THE INNER VALUE OF A BUILDING

LINKING INDOOR ENVIRONMENTAL QUALITY AND ENERGY PERFORMANCE IN BUILDING REGULATION

BPIE

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EXECUTIVE SUMMARY

An abundance of scientific studies points to evidence that indoor environmental quality (IEQ) has a direct effect on health, comfort, wellbeing and productivity. Considering that people spend a large amount of their time indoors, it is crucial that building legislation ensures sufficient levels of IEQ to promote healthy and comfortable indoor environments.

This report summarises the major opportunities to reflect the importance of IEQ in national and EU legal framework. The principal elements that determine the IEQ of a building are analysed and scrutinized, while the impact of IEQ on health, comfort, wellbeing and productivity is further examined. Indicators for evaluating the indoor environment are also defined. EU legislation is then explored to identify whether information related to the achievement of adequate IEQ is sufficient. We look at the opportunities to integrate IEQ into areas such as renovation and energy performance, and discuss a number of tools and initiatives. Finally, we give recommendations on increasing the recognition of IEQ in EU and national legislation.

According to the World Health Organization (WHO), globally 4.3 million deaths were attributed to indoor air pollution in 2012, of which 99,000 were in Europe [1] [2]. In addition, a study by the World Green Building Council on the business case for health, wellbeing and productivity shows that staff costs account for about 90% of a business's operating costs, while the corresponding energy costs account for only about 1%. Thus what can appear modest improvement in employee health or productivity, may have significant financial implication for employers [3].

Key factors of IEQ include indoor air quality, thermal comfort, lighting and acoustics. Indoor air quality refers to the air without known contaminants at harmful concentrations with which the great majority of exposed people are satisfied [4], and thermal comfort is the condition of mind that is satisfied with the thermal environment [5]. Adequate ventilation rates, combined with the restriction and control of internal pollutant sources, are critical in removing air contaminants and ensuring good indoor air quality and thermal comfort. Sufficient lighting levels are necessary to perform various visual activities efficiently and accurately, and studies have shown that windows and daylight exposure have a significant positive impact on the overall health and sleep quality of office workers. Acoustic comfort includes the capacity to protect building occupants from noise and provide a suitable acoustic environment to fulfil the purposes that the building is designed for. According to the Smart Building Alliance noise can result in productivity loss of up to 8% [6].

To ensure satisfactory IEQ, the indoor environment needs to be evaluated. Long-term indicators for evaluating the indoor environment, based on the European standard EN15251, are design criteria, calculations, measurements and subjective evaluations. The design criteria should aim at maximising the level of satisfaction of building occupants; and measurable limits or ranges of values need to be specified for each of the major indoor environmental factors. Calculations include, amongst others, building simulations, while measurements are a quantitative indicator for the evaluation of the indoor environment [7]. Building occupant surveys are another crucial qualitative indicator for the evaluation of the indoor environment.

While the recently revised Energy Performance of Buildings Directive (EPBD 2018/844) includes elements of health, comfort, indoor air quality and indoor climate conditions, it falls short on information related to the achievement of satisfactory IEQ. In addition, significant variation in IEQ requirements exists at national level.

Despite substantial gaps in the existing European building regulations, the real opportunity lies at national level; it is therefore necessary to develop approaches for the integration of IEQ in national policy frameworks. To achieve this, we identify four areas of opportunities: (i) long-term renovation strategies, (ii) Energy Performance Certificates (EPCs), (iii) smart readiness indicator, and (iv) compliance and quality control measures.

Long-term renovation strategies should ensure that IEQ is taken into account, while Member States should highlight that ensuring IEQ in energy-efficiency retrofits can achieve significant health benefits [8]. In addition, the current cost-optimal methodology is narrow and overlooks many of the societal gains of getting healthier nearly zero-energy buildings. Integrating such societal gains would boost the renovation rate and promote the move toward healthy, comfortable and nearly zero-energy buildings.

EPCs should provide recommendations for the cost-effective or cost-optimal upgrading of the energy performance, and should ensure that recommendations for renovation include IEQ aspects to promote the health and wellbeing of building occupants [9]. EPCs along with the Building Renovation Passport could include evidence-based IEQ aspects originating from measurements, building occupant questionnaire survey outcomes and/or computer simulations [10].

The **smart readiness indicator** should capture and promote the benefits of smart buildings for building users and occupants, the energy system, the economy and society as a whole [11]. Smart buildings need to go beyond being energy efficient and healthy by recognising and reacting to users' and occupants' needs to optimise comfort, indoor air quality, wellbeing and operational requirements [11].

Finally, to support the integration of IEQ within the regulatory framework, adequate **compliance and quality control** mechanisms must be in place to ensure enforcement and implementation

SUMMARISED RECOMMENDATIONS

EU LEVEL

- Harmonise calculation methodologies and IEQ requirements
- Enforce the IEQ aspects in the EPBD implementation

NATIONAL LEVEL

- Use long-term national renovation strategies to boost improvements in IEQ
- Use the new Building Renovation Passport concept to ensure effective IEQ improvements
- Address IEQ in major energy renovations
- Integrate IEQ aspects in the smart readiness indicator
- Make Energy Performance Certificates more useful for owners
- Ensure comprehensive compliance and quality control
- Raise awareness of building occupants on IEQ aspects
- Expand the training of energy experts

INTRODUCTION

As Europeans spend approximately 90% of their time indoors, the indoor environment has a significant influence on people's health and comfort. Indoor air quality, thermal and acoustic comfort and sufficient levels of lighting are the major determinants of the indoor environmental quality (IEQ), and play an important role in ensuring the quality of life and general wellbeing of building occupants [1]. Effective building regulation needs to sufficiently integrate the IEQ perspective.

The building regulatory framework covering energy aspects is designed to continuously improve the energy performance of the building stock and reduce CO_2 emissions, while at the same time ensuring good IEQ. The recently revised Energy Performance of Buildings Directive (EPBD, 2018/844), the EU's main legislation in this area, says that energy performance requirements should optimise health, indoor air quality and comfort levels [12] [13].

Frontrunner projects and voluntary standards prove that buildings can be very energy efficient, while ensuring outstanding indoor air quality, thermal comfort, daylight and acoustics. Unfortunately, the update of the EPBD did not take the chance to address how to ensure healthy and comfortable homes for EU citizens. The responsibility now lies at national level: EU Member States need to adopt building regulations that reduce the climate footprint of the building stock and empower occupants with a healthy and prosperous environment.

Smart building design and smart control technologies will provide us with crucial insights into energy use, indoor climate conditions and user behaviour. In order to harness the potential benefits of this technology, a holistic assessment of a building is required, resting on three main pillars: (i) energy performance; (ii) indoor climate conditions; and (iii) the smartness of the building.

This report aims to define an approach on how aspects of IEQ could be reflected in the implementation of the European regulatory framework on the energy performance of buildings. It refers to both residential and non-residential buildings. The main objectives of this report are:

1. **TO DEFINE THE MAJOR PARAMETERS THAT DETERMINE IEQ**
2. **TO DETERMINE THE MAJOR INDICATORS FOR THE EVALUATION OF IEQ**
3. **TO PROPOSE RECOMMENDATIONS FOR INTEGRATING IEQ IN THE IMPLEMENTATION OF THE EUROPEAN LEGISLATIVE FRAMEWORK**

INDOOR ENVIRONMENTAL QUALITY PARAMETERS

The most important factors that determine the IEQ of a building are indoor air quality, thermal comfort, lighting and acoustics. Each of these factors contribute to the overall indoor climate to a similar extent. However, occupants' behaviour (e.g. opening windows when heating is on), awareness and their level of adoption to the indoor environmental conditions is critical in maintaining good IEQ. In addition, building controls (either manual or automatic) ensuring that indoor environmental parameters such as temperature are kept within acceptable levels can also influence the overall IEQ.

Several scientific studies have indicated that the IEQ has a direct effect on the health, comfort, wellbeing and productivity of the building's occupants (Figure 1) [14]. Considering that people in Europe spend approximately 90% of their time indoors, it is essential to understand the aspects that characterise IEQ in order to ensure the health and wellbeing of building occupants [15] [16] [17].

Figure 1 - Elements and impact of IEQ

Impact of IEQ on health, comfort, wellbeing and productivity

Numerous epidemiological studies have shown that several aspects of IEQ (e.g. indoor air pollutants) are related to human health effects such as allergies, asthma symptoms, cardiovascular and respiratory morbidity and even mortality [18] [19]. According to the World Health Organization (WHO), in 2012, 4.3 million deaths globally were attributed to indoor air pollution, of which 99,000 were in Europe [1] [2]. People are 40% more likely to have asthma when living in damp and mouldy environments, while about 2.2 million Europeans have asthma due to their living conditions [20]. Each year an estimated 2.2

million estimated disability-adjusted life years (DALYs) are lost in Europe due to exposures to indoor air pollutants, while 110 million EU citizens live in buildings with high concentrations of hazardous pollutants due to inadequate levels of ventilation [21]. In addition, energy-efficient renovations can lead to a significant improvement of IEQ, resulting in substantial health benefits [22] [23].

IEQ can further impact learning and working performance and absenteeism. Table 1 summarises the impacts of IEQ aspects and building-related elements on productivity [6]. A study from the World Green Building Council on the business case for health, wellbeing and productivity shows that staff costs account for about 90% of a business's operating costs, while the corresponding energy costs account for only about 1% [3]. Hence, it is crucial to address aspects related to the productivity and wellbeing of staff within any organisation.

