Fostering Energy Efficiency and BehAvioural Change through ICT

WP2 –Users' profiling and segmentation

Comfort and indoor air quality requirements

Report on comfort and indoor air quality requirements

D2.2 Comfort and indoor air quality requirements

The FEEdBACk Consortium
2017

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EXECUTIVE SUMMARY

Energy consumption of buildings depends significantly on the criteria used for the indoor environment (temperature, CO_2 levels, humidity, and lighting) and building (including systems) design and operation. Indoor environment also affects health, productivity and comfort of the occupants.

This report, as Deliverable 2.2 within the FEEdBACk project, addresses the key aspects of comfort and air quality, within the larger context of above stated influences to establish indoor environmental input parameters for building system design and energy performance. This report expands on the information of Deliverable 5.1 on the characterisation of test sites and demonstration activities with specific indoor air quality requirements and guidelines. The comfort level requirements and indoor air quality (IAQ) indexes will serve as input for the other WPs and Deliverables; for the energy monitoring applications of WP3, for the gamification engine in WP4, for the demonstration setup and the baseline creation in WP5, and for the impact assessment in WP6. This will help achieve the energy reduction in the office buildings of INESC-TEC in Porto, the municipal buildings in Barcelona, and the residential buildings in Lippe.

There are national and international standards, which specify criteria for thermal comfort and indoor air quality (e.g. EN ISO 7730, EN 152521, CR1752). Comfort consist of both user aspects and physical aspects and cannot be measured for all users equally with objective measuring techniques. For the user aspects, behavioural, physiological and psychological adjustment play an important role in the experience of comfort. Control is central to this. For the physical aspects, factors that determine comfort such as air movement, temperature, light intensity or humidity, can only be suggested in form of guideline values.

Using the minimum requirements of a low polluted building with a ‘B-category’ indoor climate (‘good’), the thermal requirements, CO_2 levels, humidity, and luminosity demands concerning air quality can be determined for FEEdBACk. These requirements and guidelines can be found in Chapter 5. The overview summary can be found in Table 16 of the Conclusion on pages 56 to 58.

1. INTRODUCTION

Energy consumption of buildings depends significantly on the criteria used for the indoor environment (temperature, ventilation, and lighting) and building (including systems) design and operation. Indoor environment also affects health, productivity, and comfort of the occupants. To be able to create a comfortable indoor environment, first an understanding of 'comfortable' is needed. Unfortunately, comfort is subjective to personal preference and dependent on multiple parameters, being psychological, medical, and building physical. Also of influence are different contextual aspects like socio-cultural and outdoor climate. There are national and international standards, which specify criteria for thermal comfort and indoor air quality (IAQ) (e.g. EN ISO 7730, EN15251, CR1752). These documents do specify different types and categories of criteria, which may have a significant influence on the energy demand. For the thermal environment, criteria for the heating season (cold/winter) and cooling season(warm/summer) are listed. These criteria are, however, mainly for dimensioning of building, heating, cooling, and ventilation systems. They may not be used directly for energy calculations and year-round evaluation of the indoor thermal environment, which is the main focus of the FEEdBACk project. Comfort cannot be measured for all users equally with objective measuring techniques. When determining factors that determine comfort such as air movement, temperature, light intensity or humidity, we can only strive to provide suggestions in form of guideline values. However, every user will sense these differently and will feel more or less comfortable. National laws pose minimum requirements on the conditions of a workplace or living environment; but typically, these requirements only serve to ensure the main determining factors. For instance, latest results in research have shown that occupant expectations in natural ventilated buildings may differ from conditioned buildings. These issues are not dealt with in detail in the above-mentioned documents. For air quality this (only) holds partly, as it is easier for humans to agree upon (poor) air quality. Nevertheless, this contextual and subjective aspects, besides of the stated norms and regulations, are important components that define the use of buildings, and thus of their energy performance, are essential to investigate and take into account for adaptation strategies related to energy use of buildings. This report, as Deliverable 2.2 within the FEEdBACk project, addressed the key aspects of comfort and air quality, within the larger context of above stated influences to establish indoor environmental input parameters for building system design and energy performance. This report complements and expands on the information of Deliverable 5.1 on the characterisation of test sites and demonstration activities with specific indoor air quality requirements and guidelines. Finally, it serves as input for the other WPs and Deliverables related to transition strategies to achieve the energy reduction in the different case studies.

2. COMFORT & CLIMATE

2.1 INTRODUCTION

According to article 25 of the Universal Declaration of Human Rights of the United Nations, one of the basic human rights is adequate housing for health, well-being, and safety. Adequate housing includes the creation of a suitable thermal environment to promote health, well-being, and safety. In most countries, to provide the right thermal environment energy should be applied for heating or cooling during various periods of the year. The more the outdoor climate differs from the desirable indoor thermal environment, the more energy the comfort system uses to restore comfort (Alders, 2016).

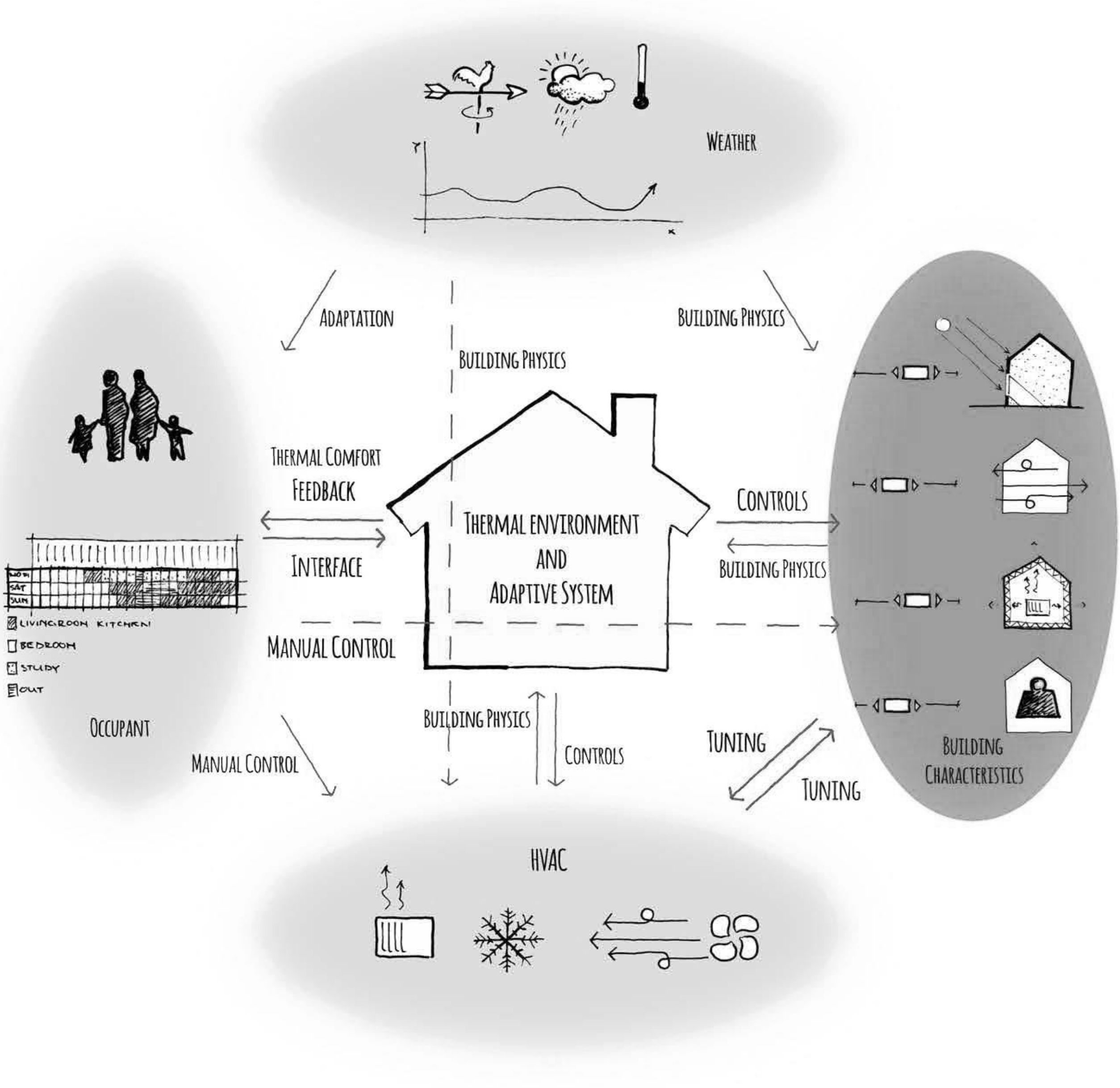


FIGURE 1 – Overview thermal environment and adaptive system (Image by Noortje Alders, 2016, TU Delft).

The outdoor thermal environment, the weather, is the most important factor on the indoor thermal environment and thermal energy balance of the indoor environment. For this reason, and the FEEdBACk cases in particular, it is necessary to have data about the (differences of the) outdoor climate, such as temperature, solar load, relative humidity, etc. The difficulty with the outdoor climate however is that it is ever changing.

2.2 OUTDOOR CLIMATE

Our earth can be divided into different climate zones. Climate zones can be categorized following two different points of view. On one hand, we can name mathematical or solar climate zones. This classification is based on the assumption that the earth as a homogenous mass is irradiated by sunrays, and that therefore different temperature zones run parallel to the equator (Bilow, 2012). Another possibility of categorizing the Earth into climate zones is a true or physical classification, whereby a zone is identified by the same climate type resulting from spatial and seasonally different co-action of climate elements and climate factors. The individual climate zones are not necessarily contiguous regions due to disproportionate amounts of land and sea, the atmospheric circulation and other local influences.

A classification that does justice to all and every aspect and characteristic is not possible. Ernst Neef, for example, has generated a generic climate classification. This means a classification based on the general atmospheric circulation. Hereby a location is allocated to a particular climate zone according to its position in a particular wind belt (Neef, 1956). The effective climate classification is based on the fact that there are interrelationships between climate elements and vegetation. Individual climates are separated from others using threshold values of the climate elements. Bilow (2012) simplified the following climate zones (see Figure 2).

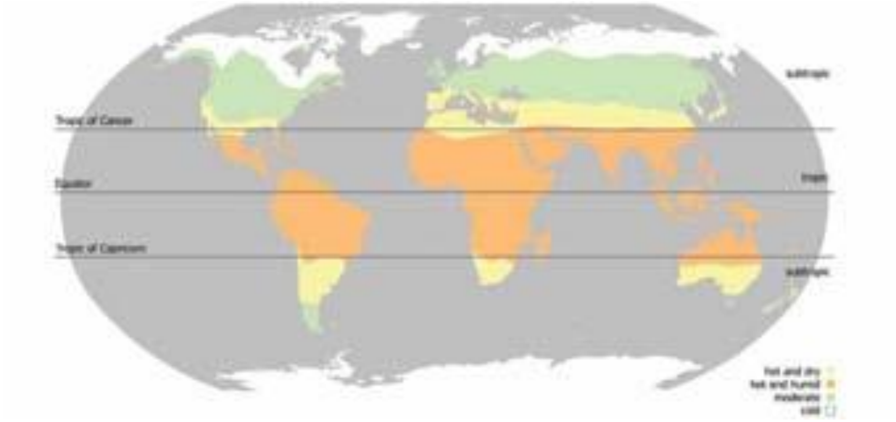


FIGURE 2 – Overview climate zones (Image by Bilow, 2012).

The subdivision is based on a simplification of the work by Köppen. But it shows that the Porto and Barcelona case are situated in similar zones, while Lippe is exemplary for the more wet/colder northern hemispherical climate. As stated, this is a simplification. For the sake of comfort and the efforts to be made to achieve comfort there are more differences than often thought of.

A closer look at Köppen's classification generated a classification around 1900 and continued to improve it until 1936 (McKnight and Hess, 2000) shows more nuances, which are of importance to distinguish between the Porto and Barcelona climate. The underlying principle of this classification is a division based on temperature, precipitation and the annual cycle of these two climate elements. For Köppen, the climate zones are basically related to the main vegetation zones (Neef, 1956). From a climate-statistical point of view this translates into five main climate groups:

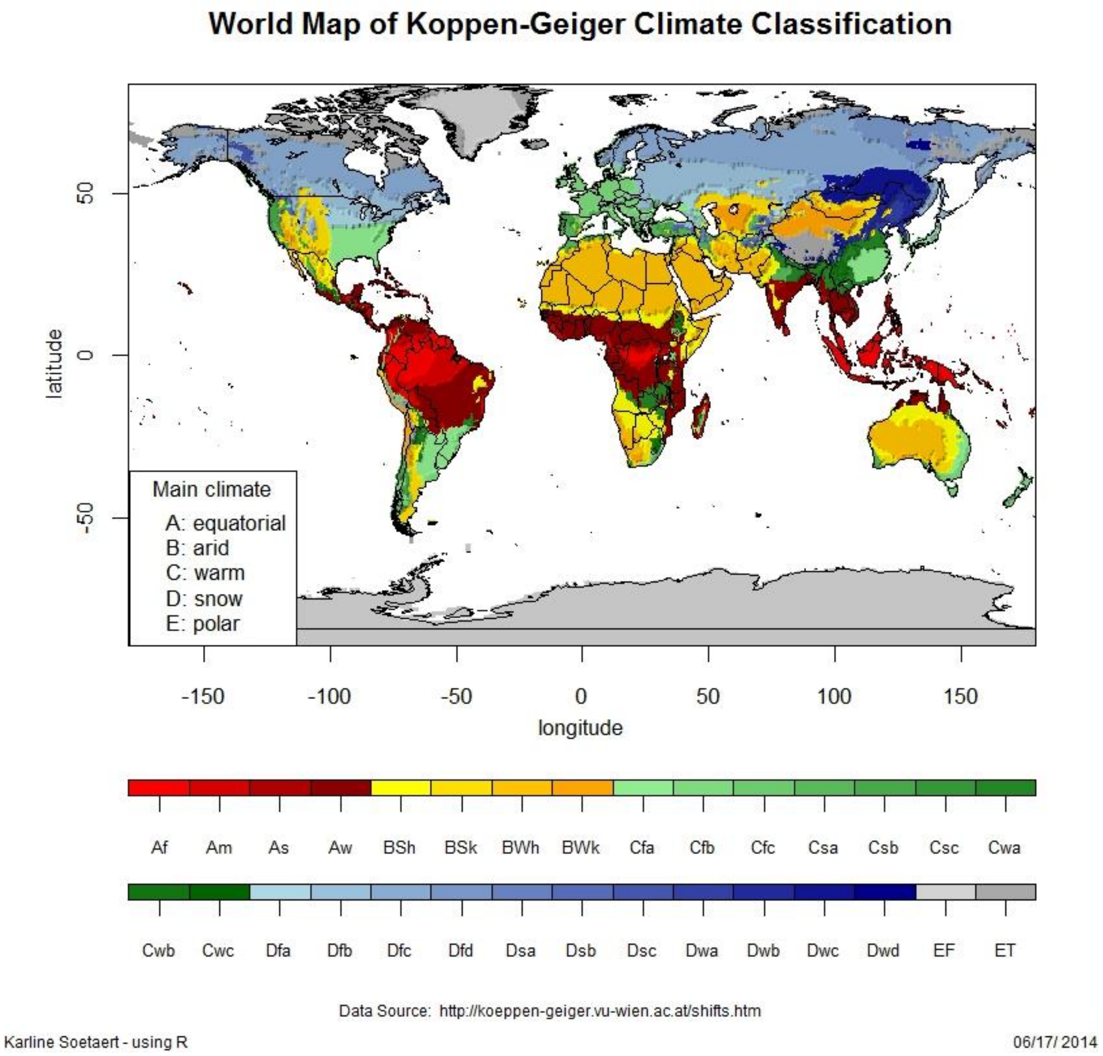
1 Tropical rain climates / equatorial (A);

2 Dry climates / arid (B);

3 Warm moderate rain climates / warm temperate (C);

4 Boreal or snow forest climates / snow (D);

5 Snow climates / polar (E)



Data Source: http://koeppen-geiger.vu-wien.ac.at/shifts.htm

Karline Soetaert - using R

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FIGURE 3 – World Map of Köppen-Geiger Climate Classification.

