EXPLORING INNOVATIVE INDICATORS FOR THE NEXT-GENERATION ENERGY PERFORMANCE CERTIFICATES FEATURES - COMFORT

MAY 2021

THIS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 845958.

Project Acronym	X-tendo
Project Name	eXTENDing the energy performance assessment and certification schemes via a mOdular approach
Project Coordinator	Lukas Kranzl Technische Universität Wien (TU Wien) Gusshausstraße 25-29/370-3, A-1040 Vienna E. Lukas.Kranzl@tuwien.ac.at
Project Duration	2019 - 2022
Website	www.X-tendo.eu

Deliverable no.	D3.1
Dissemination level	Public
Work package	WP3- Innovative EPC indicators and calculation methods
Lead beneficiary	Buildings Performance Institute Europe (BPIE)
Contributing beneficiaries	VITO, e-think, NAPE, BPIE
Author(s)	Sheikh Zuhaib (BPIE)
Co-author(s)	Guillermo Borragán Pedraz (VITO), Jan Verheyen (VITO), Jerzy Kwiatkowski (NAPE), Marcus Hummel (e-think), Vivian Dorizas (BPIE)
Reviewed by	Kalle Firus (TREA), Maarten De Groote (VITO), Lukas Kranzel (TU WIEN) Editing: Barney Jeffries & Roberta D'Angiolella (BPIE)
Date	29.05.2020
File name	X-tendo_Deliverable 3.1

Legal notice

TABLE OF CONTENT

EXECUTIVE SUMMARY

Energy performance certificate (EPC) schemes have not evolved much since their first introduction in the Member States to meet the mandatory requirements of the Energy Performance of Buildings Directive (EPBD). Stakeholders have questioned their reliability but at the same time, they have been useful for the real estate industry. All the Member States have legislation in place and existing infrastructure or systems to run EPC schemes. These schemes require evolution with the changing needs of the built environment and requirements to look beyond the energy consumption of buildings to take in elements such as better indoor comfort, reducing air pollution and others. Public authorities view them as potential instruments to improve the performance of the existing and new building stock. Extending the functionalities of existing systems will create several pathways to update and manage next-generation EPCs.

This report presents the preliminary scoping and analysis of the five technical features related to developing innovative EPC indicators proposed within X-tendo[1]: (i) smart readiness, (ii) comfort, (iii) outdoor air pollution, (iv) real energy consumption, and (v) district energy. The outcome of this report is an initial mapping and selection of the suitable options of methods for developing indicators for these five features. The follow-up activities in the project will take forward this work to elaborate and provide technical specifications of the methodologies and concepts for the five features.

This report presents an overview of existing assessment approaches and methodologies for each feature that could be adopted in the indicator development for the EPCs. Details are provided of the most suitable existing methods that can be applied in the assessment of five technical indicators when integrated with EPCs. Their suitability and applicability to EPCs is analysed in a broader context, including building typologies and ranking/scoring techniques.

The report also evaluates existing links between these methods and the energy performance of a building/EPCs to determine how these can be integrated in the feature development. Since most of the assessment methods require some type of data related to end-users, therefore, their legal boundaries are also studied. Within the scoping and analysis, a ranking and SWOT analysis of several methods is presented to assess their suitability and feasibility of application in the development of the new features. Finally, a conceptual approach is proposed for the development of each of the five features. Findings are presented, highlighting the barriers, challenges and limitations of the assessment methods for the five features.

[1] In addition to these five features, X-tendo will also provide a set of five features dealing with innovative handling of EPC data.

Across all features, the following conclusions are made:

Indicators

- 'Smart readiness' approach presents a potential method for assessing the smartness of buildings with nine domains (e.g. lighting, ventilation, envelope, monitoring and control etc.)
- 'Comfort' approach incorporates four key indicators – thermal, visual and acoustic comfort and indoor air quality – to be assessed through checklists, on-site measurements and surveys
- 'Outdoor air pollution' approach addresses a building's impact on air by two methods: an outdoor air pollution contribution index and indoor air purity index
- 'Real energy consumption' approach outlines an assessment method based on operational ratings, with options for normalisation to allow for better inter-building comparison
- 'District energy' approach focuses on predicting the potential for future development for buildings via two methods: expected future performance of district heating and heat distribution and transfer system

Cross-cutting issues

- Technical challenges that constrain the application of existing methods such as assessment time, accuracy, normalisation process, variable definitions and emission factors could be overcome by certain modifications in approach
- Features should be aligned financially to increase market acceptance and cost-effective assessments during the development
- Legal and governance issues should be addressed by dealing with challenges such as development of universal methodologies, presence of multiple standards at Member State level, control of citizen data and privacy, and acceptance of future estimations by public authorities
- From a social perspective, user acceptance and public understating of the features are key issues and should be considered in feature development
- If these indicators are well integrated within EPCs, significant environmental benefits are anticipated
- Future implementation of indicators can be strengthened by addressing lack of industry readiness, understanding of anticipated benefits and enforcement issues

Certain limitations need to be overcome to implement these innovative indicators, such as variable levels of implementation in the Member States due to different local requirements and regulations. Some indicators require extensive monitoring and measurements, and a lack or absence of data is a barrier in the development and acceptance of these features within EPC schemes.

A concise overview of all the features is given in Figure 1. Overall, a promising picture is visible with the proposed conceptual approaches for features combining new ideas with existing methods to work towards developing innovative indicators that could be tested and integrated into the EPC schemes of the implementing countries within the X-tendo project.

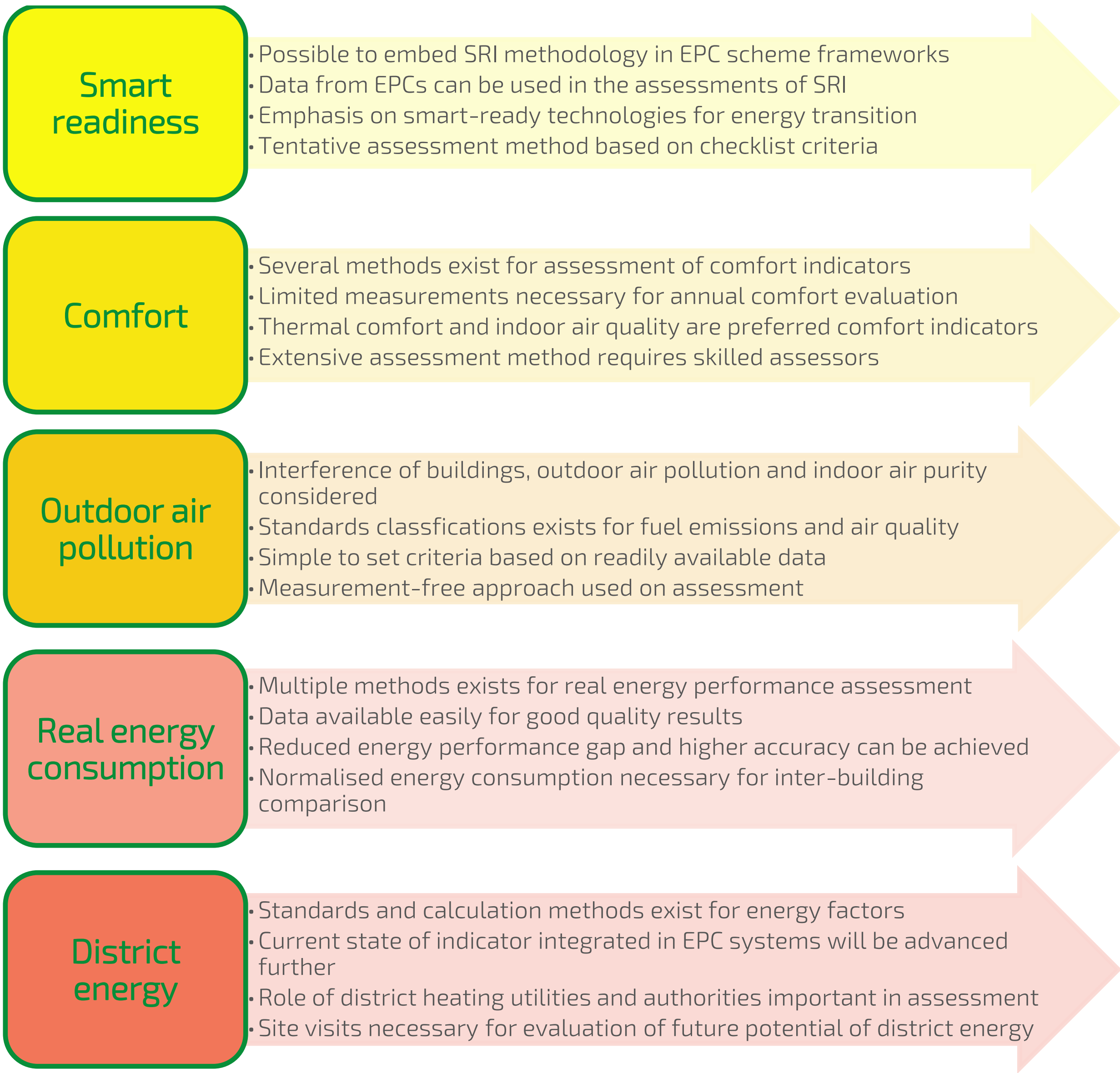


Figure 1: Overview of the five features

1 EXTENDING THE FUNCTIONALITIES OF EPCs WITH INNOVATIVE INDICATORS: SCOPING AND ANALYSIS

Energy performance certificates (EPCs) are the key source of information on the energy performance of the building stock [1]. Their role for the end-user and the real estate sector has mainly been limited to indicating and comparing the energy class of the building, helping to regulate property transaction prices and rents. They have also been attractive for end-users and builders in gaining access to funds and incentives to conduct energy efficiency improvements. EPCs have also been seen as an unreliable source of information by stakeholders in some Member States [2]. Weak enforcement, low public acceptance and awareness, quality of audits, qualifications of the auditors and widely varying certificate costs all influence the role of EPCs and how they can affect the real estate market.

Many Member States stepped up efforts in the last decade to improve their EPC frameworks after the introduction of the requirement of energy performance and assessment systems under the EPBD (2002/91/EC) and EPBD recast (2010/31/EU). The recent amendments in the EPBD (2018/844) further strengthened the existing provisions by setting out that Member States should provide information to owners and tenants on the purpose and objectives of EPCs, energy efficiency measures, and supporting financial instruments through accessible and transparent advisory tools such as direct advice and one-stop-shops.

In the current scenario, EPCs are viewed as instruments that can bring additional benefits to the end-user (e.g. property seller, buyer, or tenant) by being a vehicle for additional information other than energy efficiency.

1.1 Aim of the X-tendo project

The X-tendo project is developing a framework of 10 "next-generation EPC features", aiming to improve compliance, usability, and reliability of the EPC. The X-tendo partners cover 10 countries or regions – Austria, Belgium (Flanders) Denmark, Estonia, Greece, Italy, Poland, Portugal, Romania, and the UK (Scotland) as displayed in Figure 2.

Figure 2: X-tendo consortium and target countries

The X-tendo project approaches next-generation EPCs by exploring 10 new features in addition to their existing functionalities (see Figure 3). The features that will be explored in the project fall into two broad categories:

- New technical features used within EPC assessment processes and enabling the inclusion of new indicators in EPCs
  1) Smart readiness
  2) Comfort
  3) Outdoor air pollution
  4) Real energy consumption
  5) District energy
- Innovative approaches to handle EPC data and maximise its value for building owners and other end-users.
  6) EPC databases
  7) Building logbook
  8) Tailored recommendations
  9) Financing options
  10) One-stop-shops

Figure 3: The X-tendo toolbox representing both innovative EPC indicators and novel ways of handling EPC data

Existing EPC schemes lack focussed vision. In order to become a catalyst for energy renovations, the next-generation EPC must provide an improved and more reliable service to the end-users. The key output of the project will be the X-tendo toolbox, a freely available online knowledge hub that will be continued beyond the project duration. For each feature, the toolbox would include (i) solution concepts and good practice examples, (ii) descriptions of methodological approaches, (iii) calculation tools, and (iv) implementation guidelines and recommendations.

1.2 Scope and objective of this report

The purpose of this report is to identify suitable methods and approaches to assess the five features (i) smart readiness, (ii) comfort, (iii) outdoor air pollution, (iv) real energy consumption, (v) district energy. Before developing individual methods for their assessment, a detailed review of the existing assessment and calculation methods is presented for developing the indicators for all the five features in this report. Although the goal of the next-generation EPC will be more holistic, the relation with energy performance remains a key boundary condition for the selected approaches presented in this report.

The identification of the suitable methods will consider the objective of the modular toolbox being developed specifically for EPC assessments. The results of the report will be an initial selection of options for methods and indicators for features 1-5. Findings of the scoping and analysis are gathered in this report for these indicators.

Table 1 lists the five innovative EPC indicators that could make EPCs more than just an informative tool. It also indicates the feature leads (VITO, BPIE, NAPE and e-think) who will develop the innovative indicators and organisations (EASt, DEA, TREA, CRES, ENEA, NAPE, ADENE, AAECR and EST) from implementing/expert partner countries that would support them in the development and testing of the indicators on several test projects.

Table 1: Innovative EPC indicators

	 Smart readiness	 Comfort	 Outdoor air pollution	 Real energy consumption	 District energy
Feature lead	*VITO*	*BPIE*	*NAPE*	*VITO*	*e-think*
EASt (Austria/Styria)	Implementer	Implementer		Implementer	
DEA (Denmark)	Implementer	Implementer			Expert
TREA (Estonia)	Implementer/ Expert			Implementer	
CRES (Greece)	Implementer	Implementer			
ENEA (Italy)				Implementer	Implementer
NAPE (Poland)			Implementer/ Expert		Implementer
ADENE (Portugal)		Implementer			
AAECR (Romania)	Implementer	Implementer		Implementer/ Expert	Implementer
EST (UK)				Implementer	

The EPCs can become much more useful for the end-users, public authorities and policymakers by providing more detailed information on the existing building stock and its performance. Next-generation EPCs can support the transition to a low-carbon building sector, provided they are revised considering new indicators, with effective mechanisms to ensure compliance and high quality, reliable certifications.