Table 1 - Impact of building-related elements on productivity (Sources: Wargocki, 2000; Wyon, 2004; Heschong, 1999; Juslén, Wouters & Tenner, 2007; Allen, 2016; Barkman, 2012; Keis, 2014, cited in Buildings 2030)

Element	Impact on productivity	Context
Ventilation	Up to ~2% increase in office employee productivity from two-fold increase in ventilation rate	Offices
Air quality	6%–9% decreased productivity in poor indoor air quality environments	Offices
Lighting	Learning progress showed 7% to 26% improvement in rooms with high levels of daylight rooms compared to those with low levels	Schools
	Learning progress showed ~20% improvement when skylight provided additional access to daylight compared with non-daylight rooms	
	30% increased reading speed with cold white activating light	
	30% increased concentration performance with biologically optimized light	
	Average length of stay (hospitalization) decreased between 16% and 41% in rooms with high levels of daylight	Hospitals
Views	Learning progress showed 15% to 23% improvement in classrooms with largest windows	Schools
User control	7% to 8% improvement in classrooms with operable vs. not operable windows	Schools
	4.5% increase in productivity at workstations with lighting control	Manufacturing
Air quality and lighting	Significant improvements in cognitive functioning with improved air quality and lighting conditions	Offices
Temperature	When temperature is >25°C, each additional degree increase leads to up to 2% decrease in productivity	Offices
Biophilia	The presence of nature in indoor or exterior spaces can lead to 6% to 12% productivity increase	Offices

INDOOR AIR QUALITY

Acceptable indoor air quality refers to air without harmful concentrations of known contaminants and with which the great majority of exposed people are satisfied [4]. Sources of contaminants in residential buildings include the occupants themselves (e.g. CO2 released from human respiration); emissions from indoor combustion sources and activities such as cooking or smoking; and emissions from furnishings, construction materials or cleaning products [10]. The most common contaminants are carbon dioxide, carbon monoxide, particulate matter and volatile organic compounds (VOCs) [24]. Indoor air quality can be degraded by outdoor pollution from traffic, combustion sources, construction and agricultural activity entering the building either through the windows, infiltration or mechanical ventilation systems. Specific design criteria for indoor air quality are addressed in several standards [1] [25] [26].

Several studies have related poor air quality to increases in asthma, allergic diseases and eczema. The most frequent building-related health symptoms are eye, nose, skin and throat irritation, upper respiratory symptoms, fatigue and headaches [27]. The terminology of 'Sick Building Syndrome' (SBS) has been introduced to describe these symptoms that cannot be attributed to specific illnesses. The complaints can be localized for a particular zone or room within a building [28]. These symptoms usually disappear when the person leaves the building. SBS occurs in buildings with inadequate levels of ventilation and lighting, high levels of ambient noise and intense odours.

Ventilation is a critical method of removing contaminants from buildings, and is essential to ensuring good indoor air quality as well as thermal comfort. Ventilation is also required to provide night-time pre-cooling of the building's structure during summer months and to distribute conditioned air, as well as to extract contaminants, moisture and odour from sources such as kitchens and bathrooms [24]. With the evolution of buildings to become more energy efficient, there is increasing demand for making buildings more airtight. This increases the importance of providing adequate ventilation to ensure good indoor air quality. Ventilation can be driven by natural forces (wind and/or buoyancy) or by mechanical means (fans). A building's ventilation rates are expressed in units of air flow rates per floor area, air flow rates per number of people, flow rates and air changes per hour (ACH).

Fresh air supply rates can contribute to the removal of indoor air pollutants. However, introducing sufficient ventilation rates without addressing internal sources of air pollution (e.g. wood stoves, fireplaces etc.) may lead to a limited improvement in indoor air quality. Apart from the restriction of indoor sources, outdoor pollution concentration control is also required. Currently, there is a broad set of EU legislation dealing with air pollution. Major regulations are the Ambient Air Quality (AAQ) Directive (2008) and the National Emission Ceiling (NEC) Directive (2016), which set air quality measurement standards and limits for air pollutant concentrations and aim to reduce emissions at source [29].

THERMAL COMFORT

According to the EN ISO 7730, 'thermal comfort is that condition of mind which expresses satisfaction with the thermal environment' [5]. Although many factors determine thermal comfort, it is mainly defined by how people interact with the thermal environment. When people mention that they feel cold, hot, stuffy or draughty, they are actually responding to the quality and conditions of air within the space and the transfer of heat from their body to the surroundings [30].

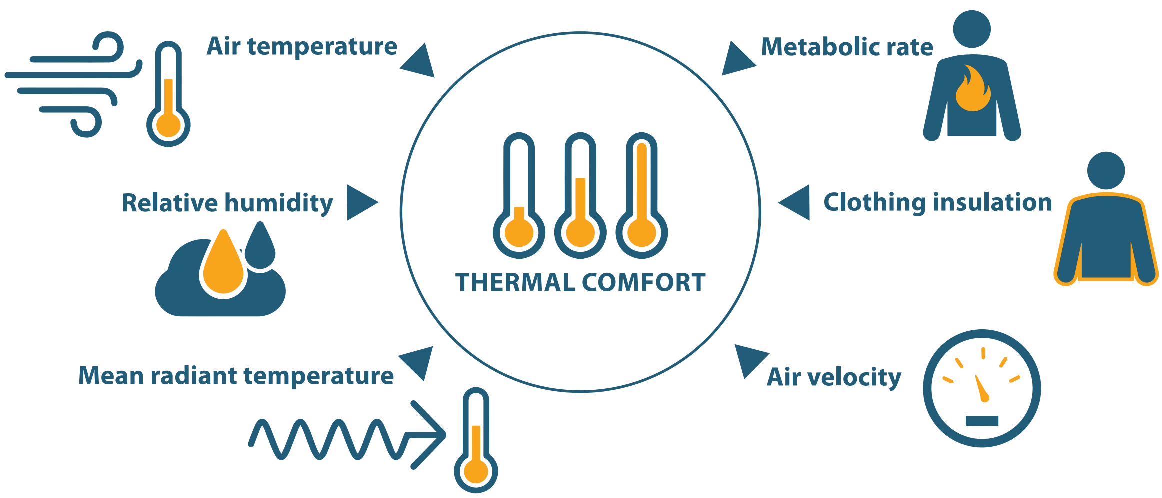
The balancing of heat gains and losses within the human body provides the sensation of thermal

[1] EN 15251:2007, EN 13779, EN 16000-1:2006 and EN ISO16814:2008

comfort. Thermal discomfort can cause negative effects on mood, productivity and performance, and can further cause fatigue and irritability [30] [31].

The thermal environment is defined by environmental parameters, such as temperature (air, radiant), relative humidity and air velocity, and by personal parameters such as clothing, level of activity, gender and age, which affect a person's metabolic rate (Figure 2).

Figure 2 - Factors that primarily affect thermal comfort (Source: Standard EN ISO 7730)



The thermal interaction of people and their environment is a complex area. Research has shown that the feeling of thermal comfort does not only depend on mechanisms of heat transfer and human physiology but also depends on social factors. The level of thermal comfort or discomfort for both laboratory and field-based approaches is often expressed as the percentage of people who are happy or not happy with the thermal conditions. It is usually difficult to achieve thermal satisfaction for all users of a building at all times [30].

Given the environmental conditions, the general thermal sensation and the degree of thermal (dis) satisfaction of exposed people can be predicted using the predicted mean vote (PMV) and the predicted percentage dissatisfied (PPD) indexes [5]. The first model of thermal comfort was developed by Fanger in 1967 (Fanger's Comfort Model) which based on the heat-balance equation can calculate PMV and PPD indexes using a seven-point scale ranging from cold (-3) to hot (+3) [5].

LIGHTING

Adequate lighting levels are necessary to perform several type of visual activities efficiently and accurately. Lighting in a building should allow building users to move safely, to conduct working tasks productively and create a pleasant appearance of the space. Excessive brightness or glare from a lighting source (either solar or electric) can be disruptive, so shading technologies and shielded lighting fixtures must be part of the lighting design of a building [6]. Appropriate lighting levels can be secured by natural and/or artificial light.

Recent studies have shown that inadequate illumination can also have negative effects on human health. Most traditional light sources do not provide the necessary dynamics and spectral qualities at different times of the day. The lack of appropriate lighting levels (through either natural or electric sources) is connected to potential harmful effects like circadian disruptions leading to lack of sleep, depressive symptoms, and reduced activity, alertness and cognitive performance [6] [31]. Lighting sources that imitate the properties of natural sunlight by changing the colour of the light during the day and by providing true colour rendering of objects within the building are possible approaches to solve the above problems.

The impact of windows and daylight exposure on the overall health and sleep quality of office workers is significant. Office workers exposed to sufficient daylight levels and high intensity short-wavelength lighting reported enhanced alertness, concentration and better mood compared to when working in standard office lighting. Their sleeping quality during the night was also improved. However, increased use of glass can increase the heat losses of a building, so a balance is needed between sufficient daylight levels and thermal losses.

Illuminance levels are used as a metric of lighting. The required levels of illuminance for certain visual tasks depend on the type of task and the visual environment where it should take place [32] [33]. The recently developed Equivalent Melanopic Lux (EML) metric considers biological effects of light on humans.

ACOUSTICS

Acoustic comfort in buildings is the capacity to protect occupants from noise and provide a suitable acoustic environment to satisfy the purposes that the building is designed for. Noise is the 'unwanted sound' which in the built environment can prevent speech communication, disturb activities and concentration, and at high levels even cause hearing damage [34]. The reverberation time, defined as the time it takes for a sound level to decrease by 60bB, is another important aspect of the acoustics in a room and is associated with the volume of the room and the amount of absorbing materials [32]. Building users are affected by internal and external noise. Road traffic, trains, aircrafts and construction sites can generate increased levels of noise. Background noise from heating, ventilation and air conditioning (HVAC) systems and office equipment or even occupant conversations can be disruptive and further obstruct occupant abilities in performing simple and complex tasks [6]. For apartment buildings in particular, noise can also come from the neighbours either as impact noise or as airborne noise.

Recently developed systems connected to sensors and user applications allow building users, depending on their preferred sound level (based on their personal concentration needs), to adapt to their working space. This allows for acoustic adaptability of spaces, based on the noise expectations of the users [6]. Exposure to noise raises a range of non-auditory concerns as it affects many human organs and systems' functioning, causing high blood pressure, heart rate anomalies and hypertension [6]. Distractions from noise have a significant impact on productivity as well [35]. According to the Smart Building Alliance noise can result in productivity loss of up to 8% [6].

