s,
$\pm$ 0.1 m/s for v_a = 0.5–1.5 m/s,
$\pm$ 4% for $v_a > 1.5$ m/s</td><td></td></tr>
<tr><td>temperature of the floor surface</td><td>T_s</td><td>$-50\,^{\circ}C \div 80\,^{\circ}C$</td><td>$\pm 0.17\,^{\circ}C$</td><td></td></tr>
<tr><td>temperature of the air at the height of ankle</td><td>T_{ank}</td><td>$-50\,^{\circ}C \div 80\,^{\circ}C$</td><td>$\pm 0.17\,^{\circ}C$</td><td></td></tr>
<tr><th>Primary outdoor parameters</th><th></th><th>Operative Range</th><th>Accuracy</th><th></th></tr>
<tr><td>outdoor temperature</td><td>T_{ext}</td><td>$-50\,^{\circ}C \div 200\,^{\circ}C$</td><td>$\pm 0.1\,^{\circ}C$</td><td>DELTA OHM</td></tr>
<tr><td>outdoor relative humidity</td><td>RH_{ext}</td><td>$0 \div 100\%$</td><td>$\pm$ 1% in the 20–90% range;
$\pm$ 2% in the 10–99% range</td><td></td></tr>
<tr><th>Derived Parameters</th><th></th><th>Operative Range</th><th>Accuracy</th><th></th></tr>
<tr><td>mean radiant temperature</td><td>T_{mr}</td><td>$-50\,^{\circ}C \div 80\,^{\circ}C$</td><td>$\pm 0.17\,^{\circ}C$</td><td>INFOGAP software</td></tr>
<tr><td>air relative humidity</td><td>RH</td><td>$0 \div 100\%$</td><td>–</td><td></td></tr>
<tr><td>Predicted Mean Vote</td><td>PMV</td><td>$-3 \div +3$</td><td>–</td><td></td></tr>
<tr><td>Predicted Percentage of Dissatisfied</td><td>PPD</td><td>$0 \div 100\%$</td><td>–</td><td></td></tr>
<tr><td>PPD for vertical thermal gradient</td><td>PPD_{vg}</td><td>$0 \div 100\%$</td><td>–</td><td></td></tr>
<tr><td>PPD for pavement temperature</td><td>PPD_{pt}</td><td>$0 \div 100\%$</td><td>–</td><td></td></tr>
</table>
IPMV was constructed in such a way that it has a maximum value (IPMV=1) for PMV equal to 0 and a minimum one (IPMV = 0) for PMV equal to −3 or +3; the intermediate values of PMV vary with a liner trend between 0 and 1.
$$I_{PMV} = \left| (|PMV| + 1) - \left(|PMV| \cdot \frac{4}{3} \right) \right|$$
This index is a part of a global comfort assessment (see §6.4).
</td>
</tr>
<tr>
<td>[60]</td>
<td>Room temperature (°C)</td>
<td>
Parameters monitored: Room temperature at 20, 25, and 30 °C.
Table 2
Thermal conditions and variations.
<table>
<tr><th>Target Temperature Relative Humidity</th><th>Measured Temp Mean (S.D)</th><th>Measure RH Mean (S.D.)</th><th>Sensation ASHRAE 55–2013</th></tr>
<tr><td>20 °C, 45%</td><td>20.21 °C (0.15)</td><td>45.36% (1.04)</td><td>Cool</td></tr>
<tr><td>25 °C, 45%</td><td>25.16 °C (0.33)</td><td>44.28% (1.37)</td><td>Neutral</td></tr>
<tr><td>30 °C, 45%</td><td>30.05 °C (0.29)</td><td>43.93% (1.26)</td><td>Warm</td></tr>
</table>
This index is related a questionnaires and is a part of a global comfort index (see §6.4)
</td>
</tr>
</table>

3 Indoor acoustic comfort

Acoustic comfort is defined [61] as “a state of contentment with acoustic conditions”. However, the evaluation of indoor acoustic comfort is usually done in terms of prevention of the occurrence of discomfort. Building location, city design, building design, vegetation, construction type, right choice of openings, materials and construction elements can help reducing the annoyance given by neighbours, traffic, outdoor noise, etc. [62].

It is possible to summarize three main approaches applied in studying acoustic quality in the built environment: physical, psychophysical and perceptual [63]. The physical approach is considered among the objective methods, it is based on physical measurements and it is referred to standards (see Table 22). The second approach (psychophysical) is based on the subjective opinion of the respondents and cross-analyses responses with on-site measurements [27,62]. The last (perceptual) focuses on the correlation between environment and people, targeting the cognitive process of sound evaluation.

Different examples of acoustic subjective surveys, which can contain structured, closed questions, single or multiple choice questions, can be found in literature and standards. In ABC 21 project we will refer to the recently updated standard 10551:2019 [27] which in its Annex B contains commonly used scales and standard questions for assessing acoustic environments.

The acoustic comfort indicators currently described in literature are shown with Table 12:

Table 12: Indoor acoustic comfort indicators literature review

Ref	Indicator	Definition / quantification
[64]	Airborne sound insulation / impact sound insulation	performance criteria stated by: - Section 7 of BS 8233:2014 - BS EN ISO 140 (replaced by BS EN ISO 16283-1:2014+A1:2017)
	Indoor ambient noise level	Section 7 of BS 8233:2014
	Reverberation control	Section 7 of BS 8233:2014 BS EN ISO 354:2003 BS EN ISO 140-7:1998 (replaced by BS EN ISO 16283-1:2014)
[65]	Sound transmission/isolation	Thresholds are defined according with the composite sound transmission class (STCc) (STCc depends on the type of room / adjacent spaces)
	HVAC background noise	Background noise levels from heating, ventilating, and air conditioning (HVAC) systems defined by 2011 ASHRAE Handbook, HVAC Applications, Chapter 48, Table 1; AHRI Standard 885-2008, Table 15; or a local equivalent
	Reverberation control	The reverberation time requirements are defined within Table 3 of LEED BD+C v4 manual. (adapted from Table 9.1 in the Performance Measurement Protocols for Commercial Buildings)
	Sound Reinforcement and Masking Systems	Designing requirements: - the speech transmission index (STI) with at least 0.60 or common intelligibility scale (CIS) rating of at least 0.77. - Have a minimum sound level of 70 dBA - Maintain sound-level coverage within +/–3 dB at the 2000 Hz octave band throughout the space. Masking Systems for buildings that use masking systems: the design levels must not exceed 48 dBA. Ensure that loudspeaker coverage provides uniformity of +/–2 dBA and that speech spectra are effectively masked.

		Adapted from ASHRAE (2007d), ASA (2008), ANSI (2002), and CEN (2007)
[66]	Sound mapping	- Background noise level - Acoustical privacy
	Limit background noise levels	Background noise levels do not exceed the protocol thresholds (which depend on kind of adjacent spaces)
	Sound barriers	- Ensure Adequate Wall Construction - Ensure Proper Door Specifications
	Sound absorption (reverberation time)	(WELL v2 rating system threshold)
	Sound absorption (sound reducing)	Spaces have ceiling finishes and wall finishes that meet the table specifications
	Sound masking	Sound masking sound levels meet the table requirements
[67]	Design for acoustic comfort	Architectural design to avoid windows of living rooms and bedrooms to be in immediate proximity/facing to noise sources within site boundary and 70 metres away from building boundary.
	Limit indoor ambient noise level	Aggregate area of not less than 10% of the room/space must be ventilated.
[68]	Design for acoustic comfort	A country with "acoustic regulations" indicates that there are requirements on residential premises at least covering sound insulation topics with regard to airborne noise, impact noise levels and noise levels of equipment, described by the international indices defined in standards ISO 140-4, ISO 140-5 and ISO 140-7 and calculated according to standards ISO 717-1 and ISO 717-2.
	Airborne noise	The equivalent level of noise due to transport infrastructure should be maximum L_{Aeq} 22h-6h of 30 dB(A) and L_{Aeq} 6h-22h of 35 dB(A). This insulation is expressed by the index $DnT_{,w+Ctr}$.
	Impact noise	In collective residences, adjoining individual residences and student accommodation, this is impact noise entering the main rooms of a residence and emitted into other areas in the building outside the residence in question, including exterior passageways.
	Noise from individual heating and air-conditioning equipment	In collective residences, adjoining individual residences and student accommodation, this is noise created by individual heating equipment and air-conditioning installed in an internal area of the residence being examined
[59]	C50 [db]	Clarity Index, defined as ten times the logarithm of the sound energy arriving within 50 ms related to the energy coming in afterwards
	D50 [%]	Definition Index, defined as the ratio of the incoming sound energy within the first 50 ms to the total energy of the impulse
	Sti [-]	Speech Transmission Index
	T60 [s]	Reverberation Time
	Leq [db]	Background Noise Equivalent level
	Is [-]	$I_S = \frac{0.3\,IBN + 0.3\,IEN + 0.2\,ISQ + 0.1\,IVP + 0.1\,ILQ}{10}$ This index is a part of a global comfort index (see §6.4)
[60]	Noise level (dba)	Monitoring noise level at 45, 55, 65, and 75 dBA. This index is related to questionnaires and is a part of a global comfort index (see §6.4)

4 Indoor visual comfort

Visual comfort is defined as "a subjective condition of visual well-being induced by the visual environment" [69]. It depends on the physiology of the human eye, on the physical quantities describing the amount of light and its distribution in space, and on the spectral emission of the light source.

Visual comfort assessment methods are mainly developed in experimental setups under electric lighting with a few exceptions that address this phenomenon in daylight conditions. These approaches are based on empirical models in which the subjective human response is correlated to physical photometric quantities representing the perceived luminance contrast at eye level.

Existing literature, standards and documentation from different buildings' certification schemes (Table 13) report indices for assessing visual comfort and in [70] a view to their use in optimization processes to support building integrated design is presented. Regarding subjective evaluations, the recently updated standard 10551:2019 [27] in its Annex C contains commonly used scales and standard questions for assessing visual environments.

Table 13: Visual comfort indicators literature overview

Ref	Indicator name	Definition / quantification
[64]	Glare control	Compliant shading measures include: - building integrated measures (e.g. Low eaves) - occupant controlled devices such as blinds (where transmittance value is < 0.1 (10%)) - bioclimatic design - external shading or brise soleil. Glare control must provide shading from both high level summer and low level winter sun. Where using fixed systems, design studies can be used to demonstrate that sunlight is prevented from reaching building occupants during occupied hours. Curtains (where used without other forms of shading) do not meet the criteria for the glare control credit, as they do not provide sufficient control to optimise daylight into the space. Furthermore, the use of curtains to control glare is likely to cause occupants to rely more on artificial lighting.
	Daylighting	Parameters under evaluation: Average daylight factor (simulated), Minimum area (m²). The room depth criterion d/w +d/HW < 2/(1-RB) must be satisfied. Where: d = room depth, w = room width, HW = window head height from floor level, RB = average reflectance of surfaces in the rear half of the room,
	View out	Distance (m) from window to workspace or desk Window or opening size (as % of surrounding wall area)
	Internal and external lighting levels, zoning and control	Internal lighting: Where appropriate lighting guides do not exist for a country, it is necessary to demonstrate the compliance with the European standards EN 12464-1 Light and lighting - Lighting of workspaces, 2011 and EN 12464-2 Lighting of work-places - Part 2: Outdoor work places, 2007. Internal lighting can be zoned to allow for occupant control in

		accordance with the criteria below for relevant areas present within the building: 11.an In office areas, zones of no more than four workplaces 11.b Workstations adjacent to windows or atria and other building areas separately zoned and controlled 11.c Seminar and lecture rooms: zoned for presentation and audience areas 11.d Library spaces: separate zoning of stacks, reading and counter areas 11.e Teaching space or demonstration area 11.f Whiteboard or display screen 11.g Auditoria: zoning of seating areas, circulation space and lectern area 11.h Dining, restaurant, café areas: separate zoning of servery and seating or dining areas 11.i Retail: separate zoning of display and counter areas 11.j Bar areas: separate zoning of bar and seating areas 11.k Day rooms, waiting areas: zoning of seating and activity areas and circulation space with controls accessible to staff 11.l Hotel bedrooms: separate zoning of hallway, bathroom, desk and sleeping area (where present in the room).
[65]	Lighting quality	A. For all regularly occupied spaces, use light fixtures with a luminance of less than 2,500 cd/m^2 between 45 and 90 degrees from nadir. B. Use light sources with a CRI of 80 or higher. C. For at least 75% of the total connected lighting load, use light sources that have a rated life (or l70 for led sources) of at least 24,000 hours (at 3-hour per start, if applicable). D. Use direct-only overhead lighting for 25% or less of the total connected lighting load for all regularly occupied spaces. E. For at least 90% of the regularly occupied floor area, meet or exceed the following thresholds for area-weighted average surface reflectance: 85% for ceilings, 60% for walls, and 25% for floors. F. If furniture is included in the scope of work, select furniture finishes to meet or exceed the following thresholds for area-weighted average surface reflectance: 45% for work surfaces, and 50% for movable partitions. G. For at least 75% of the regularly occupied floor area, meet a ratio of average wall surface illuminance (excluding fenestration) to average work plane (or surface, if defined) illuminance that does not exceed 1:10 or demonstrate area-weighted surface reflectance of at least 60% for walls. H. For at least 75% of the regularly occupied floor area, meet a ratio of average ceiling illuminance (excluding fenestration) to work surface illuminance that does not exceed 1:10 or demonstrate area-weighted surface reflectance of at least 85% for ceilings.
	Lighting control	A. Have in place multizone control systems that enable occupants to adjust the lighting to meet group needs and preferences, with at least three lighting levels or scenes (on, off, midlevel). B. Lighting for any presentation or projection wall must be separately controlled. C. Switches or manual controls must be located in the same space as the controlled luminaires. A person operating the controls must have a direct line of sight to the controlled luminaires.
	Daylight	- Spatial daylight autonomy - Illuminance calculation
	Quality views	Is a direct line of sight to the outdoors via vision glazing for 75% of all regularly occupied floor area. View glazing in the contributing area must provide a clear image of the exterior, not obstructed by patterned glazing, or added tints that distort colour balance.
[66]	Ensure Indoor Light Exposure (daylight)	Daylight in regularly occupied spaces: Buildings should be designed at least with one of the following requirements: A. Spatial Daylight Autonomy of sDA200, 40% is achieved for at least 30% of regularly occupied space.