Climate, which is a term derived from the Ancient Greek word for inclination, describes the entirety of the weather conditions and temperatures, observed over a longer period of time in a particular region. It describes the interaction of atmospheric conditions and weather phenomena at the earth's surface in the characteristic progression of a particular location or region (climate zone).

Climate can be further subdivided into (a) **mega-thermal**, (b) **meso-thermal**, and (c) **micro-thermal climates**.

(ad.a) The **mega-thermal climates** describe conditions observed over a wide area. A region can be determined by its position on the grid of longitudes and latitudes.

(ad. b) **Meso-thermal climates** describe local climates or area climates; thus, the climate of a particular city can be called a meso-thermal climate.

(ad. c) **Micro-thermal climates** are most relevant to the specific strategies of the buildings considered in the FEEdBACk project, as it describes the climate immediately around buildings (or users). It deals with the local conditions on the smallest scale. Thus, the shading of buildings or vegetation as well as wind factors caused by the geographic situation, e.g. hillside or valley location, determine the micro-thermal climate. Contrary to the more permanent macro-thermal climate, the micro-thermal climate is subject to constant changes and can also be altered by vegetal or building related activity (Schütze and Willkomm, 2000).

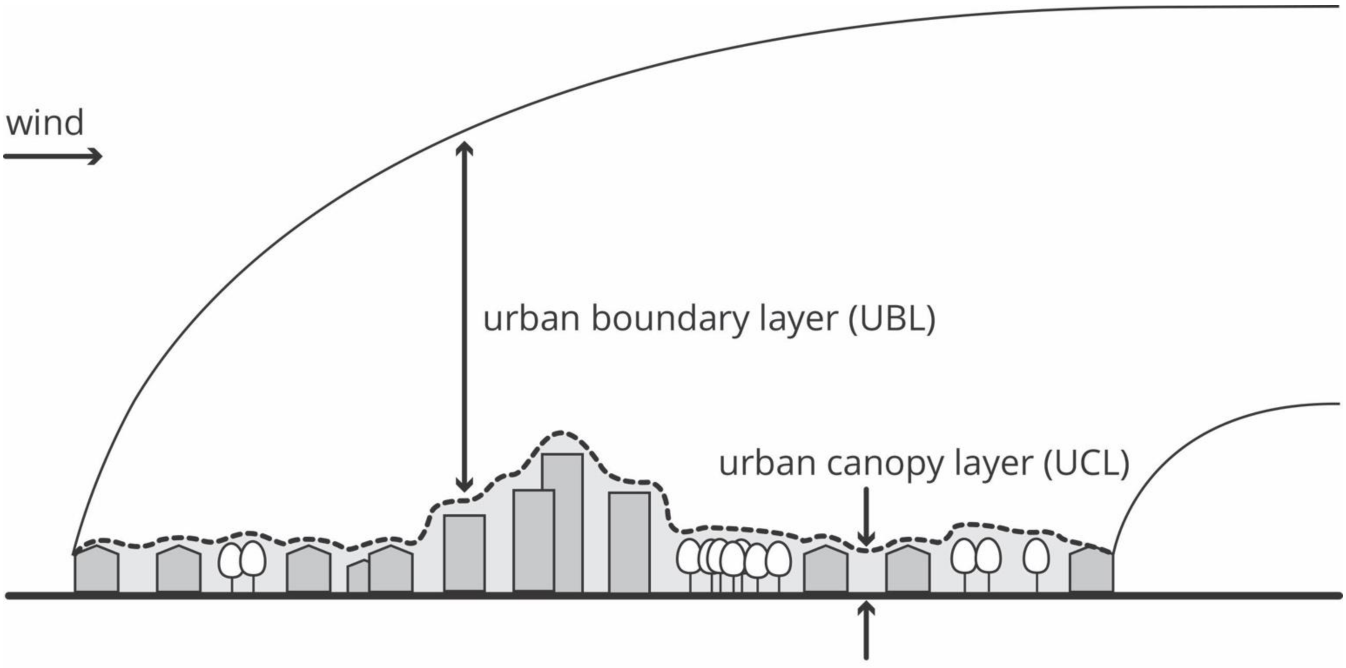

FIGURE 4 – The Urban Boundary Layer and Urban Canopy Layer (after Oke, 1987).

Regarding urban climate, or micro-thermal climate, two scales are important (Oke, 1982, 1987). The city as a whole modifies the regional climate conditions, which results in differences in climate between the city and its surrounding (rural) area. This modified climate is prevalent in the Urban Boundary Layer (UBL) - above the city's roofs - and is rather homogeneous over the urban area. In contrast, the climate in the

Urban Canopy Layer (UCL), below the roofs in the spaces between the buildings, can vary significantly within a distance of even a few metres (Figure 4). These microclimates form the immediate surroundings of people in the city and directly influence their physical well-being. The UCL is therefore most important to include into considerations of the FEEdBACk research.

Climate can be defined as the conditions of the atmosphere at a particular location over a long period of time; it is the long-term summation of the atmospheric elements (and their variations) that, over short time periods, constitute weather. These elements are solar radiation, temperature, humidity, precipitation (type, frequency, and amount), atmospheric pressure, and wind (speed and direction), (Encyclopaedia Britannica, 2014).

From the combined perspectives of urban context, i.e. the influence of the built environment on microclimates, and physical well-being, i.e. the influence of urban microclimates on health and comfort, not all of the elements of the large scale climate mentioned above are equally relevant when studying urban microclimates and their influence on building/indoor climates. Therefore, this deliverable includes solar radiation (including daylight), temperature and wind, and additionally air quality and visual and acoustical quality, as these elements can have a significant impact on physical well-being and thus use (and related energy consequences), and are influenced by the built environment on the small scale of the urban canopy. Humidity will be touched upon in relation to the subject of thermal comfort.

Our thermal environment is created by the interplay of radiation coming from the sun and the reflection, absorption and re-emission of this radiation by the earth and its atmosphere. The incoming solar radiation is short wave, the radiation emitted by earth and atmosphere is long wave. Short wave radiation contains more energy than long wave radiation.

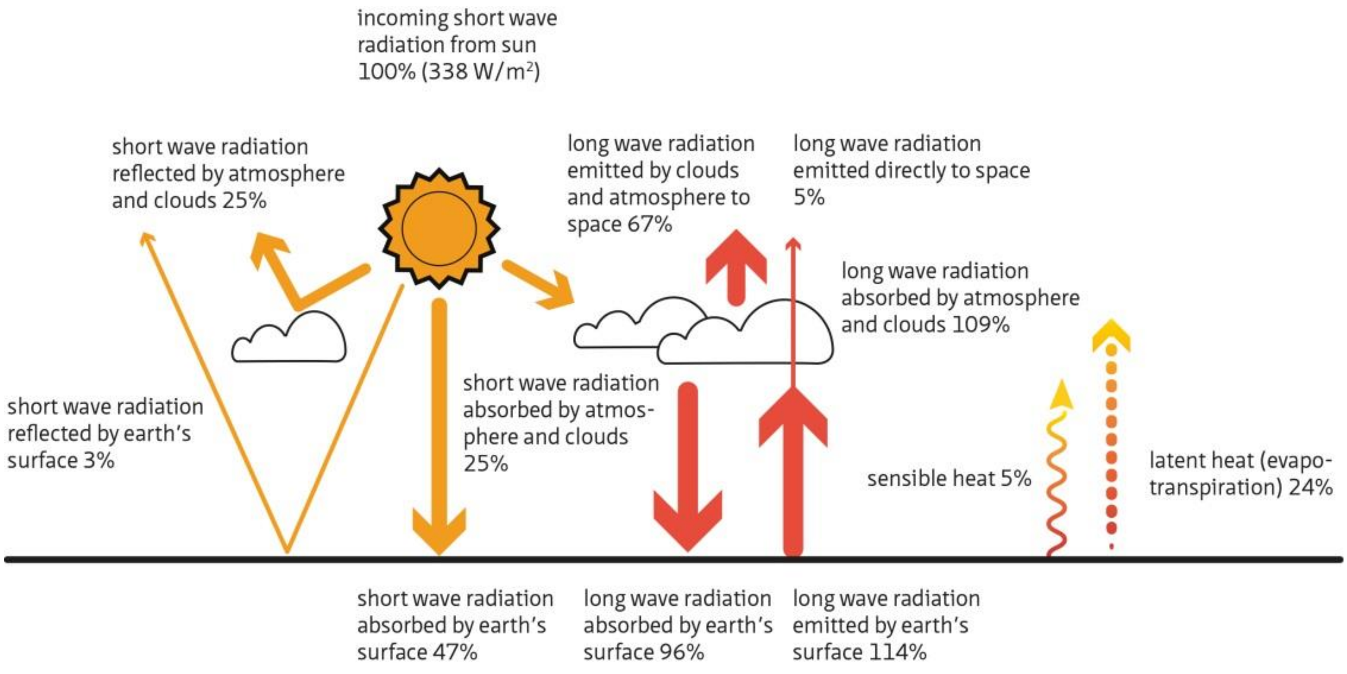

FIGURE 5 – The earth's energy balance (Pijpers Van Esch, 2015).

The net radiation exchange between the human body and its environment can be noted as (Equation 1).

Equation 1: $Rn = (K_{dir} + K_{dif} + K_{ref})(1-\alpha_s) + L_{sky} + L_{ter} - L_s$

Where:

K_{dir} = direct short-wave radiation incident on the body (direct sun beam)

K_{dif} = diffuse short-wave radiation incident on the body (scattered by the atmosphere)

K_{ref} = indirect short-wave radiation incident on the body, reflected from surfaces

L_{sky} = long-wave radiation incident on the body, emitted from the sky

L_{ter} = long-wave radiation incident on the body, emitted from (terrestrial) surfaces

L_s = long-wave radiation emitted by the body to the environment

α_s = albedo of skin/clothing

(ad. d) Often scholars speak about another (4th) climate, viz. the **indoor climates** (as we do for instance in the FEEdBACk project). However, this often-considered smallest describable climate is only relevant from an architectural or building physical point of view. In terms of purely meteorological aspects, there is no indoor climate. As it is key to (perceived) comfort, and influenced by use(rs) and technical interfaces and appliances, often part of the concepts to achieve energy reductions, the main goal of FEEdBACk, this fourth level of climate description will be distinguished in this project.

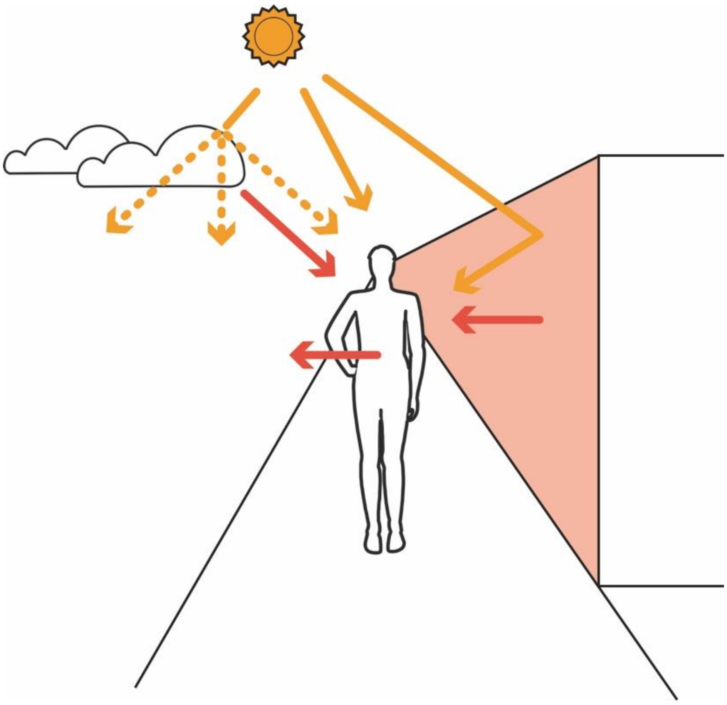

FIGURE 6 – Radiation exchange between the human body and its environment (Pijpers Van Esch, 2015).

The perceived result of this radiation exchange can be expressed as the Mean Radiant Temperature (MRT). MRT is defined as the uniform temperature of an imaginary enclosure in which radiant energy exchange with the body equals the radiant energy exchange in the actual non-uniform environment; an area weighted mean temperature of all surfaces surrounding a space, including the sky.

Together with air temperature, which is also determined by solar radiation, MRT exerts a strong influence on the human body's thermoregulatory system. The thermoregulatory system consists of various mechanisms to deal with an imbalance between heat gains and losses (Pijpers Van Esch, 2015). When heat gains are greater than heat losses, the body will initially respond by vasodilation, increasing blood flow to the skin, therewith increasing skin temperature and thus heat dissipation. If this is not sufficient, the production of sweat starts which supplies the body with evaporative cooling. These processes may cause discomfort, but are not yet threatening to health (ibid). However, if heating continues, hyperthermia might occur, which is damaging to the body. When it is too cold, the blood flow will drop through vasoconstriction, and skin temperature and heat dissipation will reduce. If this mechanism is not sufficient, the body starts to shiver; a non-controllable muscle activity that increases the heat production drastically. Ultimately, hypothermia will occur with a chance of serious harm to the human body.

Radiation and air temperature are two of the four climate elements influencing the human thermal balance, the other two being wind and relative humidity. Their separate influences on the human thermoregulatory system cannot be clearly distinguished, as the human body does not have selective sensors for the perception of the individual climate parameters, but rather senses their combined thermal effect as a 'felt temperature' (Höppe, 1999).

To summarize, for the scope of FEEdBACk, the focus of climate analysis lies only contextual/sideways on the meso-thermal climate, that describes the geographic situation, but foremost on the indoor climate and the micro-thermal climate which encompasses the topographic circumstances of the particular locations/buildings, as well as the urban morphological influences of the direct surrounding environment.

2.3 INDOOR CLIMATE

The indoor climate is influenced by many factors that together create a climate that can be experienced differently by different people. Therefore, there is no solid definition of a comfortable climate. However, the factors that create the climate can be distinguished.

Too often, when speaking of the indoor climate, people mean the thermal climate (simplified to the air temperature). However, the perceived indoor temperature (and thus directly related comfort), sometimes addressed at as the operative temperature (Hasselaar, 2013), is "a combination of the radiative temperature in a room (radiative temperature emitted by the surfaces surrounding the subject) and the air temperature in the room" (ibid, 2013).

To avoid using equations, the indoor thermal climate is the result of heat transmission through the façade through radiation (e.g. solar radiation) or conduction (which can for instance be reduced by insulation) and convection, indoor heat production (e.g. as a result of appliances such as lighting, or people and their activity), heat storage (in the thermal mass of the building and its furniture) and influences from the climate installations (e.g. heating, ventilation, humidification). Or to state it more generally, the only source of energy originating from inside is the indoor heat production (or: heat load). This means, that in case we build (almost) energetically optimal, the indoor heat production, including activity (cfr. Table 1 with average heat production of persons per activity –relevant to the FEEdBACk cases) by the users/people, and the way they dress are the most important to consider.

TABLE 1 – Average heat production of persons related to their activity (Schalkoort, 2009)

Activity	Heat production (average) in W/person
Sitting calmly	80
Sedentary office work	100
Standing office work	110
Sitting light assembly work	115
Standing light assembly work	150
Laboratory work	110
Walking (0.8 m/s)	120
Walking (1.2 m/s)	150
Gymnastics	160
Tennis	240
Squash/basketball	300

In a standard sized office space (5,4 x 3.6 m, based on a grid of 0.9 m) with two people (based on approx. 10 m^2 floor area per person) the indoor heat production can be calculated as follows, for three different scenarios with low, average and high indoor heat production (EU Energy Star, 2009; NEN5067, 1985):

(a) A **low internal heating load** would be if one person would be present (100 W), working with a laptop (12 W) with only half of the room artificially lit (~ 10 W/m^2), amounting to a low average of 15 to 20 W/m^2.