The acoustic environment must be designed to avoid these harmful effects. The criteria used to specify an acceptable acoustic environment are expressed in sound levels in decibels (dB) or sound frequencies like noise rating (NR) or noise criteria (NC). Noise criteria for several different types of buildings and spaces are mentioned in the standard EN 15251; however, these criteria do not consider outside noise but only noise from service equipment. The average sound pressure level from outside should not exceed 50 dBA [31]. Maximum reverberation time (RT60), describing the amount of time for a sound to decay by 60 dB, should be also considered for different types of spaces.

LONG-TERM INDICATORS FOR THE EVALUATION OF THE INDOOR ENVIRONMENT

The evaluation of the indoor environment is necessary to ensure a satisfactory IEQ. According to the standard EN15251:2007 the evaluation of the performance of a building in terms of IEQ can be based on the following long-term indicators: design criteria, calculations, measurements and subjective evaluations. Depending on the stage and phase of the building (e.g. before, after or during construction or renovation) these indicators apply to a different extent, which will be analysed further below.

DESIGN CRITERIA

The indoor environment should be designed in a way that occupants' health and comfort is assured. For example, the design should ensure proximity to windows and daylight in indoor spaces or proper sizing of HVAC systems for a good distribution of air within the buildings by avoiding overheating or cold drafts. As the perception and subjective evaluation differs for individuals, a certain level of dissatisfaction among the building's users is inevitable [32].

During the design stage of a construction or renovation, the design criteria should aim at minimizing the level of dissatisfaction of individuals. Measurable limits or ranges of values need to be specified for each of the major indoor environmental factors. For example, for living rooms the Chartered Institution of Building Services Engineers (CIBSE) recommends lighting levels of 50-300 lux, a noise rating of 30 NR and temperatures of 22-23°C in winter and 23-25°C in summer [30]. Table 2 summarizes a few of the major necessary guidelines for each indoor environmental category.

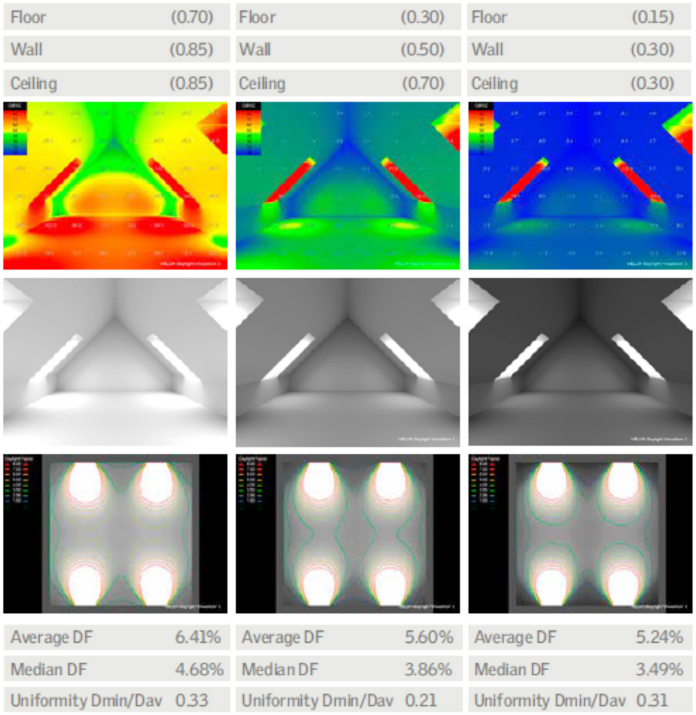
Table 2 - Indoor environmental categories and relevant guidelines

Categories of the indoor environment	Design criteria/ guidelines
Thermal criteria	EN ISO 7730, ASHRAE Standard 55-2013, ISO 7726:2001; EN 15251:2007
Air quality and ventilation criteria	EN 15251:2007, EN 16000-1:2006, EN 13779, EN ISO16814:2008, EN 16798-7, EN 15242: 2007
Lighting criteria	EN 12464-1, EN 12193, EN 15193-1, EN 17037
Acoustics criteria	EN 15251:2007

CALCULATIONS

Amongst others, the performance of buildings can be analysed through either dynamic or steady-state building simulations taking place at the design stage. Relevant assumptions, boundary conditions and validation tests required for calculation purposes are specified in the standard EN 15265: 2007. Thermal comfort conditions over time can be evaluated by, for example, calculating the percentage of time that the temperatures are outside a pre-defined specified range. Several software tools are available to simulate the thermal environment, indoor air quality, daylight and acoustics. For example, Figure 3 shows luminance simulation results on the effect of surface reflectance on daylight levels. It can be seen that less light is reflected from dark surfaces than from bright ones and therefore the colour and reflectance of the surfaces within a room are components of the lighting system.

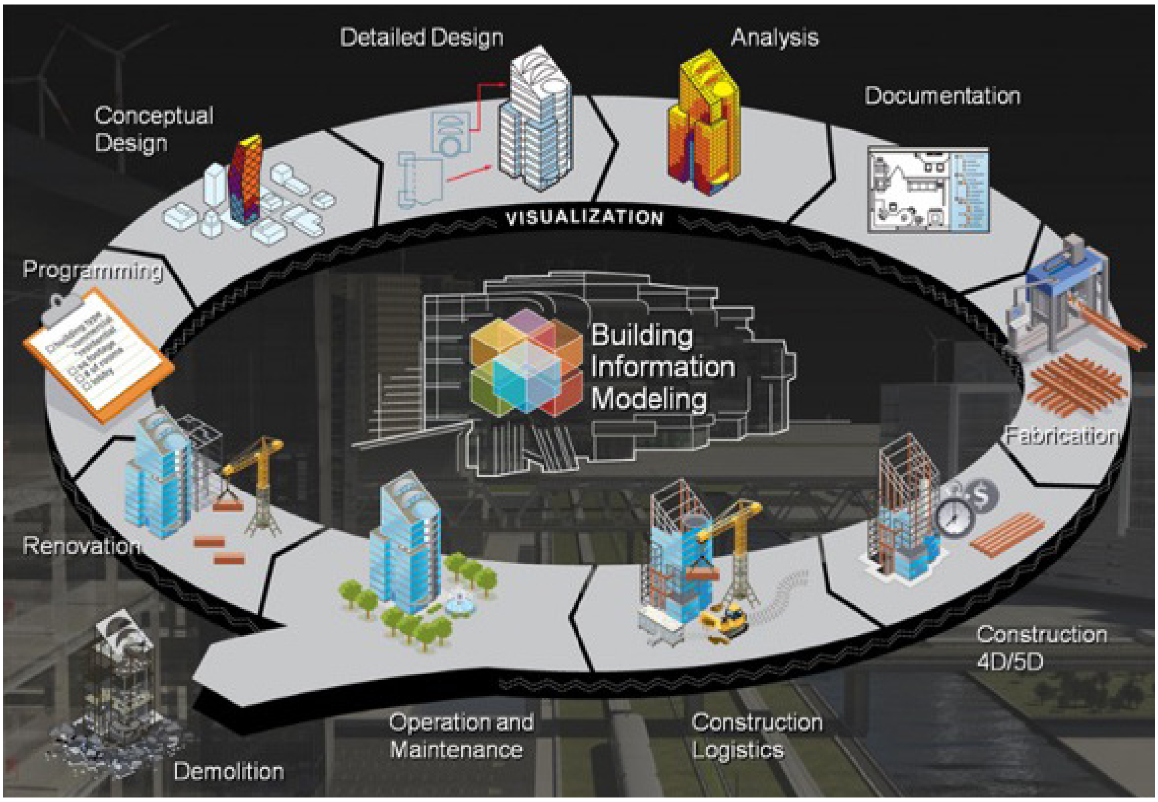
Figure 3 - Luminance simulations showing the effect of surface reflectance on daylight levels (Source: VELUX 2014)



Depending on the objective of the study and parameter being examined, the outcomes differ. For example, if the focus is on indoor air pollution when evaluating the indoor air quality, it would be necessary to predict the spatial or temporal distribution of certain air pollutants. It should be pointed out that the assumptions and boundary conditions being set as inputs during the design of the simulation are of great importance and will significantly affect the outputs.

Recently, building information modelling (BIM) has become a trending technology in construction. BIM is an intelligent 3-D model-based process for the digital representation of physical and functional characteristics of buildings which could potentially be linked to the IEQ (Figure 4). BIM allows individuals (architects, engineers and construction professionals), government agencies and businesses to effectively design, plan and construct buildings and infrastructure such as roads, tunnels, electricity, water communication utilities etc. [36].