		B. 30% of all workstations are within 6 m [20 ft] of transparent envelope glazing. Visible light transmittance (VLT) of transparent glazing is greater than 40%. C. Transparent envelope glazing area is no less than 7% of the floor area for each floor level. VLT of envelope glazing is greater than 40%. One of the following requirements should be met in each dwelling unit: A. Spatial Daylight Autonomy of sDA 200/40% is achieved for at least 30% of the space. B. Transparent envelope glazing area is no less than 7% of the floor area. Visible light transmittance (VLT) of envelope glazing is greater than 40%. C. The following requirement is met: Achieve Feature L03: Circadian Lighting Design.
	Light levels	All indoor and outdoor spaces (including transition areas) comply with illuminance recommendations specified in one of the following lighting reference guidelines: IES lighting handbook 10th edition. EN 12464-1: 2011. ISO 8995-1:2002(e) (CIE S 008/e:2001). GB50034-2013.
	Electric light quality	Ensure colour rendering quality: Electric lighting meets at least one of the following colours rendering requirements. Decorative fixtures, emergency lights and other special-purpose lighting may be excluded from these requirements. Manage flicker All electric lights (except decorative lights, emergency lights and other special-purpose lighting) used in regularly occupied spaces meet at least one of the following requirements for flicker:
	Glare control	Glare calculation: Annual sunlight exposure of ASE 1000, 250 is achieved for no more than 10% of regularly occupied space. Manage glare from electric lighting: Each luminaire meets one of the following requirements for regularly occupied spaces. Wall wash fixtures properly aimed at walls, as specified by manufacturer’s data, as well as decorative fixtures may be excluded from meeting these requirements: A. 100% of light is emitted above the horizontal plane. B. Unified Glare Rating (UGR) values C. Shielding angles D. Fixtures have a luminance of less than 10,000 cd/m^2 between 45 and 90 degrees from nadir, and/or an intensity of less than 1,000 candela between 45 and 90 degrees from nadir.
	Ensure views	Transparent envelope glazing provides access to views for at least 50% of occupants. Views meet at least two of the following requirements: A. If at ground floor, distance from fenestration to roadway is at least 7.5 m [25 ft] from the exterior of the glazing. B. View factor of 3 or greater. C. Views with a vertical view angle of at least 30 degrees from occupant facing forward or sideways provide a direct line of sight to the ground or sky.
[67]	Daylight	To encourage effective daylighting and potential for visual discomfort mitigation strategies in residential units; in bedrooms, living room, family room and study room. Two methods are available for evaluating and reporting of daylight provision (i) simplified daylit area matrix (ii) full simulation.

	Potential Glare and daylight control	Simple strategies to allow building occupants to adjust their environment to reduce discomfort glare during certain times of the day, whilst allowing effective daylight to enter functional areas
[68]	Exterior visual context	Analyse the limitations and benefits related to the site and its environment (orientation, historical monuments, panoramic views: monuments, gardens, etc.) In connection with the building surroundings.
	Natural lighting (Daylight Factor)	A. Have an aperture index (see additional information) greater than or equal to 15% for at least one room (living room or bedroom) in each residence. B. Prove that the residences fulfil the following conditions: Avg DF ≥ 2% in the living room and Avg DF ≥ 1.5% for the bedrooms (see additional information). A technical study may be carried out by residence typology justifying their representativeness in the project, preferably based on ground floor or first floor residences. The thresholds can be reduced upon the provision of proof of certain specific conditions (e.g: sky rarely overcast).
	Artificial lighting	A. A minimum of 100 lux for entrances and horizontal areas of movement in the buildings, except for stairs, which have a minimum of 150 lux; B. A minimum of 20 lux for outdoor pathways and outdoor spaces, and car parks.
[71]	Illuminance	Illuminance (lux) in a grid of horizontal sensors defined in the work plane at a height of the desks
	Daylighting Autonomy (DA):	Determine the fraction of the occupied time of the year when daylight levels exceed a specified target illuminance;
	Useful Daylighting Index (UDI).	Based on the upper and lower threshold of 2000 and 100 lux, UDI evaluates the percentage of the occupied hours of the year when the UDI was achieved (100-2000 lux), was exceeded (>2000 lux) or fell-short (<100 lux). These values are named as udi_100-2000, udi_100 and udi_2000, respectively
	Glare analysis	Glare analysis should be performed with vertical eye illuminance values, in the critical positions of the office where user and computers could be harmed by glare
[72]	Daylight control	Daylight is a very important component for human health and therefore the building envelope needs to provide precise regulation of glare, illuminance, brightness, luminous flux.
	Glare protection	Glare control by means of textiles, light shelves, (venetian) blinds
[73]	Daylight Glare Probability (DGP) index	DGP is used to quantify the percentage probability of glare perception, developed for an office room under daylight conditions. The DGP formula consists of two main components: GI and Ev.
	Glare Impact (GI)	Glare Impact (GI), is a summation of the luminance of all the glare sources weighted by their corresponding size in solid angle unit and sensitivity in the fov (field of view) measured by a position index (pi) function, and finally divided by Ev. The GI accounts for contrast-inducted glare, meaning the discomfort caused by high contrast between the centre area of the fov and the surroundings.
	Vertical illuminance at the eye level (Ev)	This parameter shows a particular sensitivity when direct sun is the cause of visual discomfort.
	Relative Contrast (RC)	The Relative Contrast (RC) was calculated based on the standard deviation of the pixels illuminance values.
	Relative Contrast based on pixel illuminance (RCpi)	This Relative Contrast is also calculated based on the pixels illuminance values weighted by the PI (RCpi).
[59]	Illuminance	The number of measurement positions was evaluated on the basis of the space index that was calculated from the width, length, and height of the classrooms. The lux-meter used is Mavolux 5032, with accuracy

		class per DIN 5032-7, appendix B of EN13032-1, CIE S 023 (0.1 lux ÷ 199.900 lux measuring range). $$I_{VC} = \frac{0.2\ ALQ + 0.1\,ALS + 0.2\,(10 - ALG) + 0.3\,(10 - NLR) + 0.2\,NLQ}{10}$$ This index is a part of a global comfort index (see §6.4)
[74]	Illuminance	The illuminance levels on the participants' desk surface used in the experiments were set at 150, 500, and 1000 lx, which cover indoor work place lighting levels according to ISO 8995:2002. This index is related to questionnaires and is a part of a global comfort index (see §6.4)

5 Indoor air quality

Indoor Air quality (IAQ) is the quality of air inside **enclosed spaces** and refers to the **types** and **concentrations** of airborne contaminants found in buildings that are known or suspected to affect people's comfort, well-being, health, learning outcomes and work performance. Health effects from indoor air pollutants may be experienced soon after exposure or years later. These include irritation of the eyes, nose, and throat, headaches, dizziness, and fatigue. Such immediate effects are usually short-term and treatable. Other health effects may show up years after exposure has occurred or only after long or repeated periods of exposure. These effects, which include some respiratory diseases, heart disease and cancer, can be severely debilitating or fatal. It is prudent to try to improve the indoor air quality even if symptoms are not noticeable.

The interest in IAQ has grown increasingly in the last few years and progress has been done in this direction. At the European Community level, the resolution of 13 March 2019, defends **clean air for everyone** and highlights that people spend almost 90% of their time in indoors. In these environments, the air can be significantly more polluted compared to outside and, therefore, considered mandatory to issue indoor air quality certificates for both new and old buildings [75]. According to the World Health Organization (WHO), natural ventilation is considered among the effective environmental measures to reduce the risk of spread of infections in health-care settings and guidelines have been developed to describe the basic principles of how to design, construct, operate and maintain an effective natural ventilation system for infection control [76].

Relevant legislation and guidelines are listed in the following:

- Directive 2018/844 (amending EPBD recast) [1],
- European Parliament resolution - 2019,
- EN ISO 16000 – Indoor air, EN 16798-1:2019 [9],
- IAQ WHO Guidelines,
- ANSI/ASHRAE Standards 62.1 [77],
- a dedicated annex by the International Energy Agency (*Annex 68 - Indoor Air Quality Design and Control in Low-energy Residential Buildings*) has been developed with a focus on low-energy residential buildings and several documents are available for consultation [78].

According to ASHRAE Standard 62.1-2019 [77] **acceptable IAQ** is the air in which there are:

- **no known contaminants at harmful concentrations**, as determined by cognizant authorities,
- and with which a substantial majority (80% or more) of the people exposed do **not express dissatisfaction**.

Understanding and controlling common pollutants indoors can help reduce the risk of indoor health concerns. In Table 14 is reported a summary of main contaminants and major sources in buildings while in Table 15 a literature review of IAQ indicators and thresholds is proposed.

However, a complete, standardized and shared reference about IAQ assessments is still not available in literature and the thresholds can differ for the same pollutant and the same exposure time depending on the data and approach used in the different source. For example, the standard CEN/TR 16798-2 [79] expresses the indoor air quality as the required level of ventilation or just considering CO_2 concentrations.

Regarding subjective evaluations, the recently updated standard 10551:2019 [27] in its Annex E contains commonly used scales and standard questions for assessing air quality environments.

Table 14: List of contaminants and major sources in buildings [80]

Contaminants	Major sources
Particulates	Dust (generated inside and outside), smoking, cooking, wood stoves, aerosol spray, etc.
Allergens	Molds, pets, foods, many other sources
Bacteria and viruses	People, moisture, pets
Carbon Dioxide (CO_2)	Occupants breathing, combustion
Odoriferous chemical	People, cooking, molds, chemicals, smoking
Volatile Organic Compounds (VOCs)	Construction materials, furniture, household cleaning products
Tobacco smoke	Smoking
Carbon Monoxide (CO)	Incomplete and/or faulty combustion, smoking
Radon (Rn)	Radioactive decay of radium in the soil under the building
Formaldehyde (HCHO)	Construction materials, furniture and wooden products texiles, household cleaning products, smoking, electronic equipment, etc
Oxides of Nitrogen (NOx)	Combustion, smoking
Sulphur Dioxide (SO_2)	Combustion
Ozone (O_3)	Electronic equipment, electrostatic air cleaners

Table 15: list of IAQ indicators reviewed in literature

Ref	Pollutant indicator	Definition / quantification
[64]	Formaldehyde	- The formaldehyde concentration in indoor air is measured post-construction (but pre-occupancy) and does not exceed 100µg/m³, averaged over 30 minutes. - The formaldehyde sampling and analysis is performed in accordance with ISO 16000-24 and ISO 16000-35. - The total volatile organic compound (TVOC) concentration in indoor air is measured post-construction (but pre-occupancy) and does not exceed 300µg/m³, averaged over 8 hours with 6. - The TVOC sampling and analysis is performed in accordance with ISO 16000-57 and ISO 16000-68 or ISO 16017-19.

Table 17: Emission criteria by product type

Product type	Emission limit*			Testing requirement	Additional requirements
	Formaldehyde	Total volatile organic compounds (TVOC)	Category 1A and 1B carcinogens		
Interior paints and coatings	≤ 0.06 mg/m³	≤ 1.0 mg/m³	≤ 0.001 mg/m³	EN 16402 [10] or ISO 16000-9 [11] or CEN/TS 16516 [12] or CDPH Standard Method v1.1 [13]	Meet TVOC content limits (Table 19). Paints used in wet areas (e.g. bathrooms, kitchens, utility rooms) should protect against mould growth (see CN3.4).
Wood-based products(including wood flooring)	≤ 0.06 mg/m³ (Non-MDF) ≤ 0.08 mg/m³ (MDF)	≤ 1.0 mg/m³	≤ 0.001 mg/m³	ISO 16000-9[14] or CEN/TS 16516[15] or CDPH Standard Method v1.1[16] or EN 717-1 (formaldehyde emissions only) [17]	N/A
Flooring materials (including floor levelling compounds and resin flooring)	≤ 0.06 mg/m³	≤ 1.0 mg/m³	≤ 0.001 mg/m³	ISO 10580 or ISO 16000-9 or CEN/TS 16516 or CDPH Standard Method v1.1	N/A
Ceiling, wall, and acoustic and thermal insulation materials	≤ 0.06 mg/m³	≤ 1.0 mg/m³	≤ 0.001 mg/m³		N/A
Interior adhesives and sealants (including flooring adhesives)	≤ 0.06 mg/m³	≤ 1.0 mg/m³	≤ 0.001 mg/m³	EN 13999 (Parts 1-4) [18][19][20][21] or ISO 16000-9 or CEN/TS 16516 or CDPH Standard Method v1.1	N/A

	VOCs	The measurement of formaldehyde and TVOC must be made in accordance with the relevant standards (as listed in the criteria). ISO 16000-24 and ISO 16000-5 provide guidance on sampling strategies for formaldehyde and VOCs, respectively.
	Asbestos	Materials containing asbestos are prohibited from being specified and used within the building.
	Limit impact of outdoor pollution	Sources of external pollution: - Highways and the main access roads on the assessed site - Car parks, delivery areas and vehicle waiting bays - Other building exhausts, including from building services plant, industrial or agricultural processes.
	Limit particulates (filtration)	HVAC systems must incorporate suitable filtration to minimise external air pollution, as defined in EN 13779:2007 Annex A3.
	Ventilation	- In air-conditioned and mixed-mode buildings or spaces: The location of the building's air intakes and exhausts, in relation to each other and external sources of pollution, is designed in accordance with EN 13779:20071 Annex A2 - In naturally ventilated buildings or spaces: openable windows or ventilators are at least 10m of horizontal distance from sources of external pollution (including the location of any building related air exhausts).
[65]	VOCs	Manufacturers' claims of compliance with the above requirements must also state the range of total VOCs after 14 days (336 hours), measured as specified in the CDPH Standard Method v1.1: - 0.5 mg/m³ or less; - between 0.5 and 5.0 mg/m³; - 5.0 mg/m³ or more. Reference standards: ISO 16000- 3: 2010, ISO 16000-6: 2011, ISO 16000-9: 2006, ISO 16000-11:2006
	Asbestos, radon, mold, lead	Any contaminants not typically included in the scope of Phase I and Phase II ESAs should be considered if the site is at risk for such contamination. If non-scope "recognized environmental conditions" (RECs) (asbestos-containing materials, radon, mold, lead, etc) are

		identified, these contaminants must be addressed in the scope of the Phase I and Phase II ESAs.
	Enhanced outdoor air provision and filtration	Filtration Indicate whether the building is in a nonattainment area for fine particulate matter (PM2.5), and if so, confirm that filters with minimum efficiency reporting values (MERV) of 11 or higher have been or will be installed. Natural Ventilation Design Calculations the system should be designed employs the appropriate strategies in Chartered Institution of Building Services Engineers (CIBSE) Applications Manual AM10, March 2005, Natural Ventilation in Non-Domestic Buildings, Section 2.4.
	Minimum outdoor air provision	Mechanically Ventilated Spaces: ASHRAE STANDARD 62.1–2010, CEN STANDARDS EN 15251–2007 AND EN 13779–2007 Naturally Ventilated Spaces For naturally ventilated spaces (and for mixed-mode systems when the mechanical ventilation is inactivated), determine the minimum outdoor air opening and space configuration requirements using the natural ventilation procedure from ASHRAE Standard 62.1–2010 or a local equivalent, whichever is more stringent. Confirm that natural ventilation is an effective strategy for the project by following the flow diagram in the Chartered Institution of Building Services Engineers (CIBSE) Applications Manual AM10, March 2005, Natural Ventilation in Nondomestic Buildings, Figure 2.8, and meet the requirements of ASHRAE Standard 62.1–2010, Section 4, or a local equivalent, whichever is more stringent. Monitoring For naturally ventilated spaces (and for mixed-mode systems when the mechanical ventilation is inactivated), comply with at least one of the following strategies. - Provide a direct exhaust airflow measurement device capable of measuring the exhaust airflow. This device must measure the exhaust airflow with an accuracy of +/–10% of the design minimum exhaust airflow rate. An alarm must indicate when airflow values vary by 15% or more from the exhaust airflow setpoint. - Provide automatic indication devices on all-natural ventilation openings intended to meet the minimum opening requirements. An alarm must indicate when any one of the openings is closed during occupied hours. - - Monitor carbon dioxide (CO_2) concentrations within each thermal zone. CO_2 monitors must be between 3 and 6 feet (900 and 1 800 millimeters) above the floor and within the thermal zone. CO_2 monitors must have an audible or visual indicator or alert the building automation system if the sensed CO_2 concentration exceeds the setpoint by more than 10%. Calculate appropriate CO_2 setpoints using the methods in ASHRAE 62.1–2010, Appendix C.
[66]	Formaldehyde	The concentration must be less than 27 ppb
	VOCs (organic gases)	VOC monitoring: - Sensors to measure total VOC at least once per hour (with accuracy 25% at 500 µg/m^3) are installed with a density of at least one per every 3,500 ft^2.