2 FEATURE 2: COMFORT

2.1 Overview of the methods to assess indoor environmental quality (IEQ)

In today's society people spend approximately 90% of their time in buildings, so IEQ has become an issue of increasing concern [19]. This has become more relevant in the current pandemic where people are staying indoors even more [18]. Occupant behaviour, awareness and level of acceptance of the indoor environmental conditions is essential for maintaining satisfactory IEQ. A large body of social science and environment-behaviour research demonstrates that improving IEQ has health benefits for occupants [20]–[22]. The International Performance Measurement and Verification Protocol (IMPVP) outlines concepts and practices for improved IEQ, that can be associated with energy conservation measures [23]. There are many energy efficiency related improvements (e.g. replacing windows, adding insulation etc.) in buildings that improve IEQ, especially with respect to thermal comfort, ventilation, lighting and acoustics. Current legislation under the EPBD [24] and EED [25] has pushed Member States in Europe to address the existing building stock through energy-efficient retrofits and achieve nZEB performance. EPCs present an opportunity to investigate the feasibility of improving both IEQ and energy efficiency in the existing building stock with well-designed retrofit measures.

Different retrofit measures under shallow, medium or deep retrofits hold great promise for improving IEQ as well as the energy efficiency of buildings. IEQ is mentioned in the multi-annual roadmap of 2020 [26] and recently amended EPBD (2018/844). However, the impacts of retrofits on IEQ are not always addressed in a cost-effective manner [27]. Deep energy retrofits (saving over 60% energy) can bring tangible and intangible benefits of enhanced performance and improved productivity in indoor environments such as residential buildings, offices, schools, colleges and commercial establishments. Only a few projects like ALDREN and RE-BUS have attempted to outline new methods for the evaluation of comfort in the light of harmonised EPC processes for the EU.

In this section, a comprehensive literature review from the existing research is presented and analysed. We assess how different methods for evaluating IEQ can be integrated in EPCs and applied to measure the "comfort" feature. The environmental factors of thermal comfort, visual comfort, acoustics and indoor air quality define IEQ [28]. Each of these is discussed in the following subsections with respect to the latest standards and research.

- Thermal comfort

According to ASHRAE 55 [29] and ISO 7730 [30] '*thermal comfort is that condition of mind which expresses satisfaction with the thermal environment*'. ASHRAE 55 and ISO 7730 specify the combination of indoor thermal environmental parameters (temperature, radiant temperature, humidity and air velocity) and personal parameters (metabolic rate and clothing insulation) for acceptable comfort conditions to occupants. There are two models to identify the thermal sensation in a space: the rational model (heat balance) based on predicted mean vote (PMV)/ predicted percentage of dissatisfied (PPD), applicable in conditioned environments (e.g. during winters when the heating is operational); and the adaptive comfort model, applicable in unconditioned environments (e.g. during summers when the building is naturally ventilated) [29], [30].

- Indoor air quality

Indoor air quality refers to the air quality within buildings. Acceptable indoor air quality refers to air without harmful concentrations of known contaminants, with which the vast majority of exposed people are satisfied. Poor indoor air quality is known to have acute and chronic effects on the health of the occupants [31]. It is directly related to the ventilation rates and concentration of indoor pollutants, which in turn are related to sick building syndrome (SBS), used to describe situations where occupants have acute health and comfort effects [32]. In closed environments, indoor air quality is related to both chemical and physical causes, such as carbon monoxide (CO) and dioxide (CO_2), radon concentration, environmental tobacco smoke, formaldehyde, volatile organic compounds (VOCs), ventilation rate, temperature, dampness, humidity, ionising and non-ionising radiation [33]. Provision of good outdoor air supply is known to provide acceptable perceived indoor air quality [34]. The World Health Organization (WHO) has published indoor air quality guidelines for selected pollutants and their health effects with the target of ensuring the provision of safer indoor environments [35].

- Visual comfort

Visual comfort is defined in the European Standard EN12665 as "a subjective condition of visual well-being induced by the visual environment" [36]. Visual discomfort can occur because of either too low or too high a level of light. Visual comfort is a subjective measure dependent on certain factors such as illumination, luminance and brightness, luminous spectrum and risk of glare [36]. The presence of a good visual environment (e.g. adequate natural and artificial lighting, reduced glare discomfort etc.) may add to the well-being and productivity of the occupants of a building [37].

- Acoustic comfort

Acoustic comfort is the presence of a comfortable acoustic environment without any uncomfortable noise [38]. Acoustic comfort is considered crucial for non-domestic buildings' IEQ and is generally given high preference among other IEQ indicators in offices and classrooms by occupants [39]–[41]. Occupants' satisfaction in workplaces can be improved by speech privacy and comfortable sound levels, which are identified as the main problems regarding acoustic quality in office workstations [42]. Building elements play a significant role in offering external and internal sound insulation by acting as a barrier, absorbing or reflecting the sound waves [43].

2.1.1 Analysis of existing building assessment, rating and certification systems for IEQ

There are several voluntary building rating and assessment systems around the world that integrate IEQ with health and well-being of occupants. These rating systems have established extensive, and very costly, criteria for evaluating both new constructions and existing buildings. Most of the indicators are based on best practices, national regulations or national/international standards. However, these rating systems are not mandatory at national level.

To understand comfort indicators and how they can be applied to EPCs, a few well-known systems were reviewed, including:

- **BREEAM:** Building Research Establishment Environmental Assessment Method (BREEAM) was launched in 1990 by Building Research Establishment UK, a world-leading, multidisciplinary building science organisation. BREEAM was the world's first environmental assessment method for buildings and is defined by building science and research. Performance is measured in nine categories: management, health and well-being, energy, transport, water, materials, waste, land use and ecology, and pollution

- **DGNB:** The basic system for assessing the sustainability of buildings was jointly developed by the German Sustainable Building Council (DGNB) and the Federal Ministry of Transport, Building and Urban Development (BMVBS), Germany in 2009. DGNB has developed a complete certification system for a wide range of building uses and quarters. The sustainability concept of the DGNB system is broad and extends beyond the well-known three-pillar model (social, economic, and environmental). It consistently considers all essential aspects of sustainable construction. These include the six subject areas ecology, economy, socio-cultural and functional aspects, technology, processes, and location.

- **LEED:** Leadership in Energy and Environmental Design (LEED) was created in 2000 by the US Green Building Council (USGBC), for rating design and construction practices that would define a green building in the United States. LEED consists of credits which earn points in seven categories: site selection, water efficiency, energy and atmosphere, materials and resources, IEQ, regional priority, and innovation in design.

- **HPI:** The Irish Home Performance Index (HPI) considers the quality of residential development under three categories: (i) costs, including energy, water and transport, (ii) wellbeing, such as comfort, indoor air quality, the levels of daylight, and other issues, (iii) planet, by considering how homes may help in reducing the ecological footprint.

- **WELL:** WELL is a performance-based system for measuring, certifying, and monitoring features of the built environment that impact human health and well-being. It was launched in 2014 by the International WELL Building Institute (IWBI). It assesses the impact on health and well-being by looking at seven concepts: air, water, nourishment, light, fitness, comfort, and mind.

In Table 2, a summary is given of the criteria related to comfort/health and well-being, with details of the indicators taken into account and the standards applied.

Table 2: Summary of criteria related to assessment of comfort in building certification systems

Assessment/ rating system	Criteria	Indicators	Standards applied	Ref
BREEAM	Visual comfort	1. Glare control (suggested design measures) 2. Daylighting (average daylight factor, average daylight illuminance) 3. View out (opening size, distance of occupant) 4. Internal and external lighting (EN13201 and EN 12464-2)	• CIBSE Lighting Guide 10 Daylighting and window design • BS 8206 Part 2. Code of practice for daylighting	[44] [45]
	Indoor air quality	1. Ventilation (national/industry standards) 2. VOC emission levels (ISO standards) 3. Natural ventilation potential (opening area)	• EN ISO 11890-2:2013 – Paints and varnishes • Determination of VOC content, Part 2 – Gas • Chromatographic method • ISO 16000-4: 2011 Diffusive sampling of formaldehyde in air • ISO 16000-6: 2011 VOCs in air by active sampling • EN ISO 16017-2: 2003 VOCs - indoor, ambient and workplace air by diffusive sampling • ISO 16000-3: 201123 Formaldehyde and other carbonyls in air by active sampling	
	Thermal comfort (for conditioned buildings)	1. Thermal modelling (PMV/PPD) (standard based) 2. Thermal zoning and controls (heating and cooling strategy) (standard practice)	• ISO 7730:2005	
	Acoustic comfort	1. Indoor ambient noise (equivalent sound pressure level – national regulations or good practice) 2. Sound insulation (national regulations or good practice values) 3. Reverberation time (national regulations	• Measurement of sound insulation: ISO 16283 series • Reverberation time: ISO 16283-1:2014	

		or good practice values)		
DGNB	Thermal comfort	1. Operative temperature (heating/cooling period) 2. Drafts (heating/cooling period) 3. Radiant temperature asymmetry (heating/cooling period) 4. Relative humidity (heating/cooling period)	• Measurement and simulation • DIN EN15251:2007 • EN ISO 7730 • DIN 4108-2	[46]
	Indoor air quality	1. VOCs measurement (specified values) 2. Ventilation rate (standard based)	• DIN ISO 16000:1/3/5/6 • EN15251: 2007	[47]
	Acoustic comfort	1. Room acoustics class (standard based) 2. Reverberation time (standard based) 3. Average equivalent sound absorption area (standard based)	• VDI 2569: 2016-02 • DIN 18041:2016-03 • DIN EN ISO 3382-2	[48]
	Visual comfort	1. Daylight factor (standard based) 2. Annual relative motive exposure (standard based) 3. Visual link with outside (specified values) 4. Absence of glare in daylight (standard based) 5. Artificial light (standard based) 6. Daylight colour rendering (specified values) 7. Exposure to daylight (specified values)	• DIN V 18599 • DIN 14057 • EN 12464-1	[49]
LEED	Minimum indoor air quality	Outdoor air rate (standard based)	• ASHRAE 62.1: 2016	[50]

		Natural ventilation: opening location and size (standard based)		
	IEQ performance	Measurements of CO_2 and TVOC (standard based)	• ISO 16000-6	
	Thermal comfort	Thermal comfort analysis conditioned and unconditioned spaces (standard based)	• ASHRAE Standard 55-2017 • ISO 7730-2005 • ISO 17772-2017	
	Interior lighting	1. Lighting quality (luminance – specified values)	• Specified values	
	Daylight and quality views	1. Spatial daylight exposure 2. Annual sunlight exposure 3. Illuminance 4. Direct line of sight to outdoors	• Specified values	
	Acoustic performance	1. HVAC noise 2. Sound transmission 3. Reverberation time (specified values)	• ASHRAE Handbook 2015 • ASTM E336-17a	
HPI	Indoor air quality	1. Ventilation (national regulations) 2. VOCs level (standard based)	• Building Regulations Part F TGD Ventilation 2009 • ISO 16000-4:2011	[51]
	Daylighting	1. Daylight factor	• Code for Sustainable Homes, HQE, Miljöbyggnad • BS 8206-2:2008 – Lighting for buildings	
	Acoustic comfort	1. Sound insulation 2. Indoor ambient noise level	• Adapted from DGNB/BNB and BREEAM • Building Regulations 2014 TGD Part E Sound	
	Summer and winter comfort	1. Summer comfort (risk of overheating) 2. Winter comfort (radiant asymmetry)	• Appendix P in the DEAP methodology, PHPP (Passive House Planning Package) • TGD Part L 2011	
WELL	Comfort	1. Accessible design (accessibility) 2. Exterior noise intrusion (sound pressure level) 3. Internally generated noise (equipment sound level) 4. Thermal comfort (conditioned and unconditioned zones)	• ISO 21542:2011 - Building Construction • ASHRAE Standard 55-2013 Section 5.3, Standard Comfort Zone Compliance • ASHRAE Standard 55-2013 Section 5.4, Adaptive Comfort Model	[52]

		5. Radiant thermal comfort (conditioned spaces) 6. Olfactory comfort (source separation) 7. Reverberation time (standard based)		
	Air	1. Ventilation effectiveness & increased ventilation 2. VOC reduction 3. Internal moisture management 4. Operable windows 5. Displacement ventilation	• ASHRAE 62.1-2013 (Ventilation Rate Procedure or IAQ Procedure) • CIBSE AM10, Section 4, Design Calculations • ASHRAE Guidelines RP-949	
	Light	1. Visual lighting design (illuminance level) 2. Electric and solar glare control (shading) 3. Colour quality (colour rendering index) 4. Daylight modelling (spatial daylight autonomy) 5. Daylighting fenestration (size and design)	• Specified values based on ISO 8995-1:2002, EN15251:2007	

2.2 Description of assessment and calculation methods

The analysis of existing rating and certification schemes in Section 2.1 provided a glimpse of well-known methods that are used in the assessment of buildings from an IEQ perspective. This section elaborates on the selected methods and calculation approaches behind them that are relevant to EPCs. Additional details on each method are provided to understand their application in Section 3.3.

2.2.1 Thermal comfort

- Heat balance model

The heat balance model works in steady state conditions and assumes that the human body's thermoregulatory system maintains constant internal body temperature. It assumes that the thermal balance of the body is influenced by human physical activity (metabolic rate) and clothing preferences (clothing insulation). It also considers environmental parameters: air temperature, mean radiant temperature, air velocity and humidity. These factors form the basis of evaluation of thermal sensation for the whole body using the PMV/PPD indexes.

- PMV/PPD

Occupant satisfaction has been investigated through surveys of subjects in laboratory settings and actual buildings. In order to determine the physical and contextual conditions in which acceptable thermal comfort can be evaluated, Fanger [53] performed an experiment on 1,296 Danish students using a steady state heat transfer model. Fanger's model is a combination of theories of heat balance and physiology of thermoregulation to determine the ranges of comfortable temperatures for the occupants of the building. The comfort equation was derived and expanded into the ASHRAE seven-point thermal sensation scale known as the 'predicted mean vote' (PMV) index. It has the following range: +3 (hot), +2 (warm), +1 (slightly warm), 0 (neutral), -1 (slightly cool), -2 (cool) and -3 (cold).

The PMV equation is a function of environmental variables as:

$PMV = f(t_a, t_{mrt}, v, p_a, M, I_{cl})$

where

- t_a air temperature (°C)
- t_{mrt} mean radiant temperature (°C)
- v relative air velocity (m/s)
- p_a humidity (vapour pressure) (kPa)
- M activity level (w/m^2)
- I_{cl} clothing insulation (clo)

Further, based on the experimental studies by Fanger on PMV, an empirical relationship was established with 'predicted percentage dissatisfied' (PPD) as:

$PPD = 100 - 95 \times \exp(-0.03353 \times PMV^4 - 0.219 \times PMV^2)$

This relationship indicates exact symmetry with respect to thermal neutrality i.e. (PMV=0). This means that if PMV=0, a minimum of 5% dissatisfied people exists due to the difference in thermal comfort from person to person [54]. Figure 4 shows the relationship between PMV and PPD. The PMV/PPD model has been adopted by various standards e.g. ASHRAE Standard 55 and ISO 7730.