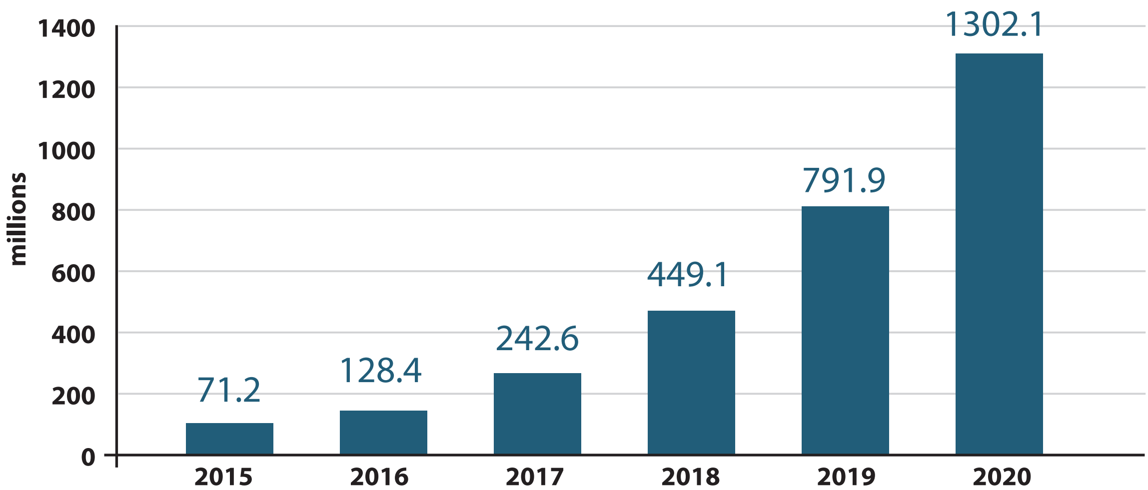
Figure 4 - Building information modelling (Source: APROPLAN, Image courtesy of Autodesk)



MEASUREMENTS

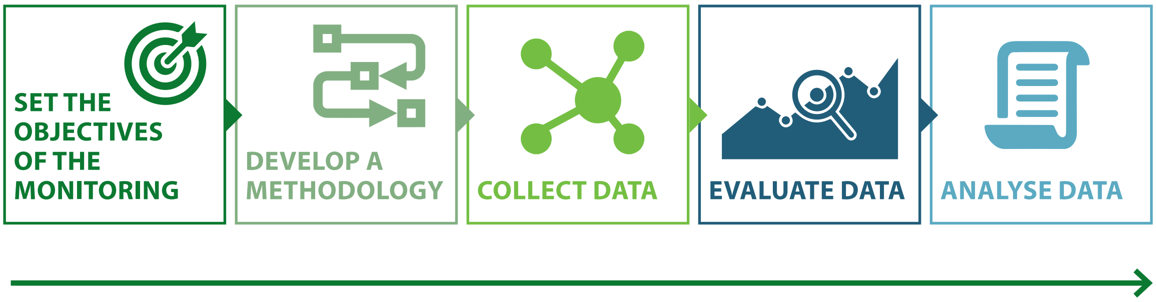
Measurements are a quantitative indicator for the evaluation of the indoor environment. Moving towards a digital society in which sensors are far more widely deployed, IEQ monitoring is becoming mainstream (Figure 5).

Figure 5 - Projected sensor deployments in commercial real estate (Source: Gartner IoT, Endpoints and associated services, Worldwide, 2015)



Measurements can be basic level (e.g. monitoring temperature through a simple desk thermometer) or high level, giving more detail and accuracy. For high-level measurements a clearly defined monitoring scope will determine the methodology, involving the accuracy, the monitoring interval, the duration of the measurements etc. Depending on the monitoring objective, measurements can be either short term or long term. Instrumentation should be calibrated before use, and should satisfy certain conditions in terms of accuracy, detection range, response time and principle of operation. Preliminary measurements either in lab or on site should be considered, while the competency of people performing the measurements should also be ensured. Figure 6 shows the steps to be followed during a measurement phase.

Figure 6 - Necessary steps to be considered during the measurement phase

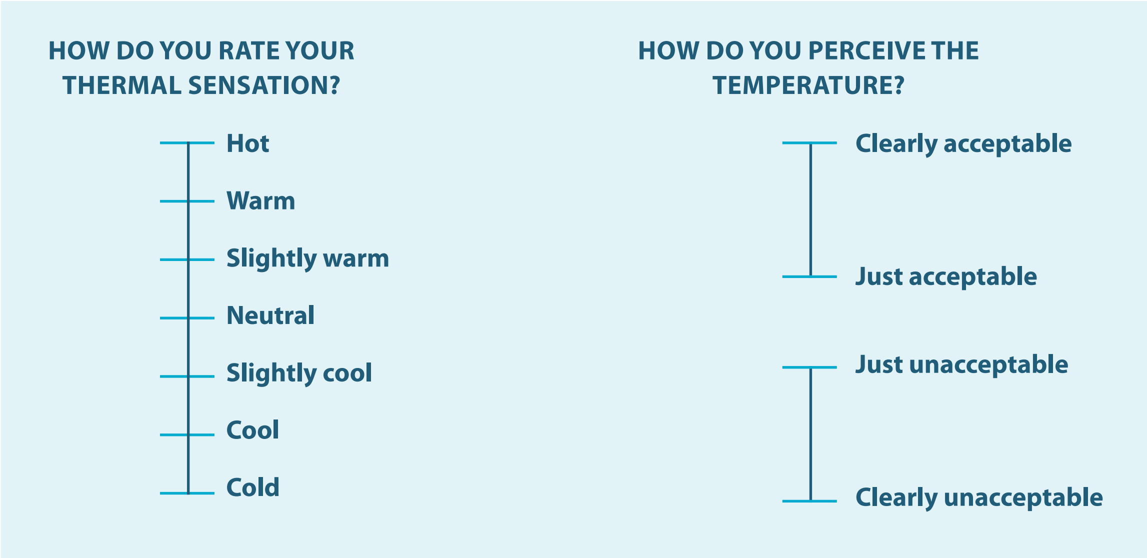


Monitoring can take place before and after occupancy or renovation of a building, and can be either short- or long-term depending on the objectives [7]. Pre- and post-renovation measurements are important to ensure the planned renovations have been applied as designed. Also post-occupancy measurements of all IEQ aspects should be considered to ensure that the building is operating as intended. In particular, measurements of indoor air quality and ventilation can involve monitoring of CO_2 concentrations and particulate matter. Temperature, relative humidity and air velocity are today the major parameters to be considered when designing a measurement campaign on IEQ, but sensor prices are dropping rapidly, so volatile organic compounds and particles might also be part of this in the near future. Illuminance levels and average sound pressure levels can also be included.

QUALITATIVE EVALUATIONS

A great number of scientific studies have shown that job satisfaction, job enjoyment and health are greatly affected by the level of comfort offered by the working environment [37]. For this reason, building occupants' surveys are a crucial qualitative indicator for ensuring the satisfactory operation of a building. It should be noted that this also covers other non-office building environments such as residential buildings, schools, etc. Pre- and post-renovation surveys are important to ensure the renovations have been applied as intended. Post-occupancy evaluation surveys on the acceptance and general perception of IEQ are important. A survey is also important to assess the effects of energy upgrades. Recommended questionnaires and guidelines are given in EN 15271 and in ASHRAE's publication 'Performance Measurement Protocols for Commercial Buildings' [10] [38] (Figure 7). Questions can reflect the perception, preference and acceptance of the indoor conditions.

Figure 7 - Subjective scales on the perception of the thermal environment (Source: EN 15251: 2007)



One example of a practical tool that measures comfort and satisfaction in a workplace is the Comfortmeter, the result of a collaboration between international authorities involved in efficient sustainable and performance oriented office buildings [37]. It is a measuring instrument offering information on the level of comfort inside the building and can further estimate the impact of the building scores on employee productivity (€/year). The tool can also determine the potential for comfort improvements [37]. Connecting indoor air quality to benefits and costs for the building owner is a crucial step to boost knowledge and interest.

BUILDING REGULATIONS

Having defined the major aspects of IEQ and indicators for the evaluation of the indoor environment, this chapter explores relevant text appearing in the Energy Performance of Buildings Directive (EPBD). While the EPBD (2010/31/EU) acknowledged 'indoor climate' (Table 3) and clearly mentioned the inter-independent relationship between energy efficiency and indoor climate, it did not include clear requirements and clarifications on indoor climate indicators, nor how they can be achieved.

In the recently revised EPBD (2018/844), elements of health, comfort, indoor air quality and indoor climate conditions are present; however, details related to their achievement are still not addressed. Since the EU legislation falls short, it is important to understand the role of indoor climate requirements in national regulations, compare them to the European technical standards and propose evidence-based future improvements [39].

Table 3 - 'Indoor climate' in the Energy Performance of Buildings Directive (Source: EPBD 2010/31/EU)

Where in text	Narrative
Recital 8	'Measures to improve further the energy performance of buildings should take into account climatic and local conditions as well as indoor climate environment and cost-effectiveness. These measures should not affect other requirements concerning buildings such as accessibility, safety and the intended use of the building'.
Recital 9	'The energy performance of buildings should be calculated on the basis of a methodology, which may be differentiated at national and regional level. That includes, in addition to thermal characteristics, other factors that play an increasingly important role such as heating and air-conditioning installations, application of energy from renewable sources, passive heating and cooling elements, shading, indoor air-quality, adequate natural light and design of the building. The methodology for calculating energy performance should be based not only on the season in which heating is required, but should cover the annual energy performance of a building. That methodology should take into account existing European standards.'
Article 1: Subject matter	'This Directive promotes the improvement of the energy performance of buildings within the Union, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness.'
Article 2: Definitions	'1. Building means a roofed construction having walls, for which energy is used to condition the indoor climate.'
Article 4: Setting of minimum energy performance requirements	'These requirements shall take account of general indoor climate conditions, in order to avoid possible negative effects such as inadequate ventilation, as well as local conditions and the designated function and the age of the building.'
ANNEX I: Common general framework for the calculation of energy performance of buildings	'(h) Indoor climate conditions, including the designed indoor climate.'

The following subsection highlights elements of the revised EPBD (2018/844) related to the indoor climate, while the next sections summarise requirements on IEQ aspects across Europe.

NEW ELEMENTS OF THE AMENDING DIRECTIVE ON ENERGY PERFORMANCE OF BUILDINGS

In late 2016, the European Commission presented a 'new package of measures with the goal of providing the stable legislative framework needed to facilitate the clean energy transition'. This package comprises a revision of eight different directives, including the EPBD, Energy Efficiency Directive and the Renewable Energy Directive [40].

In the EPBD (2018/844), a few elements on the 'indoor climate' have been included (Table 4). In particular, for buildings undergoing major renovations, Member States are expected to address healthy indoor climate conditions, while energy needs should be calculated aiming to optimise health, indoor air quality and comfort levels. On the general framework for rating the smart readiness of buildings, the Commission will define a smart readiness indicator and develop a methodology which, amongst other things, will take into account benefits for the indoor climate conditions. One key aspect to be considered is the ability of the building to adapt its operational mode in response to occupant needs by maintaining healthy indoor climate conditions. The methodology of the EPBD (2018/844) should further consider the interoperability between systems including smart meters, self-regulating devices for indoor temperature, indoor air quality sensors and ventilation.