(b) An **average heat production** would be with two persons present, with each their own computer (average desktop computer with 17" LCD screen; ~ 90W) and the entire room artificially lit, and thus an average amount of 30 to 40 W/m^2.

(c) A **high indoor heating load** comes from 2 people, each with a high-powered desktop computer (190 W) and a large screen (e.g. 30"; ~ 108 W) and a laser printer (~ 13 W in standby mode) with ample lighting (12 W/m^2), thus amounting to a high average of around 50 to 60 W/m^2.

Together with the climate installations and general (macro/meso/micro) climate and building characteristics, these factors determine to large extent the indoor climate, and thus comfort of users. However, it is important to mention that here comes in the difficult part of comfort: as stated before perceived comfort is different for different people, but actually including different for the same kind of people.

3. ADAPTIVE TECHNIQUES: PHYSIOLOGICAL AND PSYCHOLOGICAL ADAPTATION

3.1 INTRODUCTION

A basic measure of the quality of the indoor climate is the degree of satisfaction experienced by people who work in it (Hasselaar, 2013). Adapted from Manchanda and Steemers (2012), the general notion of comfort lies between health and happiness. Happiness is a qualitative state and derived from aspects like delight, pleasure, satisfaction, perception, and beauty. Health is a quantitative state and derived from aspects like body temperature, body function, air temperature, sound levels, luminance, and pollution concentration. Manchanda and Steemers (2012) capture this wide range of well-being aspects by defining a spectrum extending from the directly measurable (e.g., symptoms including body temperature, blood chemistry, etc.) to the immeasurable (e.g., quality, delight, pleasure, etc.). On one end of their spectrum lies "health", defined as the absence of disease, on the other end lies "happiness". "Comfort" lies at the intersection of the two, and thus between quantifiable parameters (e.g., temperature, luminance, etc.) and qualitative concerns (e.g., perception, beauty, etc.). Manchanda and Steemers further point out that the parameters of comfort, health, and happiness are also further interrelated in that unhappiness and discomfort can lead to poor health, psychological or physical.

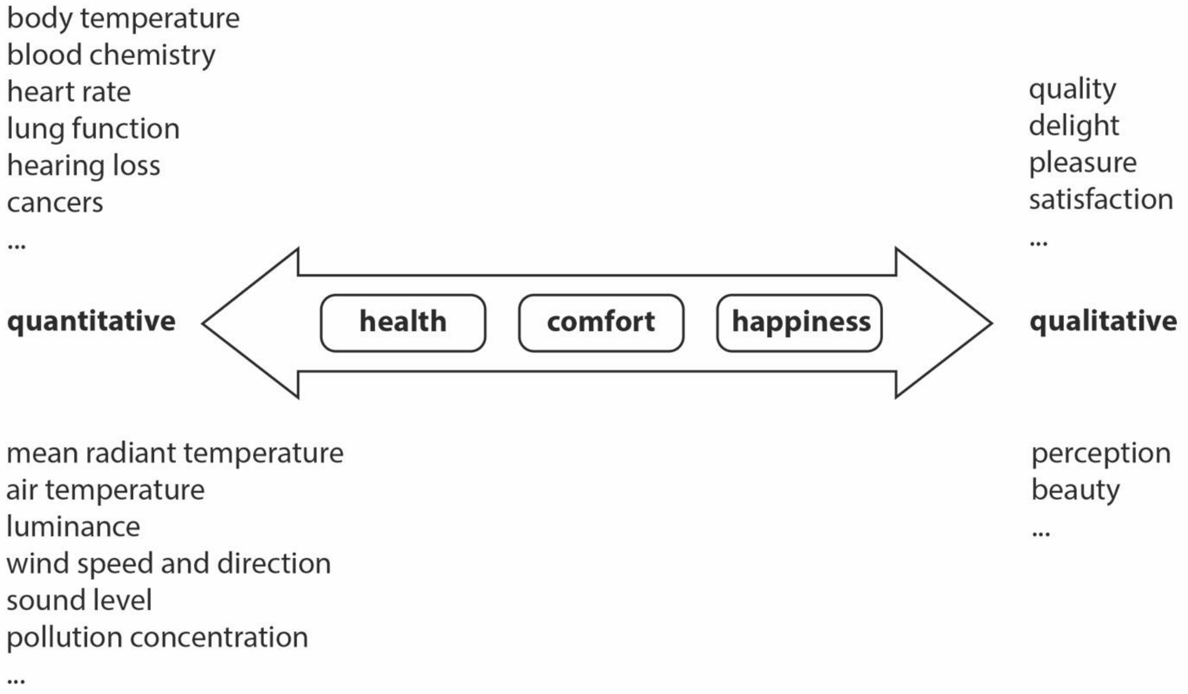

FIGURE 7 – Spectrum of wellbeing, adapted from Manchanda & Steemers (2012).

Human comfort is clearly influenced by the physical environment: a 'comfortable' temperature and indoor air quality (IAQ), the absence of disturbing odours and other polluting substances, appropriate lighting distribution and low noise levels, to name most important (but not all) aspects that contribute to a comfortable indoor climate. However, the perception of the physical factors is strongly influenced by physiological, behavioural, and psychological variables.

Many building related environmental factors are linked to human health, e.g. related to the sick-building syndrome (SBS) symptoms, with most attention going to indoor air quality. Other factors also play a role in SBS, such as noise, light, thermal climate, and psychosocial factors (dissatisfaction with the working atmosphere, a person's position within a company, private problems, etc.). Research has shown that many health complaints are related to building characteristics. Minor problems that are not building related can be triggered to become major obstacles through an uncomfortable working environment (Nilsson, 2003).

In office buildings the productivity of the employees is linked to their sensation of comfort. Depending on the source consulted, the annualised cost for the construction of an (office) building is stated between 5 to 10% of the total annual costs for an enterprise over 20 years, while employee cost varies between 75 and 92% of total expenditure (Winch, 2005; Ree & Hartjes, 2003). Although productivity (defined as "the ability to perform various tasks, both mentally and physically demanding" (Hasselaar, 2013)) has been shown to be influenced by the indoor environment (perception), particularly the thermal, acoustic, and atmospheric (air quality related), measuring this productivity is not an easy process (ibid, 2013). A Dutch governmental study on 61 buildings (occupying 7000 employees) related to (perceived) comfort, concluded that at least 20% of the employees had complaints about the indoor climate, adding up to an estimated one million days of absence from work per year (VROM et al., 1991).

Comfort related physical factors of importance for the indoor climate, and thus energy use for its continued adapting to realise such comfort, consists of four factors: thermal climate, indoor air quality, sound, and light. Previous stated psychological aspect on top of that are considered increasingly of importance lately.

FEEdBACk focuses on the aspects of well-being that are universal, looking for general criteria that apply to as many people as possible.

3.2 THERMAL COMFORT

3.2.1 INTRODUCTION

The following (different) definitions of (thermal) Comfort will be taken as a starting point here:

Comfort (Oxford, 2012): a state of physical and material well-being, with freedom from pain and trouble, and satisfaction of bodily needs; the condition of being comfortable.

Thermal environment (De Dear et al., 1997): the characteristics of the environment which affect a person's heat loss.

Thermal comfort (De Dear et al., 1997): that condition of mind which expresses satisfaction with the thermal environment; it requires subjective evaluation. Optimum thermal comfort is assumed to correspond with a thermal preference vote of "want no change".

Thermal neutrality (De Dear et al., 1997): the indoor thermal index value (usually operative temperature) corresponding with a maximum number of building occupants voting “neutral” on the thermal sensation scale.

Many studies have been performed to define the thermal circumstances under which (most) people feel comfortable. As early as 1936 by Bedford about the thermal comfort at the workplace, especially in factories (Bedford, 1936) and later on Victor Olgyay studied the thermal comfort of the outdoor environment related to the combination of ambient temperature, relative humidity, air velocity and solar radiation giving design guidelines in the extensive book "Design with Climate" (Olgyay, 2015). Givoni wrote a similar work called "Man, climate and architecture" (Givoni, 1976).

Up until the late 1950’s in the US, and 1960’s elsewhere, buildings in general were built without mechanical cooling: the temperature was controlled using architectural or building physical solutions. As a consequence, measures to prevent uncomfortably high indoor temperatures were an important part of the architectural design and architects (in general) realised that a comfortable indoor climate was for a large part dependent on the design choices they made. This situation slowly changed with the introduction of air conditioning (HVAC), which made conditioning of indoor spaces possible to become (more or less) independent of the (building physical) quality of the building. Within this context, little by little specialised consultants and contractors took over this responsibility, leaving the architects mostly to concentrate more (or just) on shape and visual appearance of the buildings. The specialised consultants in this changed setting, though, mostly were bound by the boundaries set by the architect.

Through developments of HVAC technologies, a need arose for better (or more substantial) data concerning comfortable indoor temperatures (in a way a shift from implicit to explicit data). The best known and most used research into comfort as a result to that was that by the Danish researcher Fanger (Fanger, 1972), who investigated thermal comfort in a climate chamber with 1300 students. People were asked how they felt using a 7-point thermal scale (see Table 2).

TABLE 2 – Fanger comfort scale ranging from +3 (hot) to -3 (cold)

+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

Using these assessments and data from the climate chamber, the "average thermal sensation of a theoretical group of people in a homogenous indoor climate" could be predicted ('Predicted Mean Vote', or PMV) with the corresponding theoretical percentage of people dissatisfied with the climate the Predicted Percentage of Dissatisfied (PPD). The equation is based on the thermal heat balance model of the human body (see Figure 8).

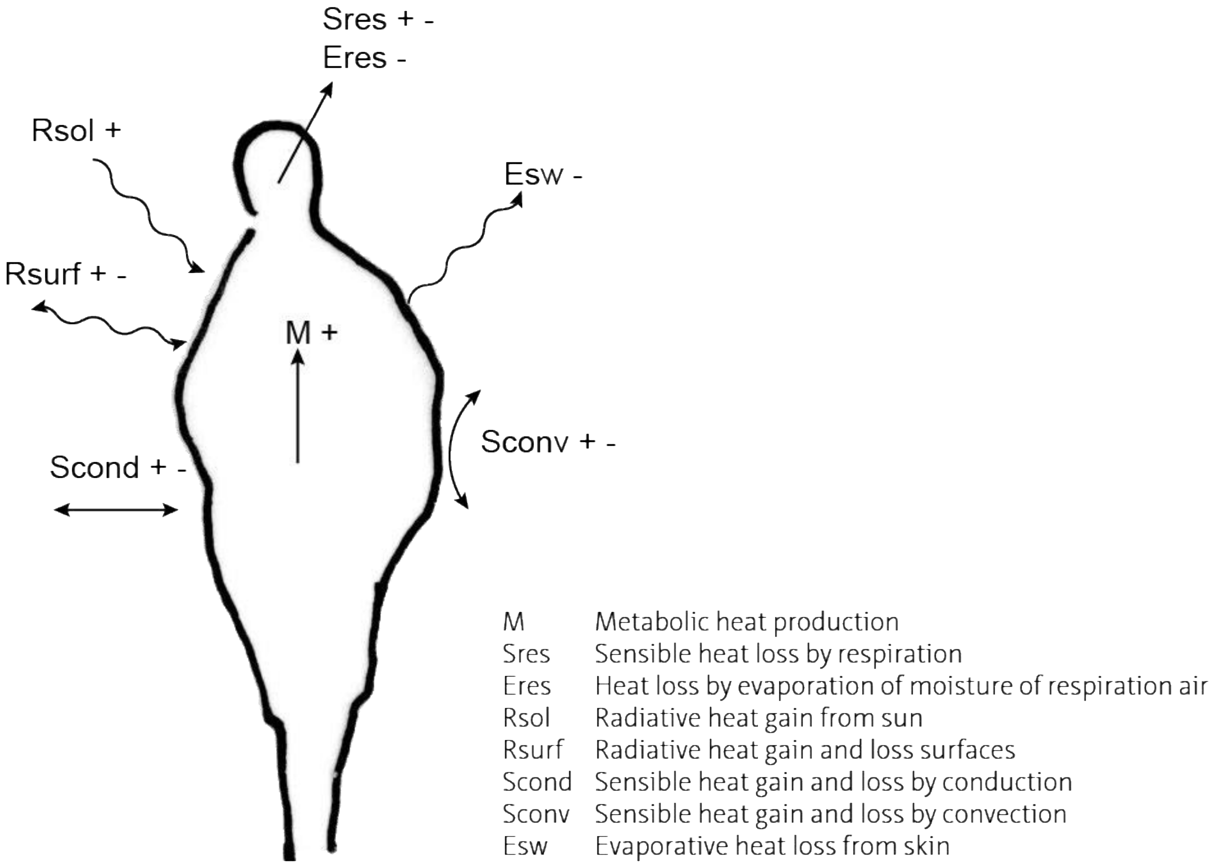

FIGURE 8 – Variables of the thermal heat balance model of the human body (Fanger, 1972)

A PMV of, for example 0.5 corresponds with 10% of the people who are dissatisfied with the indoor climate (see Figure 9). According to Fanger (ibid, 1972), it is impossible to create one indoor climate condition that pleases every person in the building. Because of differences between people's personal preferences, at least 5% of the people will be dissatisfied with the current ambient climate.

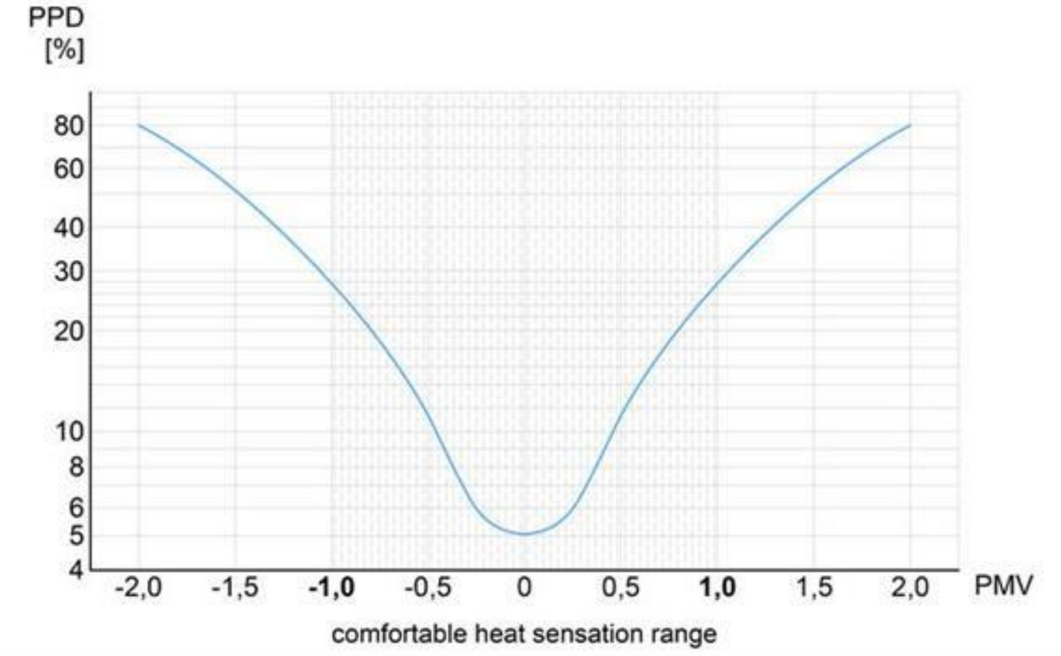

FIGURE 9 – Thermal comfort PMV/PPD model with PMV (Predicted Mean Vote) on the x-axis and PPD (Predicted Percentage of Dissatisfied) on the y-axis.