		- Data covering at least the previous one month demonstrate total VOC levels of 500 μg/m³ or lower for at least 90% of regularly occupied hours for all sensors. Thresholds: - Acetaldehyde: 140 μg/m³ or lower - Acrylonitrile: 5 μg/m³ or lower - Benzene: 3 μg/m³ or lower - Caprolactam: 2.2 μg/m³ or lower - Formaldehyde: 9 μg/m³ or lower - Naphthalene: 9 μg/m³ or lower - Toluene: 300 μg/m³ or lower
	Inorganic gases	Thresholds: - Carbon monoxide: 10 mg/m³ [9 ppm] or lower - Ozone: 100 μg/m³ [51 ppb] or lower
	Lead and mercury Asbestos Pcbs	Thresholds defined by: - Furuya S, Chimed-Ochir O, Takahashi K, David A, Takala J. Global Asbestos Disaster. International Journal of Environmental Research and Public Health. 2018;15(5). - Agency for Toxic Substances Disease Registry. Toxicological Profile for Lead. Published 2007. Accessed January 2, 2020. Agency for Toxic Substances Disease Registry. Toxicological Profile for Polychlorinated Biphenyls (PCBs). - World Health Organization. Brief guide to analytical methods for measuring lead in paint. 2011. - US Environmental Protection Agency. Dust-Lead Hazard Standards; Definition of Lead-Based Paint. In: US EPA, ed. Vol 2019-14024. Washington, DC2019. - US Environmental Protection Agency. How to Test for PCBs and Characterize Suspect Materials. Published 2018. Accessed December 16, 2019, 2019
	Radon	A. The radon level must be less than 0.15 Bq/L [4 pCi/L], as tested by a professional demonstrated not to have a conflict of interest. One test is conducted per 2,300 m² [25,000 ft²] of regularly occupied space at or below grade. B. All regularly occupied spaces at or below grade meet the 'Mechanically ventilated spaces' option of Part 1: Ensure Adequate Ventilation in Feature A03: Ventilation Effectiveness.
	Limit particulates (filtration)	Thresholds: - PM2.5 less than 15 μg/m³. - PM10 less than 50 μg/m³. The following thresholds are destinated for a building located where the annual average ambient PM2.5 level is 35 μg/m³ or higher. - PM2.5 equal to 30% of the 24- or 48-hour average of outdoor levels on the day(s) of performance testing. - PM10 equal to 30% of the 24- or 48-hour average of outdoor levels on the day(s) of performance testing.
	Minimum outdoor air provision	Naturally ventilated spaces: Buildings using natural ventilation only (no mechanical ventilation) meet the following requirements: A. Outdoor PM2.5, PM10, carbon monoxide and ozone levels within 4 km [2.5 mi] of the building are compliant with the

		levels specified in Feature A01: Air Quality Standards for at least 95% of all hours in the previous year. B. One of the following design criteria: 1. Natural Ventilation Procedure in ASHRAE 62.1-2010 or any more recent version (as appropriate for number of floors above grade). 2. CIBSE AM10: Natural Ventilation in Non-Domestic Buildings (2005 or any more recent version) section 2.4 – Natural ventilation strategies and chapter 4 – Design Calculations. Mechanically ventilated spaces: Projects utilizing mechanical ventilation comply with ventilation supply and exhaust rates set in one of the following: A. AS 1668.2-2012 or any more recent version. Note that projects that wish to comply with AS 1668.2 must assume a minimum density of 16 m² [170 ft2] per person. B. CIBSE Guide A: Environmental Design, version 2007 or any more recent version. C. ASHRAE 62.1-2010 or any more recent versions (Ventilation Rate Procedure or IAQ Procedure). D. CEN Standards EN 15251:2007 and EN 16798-3:2017 or any more recent versions. The requirements of CEN Standard EN 15251:2007 must be met as well as the performance requirements of CEN Standard EN 16798-3:2017 related to ventilation and room conditioning systems (excluding sections 7.3, 7.6, A.16 and A.17). Naturally ventilated spaces: Outdoor air meets the following thresholds as an average for the previous year: - PM2.5 less than 35 µg/m³. - PM10 less than 70 µg/m³. One of the following design criteria: Natural Ventilation Procedure in ASHRAE 62.1-2010 or any more recent version (as appropriate for number of floors above grade). CIBSE AM10: Natural Ventilation in Non-Domestic Buildings (2005 or any more recent version) section 2.4 – Natural ventilation strategies and chapter 4 – Design Calculations.
	Moisture (humidity, leaks)	Condensation management: A. High interior relative humidity levels, particularly in susceptible areas like laundry rooms, below-grade spaces and other high-humidity areas. B. Air leakage that could wet either exposed interior materials or interstitially hidden materials. C. Cold surfaces such as basements, slab-on-grade floors or the inside of exterior walls. D. Oversized air conditioning units. Mold inspections: A. Annual inspections for signs of water damage or pooling, discoloration and mold on ceilings, walls and floors is performed by a professional demonstrated not to have a conflict of interest. B. One of the below is met: 1. Project achieves cooling coil mold reduction as per Part 1: Implement Ultraviolet Air Treatment.

		2. All cooling coils (where applicable) are inspected on a quarterly basis for mold growth and cleaned if necessary. c. For projects with tenants, there is a system in place for notifying building management about mold or water damage and addressing concerns
[67]	VOCs	More Stringent VOC Limits for Interior Fittings and Finishes Minimise airborne contaminants, mainly from inside sources to promote a healthy indoor environment. To encourage use of low VOC emitting interior finishes that are certified by approved local certification bodies - Adhesives & sealants (including tile grouting) - Floor coverings such as carpets, vinyl flooring (excluding tiles) - Ceiling coverings such as ceiling boards, - Wall coverings (excluding tiles) - Varnish, stains, lacquers or other trims (including doors and furniture) Test methods shall comply with ISO 17895 or ISO 11890
	Minimum outdoor air provision	Clean Outdoor Air Provision of a space/room in the unit with minimum outdoor air in occupant space when windows are closed, particularly when there is poor outdoor air quality condition
	Moisture (humidity, leaks)	For windows and curtain wall systems, air leakage rates shall not exceed the limit specified in SS212 and SS381 respectively
[68]	Formaldehyde	Thresholds: - 30 µg/m³: point of reference value for air quality (the High Council of Public Health, HCSP) - 50 µg/m³: maximum admissible value for long- term exposure (HCSP) - 100 µg/m³: long-term value
	Total volatile organic compounds (TVOC)	- Level 1: <300 µg/m³ : target value, no health impact - Level 2: > 300 - 1000 µg/m³: no specific impact but increased ventilation recommended - Level 3: > 1000 - 3000 µg/m³: some impacts on health. Level tolerated for a maximum of 12 months. Locate sources, increase the recommended ventilation. - Level 4: >3000 - 10,000 µg/m³: major impacts. Cannot be tolerated for more than one month. Locate sources, intensified ventilation required - Level 5: >10,000 – 25,000 µg/m³: unacceptable situation. Use only if unavoidable for short periods (hours) and only with intensive ventilation. Reference: Indoor Air Hygiene Commission of the German Federal Environment Agency
	Radon	100 µq/m³: reference level recommended 300 Bq/m³: reference level the exceeding of which is not desirable

<table>
<tr><td rowspan="4"></td><td>Carbon monoxide (CO) if source</td><td>7 mg/m³ for exposure over 24 hours 10 mg/m³ for exposure over 8 hours 35 mg/m³ for an hour of exposure 100 mg/m³ for an exposure of 15 min</td></tr>
<tr><td>Nitrogen dioxide (NO_2)</td><td>40 µg/m³</td></tr>
<tr><td>Particulate matter (PM 2.5 and PM 10)</td><td>Short term: PM 10: <50 µg/m³ and PM 2.5: <25 µg/m³
Long term: PM 10: <20 µg/m³ and PM 2.5: <10 µg/m³</td></tr>
<tr><td>Minimum outdoor air provision</td><td>- Natural ventilation: Provide ventilation that does not affect the building or occupants during periods of occupancy or vacancy (mould, poor air quality, damp, etc.) and describe the air flows in residences.
- Mechanical or natural fan-supported ventilation system Comply with local regulations if they exist, referring to the minimum air-renewal rates, or if no such regulations exist, allow for an air-renewal rate of:
- 0.5 vol/h from a studio to a residence with three living spaces
- 0.7 vol/h for residences with 4 living spaces or more.</td></tr>
<tr><td rowspan="3">[57]</td><td>Carbon dioxide CO_2</td><td rowspan="3">Standard sequence of indoor air quality evaluation.
<table>
<tr><th>Contaminant</th><th colspan="4">Grade</th></tr>
<tr><th></th><th>Clean</th><th>Non-pollution</th><th>light pollution</th><th>Heavy pollution</th></tr>
<tr><td>CO_2 (ppm)</td><td>400</td><td>650</td><td>1000</td><td>1800</td></tr>
<tr><td>TVOC (mg/m³)</td><td>0.1</td><td>0.3</td><td>0.6</td><td>1.2</td></tr>
<tr><td>PM2.5 (µg/m³)</td><td>25</td><td>35</td><td>75</td><td>150</td></tr>
</table></td></tr>
<tr><td>TVOC</td></tr>
<tr><td>Particulate matter (PM 2.5)</td></tr>
<tr><td>[81]</td><td>No one</td><td>Indoor Air Quality (IAQ): The literature shows that IAQ is negatively affected by outdoor air pollution when natural ventilation is used without filters. Windcatchers and solar chimneys demonstrated good ability to remove indoor generated pollution due to their ability to induce air movement. However, no studies were found linking them with air filters.</td></tr>
</table>

6 Comfort indicator overview

To summarize, human comfort can be divided into several sub-categories, such as visual comfort, acoustic comfort, air quality and thermal comfort. These sub-categories are interconnected with each other and their interactions should be carefully considered (e.g. as reported within the Building Bulletin 101 ventilation guidelines relating to thermal comfort and indoor air quality in schools [82] (Figure 10). The arrows represent the relations of each aspect of comfort.

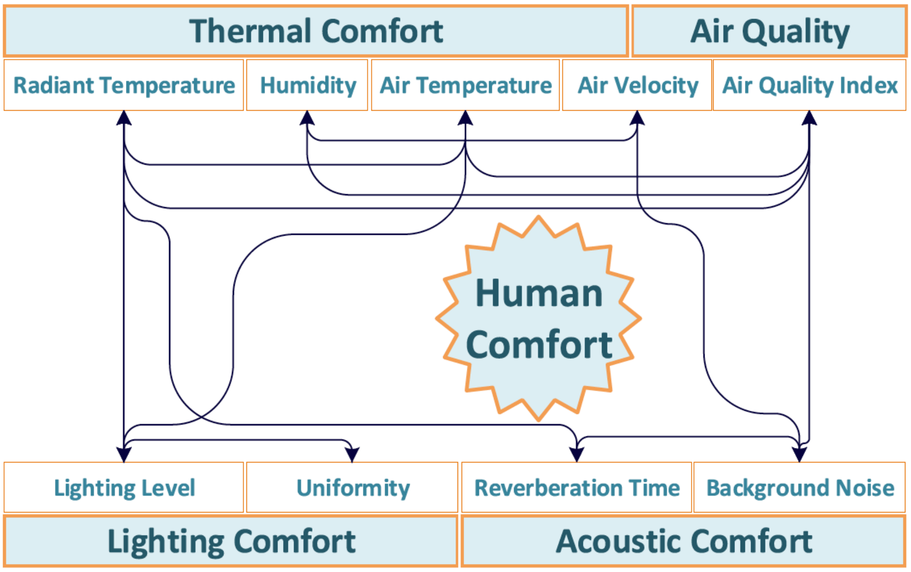

Figure 10: Human comfort aspects and their relations [83]

It can be said that thermal comfort is defined as a function of four environmental variables (air temperature, average radiant temperature, relative humidity and air velocity) and two personal variables (metabolic activity and level of clothing). Among the various comfort models mentioned in Chapter 2, the adaptive model and the Givoni bioclimatic chart are particularly important for ABC 21. They generally involve lower energy consumption as long as convenient, responsive and effective means are available to allow occupants to improve their environment (for example, opening windows or using fans) [51].

Perspectives on visual comfort have also recently evolved in connection with the reduction of electricity consumption and the importance of daylight for occupants' health and well-being. Visual comfort is influenced by the size, position and type of window, geometry and interior finishes. Daylight glare can be controlled using fixed systems (for example, fixed lamellas) and dynamic shading devices (for example, curtains/blinds). Acoustic comfort, on the other hand, is often overlooked during design because it can conflict with good daytime lighting and natural ventilation design. Recent reports on the post-occupancy assessment of low-energy buildings have revealed that they generally score high for all occupant satisfaction categories except acoustic quality and privacy. Acoustic comfort is directly linked to health and productivity [83]. Furthermore, poor acoustic quality can compromise energy saving strategies such as natural ventilation because occupants must choose between thermal comfort and at the same time have a quiet indoor environment. Conditions in the surrounding of the building are hence important; districts without cars, or with speed limits, openings towards quiet courtyards can enhance the possibility of a successful passive design and will be analysed in subsequent deliverables.