Depending on the values of PMV and PPD four types of comfort ranges are defined in the standard EN15251: 2007 [55] (superseded by EN16798-1 in 2019 [56]) based on previous ASHRAE 55 and ISO 7730 standards. The comfort ranges form the basis of the design and assessment of thermal comfort and energy performance of buildings as shown in Table 3.

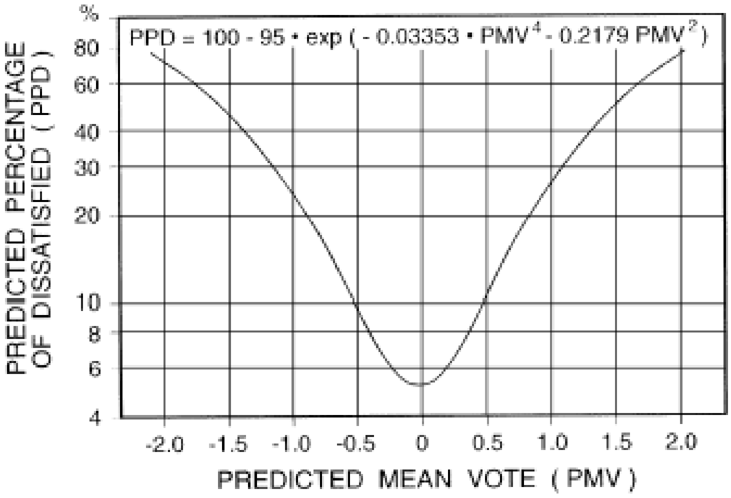


Figure 4: PPD as a function of PMV [29]

The PMV and PPD generally express thermal sensation as warm or cold for the whole body but a different criterion of local thermal discomfort can also be applied for design and dimensioning which includes draft, vertical air temperature differences, floor temperature and radiant temperature asymmetry, as described in ISO 7730. This model applies to people with light sedentary activity sensitive to local discomfort.

Table 3: Recommended categories for design of mechanically heated and cooled buildings [56]

Category	Explanation	PPD (%)	PMV
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like disabled, sick, very young children and elderly people	<6	-0.2 < PMV < +0.2
II	Normal level of expectation and should be used for new buildings and renovations	<10	-0.5 < PMV < +0.5
III	An acceptable, moderate level of expectation and may be used for existing buildings	<15	-0.7 < PMV < +0.7
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year	<25	-1.0 < PMV < +1.0

Adaptive model

While the heat balance model is applicable to air-conditioned spaces, the adaptive model is applicable to naturally conditioned spaces. This allows for the occupants to adapt to the surrounding environment by three means: physiological (acclimatisation), behavioural (changing activity, clothing level, opening/closing windows) and psychological (cognitive, social and cultural variables) [57].

The experiments to establish the relationship between PMV and PPD were conducted in climatic chambers, so did not reflect the thermal perception of occupants in environments that allow adaptation [54]. The adaptive approach was derived from field studies that determined the real conditions of the thermal environment. In real situations, people constantly interact with the immediate environment and adapt to it, making it comfortable for themselves. To apply this method in the field, the space must have operable windows with no mechanical cooling. There can be mechanical ventilation with unconditioned air, and the heating system must not be in operation. Among the key findings from the field studies on adaptive thermal comfort, a correlation was established between the mean outdoor temperature (T_o) and indoor neutral temperature (T_n) by Humphreys [58] for 'free running buildings' (without mechanical cooling):

T_n= 11.9 + 0.534 T_o (coefficient of determination R^2= 0.94)

Figure 5 shows the acceptable operative temperature ranges for naturally conditioned spaces as per ISO 7730. This model accounts for local thermal discomfort effects for typical buildings. It also accounts for people adapting their clothing by relating indoor operative temperature to the outdoor running mean temperatures and excludes the humidity and air velocity from its calculations.

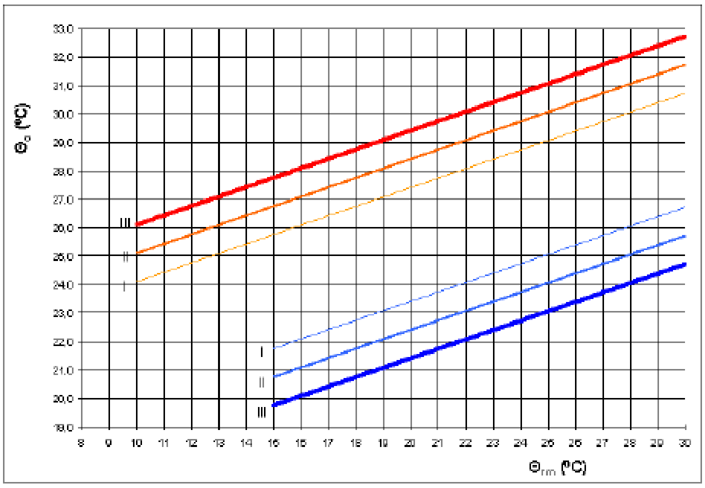


Figure 5: Acceptable operative temperature ranges for naturally conditioned spaces, $\boldsymbol{\theta rm}$ = $\boldsymbol{outdoor\ running\ mean\ temperature\ and\ \theta o = operative\ temperature\ (indoor)}$ [30]

Table 4: Adaptive comfort temperature limits [30]

Category	$\boldsymbol{\theta o}$ (°$\boldsymbol{C}$)
I	$\theta o - 2 \leq \theta i \leq \theta o + 2$
II	$\theta o - 3 \leq \theta i \leq \theta o + 3$
III	$\theta o - 4 \leq \theta i \leq \theta o + 4$
IV	$\theta i < \theta o - 4$ and $\theta i > \theta o + 4$

The adaptive approach to comfort includes conditions compatible with low-carbon buildings [59]. Studies have shown that adaptive opportunities should be made an important part of future refurbishment strategies for existing office buildings, and that adaptive comfort models predict thermal sensation and thermal comfort better [60][61]. Adaptive comfort limits are given in Table 4.

- Running mean outdoor air temperatures

To calculate the adaptive comfort ranges during summer, the indoor air operative temperatures are predicted based on a function of the exponentially weighted running mean of the outdoor temperature [55]. The exponentially weighted outside running mean temperature accounts for time-dependency over which the occupants adapt to their environment and is calculated based on equations (1) and (2) below:

$$t_{rm} = (1-\alpha)t_{ed-1} + \alpha t_{rm-1} \quad (1)$$

$$t_{rm} = \frac{t_{ed-1}+0.8t_{ed-2}+0.6t_{ed-3}+0.5t_{ed-4}+0.4t_{ed-5}+0.3t_{ed-6}+0.2t_{ed-7}}{3.8} \quad (2)$$

where

- t_{rm} the running mean indoor air operative temperature for today
- t_{rm-1} the running mean indoor air operative temperature for the previous day
- t_{ed-1} the daily mean external temperature for the previous day
- t_{ed-2} the daily mean external temperature for the day before (and so on)
- α a constant between 0 and 1 (recommended as 0.8 for use if the running means are calculated weekly)

The indoor air operative temperature (t_{rm}) obtained for the rooms using the outdoor air temperature (t_{ed}) was used to determine the comfort ranges and cross-evaluate them based on categories defined in EN 16798-1 [56]. These are shown in Table 5.

Table 5: Indoor operative temperature limits – EN16798-1[56]

Category	Lower limits	Upper limits
I	$t_{i\,min} = 0.33t_{rm} + 18.8 - 2$	$t_{i\,max} = 0.33t_{rm} + 18.8 + 2$
II	$t_{i\,min} = 0.33t_{rm} + 18.8 - 3$	$t_{i\,max} = 0.33t_{rm} + 18.8 + 3$
III	$t_{i\,min} = 0.33t_{rm} + 18.8 - 4$	$t_{i\,max} = 0.33t_{rm} + 18.8 + 4$

Note: *These limits apply when $10 < t_{rm} < 30$°C for the upper limit and $15 < t_{rm} < 30$°C for the lower limit.*

Overheating risk

Overheating is a growing risk in Europe's residential building stock. Overheating is described as situations where the indoor temperature of a home becomes uncomfortably or excessively warm. This happens most often during warm weather in the summer season, but it can also happen in winter months due to airtightness and internal gains. Both sudden spikes in temperature and prolonged periods of excess heat can be difficult for people to cope with, especially if they have an underlying health condition. Only a few Member States have requirements regarding the overheating risk in existing buildings and new buildings. The UK standard assessment procedure, for example, includes an additional appendix for its calculation. This evaluates the risk of overheating for the months of June, July and August. Average mean temperature above 23.5°C is predicted to bring a high risk of overheating. Several factors are considered in the calculation such as solar gains, natural ventilation, air change rate, thermal mass, weather data and internal gains. Chartered Institution of Building Services Engineers (CIBSE) standards specify the criteria for overheating [62]. The EN 16798-2:2019 (Annex-E) [63] also specifies a method for evaluation of annual temperatures in terms of percentage outside the comfort ranges. These criteria can be used for assessment of overheating in summer and winter; however, this requires measurements.

2.2.2 Indoor air quality

A common standard index for indoor air quality does not exist. Indoor air quality is therefore expressed as the required level of ventilation or CO_2 concentrations. It is accepted that the indoor air quality is influenced by emissions from people and their activities (bio-effluents, cooking), from the building and furnishings and from the HVAC system [63]. A recent study among European countries showed that regulations for indoor air quality in domestic buildings were not comprehensive and need additional attention as they were recognised to be the most crucial aspect in building codes by the focus countries: Belgium (Brussels Region), Denmark, France, Germany, Italy, Poland, Sweden and the UK (England and Wales) [64]. A review of studies on indoor air quality highlighted [65] inadequate ventilation causes health-related symptoms due to high concentrations of CO_2, exposure to VOCs, moulds and microbial VOCs and allergens. Many studies have investigated the influence of indoor CO_2 on occupants' health and perceived air quality [66]–[68]. A study on the association of CO_2 with occupants' health in commercial and institutional buildings, covering 30,000 occupants in about 400 buildings, indicated the prevalence of SBS symptoms [69].

- CO_2 concentration

The CO_2 concentration is considered an effective indicator of the rate of ventilation per occupant [69]. Since there are no other low-cost methods available for measuring the concentration of indoor pollutants, it is used as a reliable proxy for measuring indoor air quality [70][55]. European standard EN 6798-2:2019 [63] defines the limits of concentration expected in different IEQ categories based on non-adapted occupancy requirements above outdoor concentration (default: 400ppm) assuming a standard CO_2 emission of 20 L/h/person.

- Ventilation rate or air change rate

The outdoor ventilation rates vary in different zones of buildings and depend on the fresh air requirements for that zone and requirements of different health criteria. Ventilation rate impacts the indoor air quality in terms of concentration of indoor airborne pollutants and CO_2 [71]. It also affects the thermal comfort and indoor humidity levels. The steady state decay method using the concentration of CO_2 can be used to determine the air change rate in a zone.

The air change rate (A_S) can be calculated based on the average CO_2 generation rates [72][73] as:

$$A_S = \frac{6\,X10^4 n\,C_p}{\{V(C_S - C_R)\}}$$

where A_S is the air change rate [h^{-1}], n is the number of people in the space, C_p is the average CO_2 generation rate per person (generally 0.46 [$l.min^{-1}.person^{-1}$]); V is the volume of the room [m^3]; C_s is the steady state indoor CO_2 concentration [ppm]; C_R is the CO_2 concentration in supply air (outdoor air) [ppm].

Ventilation rate requirements are defined for residential and non-residential buildings in EN 6798-2:2019 [63] for different categories under three different methods: (i) perceived air quality, (ii) using limit values of gas concentration (CO_2), and (iii) based on pre-defined ventilation flow rates. Ventilation rates can be achieved by different ventilation systems: mechanical, natural or hybrid (which combine mechanical and natural principles)

- Mechanical ventilation

Mechanical residential ventilation systems mostly consist of self-contained equipment with elementary air ducts if needed. Mechanical ventilation ensures the provision of regulated ventilation control for different zones of the building. These are identified in four categories: (i) exhaust ventilation systems, (ii) supply ventilation systems, (iii) balanced ventilation systems, and (iv) un-ducted units for single rooms.

- Natural ventilation

Residential natural ventilation systems use stack effect and wind pressure to drive the ventilation airflow through the building. Typical inlet components are facade grilles, window grilles, roof window ventilation flaps and air inlets. Typical extract components include extract stack ducts. The system is typically designed to allow air entry in living rooms and bedrooms, and to extract air from kitchens, toilets and bathrooms. The operation of the ventilation system can be based on always-open ventilation openings, which provide acceptable indoor air quality on weekly, monthly and annual levels. The operation can also be automated, based on sensors of e.g. humidity or CO_2. Manual control of ventilation is not considered a natural ventilation system as it must be observed and regulated manually. EN 6798-2:2019 [63] lists the natural ventilation requirements based on (i) air changes per hour (ACH), (ii) supply air flow per person, and (iii) perceived indoor air quality for adapted persons.

2.2.3 Visual comfort

Standard EN 12464-1 [74] describes minimum standards of illuminance for workplaces that are required to be maintained to fulfil visual comfort and performance needs [74]. EN 6798-2:2019 [63] also lists the criteria for lighting required in different buildings and spaces. A literature survey by Fabi et al. [75] covered several psychological (attitudes), social (occupancy), physical (direct sunlight) and contextual (orientation) driving forces responsible for visual comfort in buildings. Occupants find it challenging to maintain good visual comfort as individuals have varied perception of glare and lighting levels in workplaces [76]. Loss of privacy is also a factor that could be considered for visual comfort.

There are three aspects that are generally studied to evaluate visual comfort, and these include the lighting levels, presence of glare and quality of outdoor view. Some of the commonly used metrics to assess visual comfort are described below.

Assessing lighting levels

Illuminance

Illuminance at a surface I_D is defined as a physical quantity measured in lux that is calculated as a ratio between the luminous flux falling on the surface with an area (A_{ill}).

$$I_D = \frac{d\varphi}{dA_{ill}} [lux]$$

where I_D is illuminance [lux]; φ is luminous flux.

Therefore, illuminance is used as a single criterion to assess the availability of the amount of light falling at a single plane that is easy to measure using a lux meter. As per the standard EN-12464-1 [74], the minimum amount of illuminance required in a standard office work plane is 500 lux. This metric has certain limitations as (i) it does not indicate any information about the quality of light, (ii) it does not refer to the type of light such as artificial or daylight, and (iii) it does not account for glare as it does not measure the observer's perspectives.