Nowadays most important research and research fellows (e.g. De Dear et al. (1997) and Nicol and Humphrey (2002)) quantify thermal comfort with the PMV/PPD model, using Fanger's equations. The PMV/PPD model, also known as the 'Steady State model', presumes that the human body has to be in thermal steady state in order to feel thermal comfort. This sense of comfort is a state of mind where one is satisfied with the thermal environment at a certain level of activity and type of clothing. Whether this sense of comfort (and therefore the steady state) is achieved, is determined by the balance between the amount of energy going out of the body has to be equal to the amount of energy going in (Melet, 2017). This PMV/PPD model is used to assess thermal comfort by a number of physical aspects of the indoor environment like air temperature, relative humidity, ventilation, but also personal aspects like metabolic rate and clothing. With this model, one can assess what percentage of people will be dissatisfied with the thermal environment.

3.2.2 THERMAL COMFORT GUIDELINES

When deciding what factors determine comfort, such as air movement, temperature, light intensity or humidity, we can only strive to provide suggestions in form of guideline values. However, every user will sense these differently and will feel more or less comfortable. National laws pose minimum requirements on the conditions of a workplace or living environment; but typically these requirements only serve to ensure the main determining factors. For FEEdBACk, EU standard EN15251 is of importance to consider (Annex 1). However, design values for the indoor temperature for heating load and cooling load calculations, are specified at national level.

Differences in comfort guidelines between the different countries exist, but in most cases (all as for the countries of the demo sites considered within FEEdBACk) guidelines are (still) based upon the work by

Fanger. The research of (mainly) Fanger is adopted in the international standards like EN ISO 7730 and EN 15251. These criteria for the thermal environment shall be based on the thermal comfort indices PMV-PPD with assumed typical levels of activity and thermal insulation for clothing (winter and summer) as described in detail in EN ISO 7730 (instead of using temperature as the design criterion the PMV-PPD index can be used directly; in this way the effect of increased air velocity will be taken into account). Also, the selection of the category is building specific, and the needs of special occupant groups such as elderly people (low metabolic rate and impaired control of body temperature) shall be considered (ISO/TS14415); this user related aspect is also addressed more in detail in the following section, 3.3).

Based on the selected criteria (comfort category) a corresponding temperature interval is established. The values for dimensioning of cooling systems are the upper values of the comfort range and values for dimensioning of the heating system are the lower comfort values of the range. In general, guidelines state that a ‘good’ indoor climate should meet **-0.5 < PMV < +0.5** (or in other words: **10% dissatisfied**). In EN ISO 7730 this is termed as a ‘category B’ thermal environment. Exceeding these boundaries in most of the guidelines (e.g. in the Netherlands) in the beginning (from approx. the 1970’s on) was allowed during special circumstances (heat or cold wave, or malfunctioning in the climate installations) within **-1.0 < PMV < +1.0** (or: 25 % dissatisfied) during **a maximum of 10 %** of the time people are present (100 hours in summer). As in particular the latter, the rules for exceeding the general rule (10%) were still quite spacious, later this evolved in rules like for instance ‘the Exceeding Hour (TO)-method’, stating that an indoor temperature corresponding to a **PMV of (+ or -) 0.5** is allowed to be undershot or exceeded for a **maximum 100 hours per year** (each). On top of that a **minimum temperature (18°C) and maximum temperature of 28°C** is allowed to be **undershot/exceeded for a maximum 1% of the year** (or 20 hours each). Later the Weighted Exceeding Hour (known as the GTO method) was added to this, weighting the extent of how much a temperature is exceeded with the PPD and the duration of the exceeding hours: the **weighting factor** is 1 at a PMV of 0.5, so one hour with a PMV of 0.7 has approximately the same impact as 1.5 hours with a PMV of 0.5.

In most countries, for office buildings, the maximum total of weighted exceeding hours per year is also limited. Like for instance in the Netherlands, where this is put at 150 hours per year, based on a “category B” building (‘good’), which is the ‘normal reference’. A “category A” building here is allowed a maximum total of weighted exceeding hours per year of 100 (‘very good’), while a “category C” building is allowed 250 hours a year (‘acceptable’).

In all cases and countries rules are based on the work and method by Fanger, but also on so-called reference years. This is different per country (e.g. in the Netherlands this is the year 1964 (Alphen et al., 2008; Linden et al., 2006)). The idea behind this is that it leads to representative values for energy consumption for heating and cooling, while it also has sufficient hot days in summer and cold days in winter to predict the performance of the building its very warm/cold climate conditions. Lately however, also as a result of changing global temperatures, it became more and more apparent that such reference years include certain risks, as they may lead to too conservative predictions (Hasselaar, 2013). In the previous example of the Netherlands this led to the recommendation to also include the year 1995 in calculations (which was a much warmer year than 1964 there; (Schijndel and Zeiler, 2006)). The thermal comfort requirements per demonstration site will be further discusses in Chapter 5.

3.3 USER BEHAVIOUR & PERCEPTION

In the built environment, technical (component) measures of sustainability are being applied in order to decrease energy usage and increase energy efficiency. The users are often not taken into account when designing and implementing these measures. This is problematic for two major reasons:

1. Often the calculated energy savings of technical measures are not met. User behaviour is not factored in these calculations, which means the energy usage is higher than that calculated beforehand. This is known as the rebound effect. This (indirect) rebound effect can cause users to increase the energy usage following a technical (sustainable) renovation.
2. Comfort and IAQ are important factors for human health and productivity. Poor IAQ is recognized as an important risk factor for human health and well-being as people spend a large proportion of their time inside buildings. People in developed countries spent an estimated 90% of their time indoor (Frontczak & Wargocki, 2011). The comfort and ability to work is tightly knit to the IAQ as it can affect the concentration and the productivity of occupants. On the other hand, the reduction of buildings' energy demand can affect IAQ levels since ventilation, heating/cooling, and lighting systems are normally powered with electricity. It is therefore essential to guarantee that IAQ and other aspects of indoor climate are not overlooked fostering energy efficiency in buildings.

As mentioned in section 3.2.1, the most prevalent model to take comfort and IAQ into account is the Fanger model (PMV/PPD-model). The main problem with this Fanger model, adopted by American ASHRAE 55 (2004) standard and European EN-ISO 7730 (2005) standard and thus very influential, is that the defining experiments were held in a climate chamber. This means a steady state and uniform environment, which seldom occurs in real life. Furthermore, it requires the knowledge of metabolic rate and type of clothing. This is often hard to predict as both variables are individually dependent. The value of clothing insulation used can be read from tables in which clothing insulation is listed against descriptions of items or ensembles of clothing. The values of clothing insulation were determined in experiments using heated manikins. The metabolic rate was similarly obtained from tables of activities for which the appropriate metabolic rate is given. This is based on averaging measurements of people performing these activities (Alders, 2016). Moreover, as stipulated by the thesis of Ed Melet (2017), the idea of 'thermal neutrality' can be called into question since this is a situation which can never truly exist (Heschong, 1979). The human body is not static, differs per region, and does not always want 'thermal neutrality' (ibis, 1979). Expending on that last point of criticism of the Fanger model, people who have chosen +2 or -2 on the ASHREA scale, are not always dissatisfied with the indoor environment (Von Grabe & Winter, 2008). A possible explanation is that the outdoor temperature is also an influence for the perceived indoor environment, which the Fanger model does not take into account (Humpreys & Hancock, 2007). Furthermore, this model also does not take into account aspects like social, cultural, gender, and age differences (Kempton & Lutzenheiser, 1992). This aspect will be expended on in section 3.4 where the individual and cultural differences in experiencing comfort will be discussed.

Additionally, globally standardizing thermal comfort led to what Shove calls social, architectural, and environmental convergence (Shove, 2004), i.e. standards and expectations becoming increasingly similar across the world. Imposing this "ideal" situation to places all over the world, regardless of people's diversity, caused a growing need for artificially created comfort in the built environment, instead of meeting pre-existent needs. So, creating the same thermal environment in every climate leads to excessive energy use. Comfort however is culturally relative, framed by issues of social convention, symbolism and status and comfort. Fine & Leopold (1993) found that perception of comfort and that of the systems through which particular services are produced, delivered, distributed, and used mutually influence each other and cannot be explained in terms of consumer demand alone.

These missing aspects in the Fanger model mean two things. Firstly, being able to personally adjust (some aspects of) the indoor environment is crucial for comfort. Secondly, another model may be used to improve the specifications and measurements of comfort in the FEEdBACk project.

A theory that does take into account adaptation and is increasingly applied all over the world is the Adaptive Comfort Algorithm (ACA) which was developed by both Australian researchers for ASHREA as British researchers (De Dear et al., 1997; McCartney & Nicol, 2002). The adaptive approach assumes that people get accustomed to the circumstances they are exposed to regularly, because of various actions of adaptation (De Dear et al., 1997; Nicol & Humphreys, 1998). According to De Dear et al., there are three categories of adaptation:

1. **Behavioural Adjustment**; All modifications made to modify the thermal balance between body and environment such as adjusting clothing, activity, posture, windows, fans, moving to a different location, scheduling activities, siestas, and dress codes.
2. **Physiological Adjustment**; All changes in the physiological responses to thermal environmental factors which lead to a gradual diminution in the strain induced by these factors ('acclimatisation', like sweating, changing metabolic rate, changing muscle tension).
3. **Psychological** (habituation and expectation); Relaxation of indoor climatic expectations can be associated with the concept of habituation in psychophysics; repeated or chronic exposure to an environmental stressor leads to a reduction of the induced sensation's intensity. In this respect, the duration of exposure to a thermal environment is also important. For instance, 'past experience' plays a role: people expect a higher indoor temperature if there has been a long spell of warm weather. Also 'the context of the surroundings' plays a role: people expect a different climate in a church than in a sports building, train platform or train station. Finally, people prefer the indoor climate to vary somewhat through time rather than have a very steady or monotonous climate (Brager and de Dear, 1998; Kurvers et al., 2010; Hasselaar, 2013).

Both De Dear et al. (1997) and Nicol & Humphreys (2002) found that recently experienced outdoor conditions best predict the thermal preference of people. Based on regression analysis of their extensive field surveys they derived similar linear equations to relate the outdoor temperatures of the past few days or month (Te,ref) to the comfort temperature. The basic equation is as follows (Equation 2):

Equation 2: $T_c = a * T_{e,ref} + b$

The constants a and b can vary per group of people or room function. The equations adopted by the standards are based on a wide group of occupants in office environments. Calculation of the reference temperature Te,ref can also vary.

An Adaptive Thermal Comfort (ATC) system (originally The Adaptive Dwelling (DEPW, 2006)) is defined as the whole of passive and active comfort components of the dwelling that dynamically adapts its settings to varying user comfort demands and weather conditions (seasonal, diurnal and hourly depending on the aspects adapted), thus providing comfort only where, when, and at the level needed by the user, to improve possibilities of harvesting the environmental energy (e.g. solar gain and outdoor air) when available and storing it when abundant (Alders, 2016).

The ATC model adds the outdoor environment and control over the indoor environment as factors in the determination of the comfort of an occupant. This makes that there are 6 domains to be distinguished that potentially influence the Comfort (and related energy use): Occupancy, Weather, Layout of the building internally, Materialization, HVAC, and other installations and Controls.

The control aspect is clustered into two types, depending on the types of control that can be carried out in the building. Two different types of buildings (or rooms) are Alpha buildings (without mechanical cooling) and Beta buildings (with mechanical cooling). In Beta type buildings (or rooms), there are generally a few or no windows and the influence of the user on the indoor environment is little.

In Alpha type buildings (or rooms), the influence of the users is generally greater. In order to classify as an alpha building, the building should not have a sealed façade and people in the building should have the ability to adjust their clothing. Furthermore, the building must have either:

1: At least one operable window per two occupants without mechanical cooling, or

2: At least one operable window with mechanical cooling and one temperature control per two occupants, or

3: At least one temperature control per two occupants with mechanical cooling but less than one operable window per two occupants.

If neither of these options are fulfilled, the building is classified as a beta building. Figure 10 shows an overview of the characteristics for the alpha/beta building classification.

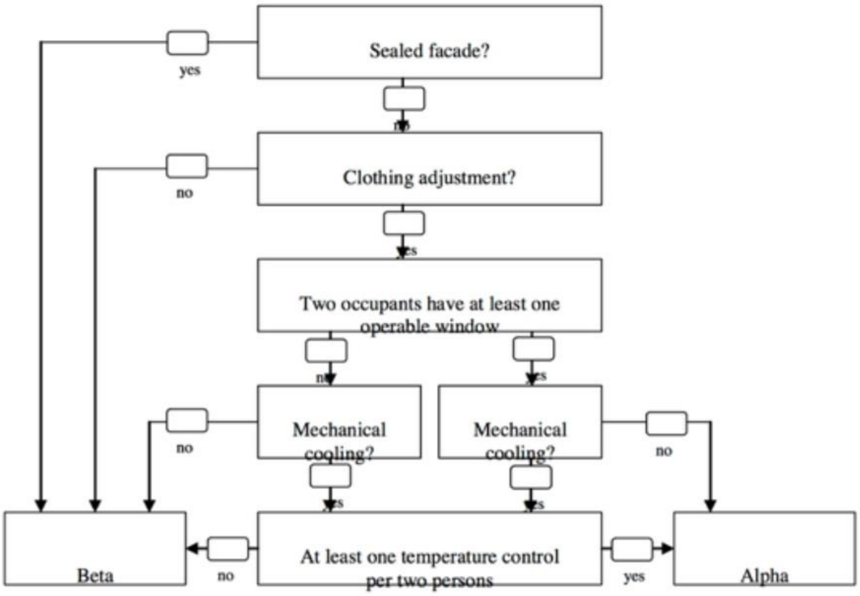

Diagram for determining type of building/climate Alpha or Beta

FIGURE 10 – Overview of the characteristics for the alpha/beta building classification (Ed Melet, 2017, TU Delft)

Due to the different functions and layout within a building, it is not possible to define each building as purely an alpha or beta building. For example, within one building, single offices would be classified as an alpha 'building', while the open space offices would be classified as a beta 'building' due to the lack of operable windows. Therefore for the FEEdBACk demonstration site buildings, this alpha/beta classification serves more as an illustration of the behavioural adjustment possible and the effect on indoor air quality.

A limitation of this ATC model is that the method acknowledges the influence of perceived control (whether people feel in control over their thermal environment or not, regardless of the real possibilities of control). With greater perceived control, the tolerance regarding the thermal environment significantly increases. However, this influence is hard to quantify and the adaptive method does not propose a method to do so (Alders, 2016). The Adaptive Temperature Model better predicts the thermal sensation in non-conditioned spaces or situations with high level of control than the PMV model; however, in the way they are applied now in the standards, they still regard average people and the same standards are too easily applied transregionally without regarding the differences of different populations. From the thermal comfort models developed from the 1930s, the standards based on the adaptive comfort models (for example, ASHRAE 55 (ASHRAE, 2004) or EN15251 (EN-ISO, 2007)) best describe the situation in living rooms (Ubbelohde et al., 2003). However, all of these standards were developed for offices which means that they don't per say comply to other uses (residential like in the FEEdBACk Lippe case, or sports buildings and other amenities like in the FEEdBACk Barcelona case). Therefore, a translation needs to be made to the context of the dwelling and to make further improvements.

3.4 MEASUREMENTS ON THE THERMAL ENVIRONMENT

The measurement instrumentation used for evaluation of the thermal environment shall meet the requirements given in EU standard EN ISO 7726. Measurements shall be made where occupants are known to spend most of their time and under representative weather condition of cold and warm season. For the winter (heating season) measurements at or below mean outside temperatures for the 3 coldest months of the year, and for the summer (cooling season) measurements at or above statistic average outside temperatures for the 3 warmest months of the year with clear sky. The measurement period for all measured parameters should be long enough to be representative, for example 10 days. Air temperature in a room can be used in long term measurements and corrected for large hot or cold surfaces to estimate the operative temperature of the room.