6.1 Key Performance Indicators for ABC 21

In order to assess the indoor environmental quality, Table 16 reports a selection of the reviewed indicators divided by comfort category (thermal, acoustic, visual and indoor air quality), which are particularly important for assessing IEQ in bioclimatic buildings.

A further selection will be done in relation to the parameters available from simulations or in-situ measurements in the specific case studies analysed in Task 3.4.

Table 16: Long-term thermal comfort indicators

n	Thermal comfort index	UoM	Definition
1	Percentage of time outside an operative temperature range (Adaptive)	%	Calculate the number or percentage of hours, during the hours the building is occupied, the operative temperature is outside a specified range calculated according to the adaptive thermal comfort model.
2	Percentage of time outside an operative temperature range (Fanger)	%	Calculate the number or percentage of hours, during the hours the building is occupied, the operative temperature is outside a specified range defined according to the Fanger comfort model.
3	Degree-hours (Adaptive)	h	The time during which the actual operative temperature exceeds the specified range (calculated according to the adaptive thermal comfort model) during the occupied hours is weighted with a factor which is a function of how many degrees the range has been exceeded.
4	Degree-hours (Fanger)	h	The time during which the actual operative temperature exceeds the specified range (defined according to the Fanger comfort model) during the occupied hours is weighted with a factor which is a function of how many degrees the range has been exceeded.
5	Percentage of time inside the Givoni comfort zone for air velocity at 1 m/s	%	Calculate the number or percentage of hours during the hours the building is occupied, when the operative temperature is inside the specified comfort zone
6	Percentage of time inside the Givoni comfort zone for still air conditions, i.e. v = 0 m/s	%	Calculate the number or percentage of hours during the hours the building is occupied, when the operative temperature is inside the specified comfort zone
7	Number of hours during which the operative temperature is within a certain range	-	Calculate the number of hours during which the operative temperature is within a certain temperature range

Table 17: Visual comfort indicators

n	Visual comfort index	UoM	Definition	Measurement on site / Virtual simulation
1	Light level (illuminance $\bar{E}$m)	lx	Illuminance at a specific point of a given surface is a physical quantity, measured in lux and defined as the ratio between the luminous flux incident on an infinitesimal surface in the sorroundings and the area of that surface. Lighting reference guidelines: EN 12464-1:2011, EN 12464-2:2014, ISO/CIE	can be measurement on site by: -Illuminometer -Photometer _or_ simulated with: - radiance - ecotect - radianceIES (IESVE)

			8995-3:2018, IES Lighting Handbook 10th Edition.	- open studio (Energy plus) - honeybee/ladybug (Rhino)
2	Daylight (DF) (sDA) (DA) (UDI)	%	It's the illumination of indoor spaces by natural light. It can be calculated by means of: Daylight Factor (DF): is the ratio between the internal illuminance level at a specific point to exterior horizontal illuminance, under a CIE overcast sky. For instance, if we have 1000 fc exterior, and 20 fc at a given location inside the room, that is a 2% DF. Daylight Autonomy (DA): is a metric defined as the fraction of occupied time of a day, week, month, or a year, that the daylight levels exceed a specified target illuminance, 300 lux. Spatial Daylight Autonomy (sDA): sDA is defined as the percent of an analysis area that meets a minimum illuminance level for a specified fraction of the operating hours per year. It reports a percentage of floor area that exceeds a specified illuminance level, e.g. 300 lux for a specified amount of annual hours. Useful Daylight Illuminance (UDI): UDI is defined as the fraction of the time in a year when indoor horizontal daylight illuminance at a given point falls in a given range. 100 lux is often used as the lower threshold of useful illuminance, and 2000 lux as the upper bound.	can be simulated with the following software: - radiance - ecotect (radiance) - radianceIES (IESVE) - open studio (Energy plus) - honeybee/ladybug (Grasshopper/Rhino)
3	Glare control (DGP) (DGI)	%	Glare control indexes that are used to assess daylit spaces for large-area sources of daylight glare such as glazed façades. In particular: Daylight Glare Probability (DGP) is used to quantify the percentage probability of glare perception, developed for an office room under daylight conditions. Daylight glare index (DGI) aims at predicting glare from large sources, such as a window, described by its luminance.	can be measurement on site by: Luminance meters or luminance cameras *or* simulated with: - radiance - ecotect (radiance) - radianceIES (IESVE) - honeybee/ladybug (Rhino)
4	Quality view	n/a	its aim is to give building occupants a connection to the natural outdoor environment (i.e. flora, fauna, or sky). Outside views can improve satisfaction and productivity of workers and reduce stress of patients, healthcare facilities. Views to the outdoors also connect the occupants with natural environmental cues, such as diurnal changes from light to dark and the changes in light from season to season, which are important for maintaining natural circadian rhythms. Disruption of these rhythms can lead to long-term health care problems, including mental disorders.	N/A *qualitative indicator*
5	Zoning control	n/a	Lighting controls provided for individual and group needs promote occupants' productivity, comfort, and well-being.	N/A *qualitative indicator*

Table 18: Acoustic comfort indicators

n	Acoustic comfort index	UoM	Definition	Measurement on site / Virtual simulation
1	Airborne sound insulation (Dw) (Rw)	db	Sound reduction index: Dw represents the sound insulation between rooms on-site; Rw represents the lab tested sound insulation of an element making up a partition wall/floor type. Reference: EN ISO 16283:2014, EN ISO 354:2003	Sound level meter (ISO 3382-1:2009) / analytic calculation or software simulation
2	Equivalent continuous sound Level (L_{eq})	db	is the constant noise level that would result in the same total sound energy being produced over a given period.	sound level meter (which provide integrated L_{eq} and sound exposure level measurements) / analytic calculation or software simulation
3	HVAC noise level	db	Measured sound pressure level in the receiving room from all sources except the loudspeaker in the source room. Reference: (HVAC) systems per 2011 ASHRAE Handbook, HVAC Applications, Chapter 48, Table 1; AHRI Standard 885-2008, BS 8233:2014; or a local equivalent	Unit Under Test (UUT) ANSI-AHRI STANDARD 230-2013 / analytic calculation
4	Reverberation	s	Time required for the sound pressure level in a room to decrease by 60 dB after the sound source has stopped. Reference : EN ISO 354:2003	sound level meter (which provide t60 t30 t20 measurements) ISO 3382-2:2008 / analytic calculation
5	Masking/barriers	n/a	Additional installed structures which lead to reduce sound pressure level	N/A *qualitative indicator*

Table 19: Indoor Air Quality indicators

n	IAQ indicators	UoM	Definition	Measurement on site / Analysis
1	Organic compound	μg/m³	Formaldehyde (systematic name methanal) is a naturally occurring organic compound polychlorinated biphenyl (PCB) is an organic chlorine compound with the formula	Formaldehyde (HCHO) sensor
2	VOCs	μg/m³	Volatile organic compounds (VOC) are organic chemicals that have a high vapour pressure at room temperature. High vapor pressure correlates with a low boiling point, which relates to the number of the sample's molecules in the surrounding air, a trait known as volatility	PID lamp
3	Inorganic gases	μg/m³ - mg/m³ - ppm	Carbon monoxide (CO), Carbon dioxide (CO_2)*, Nitrogen dioxide (NO_2), Sulfur Dioxide SO_2, Ozone O_3	Electrochemical sensor (CO_2), NDIR sensor (CO), Nitrogen Dioxide sensor (NO_2), Sulphur

				Dioxide sensor (SO_2), Ozone sensor
4	Particulates (filtration)	$\mu g/m^3$	defined as atmospheric aerosol particles, atmospheric particulate matter, particulate matter (PM), or suspended particulate matter (SPM)	Highly sensitive nephelometric (photometric) monitor
5	Minimum outdoor air	m^3/h - l/s	- In air-conditioned and mixed-mode buildings or spaces: The location of the building's air intakes and exhausts, in relation to each other and external sources of pollution, is designed in accordance with BS EN 16798-3:2017 or ASHRAE Standard 62.1-2019, Ventilation for Acceptable Indoor Air Quality, ASHRAE Standard 62.2-2019, Ventilation and Acceptable Indoor Air Quality in Residential Buildings. - In naturally ventilated buildings or spaces: openable windows or ventilators should be far from sources of external pollution.	Air quality meter / analytical verification according with standards
6	Moisture (humidity, leaks)	n/a	Condensation management and Mold inspections	Site inspection / condensation verification
7	Hazard material	n/a	the site should not contain environmental contamination as asbestos lead mercury radon	Site inspection

*CO_2 is rarely a health issue in itself. It is nevertheless a **very good indicator of human presence and the level of ventilation**. Outdoor air contains approximately 400 ppm; breathing generates CO_2, so the indoor CO_2 concentration will always be at least 400 ppm and usually higher. CO_2 is most relevant as an indicator in rooms where the need for ventilation is linked to the presence of people, e.g. in bedrooms, children's rooms, living rooms, dining rooms, classrooms and offices.

6.2 Indoor Environmental Quality monitoring

In recent years progress on the IEQ sensor technology has been done, resulting in smaller sensors, higher reliability and accuracy and lower costs [84]. Recent technologies like smart meters, smart home applications and building management systems facilitate the implementation of continuous monitoring which is fundamental to recognize and react to users' and occupants' needs and optimize comfort, indoor air quality and wellbeing. At EU level, the revised EPBD requires the development of a voluntary European scheme for rating the smart readiness of buildings, the **"Smart Readiness Indicator" (SRI)**, currently under development, which could include an index or metric to consider the most important physical parameters of IEQ [85].

The main standards relevant for the measurements of IEQ parameters are reported in Table 22. Among this, we highlight the EN ISO 7726 [29] which specifies the minimum characteristics of instruments for measuring physical quantities characterizing an environment as well as the methods for measuring the physical quantities of this environment. To properly assess indoor conditions, it is necessary that information about outdoor climate is also available.

Table 20 reports the list of the main parameters to assess thermal comfort, acoustic comfort, visual comfort and air quality for the indoor environment and the related measuring devices. In

ABC 21 different case studies will be taken into account as examples of bioclimatic buildings. Data will be collected where already produced by previous studies. Some of the case studies are already provided with dedicated automatic systems which allow for the detailed monitoring of comfort performance (e.g. Botticelli case study, Mascalucia, Italy). For some others, we are currently developing a simplified plan of measurement and verification of IEQ parameters, according to the time and budget available for this task.

With reference to the existing documentation developed by the *IEA Task 40/Annex 52 Towards Net Zero Energy Solar Buildings,* Table 21 shows different standard level of monitoring strategies applicable to the Net ZEB verification procedure. Since air velocity has been proven to be significant for warm climates and recognized in European and American standards, we plan to include indoor air velocity measurements also in the basic monitoring.

Table 20: List of parameters necessary to assess thermal comfort, acoustic comfort, visual comfort and air quality for the indoor environment

Environmental parameter	Measuring device
Thermal comfort	
Air temperature	Resistance thermometer (e.g PT-100)
Mean radiant temperature	Globe Thermometer + resistance thermometer + anemometer
Air velocity and turbulence	Anemometer
Relative humidity	Hygrometer
Radiant asymmetry	Radiometer
Surface temperature	Contact resistance thermometer (e.g. PT-100)
Acoustic comfort	
Sound pressure level	Multi-function meter for all sound and vibration measurements
Reverberation time	
Airborne and impact sound insulation	
Visual comfort	
Illuminance and its uniformity	Photometer
Glare	Luminance meters or luminance cameras
Colour rendering	Illuminance Spectrophotometer
Flicker rate	High speed (il)luminance measurement device or a colorimeter
Amount of daylight	
Air quality	
TVOCs	PID lamp
Carbon Dioxide	Electrochemical sensor
Carbon Monoxide	NDIR sensor
Nitrogen Dioxide NO_2	Nitrogen sensor
Sulfur Dioxide SO_2	Sulfur Dioxide sensor
Ozone O_3	Ozone sensor
Particle mass concentration	The instrument uses a laser-diode light source and collection optics for particle detection
Aerosol concentration (Particulate Matter – PM)	Highly sensitive nephelometric (photometric) monitor
Formaldehyde	Formaldehyde (HCHO) sensor
Temperature	Resistive sensor (Pt100)
Relative Humidity	Capacitive sensor
Air velocity	Anemometer

Table 21: Levels of IEQ monitoring (extract from Annex B [86])

1. Basic monitoring	2. Advanced Basic monitoring	3. Detailed monitoring	4. Advanced detailed monitoring
- Indoor air temperature - Outdoor air temperature - Global irradiation - General satisfaction surveys (once a year)	- Indoor air temperature - Indoor humidity - Operative temperature - Outdoor air temperature - Global irradiation - General satisfaction surveys (twice a year in different seasons)	- Indoor air temperature - Indoor humidity - Operative temperature - Indoor air velocity - CO_2 concentration - Outdoor air temperature - Outdoor humidity - Global irradiation - General satisfaction surveys (each year for 5 years) - Spot surveys (at the end of second year)	- Indoor air temperature - Indoor humidity - Operative temperature - Indoor air velocity - CO_2 concentration - Volatile Organic Compounds - Daylight factor - Outdoor air temperature - Outdoor humidity - Global and diffuse irradiation - Wind direction and speed at 3m and 10m - General satisfaction surveys (each year for 5 years) - Spot surveys (several time during the two years)

6.3 Standards for quantification and measurements

In Table 22 we have summarizes the most relevant standards for the assessment of IEQ, considering each comfort area.

Table's indications:

- IEQ_{cat} stands for "Indoor Environment Quality Category";
- TC stands for "Thermal Comfort";
- AC stands for "Acoustic Comfort";
- VC stands for "Visual Comfort";
- IAQ stands for "Indoor Air Quality".