Daylight factor

The daylight factor (DF) for daylight access is applicable under the International Commission on Illumination (CIE) overcast sky. It is useful for early design decisions and is a useful technique for assessing daylight potential of interior spaces. Daylight factor does not consider direct sunlight and its effects.

$$DF = \frac{E_I}{E_O} \times 100\%$$

where:

- DF the daylight factor measured at a specific point (%)
- E_i available lux indoors at a specific point on a working plane (lux)
- E_o simultaneous available lux outdoors under a CIE overcast sky (lux)

The daylight reaching any point inside a room is usually made up of three components: (i) sky component, (ii) externally reflected component, and (iii) internally reflected component.

If there is no external obstruction like trees, buildings etc. the externally reflected component is omitted. Several techniques, manual as well as computerised, may be used to calculate these components for a building. In side-lit rooms, the maximum DF is near the windows, and is due to the sky component. In the initial stages of building design, the average DF may be used to assess the adequacy of daylight:

$$\text{Average DF} = \frac{W}{A}\,\frac{T\theta}{(1-R^2)}$$

where:

- *W* area of the windows (m^2)
- *A* total area of the internal surfaces (m^2)
- *T* glass transmittance corrected for dirt
- *Θ* visible sky angle in degrees from the centre of the window (deg)
- *R* average reflectance of area A

The values of these quantities are determined from the given data and W, T and R are corrected by using factors given in the EN 17037 Daylight Code [77][78].

- **Spatial daylight autonomy**

Spatial daylight autonomy (sDA) is defined by the amount of daylight that a particular space receives during the standard operational hours (8:00 to 18:00) on an annual basis [79]. The hourly illuminance grids are used on the horizontal work plane to map the daylight received. sDA is calculated through computational simulation with parameters such as location and weather conditions throughout the year. The percentage of light that a specific point receives above a required threshold illumination within the annual daytime hours is termed as sDA [79].

$$sDA = \frac{\sum_i (w_f . t_i)}{\sum_i t_i} \in [0,1] \text{ with } wf_i \begin{cases} 1 \; if \; E_{daylight} \geq E_{limit} \\ 0 \; if \; E_{daylight} < E_{limit} \end{cases}$$

where t_i is each occupied hour in a year; w_{fi} is a weighting factor depending on values of $E_{Daylight}$ and E_{limit} that are the horizontal illuminance at a given point due to the sole daylight and the illuminance limit value, respectively.

sDA uses the geographic location and annual weather data containing the global, diffuse and direct irradiance measurements. Therefore, it is advantageous over the daylight factor, D_F. Another benefit of this metric is the ability to calculate artificial light savings, which is possible by measuring the daylight received during each hour and providing sufficient artificial light if the total is below a minimum threshold.

Measuring the impact of glare

- **Daylight Glare Index**

To measure the impact of glare on visual comfort, metrics like the Daylight Glare Index (DGI) are used. This considers large glare sources such as windows and specifically diffuse sky visibility through the window. The DGI metric was studied using human subjects in day-lit interiors, where the sky brightness was measured and given a position index and size [79]. This is not considered to be accurate when there is direct light or reflections present in the field of view. DGI is a correlation between the source of luminance, size and its position in the field of view against a background of sky luminance, with a small percentage of the source luminance compensating for additional eye adjustment to the visible luminance. The DGI value generally varies from 18 to 31, where 18 corresponds to barely perceptible glare and 31 or greater corresponds to intolerable glare.

- Annual sunlight exposure

The annual sunlight exposure (ASE) metric is intended to help designers limit excessive sunlight in a space. While ASE is a crude proxy for glare phenomena, it measures the presence of sunlight using annual hourly horizontal illuminance grids rather than luminance measures, so it is technically not a glare metric. It evaluates the potential source of visual discomfort from direct sunlight. LM-83 [77] provides preliminary guidance for recommended ASE limits, cautioning that spaces with ASE values exceeding 10% will likely result in visual discomfort. ASE is defined as the percentage of an analysis area that exceeds a specified direct sunlight illuminance level, e.g. 1000 lux, for more than a specified number of hours, e.g. 250 hours per year. ASE values range from zero to 100%, with the latter suggesting that the entire floor area of the space in question exceeds the simulated value of 1000 lux for at least 250 hours per year. To reduce the potential for glare and thermal stress, designers should aim for low ASE values (preferred threshold: $ASE_{1000,250h} <$ 3% of analysis area, and nominally acceptable threshold: $ASE_{1000,250h} <$ 7% of analysis area).

Outdoor views

It is desirable to provide comfortable outdoor views for building occupants to connect them to the natural environment. Views connect the indoors with outdoors and are highly desirable for residential, office, healthcare and commercial buildings. The factors on which outdoor views depend are the optical characteristics, colour of glazing, size and shape of openings, surrounding lighting levels and composition of the outdoor scene. For this purpose, the method defined in LEED manual BD+C [50] can be used to determine the quality of views:

A direct line of sight to the outdoors via vision glazing for 75% of all regularly occupied floor area must be achieved. View glazing in the contributing area must provide a clear image of the exterior, not obstructed by frits, fibres, patterned glazing, or added tints that distort colour balance.

Additionally, 75% of all regularly occupied floor area must have at least two of the following four kinds of views:

- multiple lines of sight to vision glazing in different directions at least 90 degrees apart
- views that include at least two of the following: (1) flora, fauna, or sky; (2) movement; and (3) objects at least 25 feet (7.5 metres) from the exterior of the glazing
- unobstructed views located within the distance of three times the head height of the vision glazing; and

- views with a view factor of 3 or greater, as defined in "Windows and Offices; A Study of Office Worker Performance and the Indoor Environment"

Calculation should include any permanent interior obstructions. Movable furniture and partitions may be excluded. Views into an interior atrium may be used to meet up to 30% of the required area.

2.2.4 Acoustic comfort

The indoor system noise criteria (sources such as ventilation system, dishwasher etc.) of some spaces and buildings are given in terms of A-weighted sound pressure levels (dB(A)) normalised with reverberation time in EN16798-1 [56]. These criteria are used to assess the relative loudness as perceived by the human ear using a measuring instrument. These criteria apply to sources from both outside and inside the building so that relative loudness is measured and used to limit the sound pressure levels inside the space. This method is very much suitable for assessment in EPCs.

Noise levels can exceed these levels in case of occupants opening windows or the operation of HVAC units. Retrofits can enable the reduction of indoor noise, while addressing solutions for thermal comfort and energy efficiency [80]. Noise criteria do not causally relate to energy performance, but the relationship depends on the opening of fenestrations. For example, to minimise outdoor noise occupants may close windows in summer; this would limit natural ventilation and cooling energy may be required to maintain indoor thermal comfort. The WELL standard comprehensively lists several criteria such as sound barriers, masking, absorption and mapping to assess the acoustics of a space in dwellings, offices and commercial buildings utilising on-site assessments and document verification processes [52]. Similarly, LEED also outlines a comprehensive set of criteria that may be applicable to assessment for EPCs [50].

Table 6 shows a list of indicators that could potentially be explored and used for assessment of acoustic comfort. All the associated standards are also listed in the table.

Table 6: Description of some acoustic indicators used [81]

Indicator	Description	Standards
STC	Airborne sound transmission class, calculated as R_w	ASTM E413
$L_{Aeq,nT}$	Equivalent continuous sound pressure level (background noise levels)	EN 16798-1:2019
$L_{n,w}$	Weighted standardised impact sound pressure level	ISO EN 12354-2
R_w	Apparent airborne sound reduction index	ISO EN 12354-1
R_t	Reverberation time	ISO 3382-2:2008

2.3 Application of assessment methods for the indicator

2.3.1 Voluntary or mandatory methods for EPCs

Table 7 gives an indicative list of indicators under each category. To assess each category minimum and alternative/additional indicators have been identified and listed. However, no assessment has yet been made on which category is voluntary or mandatory for EPCs. This will be further studied in X-tendo based on individual country and building stock requirements.

Table 7: List of required indicators

Category	Minimum required indicators	Alternative/additional indicators
Thermal comfort	PMV/PPD (conditioned spaces), overheating risk (summer, winter)	Adaptive comfort (unconditioned spaces), radiant thermal comfort, drafts
Visual comfort	Illuminance level, size of fenestrations	Spatial daylight autonomy, daylight factor, glare control, luminance quality, annual sunlight exposure,
Acoustic comfort	Indoor ambient noise level	Sound insulation, reverberation time, exterior noise intrusion, average equivalent sound absorption area
Indoor air quality	Ventilation rate, CO_2 concentration, operable windows	VOC level, internal moisture level, olfactory comfort

2.3.2 Applicability of methods to different building typologies

Table 8 lists several indicators (methods) showing their applicability to different building typologies along with existing and new buildings. Out of all the indicators only radiant asymmetry and drafts are generally not applicable to new buildings, though may apply if they are poorly designed. They are often a problem in old buildings with cold surfaces due to insufficient insulation causing uneven heating of air in the room. The building envelope is generally leaky and may have developed gaps or cracks causing drafts.

Table 8: Overview of applicability of each indicator to different buildings

Category	Indicators (methods)	Existing buildings	New buildings	Residential buildings	Non-residential buildings (office, hospitals, hotels, schools etc.)
Thermal comfort	PMV/PPD (conditioned spaces)	✓	✓		✓

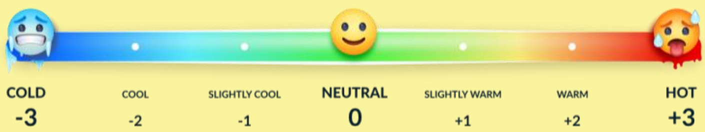
	Overheating risk	✓	✓	✓	✓
	Adaptive comfort (unconditioned spaces)	✓	✓	✓	✓
	Radiant asymmetry	✓		✓	✓
	Drafts	✓	✓	✓	✓
Visual comfort	Illuminance level	✓	✓	✓	✓
	Daylight factor	✓	✓	✓	✓
	Size of fenestrations	✓	✓	✓	✓
	Spatial daylight autonomy	✓	✓	✓	✓
	Annual sunlight exposure	✓	✓	✓	✓
	Outdoor view	✓	✓	✓	✓
Acoustic comfort	Indoor ambient noise level	✓	✓	✓	✓
	Reverberation time	✓	✓		✓
	Exterior noise intrusion	✓	✓	✓	✓
	Average equivalent sound absorption area	✓	✓	✓	✓
Indoor air quality	Ventilation rate	✓	✓	✓	✓
	CO_2 concentration	✓	✓	✓	✓
	Operable windows	✓	✓	✓	✓
	Olfactory comfort	✓	✓	✓	✓

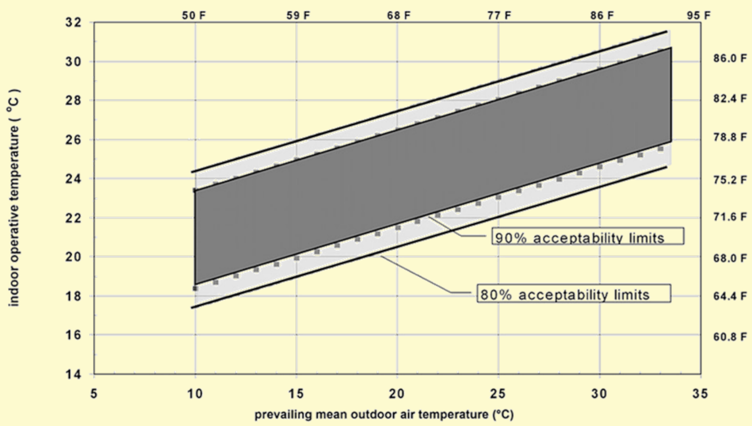
The application of several indicators to different building typologies does not vary much for residential and non-residential buildings. In the case of thermal comfort, PMV/PPD have not been tested or robustly developed for residential buildings and are more suitable for non-residential buildings with varying activities. Methods such as equivalent sound absorption area might not be suitable for residential buildings as the volume of spaces is generally not large. Indicators such as radon concentration are more relevant for residential buildings as radon tends to accumulate in high concentration areas such the lower ground floor, basement and ground floor that are not well ventilated and often occupied in residential buildings.

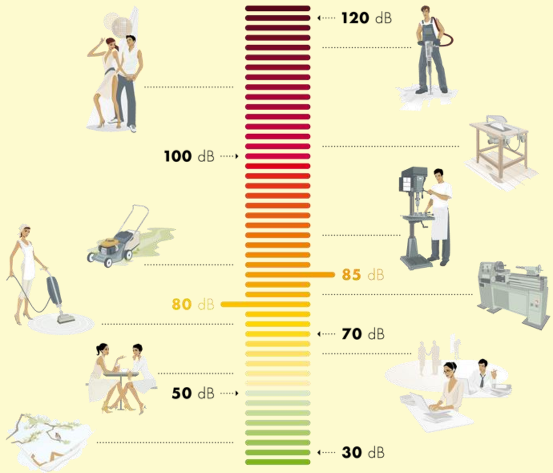
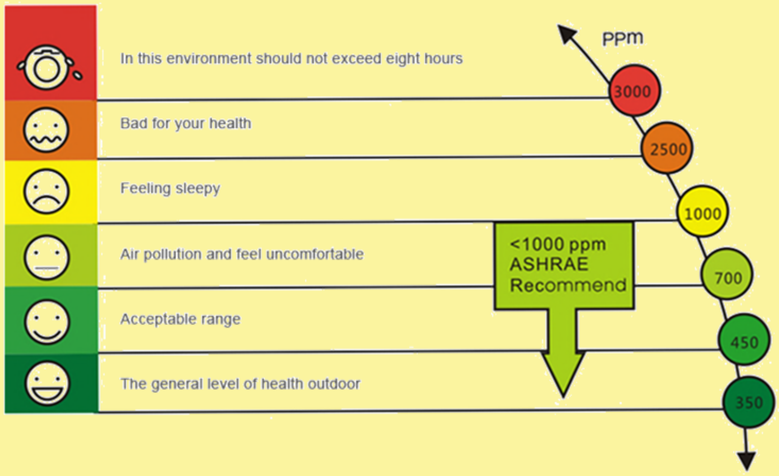
2.3.3 Presentation of the indicator

Table 9 illustrates a few examples used for presentation of ranking or score. Many methods have no scale but are represented only by their threshold criteria as defined in standards. It is possible to define innovative scales for the purpose of EPCs depending on the method to be used in the assessment of comfort.

