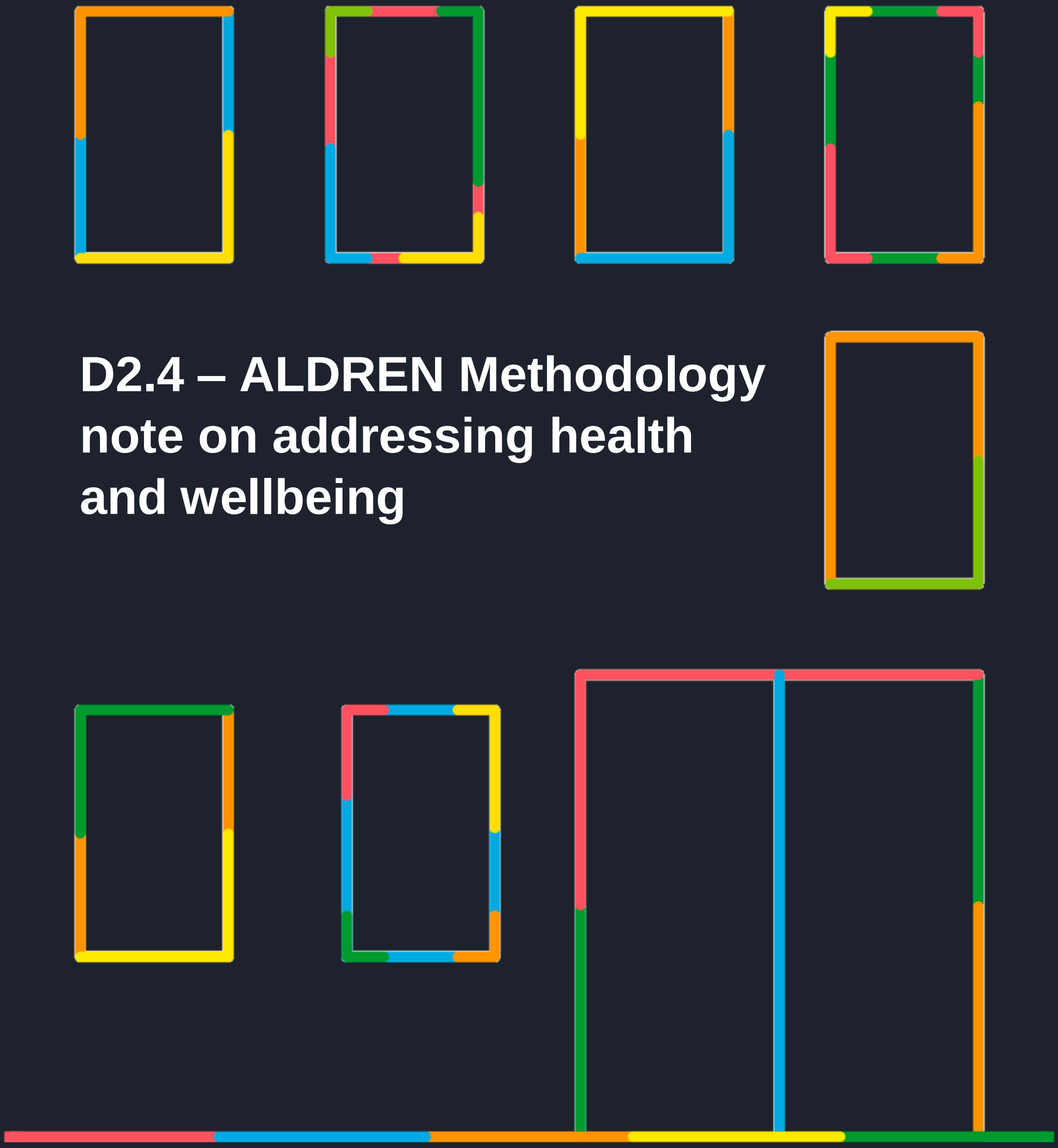
D2.4 – ALDREN Methodology note on addressing health and wellbeing



ALDREN ALliance for Deep RENovation in buildings

Implementing the European Common Voluntary Certification Scheme, as back-bone along the whole deep renovation process

Disclaimer:

Attention: The present versions are still working documents

*The aim of these **draft** ALDREN Methodology notes is to provide information on how to apply the different ALDREN protocols during the pilot phase, to test, consolidate and validate the work done on the different tasks, to collect feedback from stakeholders on their utility and applicability.*

Therefore, they are made public.

These drafts will be finalized and updated for roll-out before the end of the ALDREN project.

Project resume:

Start: 1 November 2017
End: 30 Avril 2020

The ALDREN objectives are to achieve higher renovation rates and better renovation quality by overcoming market barriers and preparing the ground for investment.

The excellence of the ALDREN solutions offered are:

1. a harmonized Energy performance rating based on the European Voluntary Certification Scheme (EVCS) verified by measurements to increase comparability, confidence and market uptake by standardized solutions (CEN / ISO);
2. associating low energy renovation with high quality indoor environments to trigger renovation and to promote health and comfort;
3. aligning market recognition of high quality with enhanced building value by financial tools and capacity building. Establishing business case for deep renovation to motivate private investment.

These solutions will be integrated in a consistent, common way in a building passport to ensure the results and effective financing also in case of step by step renovation.

The ALDREN coordinate and support actions bring together in ALDREN Alliance the main stakeholders involved in building renovation to specify the needs of the non-residential building sector and to organize the pilot use of the ALDREN procedure.

The ALDREN actions are sound and credible. They answer a market request for common reliable tools by using the EVCS policy instrument (EPBD Art. 11(9)) and by completing it to reach the needed holistic approach for deep renovation.

The implementation and dissemination of the ALDREN procedure will use existing channels of environmental scheme operators for the pilot phase, but also for further dissemination.

The ALDREN overarching outcome will be the infrastructure to enable market transformation by deep renovation driven by the business case and able to directly support the EU policies (EED, EPBD).

Coordinator:

CENTRE SCIENTIFIQUE ET TECHNIQUE DU BATIMENT	**France**

Participants:

ENBEE SRO	Slovakia
INSTITUTO VALENCIANO DE LA EDIFICACION	Spain
CERTIVEA	France
REHVA	Netherlands
VERCO ADVISORY SERVICES LIMITED	United Kingdom
DANMARKS TEKNISKE UNIVERSITET	Denmark
POLITECNICO DI MILANO	Italy

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Revision History

Date	Version	Author/Revision by	Comments
19 April 2019	Version 1.0	DTU / Pawel Wargocki CSTB / Corinne Mandin, Wenjuan Wei	First consolidated version
24 April 2019		CSTB / Olivier Greslou, Sylviane Nibel, Johann Zirngibl	Review
29 April 2019	Version 2.0	DTU / Pawel Wargocki CSTB / Corinne Mandin	Second version. Ammendments included

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1. Executive Summary

Present document is Deliverable 2.4.5 on methodology addressing health and wellbeing in ALDREN.

One of the objectives of ALDREN project is to document the quality of indoor environment in the building undergoing deep energy renovation process. The reason is twofold: 1. To document that the quality of indoor environment is not degraded during renovation to comply with the EPBD mandate; and 2. To document potential benefits for health and well-being being the result of deep energy renovation process thus to document additional value that is brought through renovation that can be monetized. This deliverable summarizes the outcomes of Task 2.4 whose aim was to address this objective.

A TAIL index was invented to document the quality of indoor environment. TAIL is a tale, a story about indoor environmental quality of an office building or a hotel that has undergone deep energy renovation. TAIL describes the quality of indoor environment before and after renovation.

TAIL integrates the four major components defining indoor environmental quality into one index. Such index does not exist at present.

TAIL stands for T= thermal environment, A= acoustic environment, I=indoor air quality and L= luminous (visual) environment. The quality of each of these four components is determined and used to determine the overall quality of indoor environment. The quality levels are linked with the levels of comfort and well-being, as well as the risks for health if relevant.

Each of the TAIL components is defined by different parameters describing the thermal, acoustic, and luminous environment, as well as indoor air quality. The parameters defining T, A, I and L were determined by reviewing major building certification schemes, EN standard 16798-1 (2019) and Level(s) (2019), an EU's voluntary reporting framework to improve the sustainability of buildings, to make the connection rather than compete with the existing methods used to document the quality of indoor environment. Twelve parameters were selected based on different criteria including feasibility.

The quality level of each of the four components of TAIL is presented by a color from green (high quality), through yellow (medium quality), orange (moderate quality), to red (low quality). This is securing simple communication. The overall quality of indoor environment is presented as one of the four Roman numbers from I (high quality), through II (medium quality), III (moderate quality) to IV (low quality) to match with the categories defined by the EN standard 16798-1 (2019); they can be replaced with letters from A to D to match classification used for energy.

The protocol for derivation of the quality of each of the four components of TAIL index and the overall quality of indoor environment is presented. The quality of each component of TAIL is determined based on measurements, modelling or observations of parameters describing them. Different levels of quality were determined by defining the ranges and levels of different parameters underlying the four components of TAIL. The main references for these quality levels are EN standard 16798-1, World Health Organization (WHO) Guidelines for Indoor and Ambient Air Quality and Level(s). TAIL shall be derived before and after renovation.