Table 22: Overview of standards relevant to Indoor Environment Quality

IEQ_{cat}	Reference Standard	
	Methods and definitions	Measurements
TC	▪ **ASHRAE 55:2020** Thermal Environmental Conditions for Human Occupancy ▪ **ISO 7730:2005** Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the	▪ **EN ISO 7726** Ergonomics of the thermal environment — Instruments for measuring physical quantities

	PMV and PPD indices and local thermal comfort criteria ▪ **EN 16798:2019** Energy performance of buildings - Ventilation for buildings. Part 1 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Part 2: Interpretation of the requirements in EN 16798-1. ▪ **ISO 17772:2018** Energy performance of buildings — Indoor environmental quality. Part 1: Indoor environmental input parameters for the design and assessment of energy performance of buildings. Part 2: Guideline for using indoor environmental input parameters for the design and assessment of energy performance of buildings.	▪ **EN ISO 10551:2019** Ergonomics of the physical environment - Subjective judgement scales for assessing physical environments
AC	▪ **EN ISO 16283:2020** Acoustics. Field measurement of sound insulation in buildings and of building elements. Impact sound insulation ▪ **EN ISO 354:2003** Acoustics. Measurement of sound absorption in a reverberation room ▪ **EN ISO 16032:2020** Acoustics. Field measurement of sound insulation in buildings and of building elements. Impact sound insulation ▪ **EN ISO 10052:2004** Acoustics. Field measurements of airborne and impact sound insulation and of service equipment sound. Survey method. ▪ **ISO 17772-1:2017** Energy performance of buildings. Indoor environmental quality. Indoor environmental input parameters for the design and assessment of energy performance of buildings ▪ **AHRI Standard 885-2008** Procedure for Estimating Occupied Space Sound Levels in the Application of Air Terminals and Air Outlets ▪ **ASHRAE Handbook (2011) - HVAC Applications** Noise and Vibration Control, Chapter 48.	▪ **ANSI-AHRI STANDARD 230-2013** Sound Intensity Testing Procedures for Determining Sound Power of HVAC Equipment ▪ **EN ISO 3382-1:2009** Acoustics. Measurement of room acoustic parameters. Performance spaces ▪ **EN ISO 3382-2:2008** Acoustics. Measurement of room acoustic parameters. Reverberation time in ordinary rooms. ▪ **EN ISO 3382-3:2008** Acoustics. Measurement of room acoustic parameters. Open plan offices ▪ **EN ISO 10551:2019** Ergonomics of the physical environment - Subjective judgement scales for assessing physical environments
VC	▪ **EN 12464-1:2011** Light and lighting. Lighting of work places. Indoor work places ▪ **EN 12464-2:2014** Light and lighting. Lighting of work places. Outdoor work places ▪ **ISO 8995:2002**	▪ **EN 12464-1:2011** Light and lighting. Lighting of work places. Indoor work places ▪ **EN ISO 10551:2019** Ergonomics of the physical environment - Subjective judgement

	Lighting of indoor work places ▪ IES Lighting Handbook 10th Edition.	scales for assessing physical environments
IAQ	▪ WHO guidelines ▪ **EN 16798:2019** Energy performance of buildings - Ventilation for buildings. Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Part 2: Interpretation of the requirements in EN 16798-1. Part 3: For non-residential buildings. Performance requirements for ventilation and room-conditioning systems. ▪ **ASHRAE Standard 62.1-2019** Ventilation for Acceptable Indoor Air Quality	▪ **EN 12599:2012** Ventilation for buildings. Test procedures and measurement methods to hand over air conditioning and ventilation systems. ▪ **ISO 16017-02:2003** Indoor, ambient and workplace air. Sampling and analysis of volatile organic compounds by sorbent tube/thermal desorption/capillary gas chromatography. ▪ **ISO 16000-3:2011** Indoor air. Determination of formaldehyde and other carbonyl compounds in indoor air and test chamber air. Active sampling method ▪ **ISO 16000-9:2006** Indoor air. Determination of the emission of volatile organic compounds from building products and furnishing. Emission test chamber method ▪ **ISO 16000-30:2014** Indoor air. Sensory testing of indoor air ▪ **ISO 16000-37:2019** Indoor air. Measurement of PM2,5 mass concentration ▪ **ISO 16000-13:2008** Indoor air. Determination of total (gas and particle-phase) polychlorinated dioxin-like biphenyls (PCBs) and polychlorinated dibenzo-p-dioxins/dibenzofurans (PCDDs/PCDFs). ▪ **ISO 16017-19:2014** Indoor air. Sampling strategy for moulds ▪ **EN ISO 10551:2019** Ergonomics of the physical environment - Subjective judgement scales for assessing physical environments

6.4 Global IEQ index

Literature reviews on indoor environmental conditions mainly examine the effects of single parameters on human comfort. However, some studies have been developed to provide a comprehensive assessment that combines all categories such as thermal, acoustic, visual and indoor air quality in an overall key performance indicator, e.g. Wargocki et al. [87] focused on the development of an index and a protocol for an integrated rating of IEQ in buildings that have undergone deep energy renovation.

In Table 23 the authors have reported examples of analysis carried out to assess a comprehensive indoor environmental quality. In Table 24 the methodology to quantify available overall IEQ indexes is shown.

Table's indications:

(table header)

- *Q stands for "analysis based on submitted questionnaires"*
- *M stands for "analysis based on monitored data"*
- *I stands for "if a quantitative IEQ indicator(s) is(are) studied"*
- *TC stands for "Thermal Comfort"*
- *AC stands for "Acoustic Comfort"*
- *VC stands for "Visual Comfort"*
- *IAQ stands for "Indoor Air Quality"*

(table body)

- ■ *stands for "present" (reference* Table 24*)*
- */ stands for "not present"*

Table 23: List of existing IEQ assessment:

Ref	Analysis	Q	M	I	IEQ Category Weighting (correlation with the overall IEQindex)			
					TC	AC	VC	IAQ
[74]	Factorial analysis of variance (ANOVA)	■	■	/	5%	26%	1%	/
[88]	Pearson coefficient with overall satisfaction Multivariate logistic regression	■	■	■	21%	20%	16%	29%
[89]	Multivariate linear regression	■	/	/	50%	39%	29%	32%
[90]	Multivariate logistic regression model	■	/	■	6.09 (-)	4.74 (-)	3.7 (-)	4.88 (-)
[91]	Relative weight vector	■	■	■	32%	22%	17%	12%
[92]	Multivariate linear regression	■	■	■	30%	18%	16%	18%
[93]	Relative weight vector	/	■	■	17% (winter) 19% (summer)	16%	15%	15%
[94]	Multivariate linear regression	■	/	■	33% (11:30 a.m.)	18% (11:30 a.m.)	38% (11:30 a.m.)	10% (11:30 a.m.)
[59]	Multivariate logistic regression Directly asked to students	■	/	■	35%	36%	30%	/
[95]	Multiple linear regression analysis	■	■	■	20% (A1) 10% (A2)	13% (A1) 17% (A2)	7% (A1) 10%(A2)	60% (A1) 63% (A2)
[96]	Weight vector	■	■	■	32%	30%	16%	22%
[97]	Linear and geometric mean regression	/	/	■	0.463 (-)	0.529(-)	0.423(-)	-0.136(-)

Table 24: Quantification IEQ indexes reviewed in Table 23

<table>
<tr><th>Ref</th><th>IEQ index</th><th>IEQ sub-indicators for each comfort category</th></tr>
<tr><td>[88]</td><td>$\mathrm{IEI}_{(\mathrm{AHP})} = \sum S_x W_x$
$= 0.203 S_{\mathrm{Acoustics}} + 0.164 S_{\mathrm{Illumination}}$
$+ 0.208 S_{\mathrm{Thermal\ Comfort}} + 0.29 S_{\mathrm{IAQ}}$
$+ 0.135 S_{\mathrm{EMF}}.$</td><td>Based on the monitored data
(below i.e. acoustic category)

Physical category — Indicators for assessment
Acoustics: TNEL_{30}
TNEL_{30}'
Equalized sound pressure level in morning time (L_{eq}M)
Equalized sound pressure level in daytime (L_{eq}D)
Equalized sound pressure level in night time (L_{eq}N)
Equalized sound pressure level in 24 h (L_{eq}24H)
L_{10}
L_{50}
L_{90}
NR curve
NC curve</td></tr>
<tr><td>[90]</td><td>$I_{IEQ} = 1 - 1/[1 + exp(6.09 I_T + 4.74 I_S + 4.88 I_{IAQ} + 3.70 I_L - 15.02)]$</td><td>A. Thermal environment ($\phi_1 = I_T$)
$\phi_1 = 1 - \frac{\mathrm{PPD}}{100}.$
B. Aural environment ($\phi_3 = I_S$)
$\phi_3 = 1 - \frac{1}{1+\exp(9.540 - 0.134\zeta_3)}; \quad 45 \leqslant \zeta_3 \leqslant 72,$
C. Illumination level ($\phi_4 = I_L$)
$\phi_4 = 1 - \frac{1}{1+\exp(-1.017 + 0.00558\zeta_4)};$
$200 \leqslant \zeta_4 \leqslant 1600.$
D. Indoor air quality ($\phi_2 = I_{IAQ}$)
$\phi_2 = 1 - \frac{1}{2}\left(\frac{1}{1+\exp(3.118 - 0.00215\zeta_2)} - \frac{1}{1+\exp(3.230 - 0.00117\zeta_2)}\right); \quad 500 \leqslant \zeta_2 \leqslant 1800,$</td></tr>
<tr><td>[91]</td><td>$I_{IEQ} = 0.075 + 0.316 S_T + 0.224 S_A + 0.118 S_{AIQ} + 0.171 S_L$</td><td>A. $S_T = -0.0063 t_o^2 + 0.287 t_o - 2.934,\ R^2 = 0.7356$
B. $S_A = -0.0230 L_A + 1.382,\ R^2 = 0.7201$
C. $S_L = -5 \times 10^{-7} E^2 + 0.0011E - 0.106,\ R^2 = 0.6032$
D. $S_{\mathrm{IAQ}} = -0.0002 C_{\mathrm{CO_2}} + 0.244,\ R^2 = 0.6738$</td></tr>
<tr><td>[92]</td><td>$I_{IEQ} = 0.30 TC_{index} + 0.18 ACc_{index} + 0.36 IAQ_{index} + 0.16 L_{index}$</td><td>A. $\mathrm{TC_{index}} = 100 - \mathrm{PPD_{TC}}$
$\mathrm{PPD_{TC}} = 100 - 95 \times \exp\left(-0.03353 \times \mathrm{PMV}^4 - 0.2179 \times \mathrm{PMV}^2\right)$
B. $\mathrm{ACc_{index}} = 100 - \mathrm{PD_{ACc}}$
$\mathrm{PD_{ACc}} = 2(\mathrm{Actual_{Sound\ Pressure\ level}} - \mathrm{Design_{Sound\ Pressure\ level}})$
C. $\mathrm{IAQ_{index}} = 100 - \mathrm{PD_{IAQ}}$
$\mathrm{PD_{IAQ}} = 395 \times \exp\left(-15.15 C_{\mathrm{CO_2}}^{-0.25}\right)$
D. $L_{\mathrm{index}} = -176.16 X^2 + 738.4X - 690.29$ where: $X = \{\ln(\ln(\mathrm{lux}))\}$.</td></tr>
<tr><td>[93]</td><td>- the generic matrix element $f_{i,j}$ represents the fraction of time during which the values of the i_{th} parameter result within the range limits defining the j_{th} category of quality.
$[F] = \begin{bmatrix} f_{1,\mathrm{I}} & f_{1,\mathrm{II}} & f_{1,\mathrm{III}} & f_{1,\mathrm{IV}} \\ f_{2,\mathrm{I}} & f_{2,\mathrm{II}} & f_{2,\mathrm{III}} & f_{2,\mathrm{IV}} \\ f_{3,\mathrm{I}} & f_{3,\mathrm{II}} & f_{3,\mathrm{III}} & f_{3,\mathrm{IV}} \\ f_{4,\mathrm{I}} & f_{4,\mathrm{II}} & f_{4,\mathrm{III}} & f_{4,\mathrm{IV}} \\ \cdots & \cdots & \cdots & \cdots \\ f_{n,\mathrm{I}} & f_{n,\mathrm{II}} & f_{n,\mathrm{III}} & f_{n,\mathrm{IV}} \end{bmatrix}$
- Environmental Quality Index: $\mathrm{EQI} = 100\bar{f}_{\mathrm{I}} + 70\bar{f}_{\mathrm{II}} + 35\bar{f}_{\mathrm{III}}$
- Building Quality Index : $BQI = \{EQI\}^T\{k\}$</td><td>Based on the monitored data

Comfort factors and corresponding representative parameters.
<table><tr><th>Comfort factor</th><th>Representative parameter</th></tr><tr><td>Winter thermal conditions</td><td>Operative temperature (°C)</td></tr><tr><td>Summer thermal conditions</td><td>Operative temperature (°C)</td></tr><tr><td>Draft</td><td>Air velocity (m/s)</td></tr><tr><td>Air Quality</td><td>CO_2 concentration above outdoor concentration (ppm)</td></tr><tr><td>Visual</td><td>Illuminance (lx)</td></tr><tr><td>Acoustic</td><td>A-weighted equivalent sound pressure level (dB)</td></tr></table></td></tr>
<tr><td>[94]</td><td>$I_{\mathrm{CCI}} = \begin{cases} 0.33 I_{\mathrm{T}} + 0.26 I_{\mathrm{S}} + 0.36 I_{\mathrm{IAQ}} + 0.25 I_{\mathrm{L}} (9:45\ \mathrm{am}) \\ 0.30 I_{\mathrm{T}} + 0.28 I_{\mathrm{S}} + 0.12 I_{\mathrm{IAO}} + 0.30 I_{\mathrm{L}}\ (11:30\ \mathrm{am}) \end{cases}$</td><td>Based on the questionnaires data</td></tr>
<tr><td>[59]</td><td>$I_{IEQ} = 0.35 I_{PMV} + 0.35 I_S + 0.3 I_{VC}$</td><td>A. $I_{PMV} = \left|(\lvert PMV\rvert + 1) - \left(\lvert PMV\rvert \cdot \frac{4}{3}\right)\right|$
PMV 13 – Predicted Mean Vote in a 13- value scale
PMV 7 – Predicted Mean Vote in a 7-value scale
B. $I_S = \frac{0.3\ IBN + 0.3\ IEN + 0.2\ ISQ + 0.1\ IVP + 0.1\ ILQ}{10}$</td></tr>
</table>