Table 4: 'Indoor climate' in the revised Energy Performance of Buildings Directive (2018/844)

Where in text	Narrative
New recital	'(11a) For new buildings and buildings undergoing major renovations, Member States should encourage high-efficiency alternative systems, if technically, functionally and economically feasible, while also addressing healthy indoor climate conditions as well as fire and seismic safety, in accordance with domestic safety regulations.'
New recital	'(11b) The 2009 WHO guidelines provide that, concerning indoor air quality, better performing buildings provide higher comfort levels and wellbeing for their occupants and improve health. Thermal bridges, inadequate insulation and unplanned air pathways can result in surface temperatures below the dew point of the air and in dampness. It is therefore essential to ensure a complete and homogeneous insulation of the building including balconies, fenestrations, roofs, walls, doors and floor, and particular attention should be paid to avoiding the temperature on any inner surface of the building dropping below the dew-point temperature.'
New recital	'(12a) Member States should support energy performance upgrades of existing buildings that contribute to achieving a healthy indoor environment, including through the removal of asbestos and other harmful substances, preventing the illegal removal of harmful substances, and facilitating compliance with existing legislative acts such as Directive 2009/148/EC1 and Directive (EU) 2016/22842.'
New: Article 7, paragraph 5	'Member States shall encourage, in relation to buildings undergoing major renovations, high-efficiency alternative systems, in so far as this is technically, functionally and economically feasible, and address healthy indoor climate conditions, fire safety and risks related to intense seismic activity.'
New: Annex I, point 2	'2. The energy needs for space heating, space cooling, domestic hot water, lighting, ventilation and other technical building systems shall be calculated in order to optimise health, indoor air quality and comfort levels defined by Member States at national or regional level.'
Annex Ia	'Common general framework for rating the smart readiness of buildings 1. The Commission shall define a smart readiness indicator and establish a methodology to assess the capabilities of a building or building unit to adapt its operation to the needs of the occupant and the grid and to improve its energy efficiency and overall performance. … The methodology shall take into account features such as smart meters, building automation and control systems, self-regulating devices for indoor temperature, built-in home appliances, recharging points for electric vehicles, energy storage and detailed functionalities and the interoperability of these features, as well as benefits for the indoor climate condition, energy efficiency, performance levels and enabled flexibility. 2. The methodology shall rely on three key functionalities relating to the building and its technical building systems: … (b) the ability to adapt its operation mode in response to the needs of the occupant paying due attention to the availability of user-friendliness, maintaining healthy indoor climate conditions and ability to report on energy use; … 3. The methodology may further take into account: - the interoperability between systems (smart meters, building automation and control systems, built-in home appliances, self-regulating devices for indoor temperature within the building and indoor air quality sensors and ventilations) …

REQUIREMENTS ON IEQ PARAMETERS AT NATIONAL LEVEL

Ventilation requirements

Several Member States have regulations on ventilation in place. Ventilation rate requirements across Member States are expressed in different units ranging from air changes per hour, air flow per floor area to air flow per number of occupants. This non-homogenised approach makes the comparison between the different regulations very difficult. Harmonization would facilitate inter-comparison and further improvement of IEQ across EU and allow a systematic approach for defining indexes and metrics.

A BPIE study in 2015 on residential building regulations in eight EU Member States on indoor air quality, thermal comfort and lighting found that half of the countries (Belgium, Denmark, France and Sweden) set only minimum ventilation requirements, while the other half had only minimum recommended ventilation rates (Germany, Italy, Poland, UK) [1]. Also, each of these countries uses its own standards (e.g. UK: Approved Doc F, Germany: DIN 1946-6) and sets its own minimum ventilation rates which are different to the EU standards of EN 15251. Table 5 shows heterogeneous ventilation rate requirements provided in national regulations across the EU. Minimum ventilation requirements have been introduced by most EU Member States; however in some cases these requirements are not legally binding and are below the comfort levels [21]. In particular, there are still some countries that do not have legal values on ventilation rates and use voluntary values from standards, e.g. in Germany and Hungary ventilation rates are calculated according to the European standard EN 15251. In addition, the requirement for the ventilation of dwellings in about one-third of the EU countries is below the health-based minimum air change of 0.5 ACH [21].

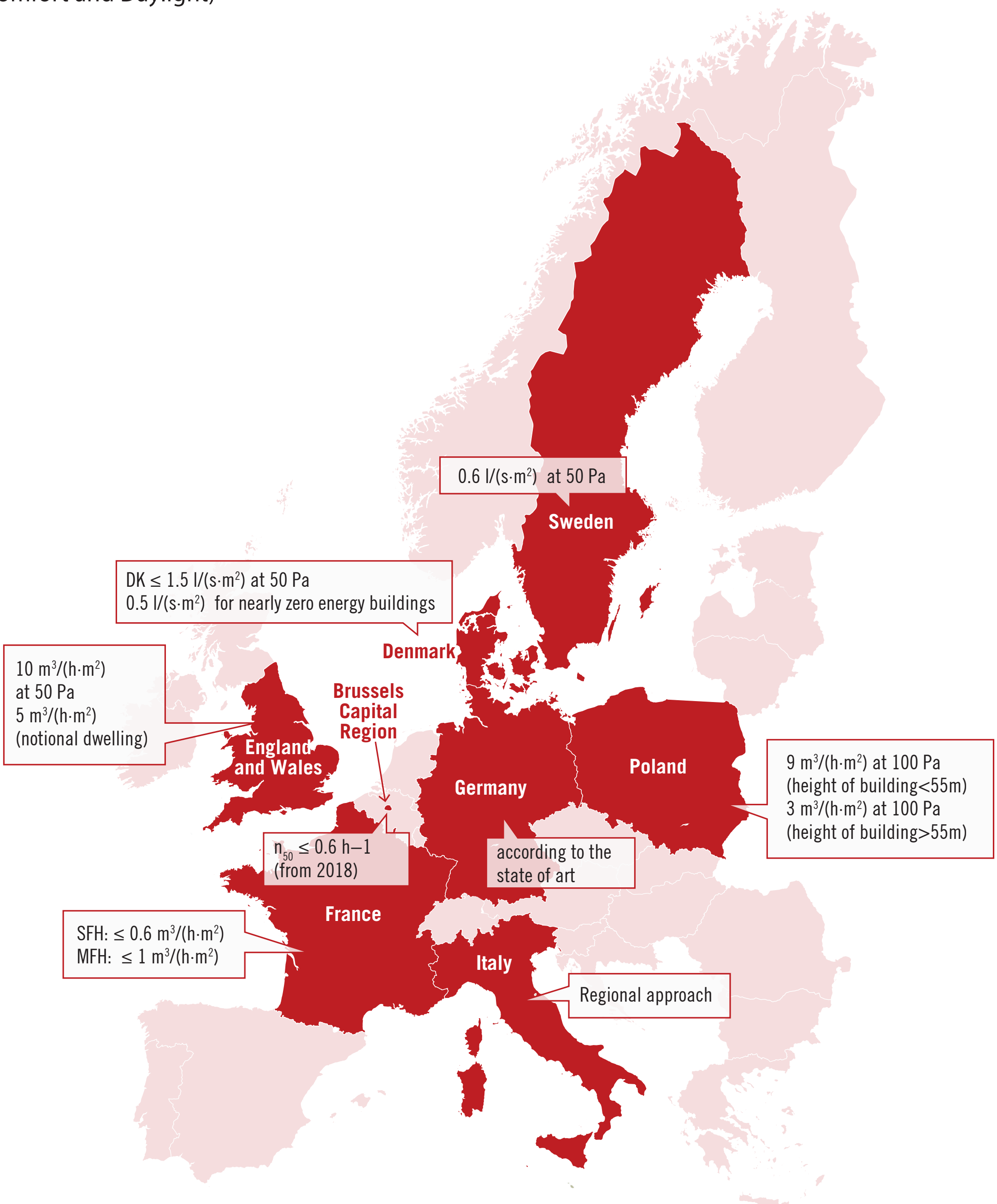
Table 5 - Ventilation requirements in residences across EU countries (Sources: HEALTHVENT WP5 report cited in JRC 2016, BPIE report on Indoor Air Quality, Thermal Comfort and Daylight)

Country (Reference)	Minimum air change rate for residences
Bulgaria (Reg.: 15/28.07.2005)	CEN/CR 1752: 4 l/s/p
Czech Republic (CSN EN 15665)	0.3 ACH
Finland (Build. Regs Part D2 Indoor Climate & Ventilation 2010)	0.5 ACH & 6 l/s/p
France (from 1982, modified in 1983)	1 room: 35 m^3/h, 2 rooms: 60 m^3/h, 3 rooms: 75 m^3/h, 4 rooms: 90 m^3/h, 5 rooms: 105 m^3/h
Germany (DIN 1946-6:2008)	55 m^3/h (30m2) … 215 m^3/h ($210m^2$)
Greece (TOTEE, 2425/86, 20701-4/2010, 20701-1/2010, KENAK, Legislation 3661)	0.7 ACH
Hungary (EN15251)	0.42 $l/s/m^2$
Italy (Dlgs 192/2005, DPR 59/2009, DM 18/12/1975)	0.3 ACH
Lithuania (STR. 2.09.02:2005, HN 42:2004)	0.5 ACH
Netherlands (The Dutch Building Code 2012)	0.9 $l/s/m^2$ (living area), 0.7 l/s/p (each room)
Norway (Building regulations Act, technical regulations TEK2010)	Occupied: 1.2 $m^3/h/m^2$
Unoccupied: 0.7 $m^3/h/m^2$	
Poland (PN-83/B-0340Az3:2000)	Total flow sum of extract flows
Portugal	0.6 ACH
Romania (15 Normative)	Same as France
Slovenia (ULRS 42/2002 SIST DIN 1946-6)	0.5 ACH
UK (UK Building regulations Part F-2010)	1 bedroom: 13 l/s, 2 bedrooms: 17 l/s, 3 bedrooms: 21 l/s
Denmark (BR10)	Min 0.3 $l/s/m^2$ (supply)
Sweden (BFS2014:13-BBR21)	Min 0.35 $l/s/m^2$ (supply)
Belgium (NBN D 50-001)	3.6 $m^3/h/m^2$

Airtightness requirements

Building airtightness describes the resistance of the building envelope to inward or outward air leakage and has a significant impact on the building's energy performance. Although airtightness is included in the energy performance regulations, there are significant differences in the way it is applied across the Member States. In particular, for certain countries airtightness can only be proved with measurements (blower-door testing) while other countries allow the use of quality management approaches (France) [39]. Airtightness requirements are also expressed in different units varying from litres per second per floor area ($l/s/m^2$) to volume per hour (m^3/h). There are countries which have either minimum airtightness requirements or maximum envelope leakage in place (Denmark, France, Belgium, Germany UK, and Sweden) (Figure 8) [1]. For other countries, airtightness tests are voluntary and are common when applying for financial subsidies or high classes in Energy Performance Certificates [1] [21].