The protocol for determining TAIL index includes the details on seasons during which the measurements shall be performed and for how long, on how many locations (rooms) per building shall be instrumented during measuring campaign, on the instruments that shall be used for performing measurements and their minimum accuracy, and on how the results of measurements shall be analyzed. It also describes when the measurements can or shall be supplemented or replaced by modelling or observations. This protocol and the concept of TAIL will be examined during ALDREN pilots.

It is proposed that TAIL becomes the integral part of EVC. The method is proposed on how TAIL index can be integrated into the scheme presenting the energy certificate.

2. Recall of the Grant Agreement

The ALDREN Project is a proposal to the call H2020 EE-11-2016-2017, focused on overcoming the market barriers and promoting deep renovation of buildings.

The overarching ambition of the ALDREN initiative is to consolidate, promote and implement an extended harmonized procedure, based on the European Common Voluntary Certification Scheme for non-residential buildings (EVCS) and a set of relevant instruments, in order to support building deep renovation operations, all along the process, tackling its organizational, financial and technical components issues. In line with the development of the EVCS, the primary scope is focused on non-residential buildings (especially offices and hotels).

Among coordination and support measures and objectives (CSOs), ALDREN has proposed the following one:

[CSO4] To integrate, beyond the assessment of energy performance, indoor air quality, comfort and health as priorities, in the scope of deep renovation. These represent fundamental qualities and expectations for any building. Moreover, in the perspective of deep renovation, the focus on energy performance is sometimes hypertrophied and overlooks associated benefits for other building issues. A special attention is to be paid on indoor air quality, health and comfort so as to ensure that energy improvement preserves or, more likely improves these aspects.

The expected outcome is additional indicators in the EVCS and the impact an increased health and well-being.

CSO4 is completed in Task 2.4 on addressing health and well-being. The leader is DTU and participants are CSTB, ENBEE, IVE, CERTIVA, REHVA, VERCO.

The work of Task 2.4 is divided into the following subtasks:

- Review of existing indicators
- Integration of existing indicators as complementary modules to EVCS
- Link indoor environment indicators with energy performance
- Task coordination and improvement of productivity and operation costs
- Elaboration of the methodology related to data collation and the assessment of the indoor environmental quality before and after renovation

All tasks have been completed, as illustrated by the present document. This document presents the results of the last subtask on the list above; all preceding subtasks provided input to the present document and without addressing them it would not be possible to complete this deliverable.

Task 2.4 produce five deliverables. The present document is deliverable D2.4.5 titled “ALDREN Methodology note on addressing health and wellbeing. Protocol document”. The first draft of the document was released on Month 12 from the start of the project. This is the protocol document that is released on Month 18 from the beginning of the project, as described in the Grant Agreement.

The Grant Agreement is hereby respected by Task 2.4.

3. Main Outcome: the TAIL index and the protocol to derive it

3.1 TAIL index

Thermal, acoustic and visual environment, as well as indoor air quality are the central and essential components characterizing the quality of indoor environment. Each of these components can be characterized by several parameters that are specific to each of them. For example, thermal environment can be characterized by indoor air temperatures, acoustic environment by sound levels, indoor air quality by concentration of air pollutants and visual environment/light by illuminance levels. Indoor environmental quality can be thus considered as a complex construct including several modalities each of them being important singly, each interacting with another and potentially modifying the effects as well as comprising the aspects of health and well-being. It is therefore difficult to represent it using one measure, one index or one score. The attempts have been made to do it but generally at present each of the components are addressed separately when indoor environmental quality is considered and no one unified index is used to describe indoor environmental quality. ALDREN project is proposing an index to respond to the call of unified and integrated metric/score that represents the quality of indoor environments.

The index proposed by ALDREN is called TAIL, T standing for thermal environment, A for acoustic environment, I for indoor air quality and L for light (visual environment). TAIL integrates thus the four central components describing indoor environmental quality. The overall principle of TAIL is that it presents the quality of each of the components defining indoor environmental quality separately and then integrates them into one index describing the overall quality of indoor environment, all shown as one label or a tag. Reporting these components is not new as they are central part of the existing standards and certification schemes addressing well-being and health of building occupants. The novelty and the uniqueness of TAIL is that these components are presented together, quality of each of them is shown and used to determine the overall quality of indoor environment, each of the components having equal importance for the overall quality. TAIL is thus a synthetic representation of the quality of indoor environment.

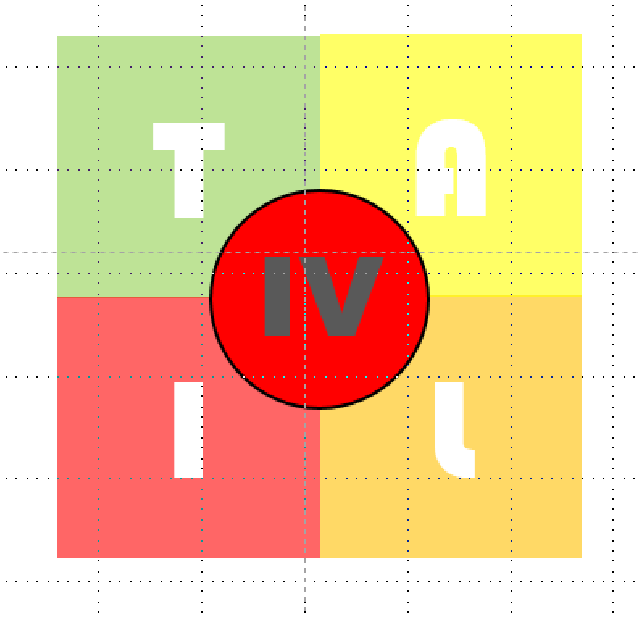


Figure 1. The TAIL index and example of its overall level of indoor environmental quality depending on the four different components

The principle of TAIL is shown in Figure 1.

To demonstrate the quality of the four components each of them is assigned a color. The color depicts the four levels of quality from high (green), through medium (yellow), moderate (orange) to low (red). The color, i.e. the quality level, is determined by the levels of parameters characterizing each of the TAIL components; these parameters are described in the following.

The overall level of quality of indoor environment is determined from the quality levels of each of the TAIL components. To demonstrate the overall quality of indoor environment, a Roman number is used from I representing high quality, through II indicating medium quality, III corresponding to moderate quality, to IV describing low quality. Roman numbers from I to IV are used to match the levels of indoor environmental quality defined by the standard EN16798-1 (2019); this is the standard supporting EPBD. It is considered to change the Roman numbers to letters A, B, C and D to align the levels of quality with the system used to denote the energy classes. But it would have to be coordinated with modification of EN 16798-1. It is made on purpose that TAIL shall comply with EN 16798-1. If letters are used instead of the Roman numbers class AA will indicate a building having mean energy class A and high indoor environmental quality, while building with class AD will have low energy use and low indoor environmental quality.

It is proposed that TAIL shall become an integral part of EVC. The proposed integration of TAIL into the EVC scheme is shown in Annex 1. Annex 1 shows the first proposal of such integration that may evolve into other versions before and after the end of ALDREN project.

3.2 Derivation of TAIL

TAIL is derived by measuring and/or modelling of 12 parameters, temperature for thermal environment, sound level for acoustic environment, ventilation rate, concentration of carbon dioxide, formaldehyde, PM2,5, Radon, benzene, and the levels of relative humidity and visual mold for indoor air quality, and illuminance level and daylight factor for light (visual environment). These parameters were selected based on different criteria and it is acknowledged that the list is incomplete and can be much longer. However, the decision had to be made especially with respect to practical application of TAIL with no compromise of the resulting quality. Furthermore, the TAIL in its present format is only the first version that will be advanced upon its use and validation. Then the number of parameters shall be modified when finding what is missing and what is not operational.

The major criterion for derivation of parameters included in TAIL was to select the parameters that are used in the existing standards and certification schemes. It was done intentionally so that TAIL could be derived using the protocols that are the part of these documents and would allow generalization of the approaches used by the different existing schemes, TAIL creating thus common ground. Additionally, it was done to ensure the adoption of TAIL by the practice, it is that it would not be considered as a new and non-validated concept or construct. To this end, a deep review was performed of parameters used to characterize and describe indoor environmental quality included in the major European and worldwide building certification schemes and in the European standards and guideline documents; with respect to the latter it has been sought that the selected parameters are included in EN16798-1 that is a standard supporting EPBD and in LEVEL(s), a common EU framework of core sustainability indicators for office and residential buildings. The review was submitted to the scientific journal *Building and Environment.* The manuscript submitted is shown in Annex 2; this manuscript has positively undergone the preliminary review and is under revision when the present deliverable has been submitted.

Another criterion for selecting parameters underlying TAIL was the connection with the deep energy renovation process. Since TAIL is proposed to assist and support deep energy renovation of buildings, the selected parameters that describe indoor environmental quality in TAIL should be the parameters that are affected by the energy renovation process. To assist this selection the list was generated with parameters that are impacted by energy renovation actions. This list is presented in the Annex 3 and is the outcome of the Danish project that was especially addressing this issue. The title of the project is Energirenoveringstiltag–katalog (The catalogue of energy renovation actions), and the report number is DTU-BYG Rapport R-223.