Table 9: Examples of ranking/scale/score/threshold used for indicators

<table>
<tr><th>Category</th><th>Indicators</th><th>Ranking/Scale/Score</th></tr>
<tr><td rowspan="2">Thermal comfort</td><td>PMV/PPD (conditioned spaces)</td><td>

ASHRAE scale (-3[cold], -2[cool], -1[slightly cool], 0 [neutral], +1[slightly warm], +2[warm], +3[hot])</td></tr>
<tr><td>Adaptive comfort (unconditioned spaces)</td><td>Acceptability limits used (70-90%) based on number of occupants. Light grey area represents 70% acceptability and dark grey represents 80-90% acceptability

</td></tr>
<tr><td rowspan="4">Visual comfort</td><td>Illuminance level</td><td>Minimum requirements according to occupancy (e.g. office=500 lux, corridor 100 lux etc.)</td></tr>
<tr><td>Daylight factor</td><td>50% of usable area throughout the building should have DF (> 3% very good, > 2% medium, > 1% slight, < 1% none)</td></tr>
<tr><td>Size of fenestrations</td><td>Values for WWR (window-wall ratio) should be between 20-60%.</td></tr>
<tr><td>Spatial daylight autonomy</td><td>Refers to the % of floor area that receives 300 lux of daylight for min. 50% of annual occupied hours (LEED requirement 55-75%)</td></tr>
</table>

<table>
<tr><td></td><td></td><td></td></tr>
<tr><td></td><td>Annual sunlight exposure</td><td>Refers to the % of floor area that receives 1000 lux of direct sunlight for min. 250 occupied hours per year (LEED requirement max. 10%)</td></tr>
<tr><td>Acoustic comfort</td><td>Indoor ambient noise level</td><td>Should not exceed 40 dB indoors

</td></tr>
<tr><td>Indoor air quality</td><td>CO_2 concentration</td><td>Specified values based on occupancy in standards


Source: https://iotfactory.eu/</td></tr>
</table>

2.4 Linking indicators to energy performance and EPCs

Thermal comfort

Thermal comfort has a direct correlation with indoor air temperature. To maintain indoor air temperature heating/cooling is required, which consumes energy. The changes in the energy performance of buildings can be observed during different seasons across different climate zones where the requirements for heating or cooling vary. In Northern Europe, the indoors requires heating in winter months and energy consumption is highest in these months to ensure thermal comfort. Provision of energy efficient strategies can also maintain thermal comfort effectively, such as natural ventilation, solar-shading and passive solar gain. Approximately 64% of the energy used in households is used in meeting the required heating demand [82].

- Visual comfort/daylight

Adequate lighting is necessary for comfortable viewing and strongly depends on the activity and areas where lighting is required. To maintain a required level of illuminance throughout the day, artificial lighting is used, which consumes energy on a daily basis. Achieving visual comfort by means of artificial lighting affects the energy requirement of a building and thus impacts its energy performance strongly. Approximately 14% of energy used in households is used in lighting [82].

- Acoustic comfort

Acoustic comfort has an indirect relation with energy performance. The acoustic performance of a space is influenced by the level of insulation. Often thermal insulation improves the acoustic performance of a space as well as the energy performance. Similarly, windows affect thermal as well as acoustic insulation. Often, houses with poorly insulated or leaky windows provide low acoustic comfort from outdoor noise. The presence of ventilation openings also negatively affects acoustic comfort.

- Indoor air quality

A supply of fresh outdoor air improves indoor air quality. The outdoor air can be provided either by natural ventilation or mechanical ventilation. Mechanical ventilation maintains a required level of indoor air quality and, therefore, impacts the energy performance of a building. Next to the auxiliary energy needs, ventilation also requires conditioning of supplied air, for which energy is used.

IEQ indicators are strongly linked with building energy consumption. There are aspects of IEQ in several EPC schemes, e.g. overheating, ventilation, lighting, heat comfort, etc. However, only a few countries have specific indicators for this, or one aggregated indicator. Countries such as Greece, Ireland and Italy collect very rudimentary information on comfort aspects, such as good air quality, thermal comfort satisfaction or overheating risk, based on observation or off-site calculations made by the auditor. Although the extension of EPC aspects such as comfort has been highlighted by many Member States, there has been no progress in the EPC schemes in this regard.

2.5 Legal boundaries or requirements of assessment methods

During the assessment of comfort indicators, the auditor or assessor would collect data on aspects such as temperature, humidity, CO_2 levels, usage of spaces, temperature regulation etc. Additionally, specific photographs or notes would be taken during the assessment. Collection of data on several indicators would require consent from the owners as the analysis of data would reveal occupant behaviour, making it vulnerable to misuse. Data could be exploited commercially if not regulated. Therefore, for data privacy and security purposes compliance with GDPR must be followed along with regulations under current EPC systems. There are no legal boundaries already defined for any of the listed methods, so each method would be checked for its legal boundaries separately in terms of data being collected.

2.6 Ranking of assessment methods to evaluate their feasibility for the feature

Table 10 evaluates the assessment methods for the four indicators discussed earlier for their application to EPCs based on their feasibility of use. Although there are no prior references to identify the suitability of methods for EPCs, their feasibility is assessed through expert judgement considering the complexity of their use in terms of evaluation procedure (e.g. measurements, on-site/off-site assessment), time, cost and overall effort.

Table 10: Feasibility of assessment methods for EPCs

Method	Ranking	Comment on feasibility/ explanation
Thermal comfort		
PMV/PPD	***	Requires extensive monitoring and occupant data collection (clothing, metabolic activity etc.)
Adaptive comfort	***	Only indoor temperature monitoring required (applicable only in non-conditioned period e.g. summer)
Thermal satisfaction survey	****	Can be conducted easily on-site with the occupants in high-occupancy buildings
Overheating risk	****	Requires annual evaluation of indoor temperature levels
Radiant asymmetry	**	Suitable for existing buildings and can be determined with on the spot measurement
Drafts	**	Suitable for existing buildings but requires expensive instruments for measurement
Visual comfort		
Illuminance	*****	On the spot measurement and easy to determine but does not differentiate between artificial and daylight
Daylight factor	****	Only applicable for assessing daylight levels indoors but ignores effect of direct

		sunlight
sDA (spatial daylight autonomy)	*	Requires annual simulations for calculation but calculates only daylight during operational hours
Annual sunlight exposure	*	Used to measure direct sunlight and as a proxy for glare. Determines visual discomfort due to glare
Outside views	*****	Easy to determine and calculate
Size of windows	*****	Relatively easy for on-site assessment and usually available as an input for EPC assessment
Acoustic comfort		
Indoor ambient noise level	****	Easy to measure and determine
Reverberation time	**	Suitable and relevant for larger spaces only
Exterior noise intrusion	****	Easy to measure and determine
Average equivalent sound absorption area	****	Can be calculated using information about the building
Indoor air quality		
Ventilation rate	****	Requires expensive instruments for measurement but can be calculated using CO2 in non-conditioned zones. Easily determined where mechanical systems are present
CO_2 concentration	****	Easy to measure on-site and small-time interval for reading
Operable windows	*****	Easy to note and use the information
VOC concentration	*	Expensive measurement device
Olfactory comfort	*****	Suitable for commercial/ office buildings and easy to determine based on subjective outputs
Likert scale used for suitability: not at all (*), slightly (**), moderately (***), very (****), extremely (*****)		

2.7 SWOT analysis of the comfort assessment methods

Overall, there are many assessment methods available to assess the IEQ indicators. Each method has its pros and cons but a general evaluation of the methods in the context of EPCs is given in Table 11 for each indicator.

Table 11: SWOT analysis of the IEQ assessment methods for EPCs

Strengths	Weaknesses
Thermal comfort	
EN/ISO standard methods available for assessment of summer/winter comfort	Long-term and short-term monitoring necessary for assessment (seasonal/annual)
Variety of measuring instruments are available	Few experts with knowledge of all the indicators
Online training material and tutorials available	No established rating or scale to be used directly in EPCs
Indoor air quality	
EN/ISO standard methods available for assessment	Measurements necessary for evaluation
Proxy measurement possible through CO_2	Variation in assessment for different buildings
Visual scale available to use	Expensive instruments to measure air quality
Visual comfort	
EN/ISO standard methods available to assess lighting levels and glare	Simulations necessary for most methods for evaluation
Guidelines available for different building typologies	Difficult to assess during overcast conditions on-site
Acoustic comfort	
EN/ISO standard methods available to assess acoustic performance	Measurements necessary for evaluation
Guidelines available for different building typologies	Mostly suitable for office and commercial buildings
Opportunities	**Threats**
Thermal comfort	
Most important driver for renovation for residential and tertiary sector	Potential on negative impact on energy performance score
High awareness of thermal comfort among end-users	Variable benchmarks for thermal comfort in different climates of Europe
Very relevant for productivity gains	Objections against using too expensive measurement methods
Indoor air quality	
Ventilation guidelines already included in	Health impacts are not well understood by

building regulations of many Member States	end-users
Very relevant for productivity gains	Too many metrics to select for assessing indoor air quality
Visual comfort	
Relatively low investments needed to meet the standard guidelines	Confusion in selection of best method for measurement
Well-established guidelines that can be adopted in EPCs	Low priority given compared to thermal comfort and indoor air quality
Acoustic comfort	
Well-established guidelines that can be adopted in EPCs	Expensive instruments for measurements
Can be combined with thermal comfort measures	Not considered as an important driver in renovation

2.8 Proposed approach to develop the feature

The literature review of the existing rating and certification systems and IEQ indicators provided details regarding the relevant indicators, criteria and parameters used to assess comfort in buildings. Most of the existing systems focus on granting rankings based on extensive criteria (e.g. technical, verification, measurements and assessments), generally with longer monitoring time requirements for evaluation (e.g. monthly/annual). The assessment of comfort for EPCs should be done in a relatively shorter time and with less effort to reduce the cost of assessment and increase the affordability for the end-user (cost is a big barrier for many households).

For the further development of the comfort indicator in the X-tendo project these constraints will be addressed and considered in the approach that will be tested in buildings. The assessment methods would consist of checklists (observations/measurements), surveys and on-site monitoring depending on the requirements of the individual parameter (see Figure 6). The approach will be developed to keep the assessments adaptable, affordable and time effective.

Four main indicators will be assessed within the comfort feature: (i) thermal comfort, (ii) indoor air quality, (iii) visual comfort, and (iv) acoustic comfort. To identify the overall IEQ level, all four indicators will be assessed independently based on multiple criteria. Under each criterion, certain parameters must be met to achieve a required score. The score will be awarded using the relevant assessment method (e.g. checklist, survey, monitoring etc.). A description of indicators, criteria and parameters is given below with an indication of the weightages assigned to them. An individual rating/scoring process is proposed for the comfort feature as shown in Figure 6. A combined rating with a single value will give an overall idea of the indoor environment but will not specify the problem areas and there is a greater chance of making errors in applying corrective measures. Therefore, an individual rating for all four indicators is proposed to provide more details for interventions.

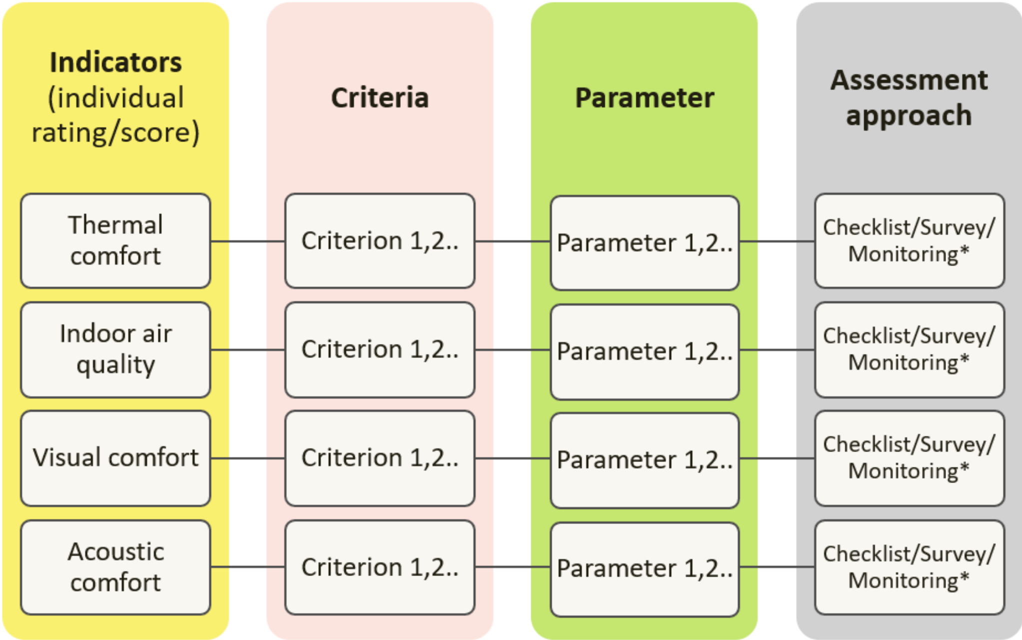


Figure 6: Individual rating process

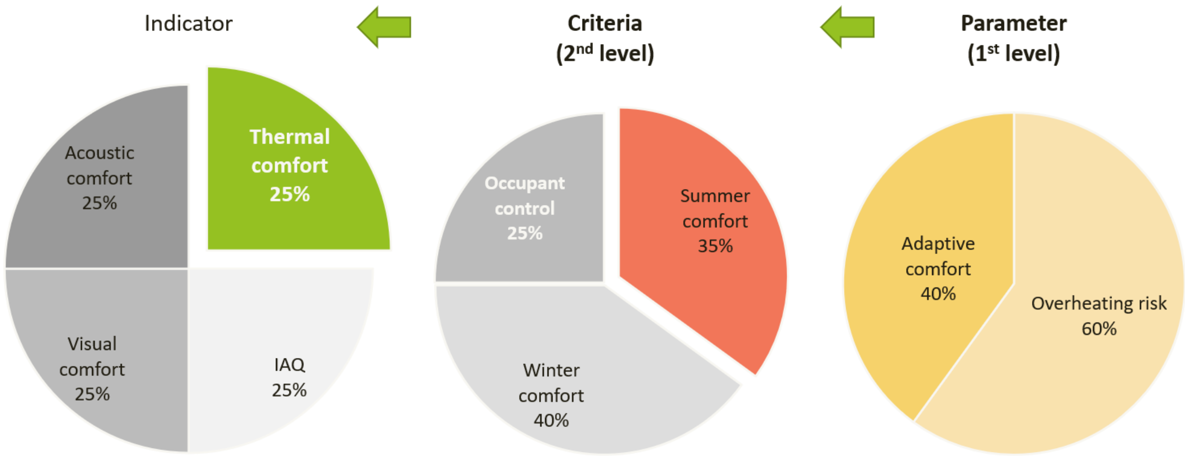


Figure 7: An example of two levels of weightage for the thermal comfort indicator

A description of the terms used in the comfort feature assessment is given below (refer to Figure 6 and Figure 7):

1. **Indicators:** This refers to the four main components of the comfort feature. These components will be assigned equal or different relative weightage (e.g. in Figure 7, thermal comfort = 25%, visual comfort = 25%, indoor air quality = 25%, acoustic comfort = 25%) depending on the different aspects, e.g. region, type of buildings etc. Each indicator will be assessed based on several criteria.