		IBN - Background Noise Index IEN – Effect of Noise Index ISQ – Sound Quality Index IVP – Voice Perception index ILQ – Listening Quality Index C. $I_{VC} = \frac{0.2\ ALQ + 0.1\ ALS + 0.2\,(10 - ALG) + 0.3\,(10 - NLR) + 0.2\ NLQ}{10}$ ALQ - Artificial Lighting Quality Index ALS - Artificial Lighting Sources Index ALG - Artificial Lighting annoying Glares Index NLQ - Natural Lighting Quality Index NLR - Natural Lighting Reflections Index
[95]	$IEQ_{Q,A1} = 0.456 - 0.125 \cdot TC - 0.043 \cdot VC + 0.085 \cdot AQ + 0.374 \cdot IAQ$ $IEQ_{Q,A2} = 0.345 + 0.059 \cdot TC - 0.060 \cdot VC + 0.102 \cdot AQ + 0.379 \cdot IAQ$ The analysis is based on two adjacent room A1 and A2.	Based on the questionnaires data. Where each IEFs (TC, VC, AQ, IAQ) are the participants' response.
[96]	$I_{IEQ} = 0.316 I_T + 0.301 I_S + (0.102 I_{AF} + 0.122 I_{AP}) + 0.157 I_L$	A. Thermal comfort $I_T = \begin{cases} -0.757\mathrm{PMV}^2 - 0.240\mathrm{PMV} + 5.573 \ \ for \ \text{summer} \\ -0.457\mathrm{PMV}^2 - 0.475\mathrm{PMV} + 4.979 \ \ for \ \text{winter} \\ -0.435\mathrm{PMV}^2 - 0.350\mathrm{PMV} + 5.638 \ \ for \ \text{transition seasons} \end{cases}$ B. Sound comfort $I_S = -0.117{*}S + 10.053$ C. Indoor air quality $I_{AF} = 7.96{*}(C_{CO_2} - 396.93)^{-0.11}$ $I_{AP} = 7.88{*}(C_{PM_{2.5}} + 11.28)^{-0.18}$ D. Light comfort $I_L = -2.05 \times 10^{-6}{*}L^2 + 3.94 \times 10^{-3}{*}L + 3.410$
[97]	$I_{IEQ} = -3.656 + 1.306\sqrt[3]{I_T \cdot I_S \cdot I_L}$	A. Thermal satisfaction $S_T = 7.88 + 0.254P + 1.51P^2$ B. Acoustic satisfaction $S_A = 16.8 - 0.203SP - 2.92 \times 10^{-3} I + 4.66 \times 10^{-5}(SP \times I)$ C. Visual satisfaction $S_V = 7.80 - \frac{4.87}{1 + \exp\left(\frac{I-210}{86.2}\right)}$ D. IAQ satisfaction $S_{IAQ} = 8.97 - 0.326 \times \exp(1.10P) - 0.011SP$

7 Conclusions: KPIs for ABC 21

Indoor environmental quality (IEQ) includes thermal comfort, acoustic comfort, visual comfort and indoor air quality: these domains are interconnected and can strongly affect the energy performance of the building. For instance, in naturally ventilated buildings, users are often faced with making compromises between acoustic quality (noise from outside), thermal comfort (introducing cooler outdoor air), indoor air quality (fresh outdoor air) and energy savings (avoiding mechanical cooling systems). An adequate measurement and verification protocol with a clear focus on IEQ should be considered from the design phase up to the commissioning and use of the building, to verify that a building performs according to design expectations and to facilitate operations and maintenance, ensuring high level of comfort, IAQ and user satisfaction. The aim of this report is to provide a clear framework about the available methodologies, standards, tools and indicators to assess all the aspects of IEQ targeted for bioclimatic architecture. The main concepts and their operative definitions have been clearly presented for effective design work and communication. A literature review has been carried out and Figure 11 synthesizes the Key Performance Indicators proposed for bioclimatic architecture in Europe and Africa. They will be used to monitor and verify the conditions of the indoor environment in the selected buildings in Task 3.4, offer a comparison between the case studies and provide guidelines for bioclimatic design in warm climates. For each specific case study, the most appropriate indicators will be selected from these lists in relation to the available measured or simulated data.

Thermal comfort indicators (Table 16)	1. Percentage of time outside an operative temperature range (Adaptive) 2. Percentage of time outside an operative temperature range (Fanger) 3. Degree-hours (Adaptive) 4. Degree-hours (Fanger) 5. Percentage of time inside the Givoni comfort zone (1 m/s) 6. Percentage of time inside the Givoni comfort zone (0 m/s) 7. Number of hours within a certain temperature range	**Acoustic comfort indicators** (Table 18)	1. Airborne sound insulation 2. Equivalent continuous sound Level 3. HVAC noise level 4. Reverberation time 5. Masking/barriers
Visual comfort indicator (Table 17)	1. Light level (illuminance) 2. Useful Daylight Illuminance (UDI) 3. Glare control 4. Quality view 5. Zoning control	**Indoor Air Quality indicators** (Table 19)	1. Organic compound 2. VOCs 3. Inorganic gases 4. Particulates (filtration) 5. Minimum outdoor air provision 6. Moisture (humidity, leaks) 7. Hazard material

Figure 11: Indoor Environment Quality indicators for ABC 21

In addition, it is worth pointing out that a review of global indexes available in literature has been performed. This type of index combines all categories (thermal, acoustic, visual and indoor air quality) and weighs their values according to different methodologies which involve monitored data and the results of subjective surveys.

ANNEX A: Example of bioclimatic tool

Climate Consultant 6.0 software (UCLA, 2008) is a free tool for evaluating various aspects of initial design related to climate and user comfort. Several charts are proposed made with the data from the imported weather file (.epw) as following:

- daily temperature range bar chart;
- chart describing global and diffuse horizontal and direct normal radiation monthly average;
- chart radiation range for hourly average and a plot radiation range for daily average;
- Wind Velocity Range chart and Wind wheel plot for every hour of the year;
- Humidity and temperature chart for mean days;
- Bioclimatic Time-Table of temperature and radiation observed every hour
- Wind Roses showing the percentage of time the wind blows from each of sixteen directions, or is calm. Do this at least for a spring, summer, fall, and winter month and for useful day periods. Point out the mean velocity and direction of wind for each season.
- Psychrometric Chart (Figure 12) is one of the most powerful design tools in Climate Consultant. It shows on the horizontal axis the dry bulb temperature in degree Celsius while on the vertical scale the absolute humidity (or humidity ratio) in kilogram of water per kilogram of dry air. The curved line on the far left is the saturation line (100% Relative Humidity line) which represents the fact that at lower temperatures air can hold less moisture than at higher temperatures. Every hour in the EPW climate data file is shown as a dot on this chart. Some dots may represent more than one hour, for example when a given temperature and humidity occurs more than once in any month. A given hour's dot might meet the criteria for more than one strategy zone, in which case it is counted in the Percentage of Hours for both zones, which is why the percentages add up to more than 100%. In addition, the software proposes a list of design strategies based on the analysis carried out through the psychrometric chart. The goal is to suggest (passive) design solutions in order to reduce the heating and cooling needs increasing the comfort zone (in terms of hours). The Design Strategies are based on Givoni-Milne, Milne, Givoni, or Stein-Reynolds charts.

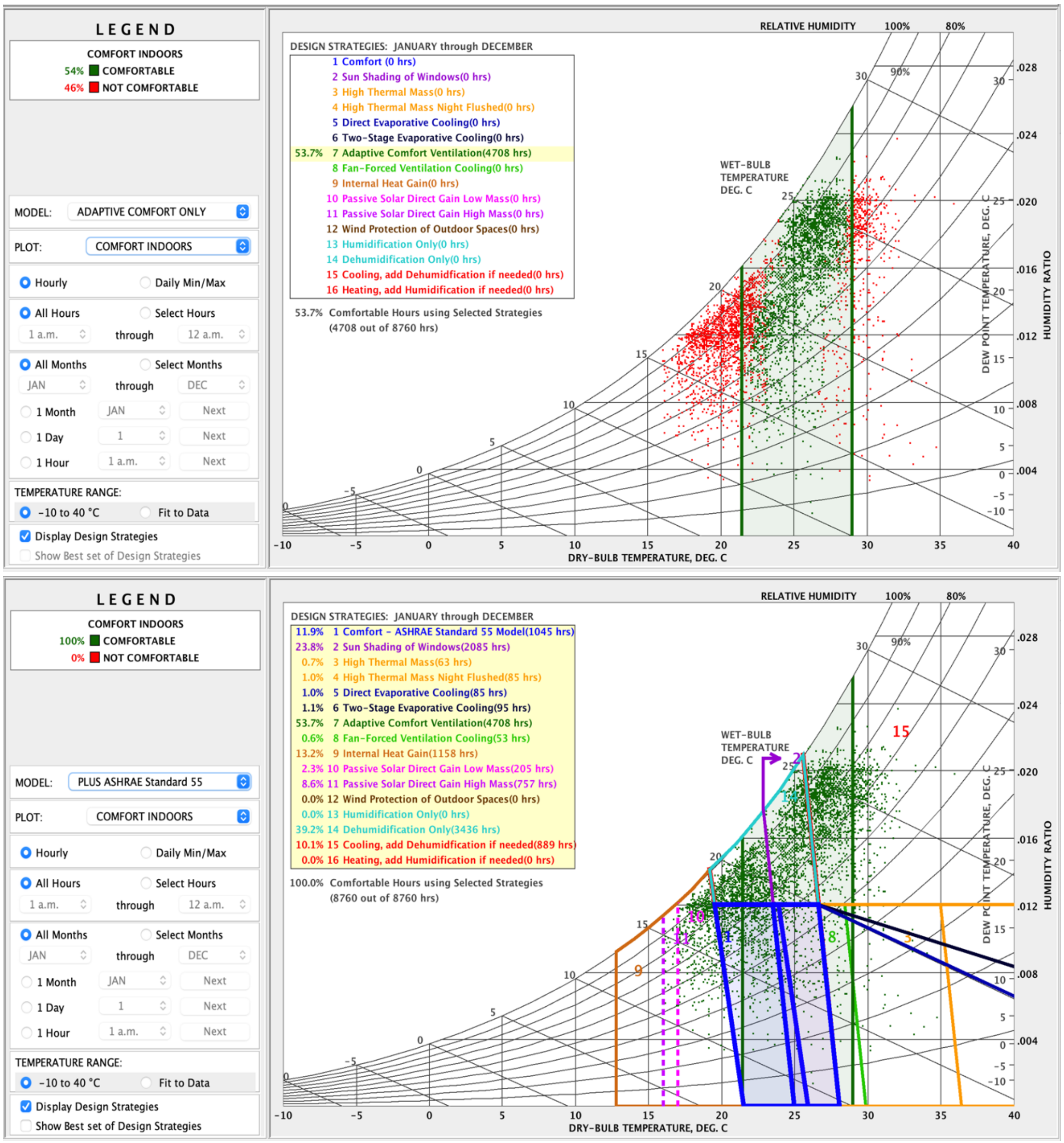

Figure 12: Examples of psychrometric chart

The **Comfort Zone** is based on the comfort model, chosen before performing the analysis, in which is defined by means of parameters such as Dry Bulb Temperature or Humidity, and Clo (seasonal clothing). The Figure 12 shows two examples of comfort models and its relative comfort zone plotted on psychrometric chart: Adaptive Comfort Model in ASHRAE Standard 55-2010 and ASHRAE Standard 55 and Current Handbook of Fundamentals Comfort Model.

In the tool it is possible to choose among different comfort models; in Table 25 are described the models according to the ASHRAE standards.

Table 25: Main comfort models available in Climate Consultant 6.0 software

Comfort model	description
ASHRAE Standard 55 and Current Handbook of	It is also known as the PMV (Predicted Mean Vote) model. It is an experimentally derived algorithm that considers dry bulb temperature, humidity, air velocity and metabolic activity. It has two comfort zones for summer and winter clothing and the slightly sloped temperature limits

Fundamentals Comfort Model	account for the fact that in dryer air people are more comfortable at slightly higher temperatures. With this model Climate Consultant assumes that mean radiant temperature (MRT) is roughly equal to dry bulb temperature.
ASHRAE Handbook of Fundamentals Comfort Model, through 2005	It shows how the comfort zone changes as a function of clothing (CLO), with the warmer zone correlating with people wearing lighter summer clothes. The temperatures are defined by slightly sloped lines that account for the effect of humidity on comfort (as it gets dryer people will be comfortable at slightly higher temperatures).
Adaptive Comfort Model in ASHRAE Standard 55-2010	It applies in naturally ventilated spaces where people can open and close windows. Indoor conditions are acceptable when average outdoor air temperatures are between 50° F and 92° F, and when indoor temperatures can be held within a specified 10 degree indoor operative temperature range. Thus thermal comfort depends in part on outdoor conditions and occupants will have a wider comfort range than in buildings with centralized HVAC systems. This model does not apply when a building's heating system is in operation, and it does not apply if there is an air conditioning system. It assumes that people will adapt their clothing to the climate (1.0 to 0.5 Clo), and that they are engaged in sedentary activities such as reading (1.0 to 1.1 Met). The Standard does not discuss how adaptive comfort is affected by the other building Design Strategies. Thus on the Criteria screen Adaptive Comfort is defined only in terms of Zone 7, Adaptive Comfort using Natural Ventilation.

Thermal comfort is defined as: “that condition of mind in humans which expresses satisfaction with the thermal environment (ANSI/ASHRAE Standard 55).” To have “thermal comfort” indicates that a person wearing a normal amount of clothing feels neither too cold nor too warm. This can be achieved when the air temperature, humidity and air movement are within a specified range often referred to as the “comfort zone.”

The most commonly used indicator of thermal comfort is air temperature – it is easy to use and most people can relate to it. But although it is an important indicator to take into account, air temperature alone is neither a valid nor an accurate indicator of thermal comfort or thermal stress. Air temperature should always be considered in relation to other environmental and personal factors. The six factors affecting thermal comfort are both environmental and personal.

Environmental factors

1. Air Temperature	This is the temperature of the air surrounding the body. In Climate Consultant this is assumed to be the outdoor Dry Bulb Temperature. The comfort low and comfort high temperatures are the primary determinants of the comfort zone, although different sources have slightly different definitions. For example, the California Residential Energy Code (the default model in Climate Consultant) specifies 70ºF as comfort low and 75ºF for comfort high (above which and below which heating or air conditioning is required), while the ASHRAE Handbook of Fundamentals Comfort Model shows how the comfort zone changes as a function of clothing, i.e. the zone is defined by warmer temperatures in the summer when people are wearing lighter clothes.