The third criterion for selection of parameters underlying TAIL was the inclusion of parameters secure well-being and comfort, and parameters securing low risk to health of building occupants.

Finally, it was decided that selected parameters describing indoor environmental quality could be either simulated using modelling tools or measured at the cost that would not create the barrier for adopting TAIL as a part of EVC.

The parameters underlying each component of TAIL are described below. It is additionally presented how these parameters are derived.

3.2.1 T - Thermal environment

T in TAIL stands for the thermal environment.

Thermal environment is addressed in TAIL index because deep energy renovation may influence indoor temperatures during different seasons due to thermal insulation of buildings and use of large glazing areas especially if no mechanical cooling is installed, see Annex 3.

To derive the level of T, it is necessary, as a minimum, to obtain information on indoor temperatures during heating and non-heating season, and if possible also in the shoulder season(s). The temperatures can be obtained through measurements or modelling. In the latter case, the detailed information about building components is needed allowing accurate input to the model. This may not always be possible especially when energy retrofit is performed for old buildings. It is therefore expected that measurements will become a major method for determining information required to derive T. Parameters used to derive T level are shown in Table 1.

The quality level of T will be determined based on the number of hours the temperatures are outside different ranges of temperatures defining conditions securing thermal comfort of building occupants. Such approach is proposed by Level(s). These ranges are defined by the Standard EN 16798-1 (2019) assuming typical clothing and activity of building occupants and secure low dissatisfaction (discomfort) with thermal environment. This standard is used as it is one of the standards supporting EPBD and it defines the levels of the parameters defining indoor environmental quality that should be used during simulations and modelling of energy use in buildings.

Table 1. Parameters used to derive the quality level of T in the TAIL index and the methods of their determination

	Measured	Modelled
Indoor air temperature in heating season (°C)	×	(×)
Indoor air temperature in cooling season (°C)	×	(×)
Indoor air temperature in shoulder seasons (°C)	×	(×)

Temperature is included in the following standard and schemes: Level(s), EN16798, HQE, LiderA, NABERS and CASBEE.

3.2.2 A - Acoustic environment

A in TAIL stands for acoustic environment.

Acoustic environment is addressed in TAIL mainly because thermal isolation of external walls and windows may reduce noise from outdoors and consequently exacerbate noise levels from indoor sources. In addition, installation of mechanical ventilation system may increase the level of noise, see Annex 3. Acoustics is particularly important in hotels to ensure high quality of sleep.

To derive A, the information about the sound level must be known. The sound level can be determined through measurements. These measurements shall be made in unoccupied spaces/building because A is characterizing acoustic performance of a building envelope, partitions and systems installed in a building. The actual sound levels can be higher when people are present in a building due to their activities, but A component does not refer to this situation. Once the methods of characterizing the quality of acoustic environment in occupied buildings are further developed, the A component of TAIL can be supplemented with other parameters, also reflecting the acoustic performance of a building with people present. Parameters used to derive A level are shown in Table 2.

The quality level of A is determined by the actual sound level following recommendations provided by the Standard EN 16798-1 (2019). This level secures no discomfort due to elevated noise produced by equipment not people. This standard is used as it is one of the standards supporting EPBD and it defines the levels of the parameters defining indoor environmental quality that should be used during simulations and modelling of energy use in buildings.

Table 2. Parameters used to derive the quality level of A in the TAIL index and the methods of their determination

	Measured	Modelled
Noise level (dB(A))	✗	

Noise level is included in the following standards and certification schemes: EN-16798, HQE, BREEAM, OsmoZ, KLIMA, IVE, LEED, WELL and NABERS. It is planned for inclusion in Level(s).

3.2.3 I - Indoor air quality

I in TAIL stands for indoor air quality.

Indoor air quality is addressed in TAIL mainly because the process of deep energy retrofit can cause that building is airtight buildings to reduce heat losses due to uncontrolled infiltration and leakages in building envelope, see Annex 3. Infiltration contributes to ventilation of buildings. Reduced ventilation due to reduced infiltration can increase concentration of air pollutants, which can degrade indoor air quality.

To derive I, the rate of outdoor air supply rate must be known. It can be measured directly or predicted using the measurements of the levels of carbon dioxide, a main human metabolite, when people are present in a building. Both carbon dioxide levels and ventilation can be modelled, but as in case of temperature this would require the knowledge of building systems as well as assumptions regarding density of building occupation. In addition, the concentration of selected potentially toxic pollutants must be known. The former will secure no discomfort due to reduced air quality while the latter will ensure low risks for health. The concentration of air pollutants shall be determined through measurements. To complete the parameters characterizing indoor air quality the level of relative humidity must be known as well as the size of visible mold: they are included to comply with Level(s). The parameters describing I in the TAIL index are shown in

Table 3. They can be either measured or modelled.

The quality level of I is determined by the levels of parameters describing I. The reference to determine their quality levels is included either in the Standard EN 16798-1 (2019) or recommendations provided by the World Health Organization (WHO). These recommendations are also referenced to in the

Standard EN16798-1 (2019). This standard is used as it is one of the standards supporting EPBD and it defines the levels of the parameters defining indoor environmental quality that should be used during simulations and modeling of energy use in buildings.

Table 3. Parameters used to derive the quality level of I in the TAIL index and the methods of their determination

	Measured	Modelled
CO_2 (ppm)	✖	(✖)
Ventilation rate (L/s)	✖	(✖)
Formaldehyde (µg/m^3)	✖	
Benzene (µg/m^3)	✖	
$PM_{2.5}$ (µg/m^3)	✖	
Radon, only in radon-prone areas (Bq/m^3)	✖	
Relative humidity of indoor air (%)	✖	(✖)
Visible mold (cm^2)	Visual inspection	

Carbon dioxide is included in the following standards and certification schemes: EN16798, Level(s), OsmoZ, KLIMA, IVE, LEED, WELL and NABERS.

Ventilation rate is included in the following standards and certification schemes: EN16798, Level(s), OsmoZ, HQE, BREEAM, DGNB, ITACA, IVE, LEED, WELL, NABERS and CASBEE.

Formaldehyde is included in the following standards and certification schemes: WHO air quality guidelines, Level(s), HQE, BREEAM, OsmoZ, KLIMA, DGNB, IVE, LEED, WELL and NABERS. Formaldehyde is strong airway irritant, carcinogen. Reducing its levels reduce health risks.

Benzene is included in the following standards and certification schemes: WHO air quality guidelines, Level(s), HQE, OsmoZ and WELL. Benzene is carcinogen

Particles (PM2,5) is included in the following standards and certification schemes: WHO air quality guidelines, Level(s), HQE, OsmoZ, LEED and WELL.

Radon is included in the following standards and certification schemes: WHO air quality guidelines, Level(s), HQE, IVE and WELL.

Relative humidity is included in the following standards and certification schemes: EN16798, Level(s), KLIMA and WELL.

Visual mold is included in Level(s).

3.2.4 L - Light

L in TAIL stands for light (visual environment).

Light is included in TAIL index because the energy renovation process may lead to use of smaller windows, which reduce the heat loss, and at the same the level of accessible light. Moreover, the new energy-efficient lighting may decrease visual comfort, see Annex 3.

To derive L, the level of illuminance and daylight factor must be determined. The former is determined through measurements and the latter is determined through modeling. Illuminance refers to the total light delivered to the space or workstation by either especially installed system or through windows (daylight). Both parameters are presented in Table 4.

The quality level of L is determined by referring to recommendations provided by the Standard EN 16798-1 (2019) and Level(s). This level secures no visual discomfort and sufficient light level. Standard EN 16798-1 is used as it is one of the standards supporting EPBD and it defines the levels of the parameters defining indoor environmental quality that should be used during simulations and modeling of energy use in buildings.

Table 4. Parameters used to derive the quality level of L in the TAIL index and the methods of their determination

	Measured	Modelled
Daylight factor (%)		✗
Illuminance (lux)	✗	

Daylight factor is included in the following standards and certification schemes: HQE, BREEAM, OsmoZ, DGNB, ITACA and CASBEE. It is proposed for the use in Level(s).

Illuminance is included in the following standards and certification schemes: EN 16798-1, BREEAM, LiderA, IVE, LEED, WELL and CASBEE. It is proposed for the use in Level(s).

3.2.6 Additional comments on the derivation of TAIL components

The parameters defining TAIL components shall be measured before and after renovation, at the same season to avoid seasonal bias; heating and non-heating seasons are prioritized, whereas inclusion of shoulder periods (spring and autumn) should only be used if supplementing the two indicated periods above.

If measurements are not possible, the parameters defining TAIL components shall be:

- Modelled;
- Retrieved from the previous monitoring campaigns performed in the building in case for the data representing the condition prior to renovation but only if the measuring methods applied were close to the methods and standards recommended in the assessment protocol. Measurements retrieved from the Building Management Energy System can also be used.

3.2.6 TAIL level

When proposing the method for derivation of TAIL level the position was taken that the overall quality of indoor environment cannot be better than the lowest quality of the components that characterize it. Such approach has been considered to be fair and encouraging for excellence and innovation.