2. **Criteria:** The criteria are the aspects that are required to be assessed under each indicator. The list of criteria is prepared based on existing literature. Criteria will be assigned different or similar relative weightage (e.g. in Figure 7, for indicator *thermal comfort*: summer comfort = 35%, winter comfort = 40%, occupant control = 25%) based on expert inputs. A criterion of occupant control is also included for all indicators, as this has been found to be an essential aspect in maintaining a satisfactory level of indoor comfort. Since each indicator interacts in certain ways with the other, which are often complicated to determine in the assessment. However, the occupant control criterion does consider how occupants may react to the combined effect of two or more main indicators (e.g. closing the window partially to block noise but continue to ventilate for fresh air). Occupant behaviour is generally challenging to measure and predict. Each criterion will be evaluated based on certain parameters via different assessment methods (checklist/survey/on-site monitoring).

3. **Parameters:** A list of parameters will be prepared to assess each criterion based on the impact on comfort and health and well-being of the occupants. A relative weightage will be assigned to each parameter based on expert inputs (e.g. in Figure 7, for the criterion *summer comfort*: overheating risk = 60%, adaptive comfort = 40%). Each parameter can obtain a score of 0 (worst) to 10 (best) which is assessed using a checklist, survey, on-site monitoring etc. Individual scales for each parameter will be developed in further work.

An example of an exhaustive list of criteria and parameters (description tree) is given in Figure 8.

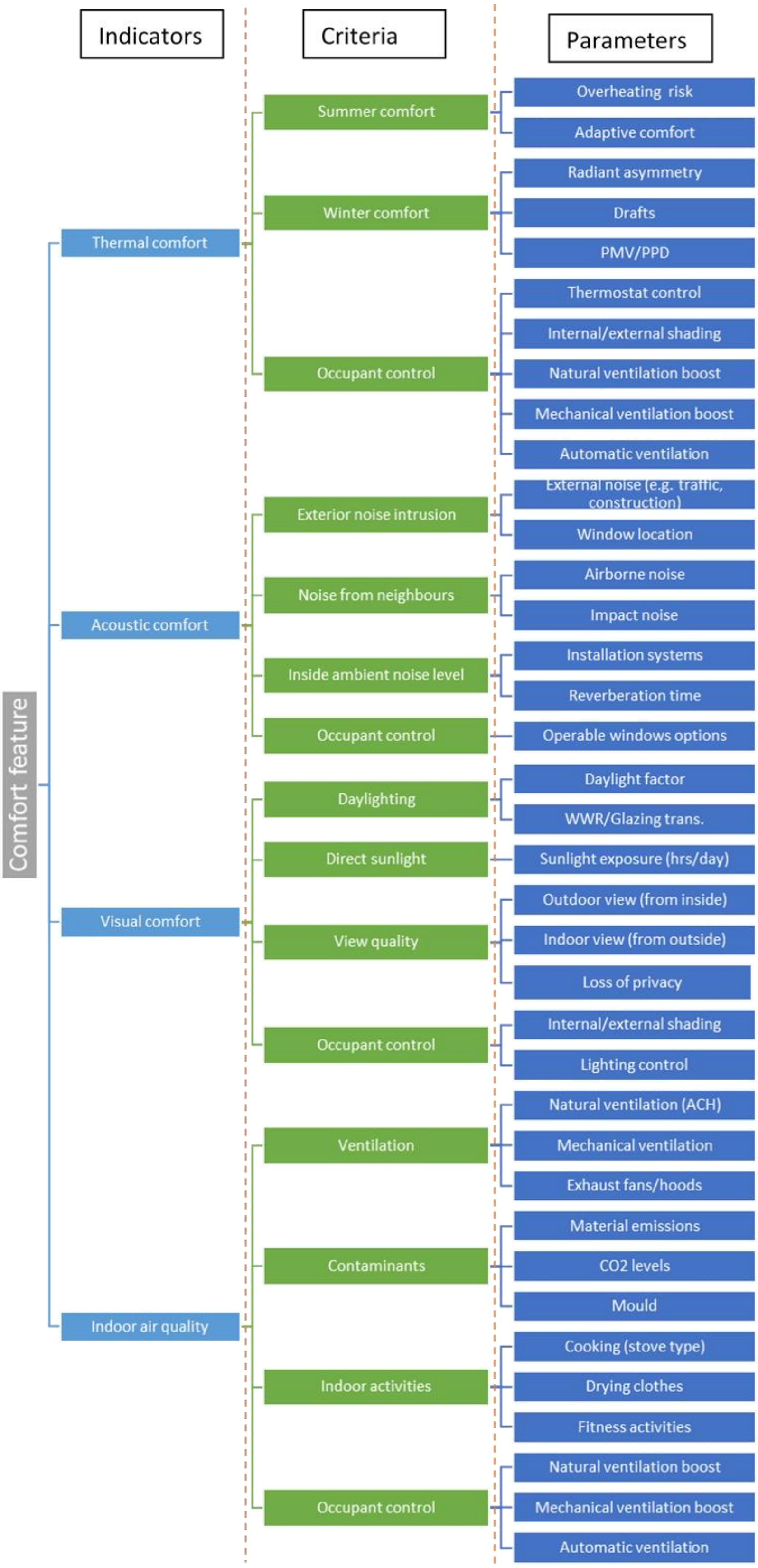


Figure 8: A description tree of indicators, criteria and parameters

The proposed scale to be used for the comfort feature in EPCs is given in Table 12.

Table 12: Scoring to the corresponding labels

Label for comfort feature	Score (maximum achievable fraction)
Very bad	0% < score ≤ 30%
Bad	30% < score ≤ 40%
Acceptable	40% < score ≤ 60%
Good	60% < score ≤ 80%
Excellent	80% < score ≤ 100%

The scores will be calculated individually for the four indicators (see Table 13) based on Table 12.

Table 13: Individual ratings for indicators

Indicator	0%-----------------------100%	Label
Thermal comfort	90%	Excellent
Indoor air quality	80%	Good
Acoustic comfort	65%	Good
Visual comfort	50%	Acceptable

3 FINDINGS

This section presents a summary of key findings (Table 14) related to the indicators that will be developed for the five innovative features in the X-tendo toolbox. This summary will be a precursor for further work in WP3. The findings have been categorised into key barriers, challenges, limitations, delivery actors, presentation, target audience and link with energy performance.

Table 14: Key findings of the scoping and analysis of all features

	Feature 1: smart readiness	Feature 2: comfort	Feature 3: outdoor air pollution	Feature 4: real energy consumption	Feature 5: district energy
Key barriers					
Technical/ methodological	Dealing with differences in building services (heating, EV presence, etc.) and characteristics (age, type or geographical location) Weighted measures and theoretical building maximums need to be developed	Assessment methodology for different building typologies	Proper definition of outdoor air quality	Length of the monitoring duration	Implementation of a certification scheme for calculating future PEF, REF and CEF could be a major barrier for some countries
Financial /economic	Existence of several schemes (market saturation)	-	-	Normalisation for user behaviour financially	-
Legislative/ governance	Differences across MS in smart readiness levels	Various standards at MS level	-	Enforcement frame Accounting for bulked quantities	-
Social	Novelty of the indicator requires the presence of useful information	Benefits are not well understood by public	-	Landlord/tenant split	-

	for the majority of the public				
Environmental	ICT technology might have a significant environmental impact	-	-	Monitoring infrastructure cost in relation to benefits	Additional efforts and committing to values stated in EPCs might be a reason for district heating utilities to oppose these indicators
Industry	Potential lack of readiness of the industry to satisfy the demand of new ICT	Application of industry-based solutions in building sector	-	Strict enforcement is difficult or even not feasible	Implementation of a certification scheme for calculating future PEF, REF and CEF could be a major barrier for some countries
Key challenges					
Technical/ methodological	Quick assessment -> Method A is created to reduce assessment time	Provision of single rank/score Accuracy of methods with or without measurements	Estimation of filter classification for each county Proper definition of reference values of emission rates Scale of indexes and weights for each country	Development of suitable models for missing data (e.g. DHW energy consumption) Differentiation of method for various functions (especially non-residential) Normalisation versus maintaining the link with actual measured energy consumption Normalisation for indoor environmental	Variable definitions of PEF, REF and CEF

				quality and service provision	
Financial/ economic	Low cost and easy-to-use option	Developing cost-effective assessment criteria	-	Cost/accuracy or effectiveness balance	Estimation of data for future years for a district heating system (mainly plant capacities and full load hours)
Legislative/ governance	Universal methodology applicable to all MS (in contrast to EPC)	No reference for EPCs available from MS	Multiple standards and regulations in different MS	Minimising fraud GDPR (especially in the case of individual dwellings or buildings with low number of users) Citizen security and data privacy	Estimation of data for future years for the public electricity grid so that it is accepted by the district heating utilities and authorities
Social	Acceptability and appropriation	-	-	User acceptance; maintaining the link with energy billing/metering information	Method for verification between roadmap of district heating utility and estimated data
Environmental	Benefits vs. costs understudied	Integration in decision-making for renovation measures	Integration of variable sources of emissions in different MS	Positive balance of environmental benefits of EPC method effectiveness improvement versus environmental impact	-
Industry	Demand satisfaction	Quantified benefits not well integrated in assessments	-	-	-

Limitations	Might work at the level of some MS but not all Higher smartness levels should reflect better quality of life for occupants and building performance	Reduction of measurements for cost-effectiveness Limited complexity to simplify training of experts	AQI data is required	For the design, calculation is still required; duration of measurement period (relevant for new/renovated buildings) Monitoring infrastructure roll-out may not be supported in all MS	-
Presentation	Well-developed presentation approach	Few examples of presentation available	Existing colourful scale exists	As part of EPC, printed, digital, as part of building logbook, complementary to current EPC information or replacing it.	-
Delivery actors	EPC assessors, qualified experts but also owners (self-assessment)	EPC assessors, qualified building professionals	EPC assessors, energy auditors	EPC assessors, qualified building professionals/ experts Depending on data availability, potentially fully automated	EPC assessors, district heating utilities
Target audience	Whole building ecosystem: property owners, buyers, renters, tenants, facility managers, public authorities	Property owners, buyers, renters, tenants, facility managers	End-users, owners, occupants	Same as current EPC target audience, although focus is more user-oriented.	Property owners, buyers, renters, tenants, facility managers, research, public authorities responsible for planning heating and cooling
Link with energy performance	Monitoring and operation at the building level and	Thermal comfort and indoor air quality have a	Pollutant emission and indoor air purity	Real energy consumption directly links with energy	All indicators have a strong link to the energy

	improved interoperability with the grid	strong link with energy performance	have a strong link with building thermal and installation characteristics	performance and additional operational (energy) performance Potentially contributes to mitigation of energy performance gap	performance of the building

4 CONCLUSIONS

This report provides useful and crucial insights into working out the indicators for the five features during the X-tendo project. For all features, we have outlined details of the existing assessment/calculation methods in the context of EPCs. Their application domain, legal boundaries, and links with energy consumption and EPCs were also studied and evaluated. A SWOT analysis and ranking of methods were presented highlighting the best fits for each of the indicators. However, further work and adjustments to these methods would be required to make them available for real testing. A proposed approach for the development of each feature based on a preliminary concept for the indicator is also presented. Finally, across all features, key findings have been presented, leading to the following conclusions in two groups:

Indicators

- 'Smart readiness' approach presents a potential method for assessing the smartness of buildings with nine domains (e.g. lighting, ventilation, envelope, monitoring and control etc.)
- 'Comfort' approach incorporates four key indicators – thermal, visual and acoustic comfort and indoor air quality – to be assessed through checklists, on-site measurements and surveys
- 'Outdoor air pollution' approach addresses a building's impact on air by two methods: an outdoor air pollution contribution index and indoor air purity index
- 'Real energy consumption' approach outlines an assessment method based on operational ratings, with options for normalisation to allow for better inter-building comparison
- 'District energy' approach focuses on predicting the potential for future development for buildings via two methods: expected future performance of district heating and heat distribution and transfer system

Cross-cutting issues

- Technical challenges that constrain the application of existing methods such as assessment time, accuracy, normalisation process, variable definitions and emission factors could be overcome by certain modifications in approach
- Features should be aligned financially to increase market acceptance and cost-effective assessments during the development
- Legal and governance issues should be addressed by dealing with challenges such as development of universal methodologies, presence of multiple standards at Member

State level, control of citizen data and privacy, and acceptance of future estimations by public authorities

- From a social perspective, user acceptance and public understating of the features are key issues and should be considered in feature development
- If these indicators are well integrated within EPCs, significant environmental benefits are anticipated
- Future implementation of indicators can be strengthened by addressing lack of industry readiness, understanding of anticipated benefits and enforcement issues

Certain limitations need to be overcome to implement these innovative indicators, such as variable levels of implementation in the Member States due to different local requirements and regulations. Some indicators require extensive monitoring and measurements, and a lack or absence of data is a barrier in the development and acceptance of these features within EPC schemes.

A range of delivery actors was identified for all the features, including EPC assessors, qualified experts, building professionals, and auditors. It is especially important to focus on them while developing the features as they will directly affect the outcomes of the assessments. While developing the features, links with energy performance are being explored and studied with reference to interoperability with the grid, energy consumption, and operational energy performance. To successfully develop the indicators and their implementation in the EPC schemes of the Member States, the features should ensure compliance with the requirements of the target audience and the framework principles of the cross-cutting criteria in X-tendo.