2. Mean Radiant Temperature	What we experience and feel relating to thermal comfort in the building is related to the influence of surface temperature and the dry air temperature in the space we are in. The mean radiant temperature is expressed as the surface temperature and is controlled by enclosure performances. The mean radiant temperature is determined by the area weighted average of each segment of wall that our body "sees" times its radiant temperature. Mean radiant temperature is not considered explicitly in Climate Consultant. It is assumed that the temperature of surrounding surfaces averages roughly the same as the Dry Bulb Temperature. Arguably this is justified because in residential settings surface temperatures are rarely more than a few degrees different from the air Dry Bulb Temperature and thus have a very small impact on the Comfort Range.
3. Relative Humidity.	Relative humidity is the ratio of the amount of moisture in the air compared to the maximum amount that the air can hold at that air temperature. Relative humidity between 30% and 80% does not have a major impact on thermal comfort. However, in some climates when outdoor temperature is high, relative humidity can be uncomfortably high. Therefore, levels of comfortable relative humidity change depending on temperature. The California Residential Energy Code gives no guidance on maximum comfortable levels of humidity, but Climate Consultant assumes 80% relative humidity at the Comfort Low Temperature of 70º F and 60% relative humidity at the Comfort High Temperature. This corresponds roughly to the ASHRAE Winter Comfort zone. While Climate Consultant sets minimum humidity levels at 20 to 30% for the California Residential Energy Code comfort model and the ASHRAE Handbook of Fundamentals model, the ASHRAE Standard 55 using Predicted Mean Vote assumes no minimum level of humidity nor does the ASHRAE 55 Adaptive Model. ASHRAE documentation does comment that "non-thermal comfort factors, such as skin drying, irritation of mucus membranes, dryness of the eyes, and static electricity generation, may place limits on the acceptability of very low humidity environments."
4. Air Velocity	The primary environmental factor for expanding the comfort zone is Air Velocity. Air motion is one of the few ways to produce a cooling effect on the human body. It does this by increasing the rate of sweat evaporation and giving the psychological sense of cooling (note that ventilation does not actually reduce the dry bulb temperature). Cooling by air motion is especially important in hot humid climates, where the most effective vernacular building type is a completely open pavilion to capture the lightest breezes, covered by a well insulated roof to block solar radiation, and that is often steeply pitched to shed rain. The most cost-effective cooling strategy is simply to open the windows when outdoor conditions are more comfortable then indoors. To achieve cross ventilation open windows on both the upwind and the down-wind sides of the building; this can achieve very high ventilation rates (10 to 20 air changes per hour). Natural ventilation is even better if the outlet is higher than the inlet, ideally at the top of a multi-story atrium. But natural ventilation is possible if the windows are on adjacent side walls or even if necessary when both inlet and outlet are on the same wall. By opening windows at night when it is cool and closing them in the morning when outdoors becomes warmer than indoors, the average indoor temperature can be kept cooler than the average outdoor temperature. Ceiling fans can make occupants feel up to 6.4 degrees F cooler even though the dry bulb temperature is unchanged. Ventilating with a Whole-House Fan is also an excellent strategy, especially if there is interior mass to store up night-time 'coolth'. Ceiling fans and whole house fans are very energy efficient because they produce roughly twenty times more cooling than the energy they use. fans are very energy efficient because they produce roughly twenty times more cooling than the energy they use. Ceiling fans have large diameter slow moving blades and are usually mounted a foot or two below the ceiling. They can blow downward or upward. They can produce either Gentle or Strong air motion in an imaginary cylinder about 1.5 blade diameters directly underneath. Because ceiling fans do not produce cool air but rather only make the occupants feel cooler, there is no benefit to running them when no people are in the area. Thus the ideal fan would have an occupancy sensor and only turn on when an occupant was nearby. Typically, however, the fans are turned on manually so they often run unnecessarily. One of the most cost-effective cooling strategies in many climates is a Whole House Fan, installed so that it exhausts the house (often by blowing up into the attic). Small fans can achieve up to five Air Changes per hour while larger fans can achieve 20 or more. A new 'smart' thermostat control can sense both indoor and outdoor temperatures and provide ventilation only

	as needed, such as when indoor air is too warm and outdoor air is cooler. This is also like a 'smart' human who turns on the fan under the same conditions. In new California homes (after 2012) a continuously running fresh air fan is required to provide the Required Fresh Air per ASHRAE Standard 62.2 This is usually calculated at 7.5 CFM per person plus .01 CFM per square foot of floor area.

Personal factors

5. Clothing Insulation (CLO)	The amount of clothing people wear is one of the factors affecting human thermal comfort. A person may add layers of clothing if he/she feels cold, or remove layers of clothing if he/she feels warm. Two of the comfort model options in Climate Consultant modify the comfort zone as a function of clothing (CLO factor) and level of physical activity (see MET below). By assuming that people will wear lighter summer clothes when it is warm, the minimum and maximum comfort temperatures for summer are higher than those defining the comfort zone in winter. Indoor winter clothing of long pants and a sweater is about 1.0 CLO while indoor summer clothing of shorts and a light top is .5 CLO. These are the defaults used for comfort models in Climate Consultant.
6. Work Rate / Metabolic Heat (MET)	The amount of physical activity people engage in is another factor affecting human thermal comfort. The work or metabolic rate is essential for a thermal comfort assessment. It describes the heat that we produce inside our bodies as we carry out physical activity. The MET rating is a measure of this amount. Climate Consultant defaults to a MET rating of 1.1 which represents a person sitting and reading. Sleeping is 0.5 MET and normal casual activities around the house throughout the year averages about 1.0 MET for both men and women.

ANNEX B: Measurement and Verification protocol for Net Zero Energy Buildings – Levels of monitoring [86]

LEVEL 1 - BASIC MONITORING					
Indicators	Sensors	Range	Time resolution	Time span	Questionnaires
- Indoor air temperature - Outdoor air temperature - global irradiation	Temperature sensors wireless (ideally solar powered) with data radio transmission or internal datalogger. If monitoring is planned for long duration, wired is a feasible option. Advantages: - No wiring necessary - Installation of data loggers after completion of user´s equipment and devices (minimization of interference factors or unfavourable position) - Inexpensive monitoring equipment, possible to equip all apartments/ offices - New sensor technology reduces failures and false measurement results Disadvantages: - no further data on ieq.	Reduced positions. Indoor positions only at one height, either: - 0,6 m in zones where occupants are mainly seated - 1,1 m in zones where occupants are mainly standing Sensors for temperature in occupied zone or (if not known) in the middle of the room.	- Temperature: hourly average - Global irradiation: daily amount	Generally season or 1 year, after the 1st year.	General satisfaction survey (an example is given in the appendix section, table a1.3). Conducted in the same year as measurement, compilation to a significant number of occupants. The survey must be conducted at least one year after the building is fully occupied.

LEVEL 2 – ADVANCED BASIC MONITORING					
Indicators	Sensors	Range	Time resolution	Time span	Questionnaires
- Indoor air temperature - Indoor humidity - Operative temperature - Indoor air velocity - CO_2 concentration - Outdoor air temperature - Outdoor humidity - Global irradiation	Temperature and humidity sensors wireless (e.g., solar powered), with data radio transmission or internal datalogger. If monitoring is planned for long duration, wired is a feasible option. CO_2 sensor logged to independent logger or linked to cable network. It requires external power supply. Black globe temperature sensor for operative temperature wired Advantages: - No wiring necessary - Installation of loggers after completion of user´s equipment and devices (minimization of interference factors or unfavourable position) - Enables temperature and climate alignment of measured data to evaluate energy use Disadvantages: - The additional operative temperature sensors cause increased costs and effort to evaluate; - Unlikely to equip all rooms/ apartments/ offices - No further data on IEQ	Reduced positions for temperature and humidity. Zones with expected critical values for air velocity. Indoor positions only at one height, either - 0,6 m in zones where occupants are mainly seated - 1,1 m in zones where occupants are mainly standing Sensors for temperature in occupied zone or (if not known) in the middle of the room	- Temperature and humidity: Hourly average - Global irradiation: Daily amount. - Resolution depends on indicator and purpose	Generally 1 year, after the 1st year. Time-span depends on indicator and purpose	General satisfaction survey. If it is possible, conduct it two times a year in different seasons.

LEVEL 3 – DETAILED MONITORING					
Indicators	Sensors	Range	Time resolution	Time span	Questionnaires
- Indoor air temperature - Indoor humidity - Operative temperature - Outdoor air temperature - Global irradiation -	Temperature & humidity sensors wireless (ideally solar powered) with data radio transmission or internal datalogger. If monitoring is planned for long duration, wired is a feasible option Black globe temperature sensor for operative temperature wired. Advantages: - Feedback for optimization of building services possible - Feedback on IEQ possible - Enables additional evaluation of a broader range of IEQ indicators Disadvantages: - Installation of CO_2-sensor needs witing and has to be done in planning stage - Increased costs and effort to evaluate - Less units equipped	Positions of temperature, humidity and CO_2 sensors according to standards. Points with expected critical values for air velocity. Indoor positions only at three heights: - 0,1/ 0,6/ 1,1 m in zones where occupants are mainly seated. - 0,1/1,1/ 1,7 m in zones where occupants are mainly standing. Sensors for temperature and humidity in occupied zone or (if not known) in the middle of the room	- Temperature, humidity and CO_2: 30 min average - Air velocity: 10 sec - Global irradiation: Hourly average - Resolution depends on indicator and purpose	Generally 2 years, air velocity as spot measurements (duration about 3 min. – see ASHRAE standard) Time-span depends on indicator and purpose	General satisfaction survey conducted each year for 5 years as measurement, compilation to a significant number of / all occupants. Spot surveys to a random sample of occupants (synchronized in time and unit with detailed monitoring positions) – at least at the end of second year.

LEVEL 4 – ADVANCED DETAILED MONITORING					
Indicators	Sensors	Range	Time resolution	Time span	Questionnaires
- Indoor air temperature - Indoor humidity - Operative temperature - Indoor air velocity - CO_2 concentration - Volatile organic compounds (VOC) - Daylight factor / useful daylight index (UDI) - Mean radiant temperature - Outdoor air temperature - Outdoor humidity - Global and diffuse solar radiation - Wind direction and speed at 3m and 10m height	Temperature and humidity sensors wireless (e.g., solar powered), with data radio transmission or internal datalogger. If monitoring is planned for long duration, wired is a feasible option CO_2 sensor linked to cable network. It requires external power supply. Possible: Thermographic pictures for surface temperatures. Daylight sensors. Portable unit with air temperature, globe temperature, humidity, air velocity on site for spot measurements. Weather station on site Advantages: - Feedback for optimization of building services possible - Detailed evaluation of indoor environmental quality possible - Enables verification of energy balance in compliance with assessment of IEQ according to current standards - Quantitative and qualitative IEQ and socio-economic assessment Disadvantages: - Installation monitoring equipment requires detailed monitoring concept + good alignment during planning stage + completion of building services - Increased costs and effort to evaluate - Less rooms/apartment equipped, increased cost	Positions of temperature, humidity and CO_2 sensors according to standards. Points with expected critical values for air velocity. Indoor positions only at three heights: - 0,1/ 0,6/ 1,1 m in zones where occupants are mainly seated. - 0,1/1,1/ 1,7 m in zones where occupants are mainly standing. Sensors for temperature and humidity in occupied zone or (if not known) in the middle of the room	- Temperature, humidity and CO_2: 30 min average5-10 min during critical periods - VOC: integrated weekly value - Air velocity (accuracy 0.1m/s): 10 sec - Resolution depends on indicator and purpose	Generally 2 years, air velocity and daylight factor as spot measurements better to be done once and during an isotropic sky. Time-span depends on indicator and purpose	General satisfaction survey conducted each year for 5 years as measurement, compilation to a significant number of/all occupants. Spot surveys of a random sample of occupants (synchronized in time and unit with detailed monitoring positions) – several times during the two years.

8 References

[1] Directive (EU) 2018/ of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency n.d.:17.

[2] Heinzerling D, Schiavon S, Webster T, Arens E. Indoor environmental quality assessment models: A literature review and a proposed weighting and classification scheme. Build Environ 2013;70:210–22. https://doi.org/10.1016/j.buildenv.2013.08.027.

[3] Frontczak M, Wargocki P. Literature survey on how different factors influence human comfort in indoor environments. Build Environ 2011;46:922–37. https://doi.org/10.1016/j.buildenv.2010.10.021.

[4] Manzano-Agugliaro F, Montoya FG, Sabio-Ortega A, García-Cruz A. Review of bioclimatic architecture strategies for achieving thermal comfort. Renew Sustain Energy Rev 2015;49:736–55. https://doi.org/10.1016/j.rser.2015.04.095.

[5] ANSI/ASHRAE Standard 55-2020. Thermal Environmental Conditions for Human Occupancy. 2020.

[6] Rupp RF, Vásquez NG, Lamberts R. A review of human thermal comfort in the built environment. Energy Build 2015;105:178–205. https://doi.org/10.1016/j.enbuild.2015.07.047.

[7] Pagliano L, Zangheri P. Comfort models and cooling of buildings in the Mediterranean zone. Adv Build Energy Res 2010;4:167–200. https://doi.org/10.3763/aber.2009.0406.

[8] de Dear R, Xiong J, Kim J, Cao B. A review of adaptive thermal comfort research since 1998. Energy Build 2020;214:109893. https://doi.org/10.1016/j.enbuild.2020.109893.

[9] European Committee for Standardization. EN 16798-1 - Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics - Module M1-6. 2019.

[10] International Standard Organization. ISO 7730:2005. Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. 2005.

[11] Nicol F. Adaptive thermal comfort standards in the hot–humid tropics. Energy Build 2004;36:628–37. https://doi.org/10.1016/j.enbuild.2004.01.016.

[12] Feriadi H, Wong NH. Thermal comfort for naturally ventilated houses in Indonesia. Energy Build 2004;36:614–26. https://doi.org/10.1016/j.enbuild.2004.01.011.

[13] Cheung T, Schiavon S, Parkinson T, Li P, Brager G. Analysis of the accuracy on PMV – PPD model using the ASHRAE Global Thermal Comfort Database II. Build Environ 2019;153:205–17. https://doi.org/10.1016/j.buildenv.2019.01.055.

[14] Ole Fanger P, Toftum J. Extension of the PMV model to non-air-conditioned buildings in warm climates. Energy Build 2002;34:533–6. https://doi.org/10.1016/S0378-7788(02)00003-8.

[15] Givoni B. Comfort, climate analysis and building design guidelines. Energy Build 1992;18:11–23. https://doi.org/10.1016/0378-7788(92)90047-K.

[16] Garde F, Lenoir A, David M, Ottenwelter E. Towards Net Zero Energy Buildings in Hot Climates : Part 1, New Tools and Methods. ASHRAE Trans 2011;117, Part 1.

[17] Gagge AP, Stolwijk JAJ, Nishi Y. An effective temperature scale based on a simple model of human physiological regulatory response 1971.