A unique approach of TAIL is that no credits are given to either TAIL components or to parameters describing the quality of these components. All must be considered when the quality level of T, A, I and L is determined as well as the overall level of TAIL describing overall quality of indoor environment. This is unlike any existing certification system at present.

The final level of TAIL, i.e. the quality of indoor environmental quality is determined by the lowest quality level among the four TAIL components. There are several reasons for this to happen. One reason is that there are no data in the literature providing the method to integrate the quality levels of different components of indoor environmental quality. Consequently, the equal weighting factors have normally been used to account for the contribution of different components to the overall quality of indoor environment (see Annex 2). But there are not even adequate data to support this approach. Selecting the overall quality of indoor environment by the lowest quality level of its components creates the incentive to ensure that none of the components is compromised and no trade-offs are made to reach the higher quality level. Such trade-offs can be made in many certification schemes where credits can be traded to reach the highest certification level. As a consequence not all factors have to reach the class, level or quality corresponding to the class defined by the scheme. The approach proposed for derivation of TAIL is similar to the way different certification levels are determined in the DGNB scheme, but even in this scheme higher quality level or class is allowed even though some parameters or components of the scheme have not reached this class.

The T, A and L components of TAIL include parameters reducing the level of discomfort while the component I includes parameters referring not only to discomfort of building occupants but also to their risk of health. Consequently, the level of I could be prioritized and considered as principal and uppermost when determining the overall level of indoor environmental quality. However, following the WHO definition of health which says that health is “a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity”, it was decided not to make prioritization of any components of TAIL.

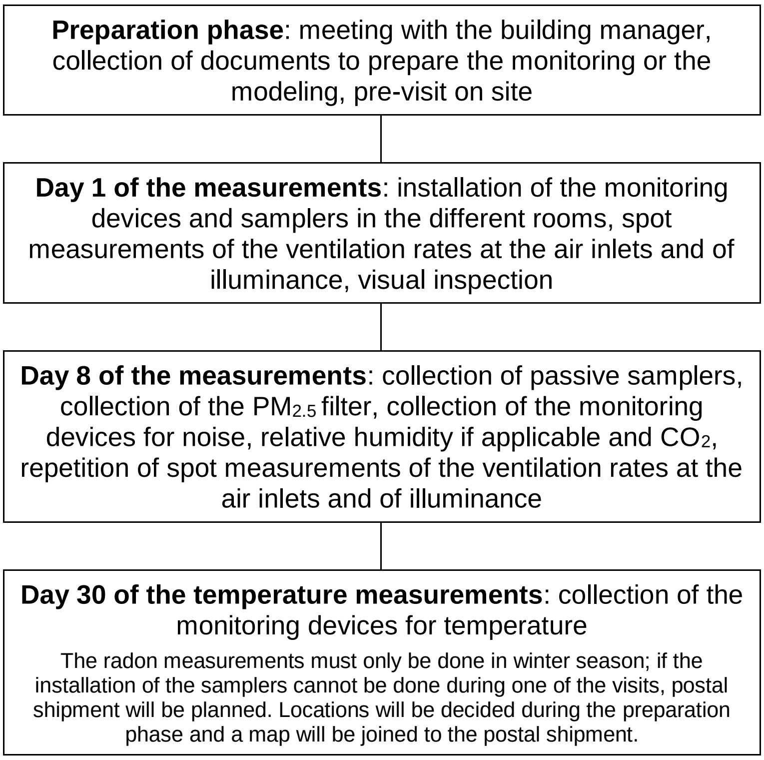
The process of derivation of the overall indoor environmental quality from the levels of all its four components can be revised in the future developments of TAIL index.

4. Protocol

4.1. Overview

The overall process to determine the TAIL index for a given building before and after renovation is presented in form of the flowchart in Figure 2.

The process comprises four phases: preparation, measurements on Day 1, measurements on Day 8 and measurements on Day 30. This process must be repeated prior to renovation and after deep energy renovation is completed. To the extent it is possible, this process must be repeated at two seasons before and after renovation. If only one season can be studied, it must be the same season before and after renovation.



Preparation phase: meeting with the building manager, collection of documents to prepare the monitoring or the modeling, pre-visit on site

Day 1 of the measurements: installation of the monitoring devices and samplers in the different rooms, spot measurements of the ventilation rates at the air inlets and of illuminance, visual inspection

Day 8 of the measurements: collection of passive samplers, collection of the $PM_{2.5}$ filter, collection of the monitoring devices for noise, relative humidity if applicable and CO_2, repetition of spot measurements of the ventilation rates at the air inlets and of illuminance

Day 30 of the temperature measurements: collection of the monitoring devices for temperature

The radon measurements must only be done in winter season; if the installation of the samplers cannot be done during one of the visits, postal shipment will be planned. Locations will be decided during the preparation phase and a map will be joined to the postal shipment.

Figure 2. Overview of the TAIL index determination process for a given phase and a given season

4.2 Detailed protocol

The detailed method for the choice of the instrumented rooms and the requirements for the measurements and modeling are presented in Annex 4. For each parameter included in the four components of the TAIL index, the different categories are presented in the Annex 5.

4.2.1 Measuring/sampling locations

The number of measuring/sampling locations is a compromise between the representativeness regarding the whole building on the one hand, and the technical and economic feasibility on the other hand. The feasibility comprises availability of monitoring devices, feasibility to start the measurement/sampling the same day with one or two operators and the costs of the analyses.

The measurements are only to be carried out in offices/workplaces in case of office buildings and in rooms in case of hotels; the lobby, the service rooms, the meeting/conference rooms, the corridors, etc. are not considered.

It has been proposed that the number of measuring/sampling locations allowing determination of parameters used to derive TAIL shall be at maximum 10 and that the sum of the areas covered by measuring/sampling locations shall address at least 10% of the office floor area in office buildings and guest room floor area in hotel buildings.

The sampling locations are chosen so that:

- The lowest occupied level and the highest occupied level are instrumented. “Occupied levels” refer to the target rooms, i.e., offices in office buildings and rooms in hotels;
- Measurements are done at different orientations (North/South/East/West) to capture influence of different outdoor environments (e.g., street versus garden);
- Measurements/sampling locations cover the different typologies of indoor spaces, a typology of space being defined by:
    - Having been built or retrofitted (during any previous renovations) at the same time;
    - Sharing the same type of mechanical ventilation and the same air handling unit, as well as the same cooling system;
    - Having similar type of building materials and furniture, installed at the same period;
    - Having similar type of solar shading devices;

Prior to the monitoring survey, the different areas of the building sharing the common features must be identified with the building manager or technical staff to facilitate the choice of measuring/sampling location.

In office buildings, if relevant, individual offices as well as open spaces shall be monitored.

In hotels, rooms of different sizes shall be monitored.

All sampling locations should be selected randomly unless indicated otherwise.

All sampling locations must be normally occupied.

4.2.2 Location of sampling devices at each sampling location

Except for the illuminance spot measurements, there is only one sampling location per room.

In each room, samplers and data loggers should ideally be put in the center of the room, not closer than 1 m to the wall, at the level of respiratory tract.

Ventilation channels and heating sources, including sun, must strictly be avoided.

Practically, the passive samplers can be fixed to the ceiling, or on a wire attached to the ceiling, or can also be placed in a metallic rack (see pictures below). Any adhesive should strictly be avoided to fix the samplers. The on-line monitoring devices for temperature and relative humidity can be placed on a table/desk or on the bedside table.

4.2.3 Observations

In case of mold the size of visible mold should be assessed. This can only be made by a person trained to perform such observations.

4.2.4 Modelling/simulations

Any simulation tool providing output in in form of the time-stamped levels of temperature, relative humidity, carbon dioxide concentration, ventilation rate can be used. Specialized simulation tool for estimating daylight factor must be used.

The input to simulation/modelling tools need to be as accurate as possible to ensure high accuracy. All the input data must be clearly specified for the reference.

In many cases, the blue prints and detailed specifications regarding materials used in buildings undergoing simulations could be nonexistent. Any assumptions regarding these input data to the models must be specified and justified. One approach that can be used is to use the specifications outlined in the building codes for the year of building completion and/or the year of major renovation in the past.

Modelling should be performed for the rooms chosen using the same selection criteria as the criteria used for selection of rooms where the measurements are to be performed.

4.2.4 Detailed assessment protocols

The quality of parameters, where relevant, are assessed against for categories of indoor environment defined by the Standard EN16798 (2019), as follows:

- Category I: High level of expectation and recommended for spaces occupied by sensitive and fragile people with special requirements like some disabilities, sick, very young children and elderly persons, to increase accessibility
- Category II: Normal level of expectation
- Category III: Moderate level of expectation
- Category IV: Low level of expectation. Poor quality. Unacceptable regarding health.

The parameters describing health indicators in the component I are assessed against the levels recommended by the WHO air quality guidelines.