3.5 INDIVIDUAL AND CULTURAL DIFFERENCES

There can be all kinds of factors that determine the differences in thermal preference such as age, gender, posture, or culture. A few of these aspects have been researched by testing subjects in different categories to try improve predict thermal preference of a specific group. In various studies it has been concluded that women are more sensitive to thermal discomfort, both hot and cold and that in general they prefer a slightly higher temperature (Karjalainen, 2012) and that they are more sensitive to local discomfort (Schellen et al., 2012). Furthermore, differences have been found in vulnerability between young adults and elderly. Elderly people are more comfortable in warmer indoor environments compared to younger people (Schellen et al., 2010; Bockelandt & De Mûelenaere, 2007). Aged people have a thermal sensation that is approximately 0.5 lower (see Table 2) than their younger counterpart, which makes them particularly vulnerable to cold. Additionally, they have been proven to recover from cold more slowly (Kingma & van Marken Lichtenbelt, 2015). However, this does not have an influence on the thermal sensation as felt during mild temperature drift (Schellen et al., 2010). Gender is also an influence on experienced comfort. Women have on average a higher surface-area-to-volume ratio, a lower size, and a higher surface-area-to-mass ratio and it is to be expected that women in general prefer high temperatures than men (Kumar Mishra & Ramgopal, 2013; Parsons, 2002). Finally, especially relevant to the FEEdBACk project, the human body adapts to the predominate climate. People in warmer areas prefer warmer indoor temperatures (Humpreys, 1976; De Dear et al., 1997; Nicol et al., 1999; Frontczak & Wargocki, 2011).

These differences in thermal preferences emphasizes the importance of control over (some aspects of) the indoor environment for comfort. Moreover, various studies point out that generally people prefer thermal circumstances at which they are exposed most. Needless to say, this varies with lifestyle, occupation, and culture. Other differences in thermal preferences occur due to the required function of the building. People expect and demand other indoor environmental qualities from an office building compared to a residential building. For example, people may put in more effort for the right indoor environment of their own home compared to their offices.

Other aspects play a significant role in the experience of comfort as well. A feeling of discomfort may not be caused by the actual temperature, but by feelings of lack of control, by air quality problems, visual effects or even illness of the perceiver. The quality of the comfort system needs to be assessed in terms of the relative ease to reach comfort status, flexibility, and energy needed to reach it rather than the actual comfort temperature reached in simulations. Criteria for local thermal discomfort such as draught, radiant temperature asymmetry, vertical air temperature differences and floor surface temperatures need to be taken into account too (when (re)designing building and HVAC systems). These criteria can be found in ISO EN 7730 or national codes.

The feeling of control plays an important role in (dis)comfort, which has been extensively researched. In air-conditioned buildings designed with the Fanger model, the indoor climate is imposed on the users (Chappells & Shove, 2005; Vroon, 1990). Having to comply with a particular climate which has been determined by someone else can have negative psychological impact (Vroon, 1990; De Dear, 2004; Humpreys et al., 2007; Brager et al., 2004; Leaman & Bordass, 2007). People therefore want to have (some) control over their environment. Control over the indoor environment has been shown to increase the feeling of ownership over the object (Pierce et al., 2003). The user is then a co-designer of the indoor environment (Leaman & Bordass, 2001). This shows the non-technical importance of control over aspects of the indoor environment, like being able to open or close windows and adjust the HVAC. More control and therefore more ability to adjust the indoor environment to their personal needs may create a stronger bond between comfort, user, and the required energy (Chapman, 2015; De Dear, 2004; Pierce et al., 2003). A research on off-grid houses in Canada shows this effect, where people are prepared to make a greater effort in order to ensure they have gathered enough energy for their home (and create a more desirable indoor environment), but also be more economical with that energy (Vannini & Taggart, 2014). Therefore, (active) control and responsibility over their own comfort and energy-use may have a beneficial effect on both comfort and energy-use.

Another aspect of indoor discomfort is precisely because of air-conditioned buildings. Thermal neutral and full air-conditioned buildings do not stimulate people enough (Stoops, 2006; Vroon, 1990). Thus, people are getting less adept at coping with both colder and warmer temperatures (Van Marken Lichtenbeld & Schrauwen, 2011). When the temperature of the building is set at 22° C, people will get used to that temperature and eventually experience this as the most comfortable temperature (Oseland & Humpreys, 1994). If that temperature is held at a very constant level, people will experience even small shift in temperature as uncomfortable (De Dear & Brager, 2002). Therefore, keeping the temperature strictly at a certain temperature may not be the optimal solution for the users.

Users may also experience discomfort in a building due to problems with operating the control panels of the installed climate systems (Brown & Cole, 2009). They may fail to operate them or operate them in the wrong way. Insufficient feedback on the performed actions is also problematic. This way the users do not know the results of their actions, which may take longer to notice. Moreover, users tend to take the most obvious course of action to mitigate their environmental discomfort and do so when the discomfort is already quite large (Brown & Cole, 2009).

There is a large number of studies that show that spaces with the following characteristics cause more health issues and lower appreciation of thermal comfort (Leijten & Kurvers, 2007);

- Cooling, humidification and recirculation of ventilated air;
- Air treatment by means of induction units;
- Insufficient control on the affected temperature per space;
- Windows that cannot be opened for any reason;

- High density of users per space in large working areas.

A survey in 95 office buildings in the United States (Mendell & Mirer, 2009) shows that in winter more health issues occur when the temperature is on the warm side of the comfort margin. In summer there are more symptoms when the temperatures measured are lower than the comfort area. In summer many buildings were found to be colder than they should be according to the standards. Therefore, there are more health symptoms when buildings are chilled too much in summer and when they are heated too much in winter. Because it also leads to unnecessary energy use, it is wise to avoid over-conditioning of the space.

3.6 VISUAL COMFORT AND RELATION TO (DIS)COMFORT

Visual comfort is also an important aspect in peoples perceived comfort. The visual requirements posed on a room have the goal to make this room appear pleasant to the people occupying it. As with thermal comfort, the visual perception and also the taste of individual users can vary significantly. In this, windows play an important role regarding the experience by users of indoor spaces. Besides of natural daylight they also provide a view to the outside. But as windows also play an important role related to (incoming heat, overheating and outgoing heat losses), strongly depending on quality of framing and glass, it is an aspect to consider.

The human eye is sensitive to radiation with wavelengths from about 380 to 750 μm. These wavelengths correspond to the radiation peak of the solar spectrum on earth, the daylight spectrum. The eye is attuned to this daylight spectrum through evolution. The wavelength of light is an important factor. The spectral quality of daylight is very difficult to imitate artificially and it is therefore that electrical light sources have a different spectral distribution than natural light. Electrical light usually lacks the blue portion of the daylight spectrum and it is particularly this portion that is thought to be most important for the biological functioning of the human body (Brainard 2006). The daylight spectrum provides the highest levels of light needed for biological functions. The biological function that is most clearly affected by daylight is the circadian system. Four main circadian biological rhythms – cycles of approximately 24 hours – can be distinguished: secretion of melatonin and cortisol (both hormones), alertness and body temperature (Veitch et al., 2004).

In general, people prefer to be close to a window and daylight is deemed more comfortable than artificial lighting (Hasselaar, 2013). This is also, as our body is accustomed to the dynamic nature of daylight, which influences our sleep-wake rhythm. Research has shown that direct sunlight and a view reduce stress and illness (Hellinga, 2013). People prefer a wide view with natural elements over a narrow one with built-up areas, which is reflected in satisfaction rates of office employees with their jobs, recovery of hospital patients and the general wellbeing of people. The benefit of a good view also is expressed by the increased prices charged for hotel rooms, apartments or other real estate with (better) views (ibid).

The access of daylight through a window can lead to glare, of which two kinds can be distinguished: discomfort glare and disability glare. Discomfort glare creates nuisance caused by high light intensity levels, but observation of objects is not impossible, in contrast to disability glare, where the difference in light intensity is so high, that it is no longer possible to observe objects. Discomfort glare is subjective and very difficult to predict. It is, among others, dependent on lighting level, quality of the view and the distance of the workplace to the window (Hellinga, 2013). Also the productivity of people can be influenced by the quality of lighting; and therefore affects working hours and indirectly energy use (Hasselaar, 2013). It is, however, difficult to demonstrate to which extent certain lighting conditions influence productivity, as other factors, such as thermal comfort, have a larger influence (ibid).

The humidification of indoor air is usually not needed. Humidity has only a small effect on thermal sensation and perceived air quality in the rooms of sedentary occupancy; however, long term high humidity indoors will cause microbial growth, and very low humidity (<15-20%) causes dryness and irritation of eyes and air ways. Requirements for humidity influence the design of dehumidifying (cooling load) and humidifying systems and will influence energy consumption. The criteria depend partly on the requirements for thermal comfort and indoor air quality and partly on the physical requirements of the building (condensation, mould etc.) For special buildings (museums, libraries, historical buildings, churches) additional humidity requirements must be taken into account. This holds for example for the library in FEEdBACk's Barcelona case. Humidification or dehumidification of room air is usually not required but if used excess humidification and dehumidification avoided. The correct values can be determined using Table B3 of Annex B in the EN12521 document (CEN, 2007).

As daylight levels are much lower indoors, in most countries regulations or standards concern indoor lighting. The design luminance levels can be secured by means of daylight, artificial light or a combination of both. For reasons of health, comfort and energy in most cases the use of daylight (maybe with some additional lighting) is preferred over the use of artificial light. Of course this depends on many factors like standard occupancy hours, autonomy (portion of occupancy time during which there is enough daylight), location of the building (latitude), amount of daylight hours during summer and winter, etc. To make sure that at least a reasonable amount of occupancy time daylight can be used, it is recommended to set demands on the daylight penetration in the spaces meant for human occupancy. EU standard EN 15193 (see Annex 1 for listing) provides details of occupancy periods and daylight availability and estimations. When it comes to illuminance a distinction in categories seems less appropriate than e.g. for temperature and fresh air supply.

The existing rules can be divided in four categories: rules concerning illuminances (the total luminous flux incident on a surface per unit area (1 lm/m^2); or a measure for the received light), rules concerning daylight factors (which is a percentage ratio of the illuminance at a point (indoors or outdoors) to the outdoor illumination level occurring simultaneously on a horizontal plane under an unobstructed hemisphere of overcast sky), rules concerning (relative) window size and rules for building dimensions and distances (obstruction angles). The purpose of most of these rules is to guarantee enough light for visual tasks (but they also (co) determine related energy use in the rooms). These light levels may partly be provided by artificial lighting and are lower than those needed for the regulation of the human circadian system. In addition to minimum equivalent daylight areas, the British and German standards recommend average daylight factors for specific spaces. For an office, the window requirements stipulate a window at eye level when sitting to provide view and daylight, combined with preferably minimum window size of at least 0.5 m^2 and at least 2.5% of the floor area.

The required task illuminance for non-residential buildings is defined and detailed in EU standard EN 12464-1 (see Annex 1 for overview). For sports lighting (in one of FEEdBACk's Barcelona's cases) EN 12193 can be used.

3.7 ACOUSTICAL COMFORT AND RELATION TO (DIS)COMFORT

Sound has auditory as well as extra-auditory effects on well-being (Passchier-Vermeer and Passchier, 2000; Stansfeld et al., 2000; Ising and Kruppa, 2004). Auditory effects, such as acoustic trauma (acute hearing damage caused by a sudden and extremely loud sound, e.g. explosion, gunshot, etc.), tinnitus (ringing of the ears) and hearing loss, are most likely to occur from occupational and social noise exposure (Pijpers-Van Esch, 2015). These extra-auditory are highly related to the occurrence of annoyance and related stress, causing significant health-effects for a possibly a considerable part of the population; according to the WHO about half of the people living in EU countries are exposed to traffic sound levels that can cause annoyance (ibid).

Since sound is related to (disturbance of) concentration, intelligibility of speech and the risk of hearing loss. It's relation with FEEdBACk's focus (energy) is that regulations related to the acoustic climate affect energy use and in particular HVAC or other systems related to climatization. Sound is expressed in decibel, or db. Since the human ear is not equally sensitive to sounds at different frequencies, a separate unit is introduced that factors in that the ear is less sensitive to especially lower, and to some extent also higher frequencies: decibel A or dB(a). The lowest sound level a healthy ear can distinguish is (by definition) 0 dB; the highest level at which sound becomes painful is around 140 dB (hearing loss can occur after prolonged exposure to sound levels of 80 dB(A)).

Within this context it is important that devices for climate control need to adhere preferably to the minimum demands regarding sound pressure level in the diverse regulatory frameworks of the different countries, which imply: no higher than 45dB(A), and preferably lower than 35 dB(A). These criteria apply to the sources from the building as well as the noise level from outdoor sources. The criteria should be used to limit the sound power level from the mechanical equipment and to set sound insulation requirements for the noise from outdoors and adjacent rooms.

4. AIR QUALITY

4.1 INTRODUCTION

Air pollution is one of the most serious health hazards. It is estimated that more than two million people die prematurely each year as a consequence of air pollution related diseases (WHO, 2006). The most important pollutants are: particulate matter, ground-level ozone, nitrogen dioxide and sulphur dioxide. These pollutants are present in a vast majority of urban areas and have serious health effects.

4.2 POLLUTANTS AND THEIR EFFECTS ON PHYSICAL WELL-BEING

Particulate matter (PM) is a mixture of extremely small solid and liquid particles suspended in the atmosphere. PM is usually divided in two components: a coarse component of parts smaller than 10µm but larger than 2,5µm (PM10) and a finer component of parts smaller than 2,5µm (PM2,5). Mechanical processes, such as building activities, as well as re-suspension of dust and sea salt by wind are the main sources of the coarse component of PM10. The fine fraction consists mainly of products of combustion processes, such as the combustion of fossil fuels and biomass and secondary particles, transported over long ranges (Vallius et al., 2005). This fine fraction is thought to be the most hazardous to human health as it can penetrate deeper into the lungs and veins.

Exposure to particulate matter contributes to the risk of developing cardiovascular and respiratory diseases, as well as lung cancer (WHO, 2011). The effects aggravate with exposure duration because of accumulation, and therefore the long-term health effects are of most concern. Especially PM from diesel exhaust seems to be hazardous to health (Bernstein et al., 2004). In the EU, average life expectancy is over eight months lower due to exposure to PM2.5 produced by human activities (WHO, 2011). Research has shown that all day mortality increases with increase in PM10, as well as hospital admissions for asthma and chronic obstructive pulmonary disease (disorders of the long causing shortness of breath, persistent coughing and frequent chest infections) among elderly people and admissions for cardiovascular disease (Brunekreef and Holgate, 2002).

Ozone (O3) on ground level can cause lung inflammation and decreased lung function, which may lead to premature death. The health effects of ozone arise within a very short term of a few hours. The effects are worse for asthma patients (Bernstein et al., 2004; WHO, 2003). Ozone is produced by human sources as well as natural sources (mainly volatile organic compounds from plants) and therefore threshold concentrations can be exceeded by natural production. Ground-level ozone concentrations are expected to increase in the future as a result of higher temperatures (Kinney, 2008).

Nitrogen dioxide (NO_2) is a poisonous gas that in high concentrations has harmful effects on a short term. These high concentrations, however, are not found in the outdoor environment. Through a photochemical reaction NO_2 reacts with carbohydrates to ground-level ozone, which is a main constituent of smog. Photochemical reactions with NO_2 also leave nitrate particles, which form a large fraction of PM2,5.

The most important function of NO_2 is its use as a marker for traffic related pollutants, such as particulate matter, nitrogen oxides, and benzene. This mixture of pollutants is thought to have significant health impacts. Bronchitic symptoms of children increase with elevated concentrations of NO_2. Long-term elevated NO_2 concentrations are also linked with reduced lung function growth in children (WHO, 2011, 2003).