Figure 8 - Airtightness requirements in Europe (Source: BPIE, 2015, Indoor Air Quality, Thermal Comfort and Daylight)



Indoor air pollutant requirements

Requirements on indoor air quality are included in the ventilation regulations of some EU countries. Due to the lack of a common guideline framework at European level, limit values and number of included pollutants in regulations vary from country to country (Table 6) [21]. Also, the averaging period varies and only a few pollutants are included in the national regulations. Limit values of air pollutants are not specified in the regulations of many countries and are often higher than those recommended by WHO guidelines.

Table 6 - Limit values for air pollutants across different countries (Source: REHVA, Indoor air quality and energy efficiency, Seppänen 2013)

	WHO	Finland	Lithuania	Norway	Portugal	Romania	Slovenia
Ammonia (μg/m^3)	-	20	40	-	-	-	50
Asbestos	-	0 fb/cm	0.1 mg/m^3	0.1 fb/cm	-	-	-
CO (mg/m^3)	7$^{\#2}$	8	3	10$^{\#5}$	12.5	6$^{\#3}$	10
CO_2 (ppm)	-	1200	-	1000	1000	-	1670
Formaldehyde (μg/m^3)	100	50	10	100$^{\#3}$	100	35$^{\#3}$	100
NO_2 (μg/m^3)	40	-	40	100$^{\#4}$	-	-	-
Ozone (mg/m^3)	0.1$^{\#5}$	-	0.03	-	0.2	-	0.1
PM10 (μg/m^3)	20	50	50	-	150	-	100
Radon (Bg/m^3)	-	200$^{\#1}$	-	100	400	140$^{\#6}$	400
Styrene (μg/m^3)	-	1	2	-	-	-	-

#1 = annual average; #2 = daily average; #3 = 30 min. average; #4 = 1 h average; #5 = 8h average; #6 = instant mix

Thermal comfort and noise requirements

Thermal comfort requirements are also inconsistent between countries, with temperature limits varying from 25 to 28°C in the summer and from 18 to 21°C in the winter (Table 7).

Table 7 - Temperature requirements in residences across EU countries (Source: HEALTHVENT WP5 report cited in JRC 2016)

Country (Reference)	Temperature limits for summer & winter (°C)
Czech Republic (Regulation 148/2006)	-
Finland (Build. Regs Part D2 Indoor Climate & Ventilation 2010)	25 & 21
France	No summer limit & 18
Germany (EN 15251/ DIN 4109, VDI 2081)	26 & 20
Greece (TOTEE, 2425/86)	26 & 20
Hungary (EN15251)	26 & 20
Italy (UNI 10339)	No summer limit & 20
Lithuania (HN 33: 2007)	24.5±1.5 & 22±2
Netherlands (The Dutch Building Code 2012)	-
Norway (NS 8175)	-
Poland (PN EN 15251)	-
Romania (15 Normative EN 15251)	25.5-27 & 18-21
Slovenia (ULRS 07/2001)	26 & 19
UK (Building Regulations Part F/ CIBSE)	28 & 19
Denmark (DS474, 1993)	Overheating limits: Not more than 100 hours above 26°C & not more than 25 hours above 27°C
Sweden (Swedish Building Code)	Min operative temperature for dwellings: 18°C & 20°C for dwellings inhabited by older people
Belgium (Brussels)	Overheating limits: Temperature of more than 25°C has to be limited to 5% of the time during the year

Five of the eight countries that were assessed in BPIE's study (2015) required minimum temperatures during the winter (Poland, Germany, Sweden, France, UK), while five countries had overheating restrictions for the summer (Belgium, Denmark, Germany, France, UK) [1]. The same study showed that minimal solar gains in winter are only required in Danish building codes, whereas Swedish regulations recommend the use of daylight management systems for installed luminaires. Noise levels are also inconsistent across EU countries both in terms of units and limit values (Table 8) [21].

Table 8 - Noise requirements in residences across EU countries (Source: HEALTHVENT WP5 report cited in JRC 2016)

Country (Reference)	Limit values for ventilation noise in sleeping rooms of residences
Czech Republic (Regulation 148/2006)	40 dB(A)
Finland (Build. Regs Part D2 Indoor Climate & Ventilation 2010)	28 dB(A)
France	30 dB(A)
Germany (EN 15251/ DIN 4109, VDI 2081)	35 dB(A)
Greece (TOTEE, 2425/86)	NR 25
Hungary (EN15251)	26 dB(A)
Italy (UNI 10339)	35 dB(A)
Lithuania (HN 33: 2007)	35 dB(A)
Netherlands (The Dutch Building Code 2012)	30 dB(A)
Norway (NS 8175)	35 dB(A)
Poland (PN EN 15251)	26 dB(A)
Romania (15 Normative EN 15251)	26 dB(A)
Slovenia (ULRS 07/2001)	day/night: LAF,max: 35/30 dB(A), Leq: 40/35 dB(A)
UK (Building Regulations Part F/ CIBSE)	NR 25

OPPORTUNITIES TO REFLECT THE IMPORTANCE OF IEQ IN NATIONAL AND EU POLICIES

Considering the gaps in the existing European building regulations, there are more opportunities at national level, so it is necessary to develop approaches for the integration of IEQ in national policy frameworks.

To do so, four main opportunities are identified:

- long-term renovation strategies (EPBD 2018/844: Article 2a (g), (c));
- Energy Performance Certificates (EPCs) (EPBD 2018/844: Article 19, Article 20, 2);
- smart readiness indicator (EPBD 2018/844: Annex Ia); and
- compliance and quality control measures (EPBD 2018/844: Article 14 and Article 15) (Figure 9).

Figure 9 - Opportunities for the integration of IEQ in national regulations

LONG-TERM RENOVATION STRATEGIES

The objective of a long-term renovation strategy is 'to support the renovation of the national stock of residential and non-residential buildings, both public and private, into a highly energy efficient and decarbonised building stock by 2050, facilitating the cost-effective transformation of existing buildings into nearly-zero energy buildings' [12]. This is an obligation that governments should follow.

In new or retrofitted buildings, not taking IEQ into account can result, for example, in very airtight constructions with insufficient ventilation. This can lead to overheating or to the increase of indoor air pollutants, which also has implications on health and wellbeing.

Therefore, when defining renovation strategies, the objective should be to reduce the energy consumption of buildings without compromising comfort, health and wellbeing of people living inside them, in a way that optimises both building and societal costs [41].

How can IEQ be integrated in national renovation strategies?

Policies within the building renovation strategies should ensure that:

- IEQ is taken into account by also considering supporting instruments (e.g. Building Renovation Passports) which give Member States the flexibility to decide on which segment of the building sector they want to tackle first and how [42].
- While supporting some renovation strategies, Member States should highlight the impact that specific renovation measures have on both the energy performance of the building and the IEQ (see Table 9). Within this lies also a challenge in raising awareness of the importance and benefits of good IEQ.

The long-term renovation strategies developed by Member States are an opportunity to improve the quality of life of citizens by integrating IEQ aspects (Figure 10) [8]. In the last decade, there has been an increasing trend of scientific studies showing that energy-efficiency retrofits which ensure IEQ (indoor air quality, thermal comfort etc.) can have significant health benefits [43] [22] [23]. In support of this, article 2a 1 (f) of the revised EPBD mentions that long-term renovation strategies should encompass 'wider benefits related to health, safety and air quality'. IEQ should therefore be integrated in national implementation of long-term renovation, recognizing that deep renovation has far-reaching benefits for society and public spending. Increasing indoor comfort and air quality can lead to a reduction of illnesses and premature deaths associated with living in cold and damp homes, and this in turn reduces pressure on healthcare and social services [8]. The majority of renovation strategies do not report issues beyond energy efficiency such as IEQ [44], although IEQ and energy efficiency can be achieved simultaneously [22]. Neglecting IEQ when planning a renovation can result in the building's degradation. For example, in Denmark and Sweden, in response to the oil crises in the 1970s, dwellings were constructed to be airtight with inadequate ventilation, as well as having small windows and insufficient daylight. This lead to poor quality indoor environments. Rather, renovation should be viewed as an opportunity to improve the indoor air quality and the comfort and quality of life for building occupants, while at the same time achieving a high energy performance [41].