Each indicator is associated to a category at every measuring/modelling location and no integration is made. Based on these measurements the color maps are made representing the quality of each parameter underlying TAIL at each measuring location. The worst quality corresponding to Category IV receives color green, the next worst quality receives color orange corresponding to Category II, the first best quality level corresponding to Category II receives color yellow and the best quality level corresponding to Category I is depicted by color green (Figure 3).

Using the approach put forward to determine the overall quality of indoor environment it is proposed that the worst category obtained in at least one location where the measurements or modelling were carried out shall determine the level of component in TAIL. The worst category of TAIL components shall determine the overall quality of indoor environment, i.e. TAIL level/score.

Category	**Color**
Category I	🟩
Category II	🟨
Category III	🟧
Category IV	🟥

Figure 3. Assignment of colors to categories describing quality levels

5. Considerations regarding renovation process securing high level of indoor environmental quality

To promote health and well-being in building after renovation, good practices should be implemented during the design and implementation of the deep energy renovation. Some of them are described in the following with respect to each of the components defining TAIL.

5.1 Recommendations regarding renovation practices and approaches relevant to thermal environment - the component T in TAIL

Considerations should be made regarding the level of insulation and the thermal mass of the building as it may cause overheating.

External shading should be considered to reduce heat load and the requirements regarding cooling. Selection of external shading should take into account the visual environment and access to daylight.

5.2 Recommendations regarding renovation practices and approaches relevant to acoustic environment - the component A in TAIL

Attention shall be paid to sound transmission from outdoors in case of façade renovation. Any renovation of the façade (external wall, windows) should ensure minimizing sound transmission from outdoors and consider an extra sound insulation if necessary, and/or selection of products with excellent acoustic performance, if relevant. Acoustic insulation of facades shall match the prevailing levels of noise outdoors. Performance of acoustic insulation shall comply with Directive 2002/49/EC, Annex VI, ISO 16283-3, ISO 19488, or any local/national codes and standards. The requirements for homes shall be applied for hotels unless they are treated separately.

Attention shall be paid to sound transmission from the internal walls and floors/ceilings. Any renovation of the internal walls and floors/ceilings should ensure minimizing sound transmission between internal rooms and consider an extra sound insulation if necessary and relevant taking into account the prevailing sound levels in these locations. Performance of acoustic insulation shall comply with ISO 717-1, ISO 16283-1, ISO 19488, or any local/national codes and standards. The requirements for homes shall be applied for hotels unless they are treated separately.

Any renovation measures that entail the changes in acoustic performance of the room shall ensure minimizing airborne noise and ensure adequate reverberation time. Performance shall comply with ISO 717-1, ISO 16283-1, and ISO 19488.

5.3 Recommendations regarding renovation practices and approaches relevant to indoor air quality - the component I in TAIL

Considerations should be made regarding the selection of building materials used during renovation: only low-emitting materials should be used.

Examples of the schemes regulating emissions from building products that are available on the market:

- Voluntary: GUT and EMICODE in Germany, M1 in Finland, Indoor Climate Label in Denmark
- Mandatory: French emissions classes system, the Belgian VOC Regulation, the German AgBB
- Ecolabels: EU ecolabel, Blue Angel in Germany, Swan in Nordic countries

Emission tests of the materials can be performed according to the ISO 16000-9 and 16000-11 standards and compliance can be checked with EU LCI: https://ec.europa.eu/growth/sectors/construction/eu-lci/values_en.

Ventilation rates prescribed by EN16798-1 for the non-low polluting building should be used as emissions from building materials cannot be determined

Outdoor air inlet, in case the ventilation system is installed, should be located far from outdoor sources

The use of high-efficiency filtration should be promoted and filtration level should be matched with prevailing levels of outdoor air quality

Commissioning of HVAC systems must be promoted.

5.4 Recommendations regarding renovation practices and approaches relevant to light/visual environment - the component L in TAIL

Any renovation should consider the following space configuration if relevant: building plan depth ≤4-6 m, glazing ratio ≥30%, ceiling height ≤3m

Distribution of luminaires and light, and proper color rendering should be considered to ensure suitable light quality

Regarding artificial light, for offices, recommendations from the EN 12464-1:2011 standard (Light and lighting - Lighting of work places - Part 1: Indoor work places) must be followed.

6. Perspectives

The proposed TAIL index creates the framework for rating of indoor environmental quality and its components. The use of TAIL must be validated and the necessary revisions and supplements to the protocol used for deriving TAIL should be made.

In a short-time frame, within the last year of ALDREN project TAIL will be used in building pilots to document the level if indoor environmental quality. Small modifications will be implemented to the protocol describing measurements and modelling of parameters describing TAIL. They will be included in the final deliverable of ALDREN project integrating TAIL into EVC. Within the frame of ALDREN the relationship between TAIL and Task 2.2 on energy performance and 2.5 on economic benefits will be examined.

In the medium time-frame, once the ALDREN project is completed and the TAIL is accepted as a concept, sensitivity analysis of TAIL shall be performed to check the potential of TAIL index to distinguish differences in indoor environmental quality before and after energy renovation, as well as among different buildings. The performance of TAIL shall then be measured against more sophisticated measuring protocol and against the measurements performed for much longer time than is proposed in the present deliverable. The practicability of the scoring scales shall be checked additionally. The relevance of choosing the worst category among the different locations studied in the building for a given indicator in a given component and to assign it to the category will be studied. Examination of TAIL shall also include the feedback of relevant stake holders such as building and facility managers, designers and architects and engineers. The points of interest will include the acceptability of cost and time constraints, the interest to health and wellbeing evaluation, the need for specific guidance before the measurements, etc. As far as possible, the perception of occupants shall also be documented to see whether there is the match between TAIL and the occupant responses is obtained. Some of the tasks described above can be made using the measurements performed in the past and already published but generally a special project is needed to complete all these tasks.

In the long-time frame, several advancements of TAIL are foreseen. The number of parameters underlying TAIL components can be increased depending on the measuring capabilities. The duration of measuring campaigns can be increased depending on the availability of low-cost high-quality miniature sensors. One important advancement can be inclusion of elements related to occupant responses and occupant control. An important component of indoor environmental quality is an opportunity of occupants to control indoor environmental parameters according to their preference. This applies to all parameters and especially is demonstrated by access to operable windows, using blinds, changing the thermostat set points, etc. TAIL can include the component describing these elements. With regards to the former, the standardized methods for collecting occupant responses can be developed and TAIL based on occupant responses can be developed and reported together with TAIL based on measurements/modelling.

TAIL is at present used to determine the quality of indoor environment in offices and hotel rooms in relation to deep energy renovation. It may be on one hand considered to extend its applicability to other buildings and on the other hand to use it as an independent and autonomous index of indoor environmental quality that can be used on any occasion.

Application of TAIL may actually lead to improved conditions of indoor environmental quality as the teams performing deep energy renovation may pay much bigger attention to delivering the quality of indoor environment that is at least the same as before the renovation process if TAIL is to be reported with energy certificate. Use of TAIL may also lead to innovation. To support the measurement sensors which are targeting specific parameters defining indoor environmental quality can be advanced and produced on mass scale reducing their cost; they can include software that could already provide the color representing different quality classes. Also one important innovation could be the development of modelling/simulation tools that will include parameters prescribed by TAIL.

7. Conclusions

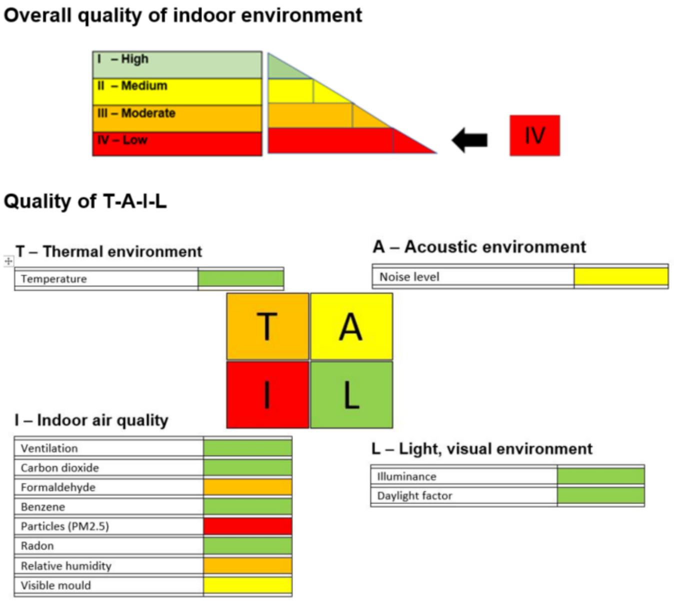
- A set of 12 parameters describing the quality level of indoor environment has been proposed. These parameters were selected based on extensive review of the indicators proposed in green building certification schemes, standards, sustainability frameworks and air quality guidelines.
- The 12 parameters are used to derive the index describing four principal components of indoor environmental quality and the overall level of indoor environmental quality. The index is called TAIL from T-thermal environment, A-acoustic environment, I-indoor air quality and L-light/visual environment. The index is a unique and sole contribution of ALDREN.
- TAIL index can be considered as the first step in developing of integrated index characterizing indoor environmental quality in buildings for a common approach at the EU-scale. Such index does not exist at present.
- TAIL index matches the existing criteria and existing green building verifications combined with an innovative approach. The index will complement, not replace, the existing approaches to characterize the quality of indoor environment used in the building certification schemes. TAIL is expected to be derived with the criteria used to characterize indoor environmental quality in these schemes.
- Unlike the approaches used in the certification schemes proposing arbitrary credit system for different parameters defining indoor environmental quality, often without any scientific background, TAIL index is including all of the four major components of the indoor environment quality, using scientific evidence and agreed reference criteria to derive the levels of its four components. No credits are given and weighting made. All components of TAIL are treated equally. In other words to achieve the high quality level all components of TAIL must be at this level.
- TAIL complies with Standard EN 16798-1 and the Level(s) framework.
- The proposed TAIL index ensures an integration of all components describing indoor environmental quality in a homogenous index. Its format is simple and communicative. Its purpose is not only to inform the public about the level of indoor environmental quality. The main purpose is to characterize the quality of indoor environment prior to and after the deep energy retrofit to address the EPBD mandate and to demonstrate additional benefits resulting from deep energy renovation. To meet the requirements of EPBD (2010) that mandates that indoor environmental quality should not be degraded during energy renovation, the TAIL index will provide information on whether deep energy renovation does not degrade the overall quality of indoor environmental quality or any of its components. TAIL index provides additionally information if any of the components charactering indoor environmental quality was actually improved providing information on additional benefits resulting from energy renovation providing the basis for their economical discounting.
- TAIL index is a certificate of quality. TAIL – I (or TAIL-A) corresponds to the diamond level in many of the current building certification schemes. TAIL index additionally alerts building users and building owners on the potential risks related with different types of exposures in buildings.
- TAIL is used to assess the quality of indoor environment in public buildings – offices and hotels in connection of deep energy renovation. Future developments can extend its application to other building types as well as the sole index of indoor environmental quality.