Sulphur dioxide (SO_2) is a product of the combustion of fossil fuels such as coal and oil. It is also released into the atmosphere in large quantities during volcanic eruptions. Health effects of SO_2 are decreased functioning of the pulmonary system and respiratory system, which may lead to premature death. As with ozone, the effects are worse for asthma patients. It is still uncertain whether these effects can be attributed to SO_2 alone or that it is a marker for a mixture of pollutants containing SO_2 (WHO, 2003).

4.3 AIR QUALITY GUIDELINES

It is possible to design for different categories of indoor air quality, which will influence the required ventilation rates. The different categories of air quality can be expressed in different ways (combination of ventilation for people and building components, ventilation per m^2 floor area, ventilation per person or according to required CO_2 level). The ventilation rates for air quality are independent of season. They depend on occupancy, indoor activities (i.e. smoking, cooking, cleaning, washing) processes (like copiers in offices, chemicals in school buildings, etc.) and emissions from building materials as well as furniture.

Maximum allowable concentrations of pollutants in the outdoor environment are regulated on European level. The Directive 2008/50/EC prescribes threshold values of concentrations that can be exceeded for a limited number of times. An overview of the EU regulations for the aforementioned pollutants is given in Table 3. These values are higher than the air quality guideline values proposed by the World Health Organization (Table 4), but most values comply with the WHO interim target values proposed as incremental steps in a progressive reduction of air pollution.

TABLE 3 – Directive 2008/50/EC values for different pollutants

Pollutant	Concentration	Averaging period	Permitted events of exceeding each year
$PM_{2.5}$	25 µg/m3	1 year	
PM_{10}	50 µg/m3	24 hours	35
	40 µg/m3	1 year	
Sulphur dioxide	350 µg/m3	1 hour	24
	125 µg/m3	24 hours	3
Nitrogen dioxide	200 µg/m3	1 hour	18
	40 µg/m3	1 year	
Ozone	120 µg/m3	Maximum daily 8 hour mean	25 days averaged over 3 year

TABLE 4 – WHO guidelines for air quality (2006)

Pollutant	Concentration	Averaging period
PM2.5	10 μg/m3	1 year
	25 μg/m3	24 hours
PM10	20 μg/m3	1 year
	50 μg/m3	24 hours
Sulphur dioxide	20 μg/m3	24 hours
	500 μg/m3	10 minutes
Nitrogen dioxide	40 μg/m3	1 year
	200 μg/m3	1 hour
Ozone	100 μg/m3	8 hours

Outdoor pollutants enter the building through ventilation and infiltration. Outdoor air quality thus influences indoor air quality. In the design and operation, the main sources of pollutants should be identified and eliminated or decreased by any feasible means. The remaining pollution is then dealt by local exhausts, and ventilation.

The European standard organization proposes design criteria for ventilation in non-residential buildings (applying to FEEdBACk's Porto and Barcelona demo sites in the report EN 13779 (EN15251) (Table 5). For most functions, the guideline proposes higher air changes rates than the Buildings Decree; the values prescribed by the Buildings Decree can be regarded as an absolute minimum.

TABLE 5 – Air change rates advised by CR 1752 (CEN 1998). Category A, B and C refer to a high, medium and moderate level of expectation with regard to environmental quality for low-polluting buildings.

Type of building/space	Occupancy m² per person	Category	Ventilation rate l/s per m²
Single office (cellular)	10.0	A	2.0
		B	1.4
		C	0.8
Landscaped office	15	A	1.7
		B	1.2
		C	0.7
Conference room	2.0	A	6.0
		B	4.2
		C	2.4
Auditorium	0.75	A	16
		B	11.2
		C	6.4
Cafeteria or restaurant	1.5	A	8.0
		B	5.6
		C	3.2
Classroom	2.0	A	6.0
		B	4.2
		C	2.4
Kindergarten	2.0	A	7.0
		B	4.9
		C	2.8
Department store	7	A	4.1
		B	2.9
		C	1.7

Related to indoor air quality in non-residential, guidelines could be given to promote natural ventilation of buildings. Such guidelines might address the influence of the orientation and spacing of buildings on air pressure differences between inlets and outlets, as well as the location of inlets and outlets in relation to outdoor air quality. The regulations and guidelines mentioned above are difficult to use for re-design purposes since no spatial information is included. Because the dispersion of pollutants is closely related to air flow (draught), the guidelines could be complemented with information on spatial configurations that support the removal of polluted air from (different types of) spaces (spatial configurations). Also, for residential buildings (FEEdBACk's Lippe case) indoor air quality depends on many parameters and sources, like number of persons (time of occupation), emissions from activities (smoking, humidity, intensive cooking), emissions from furnishing, flooring materials and cleaning products, hobbies etc. Humidity is of particular concern in residential ventilation as most of adverse health effects and building disorder (condensation, moulds,) is related to humidity. Several of these sources cannot be influenced or controlled by the designer.

Required design ventilation rates in general are specified as an air change per hour for each room, and/or outside air supply and/or required exhaust rates (bathroom, toilets, and kitchens) or given as an overall required air-change rate. Most national regulations and codes give precise indications on detailed airflows per room and shall be followed. These values can be determined using Table B5 of Annex B in the EN12521 document (CEN, 2007). Ventilation rates in naturally ventilated buildings are calculated based on building layout, location and weather conditions according to EU standard EN15242. Even during unoccupied periods minimum ventilation for the buildings should be provided. If national regulations and codes are not available, recommended values from Annex B4 of the EN12521 document may be used (CEN, 2007).

Both for residential and non-residential buildings filtration and air cleaning can be undertaken (depending on in- and outdoor air qualities). Although filtration is usually dimensioned for maintaining equipment performance, it can also be used to improve indoor air quality with:

- Treatment of outdoor air in very polluted area
- Limiting the entry of pollens from outdoors
- Removal of odours and gaseous contaminants (gas phase air cleaning).

Design guidelines on air cleaning and filtration are given in EN13779 and ISO DIS 16814.

The humidification of indoor air is usually not needed. Humidity has only a small effect on thermal sensation and perceived air quality in the rooms of sedentary occupancy; however, long term high humidity indoors will cause microbial growth, and very low humidity (<15-20%) causes dryness and irritation of eyes and air ways. Requirements for humidity influence the design of dehumidifying (cooling load) and humidifying systems and will influence energy consumption. The criteria depend partly on the requirements for thermal comfort and indoor air quality and partly on the physical requirements of the building (condensation, mould etc.) For special buildings (museums, libraries, historical buildings, churches) additional humidity requirements must be taken into account. This holds for example for the library in FEEdBACk's Barcelona case. Humidification or dehumidification of room air is usually not required but only used to avoid excess humidification and dehumidification. Chapter 5 will go into detail on the rules and regulations regarding humidity.

5. DEMONSTRATION SITES REQUIREMENTS

5.1 INTRODUCTION

This chapter aims to give more concrete comfort and indoor air quality (IAQ) requirements amongst the regulations and standards. Some of these will be based on the EU regulations, and some, where possible, more local rules will be applied. A framework of IAQ requirements will be giving per building type or space. For an accurate and effective segmentation, the choice has been made to distinguish between the following building type/spaces:

- Residential buildings (Lippe)
- Office buildings (Porto and Barcelona)
- Office areas: Conference/meeting room, auditorium, computer room (Porto and Barcelona)
- Restaurants/bars/cafeteria (Porto and Barcelona)
- Communal areas of non-residential buildings (Porto and Barcelona)
- Library Restaurants/bars & School/classrooms (Barcelona)
- Sport/amenities buildings (Barcelona)

Table 6 shows the overview of the different building types/spaces in the FEEdBACk demonstration site buildings. For more information on the layout and the technical setup of the demonstration sites, see the FEEdBACk document D5.1. This categorisation ensures the general requirements for these buildings will be met. This is still not a perfect categorisation, since typically buildings do not merely serve one function. Different spaces of the library building have different requirements (regulations and standards) than the rest of the library building. Moreover, it is impossible to specify a thermal environment that will satisfy everybody, also due to the individual differences mentioned in section 3.5. However, this chapter aims to provide general guidelines and recommendations and put side notes where relevant.

Generally, for the buildings in Porto and the residential buildings in Lippe, the European guidelines for indoor thermal environment from the overarching document EN 15251 will be used. For the buildings in Barcelona, the indoor air quality design should follow the “Reglamento de instalaciones térmicas en los edificios”, or “RITE”. This document from 2007 stipulates the regulations for thermal installations in buildings. For the other aspects of the thermal environment for the buildings in Barcelona the European guidelines from EN 15251 will be used.

This chapter will be organized as follows: Firstly, the requirements for the Porto demonstration site will be discussed. Next, the requirements for the Barcelona demonstration site will be discussed. Finally, the Lippe residential demonstration site will be discussed. For each subchapter, the temperature range, the CO_2 level requirements (plus humidity where applicable), and the luminosity requirements for the different buildings in the different demonstration sites will be discussed.

TABLE 6– Overview of the characterisation and building type/space of the different buildings of the FEEdBACk demonstration sites.

Demonstration site	Number of buildings	Name of buildings	Function of building	Building type /space in building
Porto	2	INESC-TEC headquarters	Office	Single office Open space office Conference room Auditorium Restaurants Communal areas
Lippe	30 – 40	Dörentrup village	Dwellings	Residential living spaces Residential other spaces
Barcelona	1	Municipal Offices, carrer Centre 26-30	Office	Single office Open space office Conference room Communal areas
Barcelona	1	Municipal Offices, carrer Major 2-4	Office	Single office Open space office Conference room Communal areas
Barcelona	1	Economic Promotion Centre	Office	Single office Open space office Conference room Auditorium Communal areas

Demonstration site	Number of buildings	Name of buildings	Function of building	Building type /space in building
Barcelona	1	Cultural centre “La Capsa”	Cultural centre	Single office Landscaped office Conference room Auditorium Restaurant/bar areas Communal zones
Barcelona	1	Community centre “Jardins de la Pau”	Cultural centre	Single office Open space office Conference room Auditorium Computer rooms Restaurants Communal areas Classrooms
Barcelona	1	Cultural centre Centric	Cultural centre	Single office Conference room Auditorium Computer rooms Restaurant/bar areas Communal zones Library Classrooms
Barcelona	1	“Delta del Llobregat” Job Training School	Education centre	Single office Landscaped office Conference room Auditorium Communal zones

Demonstration site	Number of buildings	Name of buildings	Function of building	Building type /space in building
Barcelona	1	Adult school "Terra Baixa"	Education centre	Conference room Auditorium Computer rooms Communal zones School Classrooms
Barcelona	1	CEM "Estruch"	Sport centre	Single office Restaurant/bar areas Communal zones Sports centre Swimming pool area
Barcelona	1	CEM "Sagnier"	Sport centre	Single office Conference room Restaurant/bar areas Communal zones Sports centre Swimming pool area

5.2 PORTO DEMONSTRATION SITE

5.2.1 INTRODUCTION

For the office buildings of Porto the European guidelines from EN 15251 will be used. As stated in Section 3.2.2, the classification of thermal environment of these buildings are category B. For this category, all of the following requirements should be met (as stated in Table A.1 of EN-ISO 7730): For the thermal state of the body as a whole, the PPD (Predicted Percentage of Dissatisfied) should be less than 10%. The PMV (Predicted Mean Vote) should be between -0.5 and + 0.5. This means that a maximum of 10% of occupants may be dissatisfied with the indoor thermal environment, with dissatisfied meaning a score of below -0.5 or above +0.5. For the local discomfort, the DR (Draught Rate) should be below 20%. Further, the PD (Percentage Dissatisfied) caused by vertical air temperature difference should be below 5%, by warm or cold floor should be below 10%, and by radiant asymmetry should be below 5%. In order to meet these requirements, the following required temperature (range) settings and CO_2 concentrations should be followed.

5.2.2 TEMPERATURE REQUIREMENTS

Using the information from EN-ISO 7730 for category B buildings, the required operative temperature range for the different types of buildings can be determined. The criteria for the thermal environment are based upon typical levels of activity and on the season (due to different clothing). Therefore, a required minimum operative temperature for the winter season (heating) can be established, as well as a required maximum operative temperature for the summer season (cooling). Further, a required temperature range can be established for the two seasons, which fulfil the requirements for the category B buildings. The overview can be seen in Table 7.

TABLE 7– Porto operative temperature range according to EN 15251 and EN ISO 7730. The table shows the minimum temperature for heating in the winter season and the maximum for cooling in the summer season. Below the temperature value is the operative temperature range for the winter and summer. Below each building (type) the associated level of activity is stated with the corresponding met-values (Metabolic Equivalent of Task), with 1 met corresponding to the activity of sitting at rest.

Porto Building type or space	Operative temperature (°C)	
	Minimum for heating (winter season temperature range)	Maximum for cooling (summer season temperature range)
Single office (cellular office) **Landscaped office (open plan office)** **Sedentary ~ 1.2 met**	20.0 (20.0 – 25.0)	26.0 (23.0 – 26.0)
Conference room **Auditorium** **Computer rooms** **Restaurant/bar areas** **Sedentary ~ 1.2 met**	20.0 (20.0 – 25.0)	26.0 (23.0 – 26.0)
Communal zones of non-residential buildings **Standing-walking ~ 1.6 met**	16.0 (16.0 – 22.0)	25.0 (21.0 – 25.0)

The design temperature range (temperature range summer and winter) in Table 7 can vary from the values shown to take account for local customs, desire for energy saving, outdoor temperature, etc., as long as the within-day variation from the design temperature is within the given range, and the occupants are given time and opportunity to adapt to the modified design temperature (from EN 15251).

5.2.3 INDOOR AIR QUALITY REQUIREMENTS

Next, there is no common standard index for the indoor air quality in terms of ventilation rates. The indoor air quality is influenced by emission from people and their activities (bio effluent, smoking, etc.), from building and furnishing, and from the HVAC system itself. The required ventilation is based on health and comfort criteria. The health criteria deal mainly with the allowed concentration of (harmful) substances in the air. The comfort criteria deal mainly with the perceived air quality: odour, irritation. For the comfort aspect, there is no general agreement of how much of the different sources of emissions is allowed. Therefore, air quality requirements serve to prevent too much emissions building up in a particular space. Since ventilation rates are not directly measured in the FEEdBACk project, the information on the recommended CO_2 concentration from the EU standards will be applied.

The recommended CO_2 concentration are determined by the outdoor CO_2 concentration. According to EN 15251, the recommended CO_2 concentration for the non-residential FEEdBACk buildings is 500 ppm above outdoor CO_2 ppm. According to the ASHREA standard, a CO_2 concentration of no higher than 700 ppm above outdoor CO_2 concentration will meet the requirements. With the average outdoor CO_2 ppm of between 350 and 500 ppm, this gives a recommended indoor CO_2 concentration of between 850 and 1000 ppm with an upper limit of 1200 ppm. Since more recent research suggests an indoor CO_2 ppm of 800 for better indoor comfort and health, this is set as the preferred lowest CO_2 ppm of the range (Muhamad et al., 2011; Van Loon & Van Morgen. 2012; Drijver et al., 2010). The overview of the CO_2 recommendations can be seen in Table 8.

Humidity is another relevant aspect of the indoor air. As stated in chapter 4, long term high humidity indoors will cause microbial growth, and very low humidity (<15-20%) causes dryness and irritation of eyes and air ways. Requirements for humidity influence the design of dehumidifying (cooling load) and humidifying systems and will influence energy consumption. When the humidity of a room is not extremely low or high, humidification or dehumidification of room air is usually not required. When (de)humidification is applied, the correct values of humidity for the Porto buildings can be determined using the EN12521 document (CEN, 2007). For all Porto buildings, where humidity criteria are set by human occupancy, the design relative humidity for dehumidification is 60% and for humidification is 25%. Besides, it is recommended to limit the absolute humidity to 12g/kg (see Table 8).