Figure 10 - Renovation of social housing in Anderlecht under the RenovActive project (Source: VELUX, RenovActive project)

Before After

Table 9 - Expected impacts of renovation on energy and IEQ (Source: Noris et al., 2013)

Retrofit	Energy impacts	IEQ impacts
Air seal envelope	Reduces heating and cooling	Reduces pollutant entry from other apartments and common areas Reduces outdoor air ventilation potentially worsening IAQ
Replace bath fan	More efficient motor decreases selectricity use Potentially more use, increases heating and cooling demand	Reduces fan noise Improves removal of cooking pollutants and moisture (if system is used)
Replace natural draft water heater with forced combustion water heater	Reduces water heater energy use	Reduces risk of combustion pollutants and moisture (if system is used)
Provide portable fan	Reduces cooling demand in air-conditioned apartments	Improves thermal comfort
Replace gas cook stove with standing pilot with electronic ignition stove	Reduces natural gas use Reduces cooling demand, increases heating demand	Eliminates indoor pollutants from pilot light
Replace HVAC ductwork and seal return plenum	Reduces heating and cooling demand	Reduces drawing of pollutants from other apartments, attics, etc. May improve thermal comfort
Replace single-pane sliding glass doors and windows	Reduces heating and cooling demand	Reduces cold drafts and radiant heat losses, improving comfort
Add insulation	Reduces heating and cooling demand	Improves thermal comfort and noise transmission
Install HEPA filter	Increases electricity consumption	Reduces indoor particle levels

Reforming the cost-optimal methodology in the EPBD

The current methodology is narrow and overlooks many of the societal gains of getting healthier nearly zero-energy buildings. The integration of such societal gains could boost the renovation rate in EU28. This would accelerate the transformation of unhealthy, uncomfortable and energy-inefficient buildings into healthy, comfortable and nearly zero-energy buildings.

In order for the cost-optimal methodology to be more relevant, it ought to include parameters to evaluate the impacts on health, comfort, productivity and IEQ. In addition to cost savings from the application of energy efficiency technologies, potential benefits could include reduced costs in the healthcare sector due to an improved indoor environment, increased productivity and wellbeing, and lower absenteeism from work [21]. Buildings with good indoor environment can lead to a reduction in healthcare costs and can also be a way to tackle energy poverty [20].

There is an increasing number of studies showing significant health benefits when good indoor air quality is ensured in new highly efficient buildings or in energy-efficient renovation of buildings. A report published by the Joint Research Centre (JRC) on 'Promoting healthy and energy efficient buildings in the European Union' shows that various studies in Europe have quantified the benefits in terms of improved life quality, less absenteeism, public spending and improved conductivity, but not in a systematic way or under a common framework. The savings in costs from the health-based benefits are estimated to be comparable to the energy savings alone [21]. Although thermal comfort, indoor air quality, adequate levels of natural lighting and acoustics are among the most important drivers and benefits of renovation, energy retrofits are often applied without considering requirements for the assessment of their impact on the overall IEQ [45] [46].

ENERGY PERFORMANCE CERTIFICATES

Energy Performance Certificates (EPCs) are an integral part of the EPBD and constitute an important instrument to enhance energy performance of buildings, which Article 19 of the recently revised EPBD says should be further improved [9].

Why EPCs are an opportunity to integrate IEQ

The main objective of the EPC is to serve as an information tool for future building owners, tenants, occupiers and real estate actors (Article 20, 2). Therefore, EPCs can be a powerful market tool to create demand for energy efficiency in buildings by targeting improvements such as a decision-making criterion in real-estate transactions, and by providing recommendations for the cost-effective or cost-optimal upgrading of the energy performance [9]. In order not to compromise the health and wellbeing of building occupants, these recommendations on renovation opportunities should go side by side with IEQ aspects. EPCs are among the most important sources of information on the energy performance of the EU's building stock and have the potential to become effective instruments to track buildings' energy performance and their overall IEQ status.

How can IEQ be integrated in EPCs?

Although increased thermal comfort and air quality, higher levels of natural lighting and improved health of occupants are among the most important benefits and drivers for renovation, they are mostly not currently covered by EPCs. As a result, the relevance of EPCs for owners (including potential owners) and their ability to stimulate the renovation of buildings is limited. Energy efficiency and IEQ improvements are inter-related and can both be achieved simultaneously [47]. Along with the Building Renovation Passport (EBPD III: Article 19a), a document outlining a long-term step-by-step renovation roadmap to achieve deep renovation for a specific building [48], EPCs could include evidence-based IEQ aspects. Building Renovation Passports provide a comprehensive set of relevant indicators (e.g. energy consumption, CO_2 emissions) and include a dynamic dimension by delivering information about recommended improvement steps in a detailed way and, by doing so, stimulate deep or staged deep renovations [49]. Evidence-based IEQ aspects could originate from measurements, building occupant questionnaire survey outcomes (Figure 11) and/or computer simulations (Figure 12) [10]. Measurements and surveys should take place both before and after renovations to ensure that energy efficiency upgrades (renovations) did not compromise the quality of the indoor environment. Certain measurements such as the airtightness of the building's construction could be integrated in the EPC (IEQ status of building).

Figure 11 - Example of subjective classification of the indoor environment (Source: EN 15251:2007)

Classification based on occupants' responses	Percentage						
People finding the thermal environment acceptable	85						
People finding the indoor air quality acceptable	80						
Distribution on thermal sensation votes	-3	-2	-1	0	+1	+2	+3
	0	5	10	53	20	10	2
Distribution of temperature preference	Colder		Unchanged		Warmer		
	20		75		5		

Figure 12 - Classification of the thermal environment and indoor air quality (Source: EN 15251:2007)

	Quality of indoor environment in % of time in four categories			
Percentage	5	7	68	20
Thermal environment	IV	III	II	I
Percentage	7	7	76	10
Indoor air quality	IV	III	II	I

For example, comfort conditions and IEQ are roughly mentioned in the Greek EPC, in which the expert issuing the document ticks the relevant boxes of indoor air quality, thermal, lighting and acoustic comfort. There is, however, no indication provided on how these IEQ parameters are achieved (Figure 13).

Figure 13 - Translated part of the Greek EPC indicating IEQ

Conditions of Comfort and Indoor Environmental Quality			
Thermal comfort ☐	Lighting comfort ☐	Acoustics comfort ☐	Indoor air quality ☐

The energy performance of a building is determined according to the calculated annual energy consumption to meet the needs associated with its use, in order to achieve thermal and acoustic comfort

Numerous researchers have stressed the need for a metric/index of the overall indoor environment that would consist of most physical parameters to be presented alongside the energy certification [47] [50]. Several studies are recommending methods for the evaluation of the IEQ using rating/scoring systems. For example, the 'Dwelling Environmental Quality Index' (DEQI) aims to improve energy efficiency based on human behaviour in social housing. DEQI should assist households and property managers to identify potential faults related to the indoor environment, while ensuring that IEQ is not compromised during energy-saving processes [47]. The index reflects the IEQ in a single value and is based on three major parameters of the indoor environment (temperature, relative humidity and CO2 concentrations) and is in compliance with the EU standard EN 15251:2007.

Examples that could be considered

A further upgrading of the certification process could be the evolution of the EPC to a more comprehensive certificate (e.g. EPC+ in Flanders). This could involve several aspects of the sustainable buildings concept beyond energy, such as IEQ, health, wellbeing, comfort, smartness level etc. The DGNB system, the WELL Building Standard and the Active House (see below) are inspiring initiatives, including sociocultural aspects, performance verification, health and recertification.

It is key that qualified professionals issuing either the extended EPC or a holistic building performance certificate should have relevant experience and training beyond energy-related matters, on all aspects of IEQ, wellbeing and cost-effectiveness.

DGNB system

The German Sustainable Building Council developed a voluntary certification system, the DGNB system. The system, applied internationally, assesses the sustainability of buildings and urban districts. Quality is assessed over the entire life cycle of the building. Several sustainability criteria are certified including ecology, economy, socio-cultural aspects etc. [55].

WELL Building Standard

The WELL Building Standard is a voluntary certification system that investigates how the design, the operations and human behaviour within spaces can be optimized to advance human health and wellbeing. WELL covers seven core concepts of air, water, nourishment, light, fitness, comfort and mind. The standard is based on verified performance and in order to maintain the certification projects must undergo recertification to prove that the building is still performing in accordance with the requirements [56].

Active House

The Active House label is a worldwide quality stamp for comfortable and sustainable buildings. It advises on elements important to people's lives and living in their home, while the Active House label is issued for buildings that meet specified requirements for indoor comfort, energy efficiency and environment. Its vision is to create healthier and more comfortable building occupants, without compromising the climate. Active House defines long-term goals for the future building stock and its purpose is to unite interested parties based on a holistic approach to building design and performance. It proposes a framework on how to design and renovate buildings that contribute to human health and wellbeing by focusing on the indoor and outdoor environment and renewable energy based on a combination of three principles of comfort, energy and environment [58].

SMART READINESS INDICATOR

A smart building is very energy efficient and covers its low energy demand to a great extent by onsite or district-level renewable energy sources. A smart building (i) stabilises and drives a faster decarbonisation of the energy system through energy storage and demand-side flexibility; (ii) empowers its users and occupants with control over the energy flows; and (iii) recognises and reacts to users' and occupants' needs in terms of comfort, health, indoor air quality and safety as well as operational requirements [51]. As part of the revised EPBD in Annex Ia, the European Commission will define a smart readiness indicator and establish a methodology which, among other things, takes into account benefits for the indoor climate conditions. To give value to smart buildings, the indicator must pull the market in the direction of smarter buildings, while also providing meaningful information on the potential of the building to prospective new tenants or buyers [11].

Why the smart readiness indicator is an opportunity to integrate IEQ

Capturing and promoting the benefits of smart buildings for building users and occupants (e.g. cost savings, an optimal IEQ), the energy system (e.g. reduced pressure on the energy markets), the economy (e.g. creation of local jobs) and society as a whole (e.g. tackling climate change, reducing air pollution) must be the underlying purpose of introducing a smart readiness indicator [11]. In addition, the implementation of the general framework methodology for the smart readiness indicator should integrate IEQ aspects such as indoor air quality. This can ensure buildings are able to adapt to the essential needs of occupants for health, wellbeing and productivity in their operation.

How can IEQ be integrated in the smart readiness indicator?