Annexes

Annex 1: Integration of additional indicators as complementary modules to the EVCS, which can be used for building certification related to indoor environment

THE HEALTH & WELLBEING INDICATORS

Before renovation



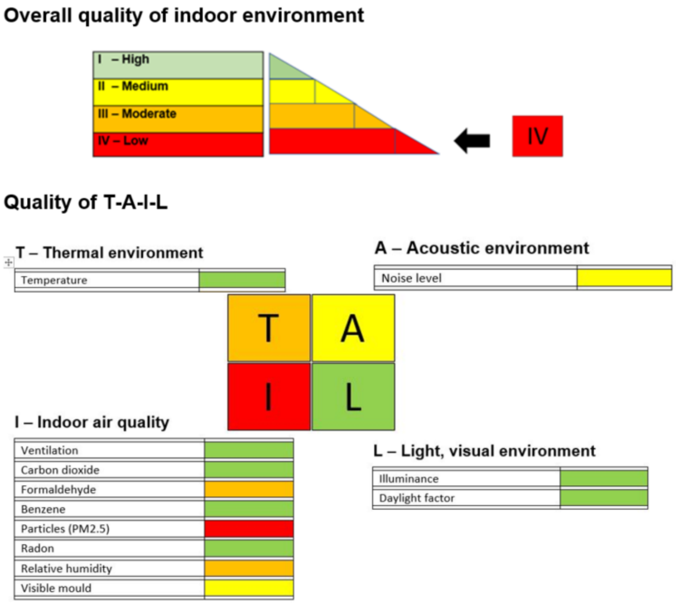
Temperature	🟩

Noise level	🟨

Ventilation	🟩
Carbon dioxide	🟩
Formaldehyde	🟧
Benzene	🟩
Particles (PM2.5)	🟥
Radon	🟩
Relative humidity	🟧
Visible mould	🟨

Illuminance	🟩
Daylight factor	🟩

After renovation



Temperature	🟩

Noise level	🟨

Ventilation	🟩
Carbon dioxide	🟩
Formaldehyde	🟧
Benzene	🟩
Particles (PM2.5)	🟥
Radon	🟩
Relative humidity	🟧
Visible mould	🟨

Illuminance	🟩
Daylight factor	🟩

Building name: Covent Garden **Building category:** **Office building**

Address: Rue de mot 24, Brussels, Belgium **Parcel No:** 3500 Cadaster: Brussels

Period targeted by the evaluation: measurements carried out after renovation, between January 8, 2019 and February 5, 2019 (radon measured over 2 months until March 8, 2019.

No. of energy certificate: 00001/SK_0001/2017

Annex 2: Definition of indicators of indoor climate based on review of credits, indicators and approaches to promote indoor climate in existing green programs and certification schemes, as well as EN 16798

Definition of indicators of indoor climate based on review of credits, indicators and approaches to promote indoor climate in existing green programs and certification schemes, as well as EN 16798

1. INTRODUCTION

To move the refurbishment of existing buildings in European countries towards deep renovation and NZEB (Nearly Zero-Energy Building) levels, the ALDREN (ALliance for Deep RENovation in buildings) project brings together several partners from different EU (European Union) member states (http://aldren.eu/). The project was launched in November 2017. The major aim of ALDREN is to consolidate, promote and implement extended harmonized procedures to overcome market barriers and support deep building renovation operations. The actions to achieve these goals include: (1) development of a harmonized energy performance rating method based on the European Voluntary Certification Scheme (EVCS) mandated by the new Energy Performance of Building Directive [1,2]; (2) reduction of the gap between predicted (modelled) and actual energy performance of buildings to increase their reliability and compliance; (3) inclusion of indoor environmental quality (IEQ) in the scope of deep energy renovation, to promote solutions supporting comfort and health and to ensure that renovations will not be detrimental to indoor environmental conditions; (4) linking the building rating in terms of energy, sustainability and IEQ with the private and national financing instruments, to emphasise enhanced building value and thus create strong incentives for investment; and (5) developing a building passport integrating, illustrating and documenting the different phases of a deep renovation process for proper documentation and dissemination. All these actions are intended to create a holistic approach towards the deep renovation of buildings and a method by which it is communicated to different building stakeholders. The transmission of information is called the ALDREN common language. Hotels and offices had been selected as the first target buildings for the implementation of the ALDREN procedure. However, it is expected that the ALDREN procedure will in future be used in all types of buildings.

One important task of ALDREN is to investigate the impact of deep energy renovation on the health and well-being of occupants. The aim is to provide IEQ classifications for existing buildings undergoing deep energy renovation. The purpose of the work presented in this paper was consequently an identification of IEQ parameters addressing health and well-being that have been used in different certification schemes, standards and guidelines so that they can be considered for use in an ALDREN protocol and create a reference for developing IEQ classification. Another aim was to examine how comparable the different parameters describing IEQ are in various documents and whether it would be possible to harmonize them. The health and well-being of building occupants can be affected by other aspects of a building, and not only by IEQ factors. These include ergonomic factors and the degree of control that occupants have over IEQ conditions, but they were considered to be outside the scope of the present work and were not identified in the review.

IEQ parameters can be generally classified into four components: thermal environment, indoor air quality (IAQ), acoustic environment, and visual environment. According to the US Green Building (GB) Council, IEQ concerns the conditions inside a building and their effects on the occupants [3]. IEQ is an important aspect of existing GB schemes worldwide as it concerns health and well-being [4,5]. A review of the weighting factors used in several BREEAM and Green Star NZ GB certification schemes has revealed that about 10% to 20% of the total credits that can be assigned to the different parameters certified by these schemes are associated with IEQ [6]. By prescribing ranges and/or thresholds that define acceptable IEQ conditions in buildings, the requirements in such documents are intended to ensure the health and well-being of building occupants.

The present paper reports a review that identifies the IEQ indicators and the ranges that have been used to prescribe conditions that ensure the health and well-being of building occupants. The review was intended to answer three questions: (1) What are the most commonly used IEQ indicators in existing GB schemes, European standards, and other IEQ evaluation methods? (2) What are the prescribed levels of these IEQ indicators? (3) To what extent do the existing GB schemes, European standards, and other IEQ evaluation methods differ in addressing IEQ?

2. METHODS

The information on IEQ indicators was obtained by reviewing selected GB schemes, peer-reviewed articles, reports of European projects and EU standards. The criteria that were applied to select the relevant literature are listed in the following paragraphs.

Fifty-five schemes from 31 certifications obtained during a study of IAQ requirements in GB certifications were used [7]. An additional search was carried out to find more recent GB schemes or any updates of the schemes published between 2015 and 2018, i.e., in the period after the above-mentioned study of IAQ requirements was made. The former included the European Level(s) [8] and the French OsmoZ schemes [9]. Since most of the schemes were commercial, not all of the information in them is available to the public, so the review was based only on documents available at the official websites of GB schemes. The schemes that defined criteria for non-residential buildings (e.g., offices, hotels, and commercial buildings) were chosen for a detailed review. Within each scheme, the IEQ indicators and their prescribed ranges were identified. In some schemes, such as LEED, non-residential buildings are classified into detailed categories such as commercial buildings, retail buildings and hotels. Such schemes were considered as well. However, only IEQ indicators applicable to offices and hotels were retained, to match the ALDREN scope, while those for other types of non-residential buildings were not included in the present review. Furthermore, as the ALDREN project addresses European building stock, priority was given to schemes developed in European countries because they are expected to comply with EU regulations, standards, climate as well as construction and building culture and heritage. Some schemes developed outside Europe such as LEED, WELL, NABERS and CASBEE were included simply because they are used globally and thus also in Europe. In this way the applicability of the results of the present review could be extended.