GLOSSARY OF TERMS

Term/words	Meaning/definition
Air Quality Index (AQI)	Index used by government agencies to communicate to the public how polluted the air currently is or how polluted it is forecast to become
Building smartness	A building's capacity to communicate with its occupants and the grid and to monitor and regulate efficiently the use of energy and other resources. It exemplifies the ability of the building to adapt to internal and external situations, relies on information and connectivity, and requires an appropriate level of cybersecurity.
Carbon emission factor (CEF)	A coefficient which allows conversion of activity data (process/processes) into CO_2 emissions
Emission rate	The emission intensity of a given pollutant relative to the intensity of a specific activity, or an industrial production process; for example grams of carbon dioxide released per megajoule of energy produced, or the ratio of greenhouse gas emissions produced to gross domestic product (GDP)
Energy Performance of Buildings Directive (EPBD)	The EPBD covers a broad range of policies and supportive measures that will help national EU governments boost energy performance of buildings and improve the existing building stock
Expectable return temperature (ERT)	Average temperature to be expected in the return of a building's heat distribution system
Filtration	A physical, biological or chemical operation that separates solid matter and fluid from a mixture with a filter medium that has a complex structure through which only the fluid can pass
Final energy consumption	Final energy consumption is the total energy consumed by end users, such as households, industry and agriculture. It is the energy which reaches the final consumer's door and excludes that which is used by the energy sector itself.
Indoor environmental quality (IEQ)	IEQ encompasses the conditions inside a building – air quality, lighting, thermal comfort, acoustic conditions, ergonomics – and their effects on occupants or residents
Information and communication technologies (ICT)	Infrastructure and components that enable modern computing
Internet of Things (IoT)	Enabling of everyday devices to send and receive data through the internet

Low emission	Emission of combustion products of solid, liquid and gaseous fuels to the atmosphere from emission sources (emitters) located at a height of not more than 40 m
Nearly zero energy building (nZEB)	nZEBs have very high energy performance, and the low amount of energy they require comes mostly from renewable sources
Necessary supply line temperature (NST)	Maximum temperature that is necessary to be supplied to a building's heat distribution system in order to ensure that the heat load can be supplied to each part of the building on the coldest day of the year
Overheating risk	Situations where the indoor temperature of a home becomes uncomfortably or excessively warm
PM2.5/PM10	Particles with an aerodynamic diameter smaller than respectively 2.5 and 10 µm
Pollutant	A substance or energy introduced into the environment that has undesired effects, or adversely affects the usefulness of a resource
Primary energy factor (PEF)	A PEF connects primary and final energy by indicating how much primary energy is used to generate a unit of electricity or a unit of useable thermal energy
Primary energy consumption	Primary energy consumption measures the total energy demand of a country. It covers consumption of the energy sector itself, losses during transformation (for example, from oil or gas into electricity) and distribution of energy, and the final consumption by end users. It excludes energy carriers used for non-energy purposes (such as petroleum not used not for combustion but for producing plastics).
Primary resource factor (PRF)	The ratio between fossil energy supply and energy used in a building
Renewable energy factor (REF)	The share of renewable energy in the heat supplied by the district heating system
Sick building syndrome (SBS)	A condition affecting office workers, typically marked by headaches and respiratory problems, attributed to unhealthy or stressful factors in the working environment such as poor ventilation
Smart readiness indicator (SRI)	Measure of the capability of buildings to adapt their operation to the needs of the occupant, optimising energy efficiency and overall performance, and to adapt their operation in reaction to signals from the grid (energy flexibility)
Smog	An atmospheric phenomenon resulting from the mixing of fog with smoke and exhaust fumes

Volatile organic compounds (VOCs)	Organic chemicals that readily produce vapours at ambient temperatures and are therefore emitted as gases from certain solids or liquids. All organic compounds contain carbon, and organic chemicals are the basic chemicals found in all living things.

REFERENCES

[1] Buildings Performance Institute Europe (BPIE), *Europe's Buildings Under The Microscope*. 2011.

[2] Buildings Performance Institute Europe (BPIE), *Energy Performance Certificates Across the EU. A mapping of National Approaches*. 2014.

[3] B. L. Risteska Stojkoska and K. V. Trivodaliev, "A review of Internet of Things for smart home: Challenges and solutions," *Journal of Cleaner Production*. 2017.

[4] I. Alam, S. Khusro, and M. Naeem, "A review of smart homes: Past, present, and future," *ICOSST 2017 - 2017 Int. Conf. Open Source Syst. Technol. Proc.*, 2018 (6), pp. 35–41, 2018.

[5] A. H. Buckman, M. Mayfield, and S. B. M. Beck, "What is a smart building?," *Smart Sustain. Built Environ.*, 3(2), pp. 92–109, 2014.

[6] D. Arditi, G. Mangano, and A. De Marco, "Assessing the smartness of buildings," *Facilities*, 33(9–10), pp. 553–572, 2015.

[7] X. Lu, D. Clements-Croome, and M. Viljanen, "Past, present and future mathematical models for buildings," *Intell. Build. Int.*, 2009.

[8] J. Yang and H. Peng, "Decision support to the application of intelligent building technologies," *Renew. energy*, 2001.

[9] A. B. R. González, J. J. V. Díaz, A. J. Caamaño, and M. R. Wilby, "Towards a universal energy efficiency index for buildings," *Energy Build.*, 2011.

[10] D. Katz and J. Skopek, "The CABA building intelligence quotient programme," *Intell. Build. Int.*, 1(4), pp. 277–295, 2009.

[11] W. L. Lee and J. Burnett, "Benchmarking energy use assessment of HK-BEAM, BREEAM and LEED," *Build. Environ.*, 2008.

[12] P. Mathew, D. Sartor, W. Lintner, and P. Wirdzek, "Labs21 Environmental Performance Criteria : Toward ' LEED TM for Labs ,'" December, pp. 1–10, 2001.

[13] W. To, L. Lai, K. Lam, and A. Chung, "Perceived Importance of Smart and Sustainable Building Features from the Users' Perspective," *Smart Cities* 1(1), pp. 163–175, 2018.

[14] N. Dodd, M. Cordella, M. Traverso, and S. Donatello, *Level(s)-A common EU framework of core sustainability indicators for office and residential buildings Part 3: How to make performance assessments using Level(s) (Draft Beta v1.0)*, August 2017.

[15] DGNB, "New DGNB 'Climate Positive' award for buildings that make an active contribution to climate protection," 2019. [Online]. Available: www.dgnb.de/de/aktuell/pressemitteilungen/2019/new-dgnb-climate-positive-award.

[16] Y. M. Stijn Verbeke, D. Aerts, G. Rynders, "Interim report July 2019 of the 2th technical support study on the Smart Readiness Indicator for Buildings," *VITO Rep.*, July, p. 281,

2019.

[17] A. Romero, P. De Agustin, and T. Tsitsanis, "Integration of Real-Intelligence in Energy Management Systems to Enable Holistic Demand Response Optimization in Buildings and Districts," in *Proceedings - 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2018*, 2018, no. 768614.

[18] S. Verbeke, D. Aerts, G. Rynders, and Y. Ma, "3rd Interim report of the 2nd technical support study on the Smart Readiness Indicator for buildings," Brussels, 2020.

[19] S. Kephalopoulos, O. Geiss, J. Barrero-Moreno, D. D'agostino, and D. Paci, "Promoting healthy and energy efficient buildings in the European Union," European Commission, Luxembourg, 2016.

[20] Y. Al horr, M. Arif, M. Katafygiotou, A. Mazroei, A. Kaushik, and E. Elsarrag, "Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature," *Int. J. Sustain. Built Environ.*, 5(1), pp. 1–11, 2016.

[21] R. Antikainen, S. Lappalainen, A. Lönnqvist, K. Maksimainen, K. Reijula, and E. Uusi-Rauva, "Exploring the relationship between indoor air and productivity," *Scand. J. Work. Environ. Heal. Suppl.*, 4, pp. 79–82, 2008.

[22] C. Dai, L. Lan, and Z. Lian, "Method for the determination of optimal work environment in office buildings considering energy consumption and human performance," *Energy Build.*, 76, pp. 278–283, 2014.

[23] DOE, "International Performance Measurement & Verification Protocol: Concepts and Practices for Improved Indoor Environmental Quality," National Renewable Energy Laboratory, Oak Ridge, 2001.

[24] EU, *Directive 2010/31/EU of the European Parliament and the Council of 19 May 2010 on the energy perfromance of buildings (recast)*. 2010, pp. 13–35.

[25] EU, *Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency*, October. 2012, pp. 1–56.

[26] EC, *Energy Efficient Buildings: Multi-annual roadmap for the contractual PPP under Horizon 2020*. Publications Office of the European Union, 2013.

[27] E. C. You, D. Dunt, and C. Doyle, "Influences on Case-Managed Community Aged Care Practice.," *Qual. Health Res.*, 2015.

[28] I. Sarbu and C. Sebarchievici, "Aspects of indoor environmental quality assessment in buildings," *Energy Build.* 60, pp. 410–419, 2013.

[29] ASHRAE, "ANSI/ASHRAE 55:2013 Thermal Environmental Conditions for Human Occupancy," American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, 2013.

[30] ISO, "ISO 7730 Ergonomics of the Thermal Environment: Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria," International Organization for Standardization, 2006.

[31] P. Wargocki, D. P. Wyon, J. Sundell, G. Clausen, and P. O. Fanger, "The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity.," *Indoor Air*, 10(4), pp. 222–236, 2000.

[32] S. R. Jurado, A. D. P. Bankoff, and A. Sanchez, "Indoor air quality in Brazilian universities," *Int. J. Environ. Res. Public Health*, 11(7), pp. 7081–7093, 2014.

[33] M. Di Giulio, R. Grande, E. Di Campli, S. Di Bartolomeo, and L. Cellini, "Indoor air quality in university environments," *Environ. Monit. Assess.*, 170(1–4), pp. 509–517, 2010.

[34] T. Godish and J. D. Spengler, "Relationships Between Ventilation and Indoor Air Quality: A Review," *Indoor Air*, 6(2), pp. 135–145, 1996.

[35] WHO, "WHO guidelines for indoor air quality: Selected Pollutants," World Health Organisation, Copenhagen, 2010.

[36] CEN, "EN 12665:2011- Light and lighting- Basic terms and criteria for specifying lighting requirements," European Commitee for Standardization, Brussels, 2012.

[37] D. K. Serghides, C. K. Chatzinikola, and M. C. Katafygiotou, "Comparative studies of the occupants' behaviour in a university building during winter and summer time," *Int. J. Sustain. Energy*, 34(8), pp. 528–551, 2015.

[38] M. Frontczak and P. Wargocki, "Literature survey on how different factors influence human comfort in indoor environments," *Build. Environ.* 46(4), pp. 922–937, 2011.

[39] I. A. Sakellaris *et al.*, "Perceived Indoor Environment and Occupants' Comfort in European 'Modern' Office Buildings: The OFFICAIR Study," *Int. J. Environ. Res. Public Health*, 13(5), 2016.

[40] S. Kang, D. Ou, and C. M. Mak, "The impact of indoor environmental quality on work productivity in university open-plan research offices," *Build. Environ.*, 124, pp. 78–89, 2017.

[41] P. Ricciardi and C. Buratti, "Environmental quality of university classrooms: Subjective and objective evaluation of the thermal, acoustic, and lighting comfort conditions," *Build. Environ.*, 127(August), pp. 23–36, 2018.

[42] K. L. Jensen, E. Arens and L. Zagreus, "Acoustical Quality in Office Workstations, as Assessed By Occupant Surveys," in *Indoor Air: 10th international conference on indoor air quality and climate*, 2005, pp. 2401–2405.

[43] ISO, "ISO 16283-1:2014 Acoustics- Field measurments of sound insulation in buildings and of building elements- Part 1: Airborne sound insulation," International Organization for Standardization, 2014.

[44] BREEAM, "BREEAM International Non-Domestic Refurbishment 2015-Technical Manual SD225 1.4," 2015.

[45] BREEAM, "BREEAM Refurbishment Domestic Buildings 2015-Technical Manual SD5077 2.2," 2015.

[46] DGNB, "DGNB- Sociocultural and functional quality- SOC1.1/Thermal Comfort," 2018.

[47] DGNB, "DGNB- Sociocultural and functional quality- SOC1.2/Indoor Air Quality," 2018.

[48] DGNB, "DGNB- Sociocultural and functional quality- SOC1.3/Acoustic Comfort," 2018.

[49] DGNB, "DGNB- Sociocultural and functional quality- SOC1.4/Visual Comfort," 2018.

[50] USGBC, "LEED v4.1 Operations and Maintenance - Getting started guide for beta participants," 2018.

[51] IGBC, "Home Performance Index," 2019.

[52] WELL, "The WELL Building Standard v1," 2019.

[53] P. Fanger, *Thermal comfort: analysis and application in environmental engineering*. Danish Technical Press, 1970.

[54] N. Djongyang, R. Tchinda and D. Njomo, "Thermal comfort: A review paper," *Renew. Sustain. Energy Rev.*, 14(9), pp. 2626–2640, 2010.

[55] CEN, *EN-15251: Indoor environemntal input parameters for design and assessment of energy performance of buildings adressing indoor air quality, thermal environment, lighting and acoustics*, 44(0). 2007.

[56] CEN, *EN 16798-1:2019 Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acous*. 2019.

[57] L. Yang, H. Yan and J. C. Lam, "Thermal comfort and building energy consumption implications - A review," *Appl. Energy*, 115, pp. 164–173, 2014.

[58] M. A. Humphreys, "Outdoor temperatures and comfort indoors," *Batim. Int. Build. Res. Pract.*, 2(2), 1978.

[59] J. F. Nicol and M. A. Humphreys, "New standards for comfort and energy use in buildings," *Build. Res. Inf.*, 37(1), pp. 68–73, 2009.

[60] S. Barlow and D. Fiala, "Occupant comfort in UK offices-How adaptive comfort theories might influence future low energy office refurbishment strategies," *Energy Build.*, 39(7), pp. 837–846, 2007.

[61] A. Wagner, E. Gossauer, C. Moosmann, T. Gropp and R. Leonhart, "Thermal comfort and workplace occupant satisfaction: Results of field studies in German low energy office buildings," *Energy Build.*, 39(7), pp. 758–769, 2007.

[62] CIBSE, "TM46: energy benchmarks." CIBSE London, 2008.

[63] CEN, *EN 16798-2:2019 Energy performance of buildings - Ventilation for buildings - Part 2: Interpretation of the requirements in EN 16798-1 - Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air*. 2019.

[64] S. Kunkel, E. Kontonasiou, A. Arcipowska, F. Mariottini and B. Atanasiu, *Indoor Air Quality, Thermal Comfort and Daylight - Analysis of Residential Building Regulations*. Brussels, 2015.

[65] J. M. Daisey, W. J. Angell and M. G. Apte, "Indoor air quality, ventilation and health

symptoms in schools: an analysis of existing information.," *Indoor Air*, 13(1), pp. 53–64, 2003.

[66] A. P. Jones, "Indoor air quality and health," *Atmos. Environ.*, 33(28), pp. 4535–4564, 1999.

[67] D. J. Clements-Croome, "Work performance, productivity and indoor air," *Scand. J. Work. Environ. Heal. Suppl.*, 4, pp. 69–78, 2008.

[68] N. Michelot and M. Carrega, "Monitoring indoor air quality in French schools and day-care centres. Results from the first phase of a pilot survey." In: *Healthy Buildings 2012, 10th International Conference*, 2014, pp. 1–6.