TABLE 8– Porto recommended CO_2 range and upper limit and relative humidity range according to EN 15251 and the ASHRAE standard (2016). The second column gives the recommended indoor CO_2 concentration above the outdoor concentration with the upper limit in parenthesis. Using the average outdoor CO_2 concentration range of between 350 – 500 ppm, the absolute indoor CO_2 range is given in the third column with the upper limit in parenthesis.

Porto Building type or space	Recommended indoor CO_2 concentrations (ppm)		Recommended relative humidity (%)
	Relative to outdoor CO_2 concentrations (upper limit)	Absolute range (upper limit)	Range for (de)humidification
Single office (cellular office) **Landscaped office (open plan office)**	500 (700)	800 – 1000 (1200)	25 - 60
Conference room **Auditorium** **Computer rooms** **Restaurant/bar areas**	500 (700)	800 – 1000 (1200)	25 - 60
Communal zones of non-residential buildings	500 (700)	800 – 1000 (1200)	25 - 60

5.2.4 LUMINOSITY REQUIREMENTS

The luminosity requirements for the Porto buildings follow the guidelines stipulated by EN 15251, EN 12193, and EN 12464-1. These guidelines concern maintained illuminances ($\hat{E}_m$: the total luminous flux incident on a surface per unit area (1 lm/m^2, or lx), the maximum UGR (Unified Glare Rating) value for the glare in rooms, and the colour rendering index (CRI) in Ra units. The purpose of most of these rules is to guarantee enough light for visual tasks (but they also (co) determine related energy use in the rooms). These light levels may partly be provided by artificial lighting and are lower than those needed for the regulation of the human circadian system. The overview of luminosity requirements for the Porto buildings can be seen in Table 9.

TABLE 9– Porto luminosity requirements according to the EN 15251, EN 12193, and EN 12464-1. The second column gives the recommended maintained luminance at working areas (lx). The third column shows the UGR (Unified Glare Rating) value, the forth the colour rendering index (Ra), and the fifth column shows addition remarks.

Porto Building type or space	Maintained luminance, Êm, at working areas (lx)	UGR	Ra	Remarks
Single office (cellular office) **Landscaped office (open plan office)**	500	19	80	at 0.8 m
Conference room **Auditorium**	500	19	80	at 0.8 m
Computer rooms	300	19	80	-
Restaurant/bar areas	-	-	80	at 0.8 m
Communal zones of buildings	100-300	22-25	40-80	at 0.8 m dependent on further properties

5.3 BARCELONA DEMONSTRATION SITE

5.3.1 INTRODUCTION

For the buildings in Barcelona, the indoor air quality design should follow the “Reglamento de instalaciones térmicas en los edificios”, or “RITE”. The RITE regulates temperature, humidity, ventilation and CO_2 concentrations in buildings. For the other indoor air quality aspects, the EN15251 document of EU regulations will be applied. The RITE distinguishes buildings in 4 categories for indoor air quality based on the building use. These indoor air quality categories (IDA’s) are the minimum requirements of this type of building. The following categories are described:

- IDA 1 (optimum air quality): Hospitals, clinics, laboratories, and nurseries.

- IDA 2 (good air quality): Offices, residences (communal zones in hotels and similar, residences for students and the elderly), reading rooms, museums, libraries, tribunals, classrooms, swimming pools and similar.

- IDA 3 (medium air quality): Commercial buildings, cinemas, theatres, meeting rooms, hotel bedrooms and similar, restaurants, cafeterias, bars, dance halls, gymnasiums, sport premises (except pools) and computer rooms).

- IDA 4 (low air quality).

Using this categorisation, the following applies (see Table 10):

TABLE 10 – Indoor air quality category (IDA) of Barcelona buildings according to the RITE.

Building Barcelona	IDA categorisation
Office building/areas	2
Computer rooms	3
Restaurant/bar areas	3
Communal zones buildings	2
Library	2
School	2
Classrooms	2
Sports centre	3
Swimming pool area	2

5.3.2 TEMPERATURE REQUIREMENTS

The temperature requirements for the Barcelona buildings of FEEdBACk follow the same requirements and recommendation as stipulated for Porto in Section 5.2.2. These requirements are updated by the 'Reglamento de Instalaciones Termicas en los Edificios' 2013 document by the Ministry of Industry, Energy and Tourism. In Table 11 the overview of temperature requirements for the different buildings is given.

TABLE 11– Barcelona operative temperature range according to EN 15251 and EN ISO 7730. The table shows the minimum temperature for heating in the winter season and the maximum for cooling in the summer season. Below the temperature value is the operative temperature range for the winter and summer. Below each building (type) the associated level of activity is stated with the corresponding met-values (Metabolic Equivalent of Task), with 1 met corresponding to the activity of sitting at rest.

Barcelona Building type or space	Operative temperature (°C)	
	Minimum for heating (winter season temperature range)	Maximum for cooling (summer season temperature range)
Single office (cellular office) **Landscaped office (open plan office)** **Sedentary ~ 1.2 met**	20.0 (20.0 – 21.0)	26.0 (25.0 – 26.0)
Conference room **Auditorium** **Computer rooms** **Restaurant/bar areas** **Library** **Sedentary ~ 1.2 met**	20.0 (20.0 – 21.0)	26.0 (25.0 – 26.0)
Communal zones of non-residential buildings **Standing-walking ~ 1.6 met**	16.0 (16.0 – 21.0)	26.0 (25.0 – 26.0)
School **Classrooms** **Sedentary ~ 1.2 met**	20.0 (20.0 – 21.0)	26.0 (25.0 – 26.0)

Barcelona Building type or space	Operative temperature (°C)	
	Minimum for heating (winter season temperature range)	Maximum for cooling (summer season temperature range)
Sports centre	20.0 (20.0 – 30.0)	26.0 (26.0 – 30.0)
Swimming pool	20.0 (20.0 – 30.0)	26.0 (26.0 – 30.0)

The design temperature range (temperature range summer and winter) in Table 11 can vary from the values shown to take account for local customs, desire for energy saving, outdoor temperature, etc., as long as the within-day variation from the design temperature is within the given range, and the occupants are given time and opportunity to adapt to the modified design temperature (from EN 15251).

5.3.3 INDOOR AIR QUALITY REQUIREMENTS

The indoor air quality in terms of ventilation rates and CO_2 concentration should follow the more local rules and regulations of the RITE wherever possible. For the recommended CO_2 concentration for the Barcelona buildings, two types of areas in buildings have to be distinguished: Areas without an elevated metabolic activity (e.g. office areas, libraries) and areas with either an elevated metabolic activity or an elevated production of contaminants (e.g. restaurant/bar areas, sport areas, pool areas).

Following the RITE, the direct method of CO_2 concentration is intended for spaces with an elevated metabolic activity and/or an elevated production of contaminants. The allowed CO_2 concentration in a building space/area is expressed in ppm above the concentration in the outdoor air. This allowed CO_2 concentration is mostly used as an indicator of (acceptance of) occupant odours (odorous bio-effluents), instead of exceeded CO_2 concentration of itself being dangerous. Using the same range of outdoor CO_2 concentrations (350 – 500 ppm), this gives a recommended indoor CO_2 concentration in these type of areas of between 1175 – 1300 ppm.

For areas without an elevated metabolic activity, the RITE does not suggest a particular indoor CO_2 concentration. Therefore, there are two options. Either follow the same regulations as the areas with an elevated metabolic activity / contaminants production, or follow the same EU regulations as the buildings in Porto (section 5.2.2). Both the EN15251 and the RITE suggest a CO_2 ppm of 500 above the outdoor CO_2 concentration for these types of areas. The ASHREA suggests no higher than 700 ppm CO_2 above outdoor concentration. Therefore, using the same range of outdoor CO_2 concentrations (350 – 500 ppm), this gives a recommended indoor CO_2 concentration of either between 850 and 1000 ppm with an upper limit of 1200 ppm. Since more recent research suggests an indoor CO_2 ppm of 800 for better indoor comfort and health, this is set as the preferred lowest CO_2 ppm of the range (Muhamad et al., 2011; Van Loon & Van Morgen. 2012; Drijver et al., 2010). The overview of the CO_2 recommendations can be seen in Table 12.

For humidity, the same rules apply as for Porto. When the humidity of a room is not extremely low or high, humidification or dehumidification of room air is usually not required. When (de)humidification is applied, the correct values of humidity for the Barcelona buildings can be determined using the EN12521 document. For the Barcelona buildings where humidity criteria are set by human occupancy, the design relative humidity for dehumidification is 60% and for humidification is 25%. Besides, it is recommended to limit the absolute humidity to 12g/kg. Special spaces, like libraries and swimming pools, may require other limits (see Table 12 for the overview).

TABLE 12– Barcelona recommended CO_2 range and upper limit and relative humidity range according to the RITE, EN 15251 and the ASHRAE standard (2016). The second column gives the recommended indoor CO_2 concentration above the outdoor concentration with the upper limit in parenthesis. Using the average outdoor CO_2 concentration range of between 350 – 500 ppm, the absolute indoor CO_2 range is given in the third column with the upper limit in parenthesis.

Barcelona Building type or space	Recommended indoor CO_2 concentrations (ppm)		Recommended relative humidity (%)
	Relative to outdoor CO_2 concentrations (upper limit)	Absolute range (upper limit)	Range for (de)humidification
Single office (cellular office) **Landscaped office (open plan office)**	500 (700)	800 – 1000 (1200)	25 - 60
Conference room **Auditorium**	500 (700)	800 – 1000 (1200)	25 - 60
Computer rooms	800	1175 - 1300	-
Restaurant/bar areas	800	1175 - 1300	25 - 60
Library	500 (700)	800 – 1000 (1200)	-
Communal zones of buildings	500 (700)	800 – 1000 (1200)	25 - 60
School **Classrooms**	500 (700)	800 – 1000 (1200)	25 - 60
Sports centre	800	1175 - 1300	-
Swimming pool area	800	1175 - 1300	-

5.3.4 LUMINOSITY REQUIREMENTS

The luminosity requirements for the Barcelona buildings follow the guidelines stipulated by EN 15251, EN 12193, EN 12464-1, and the Spanish Une-EN 12193. These guidelines concern maintained illuminances (Ê$_m$: the total luminous flux incident on a surface per unit area (1 lm/m^2, or lx), the maximum UGR (Unified Glare Rating) value for the glare in rooms, and the colour rendering index (CRI) in Ra units. These light levels may partly be provided by artificial lighting and are lower than those needed for the regulation of the human circadian system. The overview of luminosity requirements for the Barcelona buildings can be seen in Table 13.

TABLE 13– Barcelona Luminosity requirements according to the EN 15251, EN 12193, and EN 12464-1. The second column gives the recommended maintained luminance at working areas (lx). The third column shows the UGR (Unified Glare Rating) value, the forth the colour rendering index (Ra), and the fifth column shows addition remarks.

Barcelona Building type or space	Maintained luminance, Êm, at working areas (lx)	UGR	Ra	Remarks
Single office (cellular office) **Landscaped office (open plan office)**	500	19	80	at 0.8 m
Conference room **Auditorium**	500	19	80	at 0.8 m
Computer rooms	300	19	80	
Restaurant/bar areas	-	-	80	at 0.8 m
Library: Bookshelves	200	19	80	
Library: **Reading areas**	500	19	80	
Communal zones of buildings	100-300	22-25	40-80	at 0.8 m
School **Classrooms**	300	19	80	at 0.8 m

Barcelona Building type or space	Maintained luminance, Êm, at working areas (lx)	UGR	Ra	Remarks
Classrooms for adult education	500	19	80	at 0.8 m
Sports halls	200	22	80	at 0.1 m
Swimming pool area	300	1175 - 1300		

5.4 LIPPE DEMONSTRATION SITE

5.4.1 INTRODUCTION

For the residential buildings of Lippe the European guidelines of EN 15251 will be used. As stated in Section 3.2.2, the classification of thermal environment of the residential buildings are category B. For this category, the following required temperature (range) settings and CO_2 concentrations should be followed. No recommendations or requirements on luminosity are available in EN 15251.

5.4.2 TEMPERATURE REQUIREMENTS

The temperature requirements for the Lippe buildings of FEEdBACk follow the same requirements and recommendation as stipulated for Porto and Barcelona in Section 5.2.2 and 5.3.2. In Table 14 the overview of temperature requirements for the different buildings is given.

TABLE 14– Lippe operative temperature range according to EN 15251 and EN ISO 7730. The table shows the minimum temperature for heating in the winter season and the maximum for cooling in the summer season. Below the temperature value is the operative temperature range for the winter and summer. Below each building (type) the associated level of activity is stated with the corresponding met-values (Metabolic Equivalent of Task), with 1 met corresponding to the activity of sitting at rest.

Lippe Building type or space	Operative temperature (°C)	
	Minimum for heating (winter season temperature range)	Maximum for cooling (summer season temperature range)
Residential buildings: living spaces (bedrooms, drawing room, kitchen etc.) **Sedentary ~ 1.2 met**	20.0 (20.0 – 25.0)	26.0 (23.0 – 26.0)
Residential buildings: other spaces: storages, halls, etc. **Standing-walking ~ 1.6 met**	16.0 (16.0 – 25.0)	-

The design temperature range (temperature range summer and winter) in Table 14 can vary from the values shown to take account for local customs, desire for energy saving, outdoor temperature, etc., as long as the within-day variation from the design temperature is within the given range, and the occupants are given time and opportunity to adapt to the modified design temperature (from EN 15251).

5.4.3 INDOOR AIR QUALITY REQUIREMENTS

The indoor air quality requirements follow the regulations of EN15251. The CO_2 recommendations for the residential buildings in Lippe are determined with the same method as the non-residential buildings in Porto. Since the Lippe buildings also classify as category B buildings, the same CO_2 recommendations apply. According to EN 15251, the recommended CO_2 concentration for the residential buildings is 500 ppm above outdoor CO_2 ppm. According to the ASHREA standard, a CO_2 concentration of no higher than 700 ppm above outdoor CO_2 concentration will meet the requirements. With the average outdoor CO_2 ppm of between 350 and 500 ppm, this gives a recommended indoor CO_2 concentration of between 850 and 1000 ppm with an upper limit of 1200 ppm. Since more recent research suggests an indoor CO_2 ppm of 800 for better indoor comfort and health, this is set as the preferred lowest CO_2 ppm of the range (Muhamad et al., 2011; Van Loon & Van Morgen. 2012; Drijver et al., 2010). The overview of the CO_2 recommendations can be seen in Table 15.

For humidity, the same rules apply as for Porto and Barcelona. When the humidity of a room is not extremely low or high, humidification or dehumidification of room air is usually not required. When (de)humidification is applied, the correct values of humidity for the Lippe buildings can be determined using the EN12521 document. The design relative humidity for dehumidification is 60% and for humidification is 25%. Besides, it is recommended to limit the absolute humidity to 12g/kg (see Table 15 for the overview).

TABLE 15– Lippe recommended CO_2 range and upper limit and relative humidity range according to EN 15251 and the ASHRAE standard (2016). The second column gives the recommended indoor CO_2 concentration above the outdoor concentration with the upper limit in parenthesis. Using the average outdoor CO_2 concentration range of between 350 – 500 ppm, the absolute indoor CO_2 range is given in the third column with the upper limit in parenthesis.

Lippe Building type or space	Recommended indoor CO_2 concentrations (ppm)		Recommended relative humidity (%)
	Relative to outdoor CO_2 concentrations (upper limit)	Absolute range (upper limit)	Range for (de)humidification
Residential buildings: living spaces (bedrooms, drawing room, kitchen etc.)	500 (700)	800 – 1000 (1200)	25 - 60
Residential buildings: other spaces: storages, halls, etc.	500 (700)	800 – 1000 (1200)	25 - 60

5. CONCLUSION

Comfort consist of both user aspects and physical aspects and cannot be measured for all users equally with objective measuring techniques. For the user aspects, behavioural, physiological and psychological adjustment play an important role in the experience of comfort. Control is central to this. For the physical aspects, factors that determine comfort such as air movement, temperature, light intensity or humidity, can only be suggested in form of guideline values. There are national and international standards, which specify criteria for thermal comfort and indoor air quality (EN ISO 7730, CR1752).