Smart buildings need to go beyond being energy efficient and healthy, and also recognise and react to users' and occupants' needs to optimise comfort, indoor air quality, wellbeing and operational requirements [11]. The smart readiness indicator should characterise the ability of a building or its systems to sense, interpret, communicate, interact with the occupants and contribute to an optimal operation of energy-connected assets. The smart readiness indicator should aim at improving the quality of life of building occupants and also ensure the efficient operation of buildings, for example through reducing inspections by giving notice when a problem is detected. The current proposal is to develop a user-friendly and performance-based IEQ indicator that would be integrated in the framework methodology of the smart readiness indicator. The smart readiness indicator, apart from ensuring the building's effective operation and helping improve its energy performance, would further respect occupants' needs towards a healthy, comfortable and productive indoor environment. This indicator could include an index or metric (e.g. QEQI) which would consider the most important physical parameters of IEQ. By using mature and interactive ICT, it could be displayed on screens in buildings, providing real-time information on IEQ-related aspects based on real-time measurements [52]. Based on the monitored information it would then provide the building occupants with tailored advice – for example, when the CO_2 levels are high, to open windows or turn the ventilation system on [53]. Figure 14 shows possible stages that could be part of the smart readiness indicator.

Figure 14 - Possible stages that could be part of the smart readiness indicator

COMPLIANCE AND QUALITY CONTROL

Mandatory inspections, as seen in Articles 14 and 15 of the revised EPBD, commissioning and performance assessments of IEQ requirements should be implemented by Member States. Compliance should be regularly assessed during the design stage, pre- and post-occupancy and pre- and post-renovation of the building (Figure 15), while quality control checks of the heating, cooling and ventilation systems should take place to ensure the long-term operating performance of buildings in relation to the IEQ requirements.

Figure 15 - Stages at which compliance and quality control checks should take place (Source: "Promoting healthy and energy efficient buildings in the European Union," European Commission, JRC 2016)

Across the Member States, compliance and quality control checks of EPCs are of crucial importance for the effective implementation of the building regulations. According to Article 18 of the EPBD, Member States must establish an independent control system of the issued EPCs aiming to ensure compliance. To achieve compliance on the EPCs, the EU-funded project QUALICHeCK, identified a three-step approach including the following [54]:

1. **Clear procedures on determining EPC input data;**
2. **Clear legal procedures on decision-making on non-compliance and associated actions;**
3. **In case of non-compliance effective control and sanctioning mechanisms should be applied.**

To support the integration of IEQ within the regulatory framework through the previously mentioned 'boosting tools' (renovation strategies, EPCs, smart readiness indicator) adequate enforcement of implementation, compliance and control mechanisms must be in place to ensure they are adhered to. A similar three-step approach to the QUALICHeCK project recommendations above could be applied to ensure quality control of IEQ requirements.

RECOMMENDATIONS TO INCREASE THE RECOGNITION OF IEQ IN EU AND NATIONAL POLICY

Good IEQ is a cornerstone of ensuring health, comfort, wellbeing and productivity in buildings, while reducing the building stock's climate impact is essential to the EU's commitments under the Paris agreement. A balance must be ensured between the different needs of building occupants, such as energy savings, comfortable temperature, sufficient daylight and good indoor air quality. IEQ can become a driving force for energy renovation and proper implementation across Europe, which in turn triggers the need towards a cost-optimal methodology. The recently revised EPBD (2018/844) has sparked a change in the right direction, but strong action and implementation is needed at EU and Member State level.

EU LEVEL

HARMONISE CALCULATION METHODOLOGIES AND IEQ REQUIREMENTS AT EU LEVEL

Harmonising requirements and methodologies at European level would **address inconsistencies between different calculation methodologies, IEQ requirements and design criteria**, and between countries. This will allow a systematic approach for defining indexes and metrics for comparison of outcomes across all Member States. The EU should also encourage a continuous assessment and review framework, which ensures good, reliable and comparable data.

EU LEVEL

ENFORCE THE IEQ ASPECTS IN EPBD IMPLEMENTATION

The European Commission should closely **monitor and enforce implementation of the revised EPBD**. Slow implementation at Member State level, poor compliance and lack of enforcement risk the revised EPBD not delivering the changes needed.

NATIONAL LEVEL

USE LONG-TERM NATIONAL RENOVATION STRATEGIES TO BOOST IMPROVEMENTS IN IEQ

Long-term renovation strategies (as mentioned in Article 2a of the revised EPBD) should include 'an evidence-based estimate of expected energy savings as well as health, comfort and safety benefits'. In addition, **requirements and guidance are needed on how to ensure that building renovation not only results in significant energy savings, but also improves the quality of life, health and wellbeing of the people living and working within these buildings**. Cost-effective solutions to deliver good IEQ should also be integrated in national renovation strategies so that these benefits are properly considered. During implementation, Member States should design policies that improve indoor air quality and have a positive impact on comfort, health and productivity, as drivers for energy renovation. Good policies should ensure adequate levels of natural daylight, acoustics, ventilation and indoor air quality.

Deep renovation can generate great benefits for society in terms of local jobs, economic growth, lower health bills and overall better living standards. Deep renovation that ensures good IEQ can increase indoor comfort, wellbeing and productivity, and lead to a reduction in absenteeism from work. It can also reduce healthcare costs due to a decrease in illnesses and premature deaths associated with living in cold and damp homes. This in turn reduces pressures on healthcare and social services. These cost savings should be taken into account in the estimation of wider benefits (as mentioned in Article 2a 1 (g) of the revised EPBD) and when designing policies for the building stock. In addition there is a need for procedures to better value these benefits and for them to be more widely disseminated and communicated.

Related legislative hook: EPBD 2018/844, Article 2a 1, (c), (g)

NATIONAL LEVEL

ADDRESS IEQ IN MAJOR ENERGY RENOVATIONS

Major energy renovations drastically reduce the energy needs of a building. However, without considering IEQ, renovation might have adverse effects on the indoor environment. **Major renovation should reduce energy bills and increase comfort while ensuring proper air quality.** In every major energy renovation project there should be a plan to ensure energy, comfort and air quality needs are met.

Related legislative hook: EPBD 2018/844, Article 7

NATIONAL LEVEL

USE THE NEW BUILDING RENOVATION PASSPORT CONCEPT TO ENSURE EFFECTIVE IEQ IMPROVEMENTS

A step-by-step renovation roadmap that guides a building owner to a highly efficient building should incorporate IEQ aspects. **A Building Renovation Passport** based on 'quality criteria and outlining relevant measures that could improve the energy performance' (as mentioned in Article 19a of the revised EPBD) **should provide comprehensive information on relevant indicators such as energy performance, CO2 emissions and IEQ aspects, and deliver information on recommended improvements in a detailed and dynamic way.**

Related legislative hook: EPBD 2018/844, Article 2a, (c), (g) & Article 19a

NATIONAL LEVEL

MAKE ENERGY PERFORMANCE CERTIFICATES MORE USEFUL FOR OWNERS

EPCs have the potential to become effective instruments to track not only a building's energy performance but also its overall IEQ by providing evidence-based information. This could originate from measurements, building occupant survey outcomes and/or dynamic computer simulations with or without the inclusion of an overall IEQ metric or index. Therefore, **EPCs should be revised and further expanded into reliable, compliant and user-friendly 'next-generation EPCs' by also including non-energy aspects such as comfort and IEQ.** EPCs will have to be further improved by Member States (as mentioned in Article 19 of the revised EPBD). To support deep renovation including aspects of indoor climate and comfort, EPCs should be complemented by Building Renovation Passports, as seen in Article 19a.

Related legislative hook: EPBD 2018/844, Article 19, Article 20 (2)

INTEGRATE IEQ ASPECTS IN THE SMART READINESS INDICATOR

The methodology to calculate the smart readiness indicator currently developed by the European Commission (as seen in Annex Ia of the revised EPBD) will take into account, among other things, self-regulating thermal environment devices as well as the benefits to the indoor climate conditions. **The smart readiness indicator should aim to improve the quality of life of building occupants and continuously ensure the effective operation of buildings.** Integrating IEQ aspects into the general framework methodology of the smart readiness indicator will ensure a building can adapt to occupants' essential needs in terms of health, wellbeing and productivity in its operation. An overall metric or index of IEQ (e.g. DEQI), that would help building owners identify and address faults related to the indoor environment, should be an important part of the smart readiness indicator.

Related legislative hook: EPBD 2018/844, Annex Ia

ENSURE COMPREHENSIVE COMPLIANCE AND QUALITY CONTROL

Post-occupancy evaluations, post-installation/construction commissioning (e.g. for ventilation systems), user's behaviour verification, audits and regular inspections (as mentioned in Articles 14 and 15 of the EPBD) are crucial to ensure effective operation of buildings. **Compliance and quality control checks** of heating, cooling and ventilation systems **should be regularly carried out to ensure the long-term operating performance of buildings in relation to IEQ requirements.**

Related legislative hook: EPBD 2018/844, Article 14 & Article 15

EXPAND THE TRAINING OF ENERGY EXPERTS

Across Europe, energy experts in the construction sector should be properly trained and educated (Articles 2a 1 (f) of the revised EPBD). **Training, education and experience of people issuing certification documents, installers and commissioners should be expanded to go beyond energy efficiency matters and also cover IEQ, health, comfort and wellbeing.**

Related legislative hook: EPBD 2018/844, Article 2a 1 (f)

RAISE AWARENESS OF BUILDING OCCUPANTS ON IEQ ASPECTS

The behaviour of the building occupants is a crucial aspect of maintaining good IEQ. As referred to in Article 20 (2) of the revised EPBD, Member States 'shall provide information to owners and tenants through accessible and transparent tools'. **Campaigns to raise the awareness of building occupants of the importance of IEQ and its effects on health, comfort and wellbeing should be considered.** Also, gathering occupants' perceptions of the indoor environment through structured surveys will build their participatory involvement which may have positive effects on their behaviour regarding the indoor climate.

Related legislative hook: EPBD 2018/844, Article 20 (2)

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