The review identified peer-reviewed articles that contained information on how they had integrated different IEQ indicators for the purpose of building classification. Peer-reviewed journal articles and conference papers were found using the Google Scholar and Science Direct search engines regardless of the country or date of publication. The keywords for the search were as follows: (“indoor environmental quality” OR IEQ) AND (indicator OR index OR metrics). Studies examining whether any of the IEQ indicators have an impact on health and well-being were not within the scope of the present work.

Reports from previously completed and on-going European projects, were found by using Google and by interviewing ALDREN partners and IEQ specialists. A detailed review was limited to the IEQ indicators applicable to non-residential buildings, to match the scope of the ALDREN project.

Finally, IEQ indicators prescribed by the EN 16798:2018 standard [10] for non-residential buildings were reviewed because this standard belongs to the group of standards supporting adoption and implementation of the Energy Performance of Building Directive [2]; the EN 16798 standard has been recently approved and will supersede EN 15251 [11]. It provides input for the calculation and modelling of the energy performance of buildings by defining specific conditions of IEQ for different seasons, building types and classes of IEQ in buildings. Several other EU and international standards focus on such topics as measurement techniques, sampling and analytical procedures and are referenced by GB schemes when they address IEQ indicators. These standards are listed for reference and as supporting information but they have not been reviewed and are not analysed in the following sections.

3. RESULTS

3.1. Overview

Fourteen GB schemes, among which 10 were European and 4 non-European, 14 research articles, 7 reports of European projects, together with the EN 16798 standard were subject to a detailed review. The objectives of the selected European projects (Table 1) varied largely and included aspects such as sustainability, building energy performance, and social welfare, but only the Buildings 2030 project used indicators to address IEQ. The others either did not take IEQ into account or had not yet made use of any IEQ indicators.

Among the identified and included GB schemes (Table 1) Level(s) is not a GB scheme but a common EU reporting framework of core sustainability indicators. Some schemes, such as HQE and BREEAM, have been initially developed and commercialized for use in a specific country. With regard to the building type, Level(s), OsmoZ, HQE, KLIMA, ITACA, LEED and NABERS provide certification schemes for offices and/or hotels, while the others focus on non-residential buildings or multi-purpose buildings. With regard to the main objective of the certifications, OsmoZ, IVE-BES and WELL address primarily or exclusively occupants' health and well-being or the quality of life in a built environment, while the other schemes are the classic GB rating tools providing assessments of various building aspects such as energy, water and use of materials, not just IEQ.

The GB schemes assign credits to IEQ indicators that are used in concert to classify IEQ. The BREEAM, KLIMA, DGNB, ITACA, LiderA, LEED and NABERS schemes assign credits to four classical IEQ components: thermal environment, IAQ, acoustic environment and visual environment, while KLIMA assigns credits only to the thermal environment and IAQ. For other schemes, the number of credits assigned to each IEQ component could not be determined because it is not made available on public web pages.

The weightings assigned to credits assessing the four IEQ components in the GB schemes reviewed are shown in Fig. 1. The weighting of an IEQ component is defined as the percentage of the maximum credits that are assigned to each component. The LEED scheme gives higher weightings to IAQ (47% of IEQ credits) and visual environment (35% of IEQ credits) compared with the other schemes. The weightings provided by BREEAM, DGNB, ITACA, LiderA and NABERS within IEQ are similar: The weighting for IAQ is 25% to 33%, for thermal environment 17% to 33%, for visual environment 17% to 33% and for acoustic environment 17% to 22%.

Some peer-reviewed articles suggested that an overall IEQ index should be an aggregation of indexes defining thermal environment, IAQ, acoustic environment and visual environment [12–23]. The aggregation equations were approximately in the following format [24].

$$IEQ = w_1 \times TEI + w_2 \times IAQI + w_3 \times AEI + w_4 \times VEI \tag{1}$$

where *TEI*, *IAQI*, *AEI*, *VEI* are indexes for the four IEQ components, respectively thermal environment, IAQ, acoustic environment and visual environment and w_i (i = 1, …, 4) are the weightings ($\sum_i w_i = 100\%$) associated with each component index. The index for each component is itself an aggregation of several indicators that address different aspects of the component. For example, an IAQ component index may include carbon dioxide (CO_2), volatile organic compounds (VOCs), particulate matter and fungi as indicators [25]. The component index is calculated by aggregating its indicators by simple addition, weighted addition or by other methods [25,26]. The four main component indexes have the same scale (e.g., from 0 to 10) to further facilitate aggregation of the component indexes used to calculate the overall IEQ index. The component weightings determine the percentage of the score of each component index that is counted in the aggregated IEQ index.

Fig. 2 shows the weightings proposed by the published studies to develop indexes describing the overall IEQ level that is acceptable in non-residential buildings [12,13,16–22]. The weightings for component indexes vary between 12% and 38% for thermal environment, 14% and 36% for IAQ, 16% and 25% for visual environment, and 18% and 39% for acoustic environment. As can be seen, the thermal environment receives on average the highest weighting of 28%, followed by the acoustic environment of 26%, IAQ of 25%, and visual environment of 21%.

The average weightings for each IEQ component, as used in the GB schemes and by the published research articles, are compared in Fig. 3. It should be noted that the weighting in the GB schemes of a specific IEQ component depends on the maximum credits assigned to the IEQ component to achieve the best class. For example, if a GB scheme assigns the same amount of credits to the four IEQ components if the best IEQ class is achieved, the weighting for each component within the IEQ category would be 25%. The weightings in the research articles suggest the importance of an IEQ component index compared with the other IEQ component indexes in the aggregated IEQ overall index. Although the weightings are around 25% for the 4 IEQ component, the rationale for this level of weighting has rarely been discussed in the literature and there is no real scientific evidence for their justification, such as might be obtained by comparing the impact of each component on public health in epidemiological studies, or their impact on the rental value of buildings. It may merely be the result of an arbitrary decision taken when the overall IEQ index was defined or may be entirely circumstantial.

3.2. Thermal environment

Table 2 summarizes the 19 indicators used to describe the thermal environment in buildings in the documents considered in the present review. The indicators fall into three categories. The first includes indicators related to perceived thermal comfort with Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) belonging to this category. These two indicators are the most commonly used thermal comfort indicators because they have been proposed for use by respectively 8 and 6 of the documents included in the present review. The second category of indicators includes parameters describing temperature and moisture conditions. The most common ones included in this category are the relative humidity of the air, operative temperature, and air temperature. They are prescribed respectively by 7, 6 and 5 of the documents included in the present review. There are also indicators for assessing the quality of the thermal environment. They include radiant temperature asymmetry in KLIMA, DGNB and EN 16798 and vertical air temperature difference in KLIMA and EN 16798. The third category of indicators assessing the quality of the thermal environment include parameters describing air movement. The most common indicator in this category is the air speed, which has been proposed in 6 of the documents included in the present review. The OsmoZ scheme also proposes the wet-bulb globe temperature to combine the effect of temperature, humidity, air velocity and radiation.

Six indicators describing the quality of the thermal environment in terms of the resulting comfort of building occupants are included in at least five documents included in the present review. They are PMV, PPD, operative temperature, air temperature, relative humidity and air speed. Among them, PMV and PPD are ratings and are an integral part of Standard EN 16798 and the European Level(s) framework, while the other 4 indicators are indoor environmental parameters that can be measured by instruments and are used to predict PMV and PPD. Operative temperature is included in both EN 16798 and Level(s), while air speed is included only in EN 16798. Air temperature and relative humidity are included only in some national GB schemes.

Table 3 shows the ranges for PMV, PPD, room operative temperature and air speed that are prescribed by EN 16798 and Level(s). Both EN 16798 and Level(s) classify PMV and PPD into four categories and the prescribed ranges are consistent in both documents. Operative temperature is classified by EN 16798 into four categories. The recommended range for the worst category (Category IV) is 18 to 28 °C for offices and spaces with similar activity that have heating and mechanical cooling systems both in the heating and non-heating season (winter and summer) assuming a relative humidity of 50% and an air speed < 0.1 m/s. Air speed is classified by EN 16798 into three categories. The recommended air speed for the design of buildings and HVAC (heating, ventilation and air conditioning) systems is ≤ 0.21 m/s in the winter and ≤ 0.24 m/s in the summer for the worst category (Category III). When air temperatures are above 25 °C, higher air speeds (1.2 m/s) are allowed for buildings equipped with fans if occupants have direct control over it.

The Level(s) framework [8] defines maximum allowable hours (%time) with temperatures outside the specific range rather than the range of temperatures. It recommends that reporting thermal comfort indicators can be based both on calculation and measurement. The indicators can be used during the design stage (simulations) and upon completion (through measurements) to check how the building actually performs. Occupant surveys are also envisaged.