[18] Gonzalez RR, Nishi Y, Gagge AP. Experimental evaluation of standard effective temperature a new biometeorological index of man's thermal discomfort. Int J Biometeorol 1974;18:1–15. https://doi.org/10.1007/BF01450660.
[19] Gagge AP, Fobelets AP, Berglund LG. A standard predictive index of human response to the thermal environment. ASHRAE Trans 1986;92:709–31.
[20] Lenoir A, Thellier F, Garde F. Towards Net Zero Energy Buildings in Hot Climate, Part 2: Experimental Feedback. ASHRAE Trans 2011;117:8.
[21] Lenoir A, Baird G, Garde F. Post-occupancy evaluation and experimental feedback of a net zero-energy building in a tropical climate. Archit Sci Rev 2012;55:156–68. https://doi.org/10.1080/00038628.2012.702449.
[22] Attia S, Lacombe T, Rakotondramiarana HT, Garde F, Roshan G. Analysis tool for bioclimatic design strategies in hot humid climates. Sustain Cities Soc 2019;45:8–24. https://doi.org/10.1016/j.scs.2018.11.025.
[23] Fanger PO. Thermal comfort. Analysis and applications in environmental engineering. Copenhagen: Danish Technical Press.; 1970.
[24] Zhang S, Lin Z. Standard effective temperature based adaptive-rational thermal comfort model. Appl Energy 2020;264:114723. https://doi.org/10.1016/j.apenergy.2020.114723.
[25] European Committee for Standardization. EN 15251:2007 - Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. 2007.
[26] Carlucci S, Bai L, de Dear R, Yang L. Review of adaptive thermal comfort models in built environmental regulatory documents. Build Environ 2018;137:73–89. https://doi.org/10.1016/j.buildenv.2018.03.053.
[27] BS EN ISO 10551-2019--Ergonomics of the physical environment - Subjective judgement scales for assessing physical environments n.d.
[28] Erba S. D4.7 - Guideline for interviewing end-user. AZEB (Affordable Zero Energy Buildings). 2019.
[29] European Committee for Standardization, ISO. EN ISO 7726:2001 - Ergonomics of the thermal environment - Instruments for measuring physical quantities. 2001.
[30] Olesen BW. The philosophy behind EN15251 : Indoor environmental criteria for design and calculation of energy performance of buildings 2007;39:740–9. https://doi.org/10.1016/j.enbuild.2007.02.011.
[31] Nicol JF, Hacker J, Spires B, Davies H. Suggestion for new approach to overheating diagnostics. Build Res Inf 2009;37:348–57. https://doi.org/10.1080/09613210902904981.
[32] Földváry Ličina V, Cheung T, Zhang H, de Dear R, Parkinson T, Arens E, et al. Development of the ASHRAE Global Thermal Comfort Database II. Build Environ 2018;142:502–12. https://doi.org/10.1016/j.buildenv.2018.06.022.
[33] Erba S, Pagliano L. AZEB Best Practices Manual for Users. Available at: https://azeb.eu/wp-content/uploads/2020/04/AZEB-Best-Practices-Manual-for-Users.pdf. 2020.
[34] He Y, Chen W, Wang Z, Zhang H. Review of fan-use rates in field studies and their effects on thermal comfort, energy conservation, and human productivity. Energy Build 2019;194:140–62. https://doi.org/10.1016/j.enbuild.2019.04.015.
[35] Raftery P. CBE Fan Tool, cbe.berkeley.edu/fan-tool. Center for the Built Environment, University of California Berkeley 2019.
[36] Raftery P, Fizer J, Chen W, He Y, Zhang H, Arens E, et al. Ceiling fans: Predicting indoor air speeds based on full scale laboratory measurements. Build Environ 2019;155:210–23. https://doi.org/10.1016/j.buildenv.2019.03.040.
[37] Puertolas RF, Losada Gonzalez JC, Castro SS, Benito PA, Arrebola CV. A bioclimatic building in Madrid: Analysis of the thermal response and long-term comfort indices review. Dev Built Environ 2020;3:100015. https://doi.org/10.1016/j.dibe.2020.100015.

[38] Santy, Matsumoto H, Tsuzuki K, Susanti L. Bioclimatic Analysis in Pre-Design Stage of Passive House in Indonesia. Buildings 2017;7:24. https://doi.org/10.3390/buildings7010024.
[39] Marsh A. Web app - Psychrometric Chart. Available at: https://drajmarsh.bitbucket.io/psychro-chart2d.html n.d.
[40] Attia S, Lacombe T. Climate tool V1.0.0.xSlx. Available at: https://orbi.uliege.be/handle/2268/227384 2018.
[41] Givoni B. Man, climate and architecture. Applied Science Publishers L.T.D.; 1976.
[42] Baruch Givoni. Climate Considerations in Building and Urban Design. USA: John Wiley & Sons; 1998.
[43] Dama A, Lena ED, Masera G, Pagliano L, Ruta M, Zangheri P. Design and Passive strategies optimizazion towards Zero Energy target: the case study of an experimental office building in Milan. 2014 Build. Simul. Optim. Conf., London: IBPSA UK; 2014, p. 7. https://doi.org/10.13140/RG.2.1.3591.6643.
[44] Tartarini F, Schiavon S, Cheung T, Hoyt T. CBE Thermal Comfort Tool: Online tool for thermal comfort calculations and visualizations. SoftwareX 2020;12:100563. https://doi.org/10.1016/j.softx.2020.100563.
[45] Sfakianaki A, Santamouris M, Hutchins M, Nichol F, Wilson M, Pagliano L, et al. Energy Consumption Variation due to Different Thermal Comfort Categorization Introduced by European Standard EN 15251 for New Building Design and Major Rehabilitations. Int J Vent 2011;10:195–204. https://doi.org/10.1080/14733315.2011.11683948.
[46] Arens E, Humphreys MA, de Dear R, Zhang H. Are ‘class A’ temperature requirements realistic or desirable? Build Environ 2010;45:4–10. https://doi.org/10.1016/j.buildenv.2009.03.014.
[47] d’Ambrosio Alfano FR, Palella BI, Riccio G. The role of measurement accuracy on the thermal environment assessment by means of PMV index. Build Environ 2011;46:1361–9. https://doi.org/10.1016/j.buildenv.2011.01.001.
[48] ISO I. 7730: Ergonomics of the thermal environment Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. Management 2005;3:e615.
[49] Aliagha GU, Cin NY. Perceptions of Malaysian Office Workers on the Adoption of the Japanese Cool Biz Concept of Energy Conservation. J Asian Afr Stud 2013;48:427–46. https://doi.org/10.1177/0021909613493603.
[50] Koch-Nielsen H. Stay cool. A design guide for the built environment in hot climates. James & James (Science Publishers) Ltd; n.d.
[51] Carlucci S, Pagliano L. A review of indices for the long-term evaluation of the general thermal comfort conditions in buildings. Energy Build 2012;53:194–205. https://doi.org/10.1016/j.enbuild.2012.06.015.
[52] Li P, Parkinson T, Schiavon S, Froese TM, de Dear R, Rysanek A, et al. Improved long-term thermal comfort indices for continuous monitoring. Energy Build 2020;224:110270. https://doi.org/10.1016/j.enbuild.2020.110270.
[53] Daemei AB. Bioclimatic design strategies_ A guideline to enhance human thermal comfort in Cfa climate zones. J Build Eng 2019:17.
[54] Bhamare DK, Rathod MK, Banerjee J. Evaluation of cooling potential of passive strategies using bioclimatic approach for different Indian climatic zones. J Build Eng 2020;31:101356. https://doi.org/10.1016/j.jobe.2020.101356.
[55] Beccali M. Vernacular and bioclimatic architecture and indoor thermal comfort implications in hot-humid climates_ An overview. Renew Sustain Energy Rev 2018:11.
[56] Omar AI, David D, Vergnault E, Virgone J, Idriss AI. A new set of indicators to evaluate the bioclimatic performance of air conditioned buildings in a hot and humid climate. J Build Eng 2020;31:101350. https://doi.org/10.1016/j.jobe.2020.101350.

[57] Wu P, Fang Z, Luo H, Zheng Z, Zhu K, Yang Y, et al. Comparative analysis of indoor air quality in green office buildings of varying star levels based on the grey method. Build Environ 2021;195:107690. https://doi.org/10.1016/j.buildenv.2021.107690.
[58] Ghani S, Mahgoub AO, Bakochristou F, ElBialy EA. Assessment of thermal comfort indices in an open air-conditioned stadium in hot and arid environment. J Build Eng 2021;40:102378. https://doi.org/10.1016/j.jobe.2021.102378.
[59] Buratti C, Belloni E, Merli F, Ricciardi P. A new index combining thermal, acoustic, and visual comfort of moderate environments in temperate climates. Build Environ 2018;139:27–37. https://doi.org/10.1016/j.buildenv.2018.04.038.
[60] Yang W. Combined effects of acoustic, thermal, and illumination conditions on the comfort of discrete senses and overall indoor environment. Build Environ 2019:11.
[61] Navai M, Veitch J. Acoustic Satisfaction in Open-Plan Offices: Review and Recommendations 2003. https://doi.org/10.4224/20386513.
[62] Vardaxis N-G, Bard D. Review of acoustic comfort evaluation in dwellings: Part III—airborne sound data associated with subjective responses in laboratory tests. Build Acoust 2018;25:289–305. https://doi.org/10.1177/1351010X18788685.
[63] Rey Gozalo G, Trujillo Carmona J, Barrigón Morillas JM, Vílchez-Gómez R, Gómez Escobar V. Relationship between objective acoustic indices and subjective assessments for the quality of soundscapes. Appl Acoust 2015;97:1–10. https://doi.org/10.1016/j.apacoust.2015.03.020.
[64] Global: BREEAM International New Construction 2016 - Google Scholar n.d. https://scholar.google.com/scholar_lookup?title=BREEAM%20international%20new%20construction%202016%2C%20technical%20manual%20SD233%E2%80%94Issue%3A%201.0&publication_year=2016 (accessed April 18, 2021).
[65] Council UGB. LEED v4 for building design and construction. USGBC Inc 2014.
[66] International WELL Building Institute. WELL Building Standard - v2 Pilot n.d.
[67] Green Mark Certification Scheme. BCA Corp n.d. https://www1.bca.gov.sg/buildsg/sustainability/green-mark-certification-scheme (accessed April 18, 2021).
[68] Cerway. HQE Practical guide environmental performance building under construction. Pract Guide Assess Scheme Environ Perform Non-Resid Build Constr 2014:405.
[69] EN 12665:2011 - Light and lighting - Basic terms and criteria for specifying lighting requirements. ITeh Stand Store n.d. https://standards.iteh.ai/catalog/standards/cen/d7c62c9a-95ac-4ed8-9a40-862805aa5afc/en-12665-2011 (accessed April 15, 2021).
[70] Carlucci S, Causone F, De Rosa F, Pagliano L. A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design. Renew Sustain Energy Rev 2015;47:1016–33. https://doi.org/10.1016/j.rser.2015.03.062.
[71] Hernández FF, Cejudo López JM, Peña Suárez JM, González Muriano MC, Rueda SC. Effects of louvers shading devices on visual comfort and energy demand of an office building. A case of study. Energy Procedia 2017;140:207–16. https://doi.org/10.1016/j.egypro.2017.11.136.
[72] Persiani SGL, Molter PL, Aresta C, Klein T. MAPPING OF ENVIRONMENTAL INTERACTION AND ADAPTIVE MATERIALS FOR THE AUTOREACTIVE POTENTIAL OF BUILDING SKINS n.d.:10.
[73] Slipek M, Sarey Khanie M, Zukowska-Tejsen D, Kolarik J, Nielsen T. Visual Comfort Evaluation in Residential Buildings: a Simulation-Based Study. 2017.
[74] Yang W, Moon HJ. Combined effects of acoustic, thermal, and illumination conditions on the comfort of discrete senses and overall indoor environment. Build Environ 2019;148:623–33. https://doi.org/10.1016/j.buildenv.2018.11.040.

[75] Settimo G, Manigrasso M, Avino P. Indoor Air Quality: A Focus on the European Legislation and State-of-the-Art Research in Italy. Atmosphere 2020;11:370. https://doi.org/10.3390/atmos11040370.
[76] Atkinson J, World Health Organization, editors. Natural ventilation for infection control in health-care settings. Geneva: World Health Organization; 2009.
[77] ASHRAE Standard 62.1-2019, Ventilation for Acceptable Indoor Air QualityASHRAE. n.d.
[78] https://www.iea-ebc-annex68.org/results/final-reports n.d.
[79] CEN/TR 16798-2 - Interpretation of the requirements in EN 16798-1 - Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics (Module M1-6). n.d.
[80] McDowall R. Fundamentals of HVAC systems. Amsterdam: Elsevier; 2006.
[81] Ahmed T, Kumar P, Mottet L. Natural ventilation in warm climates: The challenges of thermal comfort, heatwave resilience and indoor air quality. Renew Sustain Energy Rev 2021;138:110669. https://doi.org/10.1016/j.rser.2020.110669.
[82] Montazami A. BB 101: Guidelines on ventilation, thermal comfort, and indoor air quality in schools 2018.
[83] Karyono K, Abdullah BM, Cotgrave AJ, Bras A. The adaptive thermal comfort review from the 1920s, the present, and the future. Dev Built Environ 2020;4:100032. https://doi.org/10.1016/j.dibe.2020.100032.
[84] Parkinson T, Parkinson A, de Dear R. Continuous IEQ monitoring system: Context and development. Build Environ 2019;149:15–25. https://doi.org/10.1016/j.buildenv.2018.12.010.
[85] Final report on the technical support to the development of a smart readiness indicator for buildings: final report. LU: Publications Office; 2020.
[86] Noris F, Napolitano A, Lollini R. Measurement and Verification protocol for Net Zero Energy Buildings. IEA Solar Heating and Cooling Programme; 2013. https://doi.org/10.18777/ieashc-task40-2013-0003.
[87] Wargocki P, Mandin C, Wei W. ALDREN-TAIL index for rating IEQ. ASHRAE J 2019:66–8.
[88] Chiang C-M, Lai C-M. A study on the comprehensive indicator of indoor environment assessment for occupants' health in Taiwan. Build Environ 2002:6.
[89] Astolfi A, Pellerey F. Subjective and objective assessment of acoustical and overall environmental quality in secondary school classrooms. J Acoust Soc Am 2008;123:163. https://doi.org/10.1121/1.2816563.
[90] Wong LT, Mui KW, Hui PS. A multivariate-logistic model for acceptance of indoor environmental quality (IEQ) in offices. Build Environ 2008:6.
[91] Cao B, Ouyang Q, Zhu Y, Huang L, Hu H, Deng G. Development of a multivariate regression model for overall satisfaction in public buildings based on field studies in Beijing and Shanghai. Build Environ 2012;47:394–9. https://doi.org/10.1016/j.buildenv.2011.06.022.
[92] Ncube M. Developing an indoor environment quality tool for assessment of mechanically ventilated office buildings in the UK - A preliminary study. Build Environ 2012:8.
[93] Marino C, Nucara A, Pietrafesa M. Proposal of comfort classification indexes suitable for both single environments and whole buildings. Build Environ 2012:10.
[94] Fassio F, Fanchiotti A. Linear, Non-Linear and Alternative Algorithms in the Correlation of IEQ Factors with Global Comfort: A Case Study 2014:15.
[95] Danza L, Barozzi B, Bellazzi A, Belussi L, Devitofrancesco A, Ghellere M, et al. A weighting procedure to analyse the Indoor Environmental Quality of a Zero-Energy Building. Build Environ 2020;183:107155. https://doi.org/10.1016/j.buildenv.2020.107155.

[96] Li Z. A comprehensive comfort assessment method for indoor environmental quality in university open-plan offices in severe cold regions. Build Environ 2021:15.
[97] Tang H. Interactions and comprehensive effect of indoor environmental quality factors on occupant satisfaction. Build Environ 2020:13.