This report expands on the information of Deliverable 5.1 on the characterisation of test sites and demonstration activities. Based on the previous paragraphs, on top of the thermal demands, demands concerning air quality (lighting level and acoustic properties) are set for FEEdBACk, and can be determined. Using the minimum requirements of low polluted buildings with a 'B-category' indoor climate ('good'), the thermal requirements, CO_2 levels, humidity, and luminosity demands concerning air quality demands concerning air quality can be determined for FEEdBACk. This is summarized in Table 16.

TABLE 16– Summary overview of indoor air quality requirements of the FEEdBACk demonstration site buildings regarding temperature, CO_2, humidity, and luminosity requirements. The table shows the minimum temperature for heating in the winter season and the maximum for cooling in the summer season. Below the temperature value is the operative temperature range for the winter and summer. The recommended indoor CO_2 concentration (ppm) is displayed with the upper limit in parenthesis both as relative to outdoor concentration and as the absolute range using the average outdoor CO_2 concentration range of 350 – 500 ppm. The absolute low limit is set to 800 ppm for improved indoor comfort and health. The luminosity requirements show the maintained luminance value (lx) with remarks. Chapter 5 elaborates on this.

Building type or space	Operative temperature (°C)		Recommended indoor CO_2 concentrations (ppm)		Recommended relative humidity (%)	Luminosity	
	Minimum for heating (winter season temperature range)	Maximum for cooling (summer season temperature range)	Relative to outdoor CO_2 concentration (upper limit)	Absolute range (upper limit)	Range for (de)humidification	Maintained luminance, Êm, at working areas (lx)	Remarks
Porto Single office (cellular office) **Landscaped office (open plan office)**	20.0 (20.0 – 25.0)	26.0 (23.0 – 26.0)	500 (700)	800 – 1000 (1200)	25 - 60	500	at 0.8 m
Barcelona Single office **Landscaped office**	20.0 (20.0 – 21.0)	26.0 (25.0 – 26.0)	500 (700)	800 – 1000 (1200)	25 - 60	500	at 0.8 m
Porto Conference room **Auditorium**	20.0 (20.0 – 25.0)	26.0 (23.0 – 26.0)	500 (700)	800 – 1000 (1200)	25 - 60	500	at 0.8 m

Building type or space	Operative temperature (°C)		Recommended indoor CO_2 concentrations (ppm)		Recommended relative humidity (%)	Luminosity	
	Minimum for heating (winter season temperature range)	Maximum for cooling (summer season temperature range)	Relative to outdoor CO_2 concentration (upper limit)	Absolute range (upper limit)	Range for (de)humidification	Maintained luminance, Êm, at working areas (lx)	Remarks
Barcelona Conference room **Auditorium**	20.0 (20.0 – 21.0)	26.0 (25.0 – 26.0)	500 (700)	800 – 1000 (1200)	25 - 60	500	at 0.8 m
Porto Computer rooms	20.0 (20.0 – 25.0)	26.0 (23.0 – 26.0)	500 (700)	800 – 1000 (1200)	25 - 60	300	-
Barcelona Computer rooms	20.0 (20.0 – 21.0)	26.0 (25.0 – 26.0)	800	1175 – 1300	-	300	-
Porto Restaurant /bar areas	20.0 (20.0 – 25.0)	26.0 (23.0 – 26.0)	500 (700)	800 – 1000 (1200)	25 - 60	-	-
Barcelona Restaurant /bar areas	20.0 (20.0 – 21.0)	26.0 (25.0 – 26.0)	800	1175 – 1300	25 - 60	-	-
Porto Communal zones of non-residential buildings	16.0 (16.0 – 22.0)	25.0 (21.0 – 25.0)	500 (700)	800 – 1000 (1200)	25 - 60	100 – 300	At 0.8 m Dependent on further properties of zone.

Building type or space	Operative temperature (°C)		Recommended indoor CO_2 concentrations (ppm)		Recommended relative humidity (%)	Luminosity	
	Minimum for heating (winter season temperature range)	Maximum for cooling (summer season temperature range)	Relative to outdoor CO_2 concentration (upper limit)	Absolute range (upper limit)	Range for (de)humidification	Maintained luminance, Êm, at working areas (lx)	Remarks
Barcelona Communal zones of non-residential buildings	16.0 (16.0 – 21.0)	26.0 (25.0 – 26.0)	500 (700)	800 – 1000 (1200)	25 - 60	100 – 300	At 0.8 m Dependent on further properties of zone.
Barcelona Library	20.0 (20.0 – 21.0)	26.0 (25.0 – 26.0)	500 (700)	800 – 1000 (1200)	-	200 / 500	200 for bookshelves areas, 500 for reading areas.
Porto School Classrooms	20.0 (20.0 – 25.0)	26.0 (23.0 – 26.0)	500 (700)	800 – 1000 (1200)	25 - 60	300 / 500	At 0.8 m 500 for adult education rooms.
Barcelona School Classrooms	20.0 (20.0 – 21.0)	26.0 (25.0 – 26.0)	500 (700)	800 – 1000 (1200)	25 - 60	300 / 500	At 0.8 m 500 for adult education rooms.
Porto Sports centre	20.0 (20.0 – 25.0)	26.0 (23.0 – 26.0)	800	1175 – 1300	-	300	At 0.1 m

Building type or space	Operative temperature (°C)		Recommended indoor CO_2 concentrations (ppm)		Recommended relative humidity (%)	Luminosity	
	Minimum for heating (winter season temperature range)	Maximum for cooling (summer season temperature range)	Relative to outdoor CO_2 concentration (upper limit)	Absolute range (upper limit)	Range for (de)humidification	Maintained luminance, Êm, at working areas (lx)	Remarks
Barcelona Sports centre	20.0 (20.0 – 30.0)	26.0 (26.0 – 30.0)	800	1175 – 1300	-	200	At 0.1 m
Barcelona Swimming pool	20.0 (20.0 – 30.0)	26.0 (26.0 – 30.0)	800	1175 – 1300	-	300	-
Residential buildings: living spaces (bedrooms, kitchen etc.)	20.0 (20.0 – 25.0)	26.0 (23.0 – 26.0)	500 (700)	800 – 1000 (1200)	25 - 60	-	-
Residential buildings: other spaces: storages, halls, etc.	16.0 (16.0 – 25.0)	-	800	1175 - 1300	-	-	-

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FEEdBACk DOCUMENTS

FEEdBACk Deliverable D5.1 Characterisation of test sites.

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ANNEXES

ANNEX 1

Normative References

Main standard applicable to FEEdBACk D2.2 is **<u>EN15251</u>**, **“Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics”.**

This standard is inter-related with the following other EU standards:

EN ISO 7726	Ergonomics of the thermal environment – Instruments for measuring physical quantities
EN ISO 7730	Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort
EN ISO 8996	Ergonomics – Determination of metabolic heat production
EN ISO 9920	Ergonomics of the thermal environment – estimation of the thermal insulation and evaporative resistance of a clothing ensemble
EN ISO 13731	Ergonomics of the thermal environment - Definitions, symbols and units.
EN ISO 13790	Thermal performance of buildings – Calculation of energy use for space heating and cooling – Simplified method
EN ISO 13791	Thermal Performance of Buildings — Calculation of Internal Temperatures in a Room in Summer without Mechanical Cooling— General Criteria and Validation Procedures
EN ISO 13792	Thermal performance of buildings — Internal temperature of a room in summer without mechanical cooling — Simplified calculation methods
EN 12193	Light and lighting – Sports Lighting
EN 12792	Ventilation for Buildings — Symbols, Terminology and Graphical Symbols
EN12831	Heating systems in buildings — Calculation of the heating load
EN 12464	Light and lighting – Lighting of work places- Part 1: Indoor work places
EN12599	Ventilation for buildings – Test procedures and measuring methods for handing over installed ventilation and air conditioning systems
EN 12665	Light and Lighting – Basic terms and criteria for specifying data of lamps and luminaries
EN 13032	Light and lighting – Measurement and presentation of photometric data of lamps and luminaries

EN13779	Ventilation for non-residential buildings – performance requirements for ventilation and room-conditioning systems
PrEN14788 2004	Ventilation for buildings – Design and dimensioning of residential ventilation systems
EN15203	Energy performance of buildings — Assessment of energy use and definition of ratings
EN 15217	Energy performance of buildings — Methods for expressing energy performance and for energy certification of buildings
EN 15239	Ventilation for buildings — Calculation methods for the determination of air flow rates in buildings including infiltration
EN 15240	Energy performance of buildings – Guidelines for the inspection of air-conditioning systems
EN15241	Ventilation for buildings — Energy performance of buildings – Guidelines for the inspection of ventilation systems
EN15242	Ventilation for buildings — Calculation methods for the determination of air flow rates in buildings including infiltration
EN 15243	Dynamic calculation of room temperatures and of load and energy for buildings with room conditioning systems (including solar shading, passive cooling, position and orientation
EN 15255	Thermal performance of buildings – Sensible room cooling load calculation – General criteria and validation procedures
EN 15265	Energy performance of buildings – Calculation of energy use for space heating and cooling – General criteria and validation procedures
EN 15378	Energy performance of buildings – Systems and methods for the inspection of boilers and heating systems
ISO 15927-4	Hygrothermal performance of buildings -Calculation and presentation of climatic data – Part 4: Data for assessing the annual energy for cooling and heating systems and Part 5: Winter external temperatures and related wind data
ISO/TS14415	The Application of International Standards for People with Special Requirements
CR 1752 2001	Ventilation for buildings – Design criteria for the indoor environment
CIE 69 1987	Methods for characterizing illuminance meters and luminance meters: Performance, characteristics and specifications

EN15251 could be positioned according to the following Diagram (EU CEN/TC 156/ EN15251) (:

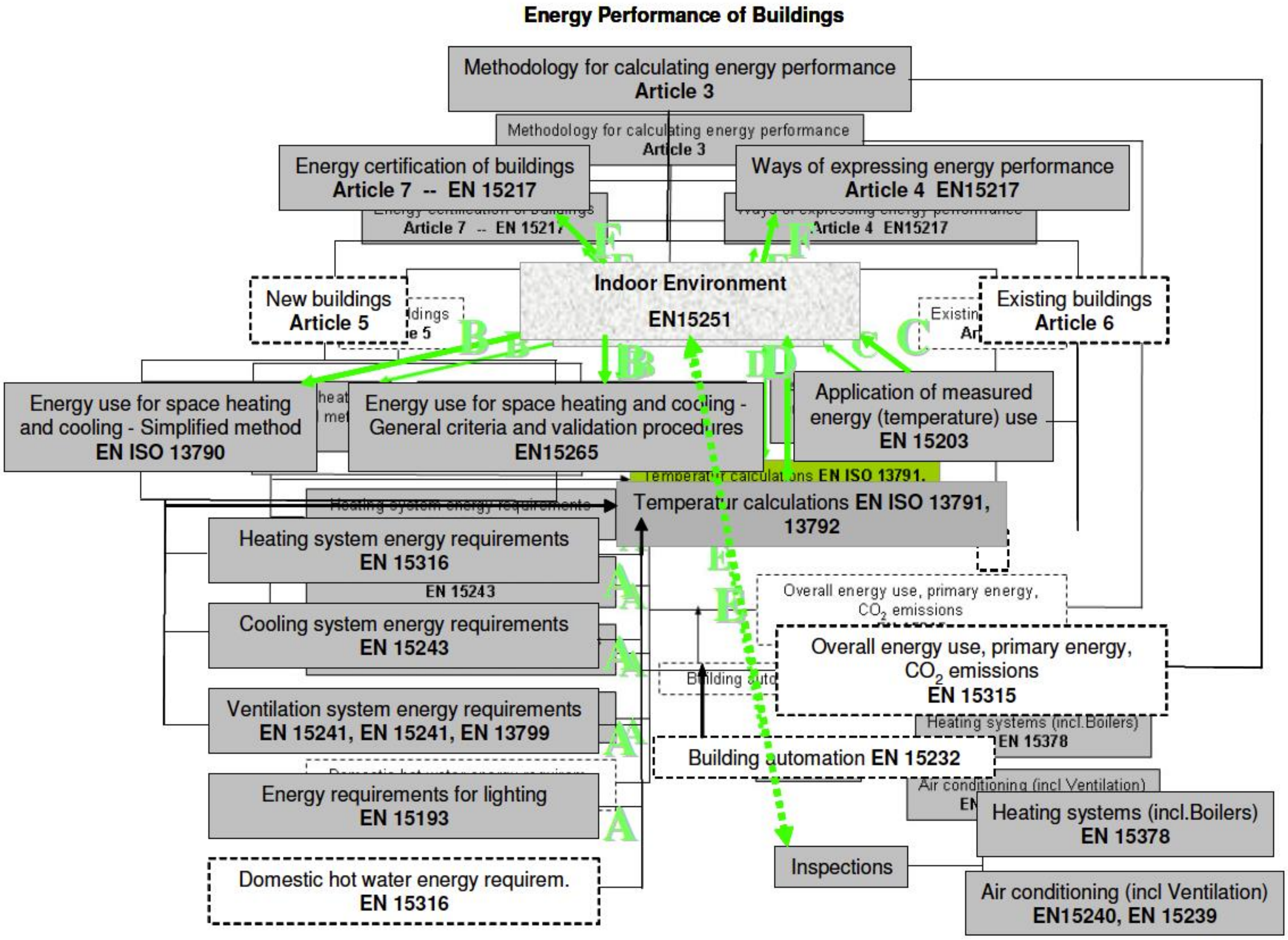

FIGURE 11 – Overview of the EU standards for indoor environment.

The relations to the above-mentioned standard references (highlighted in green (A – F)):

(taken from (EU CEN/TC 156/ EN15251))

(A): It provides indoor environmental criteria for the design of building and HVAC systems. The thermal criteria (design indoor temperature in winter, design indoor temperature in summer) are used as input for heating (EN12831) and cooling load (EN 15243) calculations and sizing of the equipment. Ventilation rates are used for sizing ventilation systems, and lighting levels for design of lighting system including the use of day lighting. The design values for sizing the building services are needed to fulfil the requirements in the article 4 of EPBD referring to possible negative effect of indoor environment and to give advice in respect improvement of the energy efficiency of existing buildings (article 6) as well as of the heating (article 8) and cooling (article 9) of building.

(B): It provides values for the indoor environment (temperature, ventilation, lighting) as input to the calculation of the energy demand (building energy demand), when the space is occupied, (EN ISSO 13790, EN 15255, EN 15265). It will also provide standardised input values which are needed for energy calculations as required calculations specified in article 3 of EPBD.

(C): Output from measured environmental parameters in existing buildings (EN 15203, temperature, indoor air quality, ventilation rates) will enable the evaluation of overall annual performance, necessary for the display of the climatic factors (indoor environment) in the energy performance certificate (article 6 and 7 of EPBD).

(D): Output from room temperature calculations (EN ISO 13791, EN ISO 13792) to enable evaluation of the annual performance of buildings. This evaluation is necessary for the display of climatic factors (indoor environment) in the energy performance certificate (article 7 of EPBD) when the evaluation is based on calculations (article 7 of EPBD).

(E): It provides methods for measurement of the indoor environment and for treating measured data related to the inspection of HVAC systems (EN 15240, EN 15239, EN 15378). This information is necessary to give advice related to the heating loads and system (article 8 of EPBD) and air conditioning load and system (article 9 of EPBD) of a building.

(F): It provides a method for categorisation of indoor environment (EN 15217), necessary to integrate complex indoor environment information to simple classification for the energy certificate (article 7 of EPBD).