[69] O. a Seppänen, W. J. Fisk and M. J. Mendell, "Association of ventilation rates and CO2 concentrations with health and other responses in commercial and institutional buildings.," *Indoor Air*, 9, pp. 226–252, 1999.

[70] JRC, "Methods for monitoring indoor air quality in schools," World Health Organization, Bonn, 2011.

[71] J. Atkinson, Y. Chartier, C. L. Pessoa-Silva, P. Jensen, Y. Li and W.-H. Seto, *Natural Ventilation for Infection Control in Health-Care Settings*. Canberra, 2009.

[72] A. K. Persily, "Evaluating building IAQ and ventilation with indoor carbon dioxide," *ASHRAE Transactions*, 103 (2), pp. 193–204, 1997.

[73] ASTM D6245-12, "Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation," West Conshohocken, PA, 2012.

[74] CEN, "EN 12464-1: 2011- Light and lighting- Lighting of work places- Part 1: Indoor work places," European Commitee for Standardization, Brussels, 2011.

[75] V. Fabi, R. Andersen and S. Corgnati, "Accounting for the Uncertainty Related to Building Occupants with Regards to Visual Comfort: A Literature Survey on Drivers and Models," *Buildings*, 6(1), p. 5, 2016.

[76] A. D. Galasiu and J. A. Veitch, "Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review," *Energy Build.*, 38(7), pp. 728–742, 2006.

[77] CEN, *EN 17037:2018 Daylight in buildings*. 2018.

[78] C. Reinhart, J. Mardaljevic, Z. Rogers and Leukos, *Dynamic Daylight Performance Metrics for Sustainable Building Design*. 2006.

[79] R. G. Hopkinson, "Glare from daylighting in buildings," *Appl. Ergon.*, 3(4), pp. 206–215, Dec. 1972.

[80] Berkowitz, "Improving the Energy Efficiency of Aging Commercial Buildings through Window Retrofits," BERKOWITZ, Pedricktown, New Jersey, 2014.

[81] N. G. Vardaxis, D. Bard and K. Persson Waye, "Review of acoustic comfort evaluation in dwellings—part I: Associations of acoustic field data to subjective responses from building surveys," *Build. Acoust.* 25(2), pp. 151–170, 2018.

[82] A. Laouadi and A. Parekh, "Lighting characteristics of complex fenestration systems." In *IBPSA-Canada Esim Conference*, 2006, pp. 1–7.

[83] EU, "Special Eurobarometer 468: Attitudes of European citizens towards the environment," 2017. [Online]. Available: https://data.europa.eu/euodp/en/data/dataset/S2156_88_1_468_ENG.

[84] EUROSAI, "Joint report on air quality," 2019.

[85] L. Myllyvirta and E. Howard, "Five things we learned from the world's biggest air pollution database," 2018. [Online]. Available: https://unearthed.greenpeace.org/2018/05/02/air-pollution-cities-worst-global-data-world-health-organisation.

[86] EEA, "Air quality in Europe — 2019 report — EEA Report No 10/2019," Luxembourg, 2019.

[87] BRITANNICA, "Smog- Atmosphere," 2020. [Online]. Available: www.britannica.com/science/smog.

[88] EMEP/EEA, "EMEP/EEA air pollutant emission inventory guidebook 2019," Denmark, 2019.

[89] EC, *DIRECTIVE 2009/125/EC of the European Parliament and of the Council – establishing a framework for the setting of ecodesign requirements for energy-related products (recast)*. 2009.

[90] ASHRAE, "ASHRAE 62.1-2010: Ventilation for acceptable indoor air quality," Atlanta, 2010.

[91] CEN, "EN 13779-2007: Ventilation for non-residential buildings – Performance requirements for ventilation and room conditioning systems," 2007.

[92] BREEAM, "BREEAM International New Construction 2016- Technical Manual," 2016.

[93] KOBiZE, "Wskaźniki emisji zanieczyszczeń ze spalania paliw – kotły o nominalnej mocy cieplnej do 5 MW," Warsaw, 2015.

[94] EEA, "European Air Quality Index- GIS Map application," *2017*. [Online]. Available: www.eea.europa.eu/themes/air/air-quality-index#tab-based-on-data.

[95] CEN, "EN 779-2002: Particulate air filters for general ventilation – Determination of the filtration performance," 2002.

[96] WHO, "The World Health Report 1999," 1999.

[97] DEA, "Implementing the Energy Performance of Buildings Directive – Country Reports 2018," 2019.

[98] Wikipedia, "Air Quality Index," 2020. [Online]. Available: https://en.wikipedia.org/wiki/Air_quality_index.

[99] IEP, "Air Quality Scale in Poland," *The World Air Quality Project*, 2015. [Online]. Available: https://aqicn.org/faq/2015-09-03/air-quality-scale-in-poland.

[100] E. H. Borgstein, R. Lamberts and J. L. M. Hensen, "Evaluating energy performance in non-domestic buildings: A review," *Energy Build.* 128, pp. 734–755, 2016.

[101] CEN, "EN ISO 52000-1:2017: Energy performance of buildings - Overarching EPB assessment - Part 1: General framework and procedures," Brussels, 2017.

[102] M.-H. Laurent, B. Allibe, T. Oreszczyn, I. Hamilton, C. Tigchelaar and R. Galving, "Back to reality: How domestic efficiency policies in four European countries can be improved by using empirical data instead of normative calculation." In: *ECEEE Summer study*, 2013.

[103] D. Majcen, "Predicting energy consumption and savings in the housing stock – A performance gap analysis in the Netherlands ." TU Delft, 2016.

[104] X. Shi *et al.*, "Magnitude, Causes, and Solutions of the Performance Gap of Buildings: A Review," *Sustainability*, 11(3), 2019.

[105] M. Rietkerk, J. Mastop and C. Tigchelaar, "Differences in real and theoretical gas consumption in households." In: *ECN*, 2015.

[106] P. X. W. Zou, X. X. Xu, J. Sanjayan and J. Y. Wang, "Review of 10 years research on building energy performance gap: Life-cycle and stakeholder perspectives," *Energy Build.* 178, pp. 165–181, 2018.

[107] M. Herrando, D. Cambra, M. Navarro, L. de la Cruz, G. Millán and I. Zabalza, "Energy Performance Certification of Faculty Buildings in Spain: The gap between estimated and real energy consumption," *Energy Convers. Manag.*, 125 (January 2014), pp. 141–153, 2016.

[108] E. Himpe, "Characterisation of residential energy use for heating using smart meter data." Ghent University, 2017.

[109] S. Seyedzadeh, F. P. Rahimian, I. Glesk and M. Roper, "Machine learning for estimation of building energy consumption and performance: a review," *Vis. Eng.* 6(1), 2018.

[110] H. Krstic and M. Teni, "Review of Methods for Buildings Energy Performance Modelling," *World Multidiscip. Civ. Eng. Plan. Symp. - Wmcaus*, 245, 2017.

[111] H. Bloem and L. Vandaele, "The building as the cornerstone of our future energy infrastructure - Outcome of the Dynastee Symposium." 2019.

[112] A. Janssens, "Reliable building energy performance characterization based on full scale dynamic measurements – Report of Subtask 1b: Overview of methods to analyze dynamic data." KU Leuven, 2016.

[113] B. Karlin, J. F. Zinger and R. Ford, "The Effects of Feedback on Energy Conservation: A Meta-Analysis," *Psychol. Bull.*, 141(6), pp. 1205–1227, 2015.

[114] S. Darby, "Making it obvious: Designing feedback into energy consumption," *Energy Effic. Househ. Appliances Light.*, pp. 685–696, 2001.

[115] R. Cohen and B. Bordass, "Mandating transparency about building energy performance in use," *Build. Res. Inf.*, 43(4), pp. 534–552, 2015.

[116] CIBSE, *TM47: Operational Ratings and Display Energy Certificates*. 2009.

[117] Boverket, "Boverkets byggregler (2011:6) – föreskrifter och allmännaråd, BBR." Boverket, 2019.

[118] VEA, "Toelichting voor de (kandidaat)-energiedeskundige type C voor de opmaak van het EPC voor publieke gebouwen." VEA, 2013.

[119] B. Staatsblad, "Belgisch Staatsblad 08.11.2007." Belgisch Staatsblad, 2007.

[120] DCLG, "Improving the energy efficiency of our buildings – A guide to display energy certificates and advisory reports for public buildings." DCLG, 2015.

[121] DCLG, "The Government's methodology for the production of Operational Ratings, Display Energy Certificates and Advisory Reports." DCLG, 2008.

[122] H. J. J. Valk and A. F. Kruithof, "Beleidskader Energieprestatie - Voorstel voor een beleidskader voor de energieprestatie van gebouwen." Ministerie van BZK, 2016.

[123] S. Roels, "Building energy performance assessment based on in-situ measurements." KU Leuven, 2019.

[124] D. Saelens and G. Reynders, "IEA-EBC Annex 58: Reliable building energy performance characterization based on full scale dynamic measurements; Report of subtask 4b: Towards characterization of buildings based on in situ testing and smart meter readings and potential for applications." KU Leuven, 2016.

[125] D. Kolokotsa *et al.*, "The role of smart grids in the building sector," *Build. Environ.*, 116, pp. 703–708, 2016.

[126] T. M. Lawrence *et al.*, "Ten questions concerning integrating smart buildings into the smart grid," *Build. Environ.*, 108, pp. 273–283, 2016.

[127] EC, "Clean energy for all Europeans package," 2017. [Online]. Available: https://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans_en.

[128] DEA, "Regulation and planning of district heating in Denmark," Copenhagen, 2016.

[129] A. Müller, M. Hummel, L. Kranzl, M. Fallahnejad and R. Büchele, "Open source data for gross floor area and heat demand density on the hectare level for EU 28," *Energies*,12(24), 2019.

[130] M. Fallahnejad, M. Hartner, L. Kranzl, and S. Fritz, "Impact of distribution and transmission investment costs of district heating systems on district heating potential," *Energy Procedia*, 149, pp. 141–150, 2018.

[131] E. Latõšov, A. Volkova, A. Siirde, J. Kurnitski, M. Thalfeldt, "Primary energy factor for district heating networks in European Union member states," *Energy Procedia*, 116, pp. 69–77, 2017.

[132] CEN, "EN 15316-4-5: Heating systems in buildings - Method for calculation of systems energy requirements and system efficiencies - Part 4-5: Space heating generation systems, the performance and quality of district heating and large volume systems," 2017.

[133] M. ENERGII, "DZIENNIK USTAW RZECZYPOSPOLITEJ POLSKIEJ 2017 poz. 1912 -

ROZPORZĄDZENIE MINISTRA ENERGII w sprawie szczegółowego zakresu i sposobu sporządzania audytu efektywności energetycznej oraz metod obliczania oszczędności energii," 2017.

[134] UNI, "UNI/TS 11300-1:2014 - Prestazioni energetiche degli edifici - Parte 1: Determinazione del fabbisogno di energia termica dell'edificio per la climatizzazione estiva ed invernale," 2014.

[135] UNI, "UNI/TS 11300-4:2016 - Prestazioni energetiche degli edifici - Parte 4: Utilizzo di energie rinnovabili e di altri metodi di generazione per la climatizzazione invernale e per la produzione di acqua calda sanitaria," 2016.

[136] MED, *Ministry of Economic Development. Applying the methods of calculating energy performance and definition of requirements and minimum standards of buildings. Decree 26.06.2015*. Italy, 2015.

[137] AGFW, "Arbeitsblatt AGFW FW 309 Teil 1 - Energetische Bewertung von Fernwärme - Bestimmung der spezifischen Primärenergiefaktoren für Fernwärmeversorgungssysteme," 2014.

[138] AGFW, "AGFW district energy systems," 2020.

[139] NEN, "NEN 7125:2017 - Energieprestatienorm voor maatregelen op gebiedsnuveau (EMG) - Bepalingsmethode," 2017.

[140] OIB, "OIB-Richtlinie 6 - Energieeinsparung und Wärmeschutz," 2019.

[141] I. Uriarte, A. Erkoreka, C. Giraldo-Soto, K. Martin, A. Uriarte and P. Eguia, "Mathematical development of an average method for estimating the reduction of the Heat Loss Coefficient of an energetically retrofitted occupied office building," *Energy Build.*, 192, pp. 101–122, 2019.

[142] H. Madsen *et al.*, "IEA-EBC Annex 58: Report of subtask 3, part 2: Thermal performance characterization using time series data – Reliable building energy performance characterization based on full scale dynamic measurements statistical guidelines." KU Leuven, 2016.

[143] C. Ghiaus, "Experimental estimation of building energy performance by robust regression," *Energy Build.*, 38(6), pp. 582–587, 2006.

[144] T. Bohlin and S. F. Graebe, "Issues in Nonlinear Stochastic Grey Box Identification," *Int. J. Adapt. Control Signal Process.*, 9(6), pp. 465–490, 1995.

[145] S. Marieline, "Characterisation of the Heat Loss Coefficient of Residential Buildings Based on In-use Monitoring Data," KU Leuven, 2019.

[146] B. Stein, T. Loga and N. Diefenbach, "Tracking of Energy Performance Indicators in Residential Building Stocks – Different Approaches and Common Results. EPISCOPE Synthesis Report No. 4." IWU, 2016.

[147] B. Stein, T. Loga and N. Diefenbach, "Monitor Progress Towards Climate Targets in European Housing Stocks - Main Results of the EPISCOPE Project - Final Project Report - (Deliverable D1.2)." IWU, 2016.

[148] N. Altmann-Mavaddat, O. Mair am Tinkhof, G. Simader, A. Arcipowska and D. Weatherall, "Report on existing monitoring initiatives and database systems; From databases to retrofit action: How European countries are using energy performance certificate (EPC) database systems - Request2Action Deliverable D2.1." Austrian Energy Agency, 2015.

[149] J. Rattenbury, V. G. Oñate, R. Fragoso, E. Costanzo, A. Androutsopoulos and D. Weatherall, "Recommendations on building Hubs support – Request2Action Deliverable D4.1." Energy Saving Trust, 2017.

[150] W. Rivers, M. Mclean, F. Downy and D. Weatherall, "Best Practices and practical advice on home energy efficiency advice tools – Request2Action Deliverable D3.1." Energy Saving Trust, 2015.

[151] P. Johansson, P. Wahlgren and J.-O. Dalenbäck, "Sweden – Differences between measured and calculated energy use in EPCs versus building permits – New field study 2016 – QUALICHeCK, Status on the ground." Chalmers University of Technology, 2017.

www.x-tendo.eu

#Xtendoproject

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 845958.