Table S1 in the Supplementary Material summarizes PMV, PPD, operative temperature, air temperature, relative humidity and air speed included in the specific GB schemes. It is worth noting that their prescribed ranges are quite similar. The same table also lists the standards referenced by the selected GB schemes that are relevant to the indicators and their assessments.

3.3. Indoor air quality

Table 4 shows the 39 indicators that are used to describe IAQ in the documents considered in the present review. The indicators fall into four categories. The first includes indicators related to determination of the required air delivery rate to a space (building) such as ventilation rate (outdoor air supply rate), CO_2 concentration, and the relative humidity. Ventilation rate is the most commonly used parameter to describe and determine the level of IAQ. It is included in 12 documents selected for the present review. The premise is that ventilation rates are strongly linked to indoor pollutant concentrations and it is assumed that the higher the ventilation rate the lower the pollutant concentrations will be. This assumes that the outdoor air is not polluted. Consequently, as no other reliable IAQ indicators exist at present and it is impractical to measure the concentrations of all pollutants in the building, and not even useful as many have no guideline values, ventilation rate is regarded as an excellent proxy of IAQ. CO_2 concentration is also commonly used to define IAQ because it is a marker of the effectiveness of ventilation in removing the indoor air pollutants emitted by occupants. It is proposed as an indicator of IAQ in 11 of the documents selected for the present review. Relative humidity is an indicator of the risk of mould formation and is proposed as an indicator of IAQ in four of the reviewed documents, including Level(s) and EN 16798. EN 16798 recommends humidity criteria for 3 design categories in occupied spaces if humidification or dehumidification systems are installed. The second category of IAQ indicators includes gaseous air contaminants and their concentrations. Among them, the ones most commonly included are Total Volatile Organic Compounds (TVOC) and formaldehyde, which are specified in 11 of the documents included in the present review. Other pollutants specified are carbon monoxide (CO), benzene, radon, ozone, and nitrogen dioxide (NO_2). The third category includes airborne particulate matter and fibres, with indicators such as PM_{10}, $PM_{2.5}$, and airborne fibres (artificial vitreous fibres and asbestos) which are specified in 7, 7 and 1 of the documents included in the present review, respectively. The fourth category includes indoor biological contaminants, such as visible mould, airborne bacteria, and airborne fungal spores. They are included in very few documents as IAQ indicators. Although biological contaminants are not often included in GB schemes, the extent to which mould is visible in the building as assessed by a qualified expert is considered by the Level(s) framework. The reason that so few documents include biological pollutants is the difficulty of their quantitative assessment and the lack of credible reference levels [27]. A total of 35 indoor air pollutants are listed by different GB schemes of which 29 are gaseous pollutants and mainly VOCs. Indoor air pollutants included in different GB schemes vary largely and there is no rationale for their choice and inclusion. Although the list is long it is far from being exhaustive. For example, the LCI lists defining the pollutants that ought to be measured during emission testing of building products include nearly 200 pollutants [28].

Besides the indicators mentioned above, many GB schemes have requirements on the emissions from indoor materials and products of hazardous chemical pollutants such as formaldehyde and VOCs. Since material emission properties are parameters used to classify materials rather than indoor air they are not regarded as proper IAQ indicators (e.g. in the LCI list [28]. However, since the pollutants emitted can affect IAQ, they and should be taken into account during building construction and renovation.

Ten IAQ indicators have been proposed in more than five of the documents selected for the present review. They are ventilation rate, TVOC, CO_2, CO, formaldehyde, PM_{10}, $PM_{2.5}$, ozone, benzene and radon; the last seven are included in the WHO air quality guidelines [29,30]. Ventilation rate, CO_2, formaldehyde, benzene, radon, PM_{10} and $PM_{2.5}$ are included in both EN 16798 and Level(s). CO and ozone are included in EN 16798, but not listed by Level(s). TVOC is included only in some national GB schemes. The LEED scheme refers to the ISO 16000-6 standard to determine the TVOC concentration, which considers the entire area of the chromatogram between n-hexane and n-hexadecane and uses the toluene response factor to determine the TVOC concentration [31,32].

Table 5 shows the prescribed ranges for ventilation rate, CO_2, CO, formaldehyde, benzene, radon, ozone, PM_{10} and $PM_{2.5}$ in EN 16798 and Level(s). Both the Level(s) and EN 16798 refer to WHO guidelines for the prescribed concentrations of pollutants [29,30]. The WHO guideline values are available for CO, formaldehyde and radon [29], as well as for benzene, ozone, $PM_{2.5}$ and PM_{10} [30]. The former guideline is for the indoor environment and the latter guideline, according to the WHO, for ambient air and the air in buildings. For ventilation rates, the prescribed range varies between 2.5 and 10 L/s per person or 0.15 and 2 L/(s m^2 floor area) depending on the level of IAQ to be attained and the load of pollutants in a given space. According to EN 16798, ventilation strategy can be designed using 3 methods: (1) based on the perceived air quality (the % of persons dissatisfied with air quality upon entering a room); (2) using criteria for individual substances (concentrations and limits of target pollutants); or (3) based on the ventilation rates prescribed in the standard.

Table S2 in the Supplementary Material presents the ten most common IAQ indicators included in different GB schemes and the standards referenced by the GB schemes that are relevant to the indicators and their assessment.

3.4. Acoustic environment

Table 6 shows 20 indicators that are used to describe the acoustic environment in buildings in the documents included in the present review. They fall into three categories. The first category includes indicators related to noise level. The ambient noise level and the background noise level are the most common indicators. They are included in 9 and 3 of the documents reviewed, respectively. In addition to these two indicators, the IVE-BES and WELL schemes also include the noise masking sound level. The second category comprises indicators defining the acoustic performance of a built environment. These are reverberation time and speech intelligibility. They were included in 8 and 2 schemes, respectively. The third category contains indicators of acoustic insulation such as the acoustic insulation of interior partitions, opening, and floorings. Several other acoustic insulation indicators are used by different GB schemes, but they are more time-consuming to assess compared with the noise level indicators.

Two indicators, i.e., ambient noise and reverberation time, have been proposed by more than five documents included in the present review. Table 7 shows their prescribed ranges, as recommended by EN 16798 and Level(s). It should be noted that the current version of Level(s) does not include indicators defining acoustic performance and the ones referred to in Table 6 are mentioned by Level(s) as potential future indicators (see Part III of Level(s)). Ambient noise level included in EN 16798 is specified as the A-weighted equivalent sound pressure level normalized with respect to reverberation time ($L_{eq,nT,A}$) and has the range between 25 and 45 dB(A) for hotels and offices. The ranges of ambient noise prescribed by national GB schemes are consistent with the ranges recommended by EN 16798. The prescribed range of reverberation time depends on the type of building and the GB scheme.

Table S3 in the Supplementary Material lists the ambient noise levels and reverberation times used in individual GB schemes and the standards referenced by the GB schemes.

3.5. Visual environment

Table 8 shows 12 indicators that are used to describe the visual environment in the documents included in the present review. The most common indicator of visual environment is the illuminance level, which is included in 10 of the documents. Other indicators fall into two categories. The first category comprises indicators that are linked to daylight. Among the various indicators in this category, the most common ones are daylight factor and spatial daylight autonomy. They are used in 8 and 5 of the documents, respectively. It should be noted that the current version of Level(s) does not include indicators defining the visual environment and that indicators addressing useful daylight illuminance and annual sun exposure are listed as potential future indicators (see Part III of Level(s)). The second category of indicators concern artificial lighting. The most commonly used ones are illuminance level, discomfort glare in artificial lighting, and the colour rendering index, which are used in 4, 4, and 3 of the documents, respectively.

Illuminance level, daylight factor and spatial daylight autonomy are three indicators that are used in more than five of the documents included in the present review. All of them are considered for use in a future version of Level(s), while spatial daylight autonomy is not included in EN 16798.

Table 9 shows the ranges of the three commonly used visual environment indicators prescribed by EN 16798 and Level(s). With regard to illuminance level, Level(s) recommend that it should be between 300 and 3000 Lux (useful daylight illuminance is between 100 and 2000 Lux), whereas the average maintained illumination in offices is specified to be 500 Lux in EN 16798. Level(s) suggests that the minimum level of daylight factor should be 2%, and EN 16798 suggests that the maximum level of daylight factor for roof lights should be 10%, to avoid overheating.

Table S4 in the Supplementary Material provides a summary of the ranges for the three common visual environment indicators prescribed by national GB schemes along with the relevant standards referenced by the GB schemes.

4. DISCUSSION

We primarily reviewed the documents that are open to the public and can be accessed by browsing the Internet. Among the 14 green building schemes selected for the present review only the Level(s), which is a common EU reporting framework of core sustainability indicators, is completely accessible. The certification process of the other schemes may not be fully accessible, including some information on the methods used to certify IEQ as acceptable. Still, we believe that principal information regarding IEQ parameters have been accessed and that the results of the present review are trustworthy.

The IEQ indicators and their prescribed ranges and recommended levels found in the present review were compared to examine whether there were any differences or discrepancies between them. Their relevance and suitability or whether they are adequate and sufficient to describe the IEQ in buildings, were not assessed, as this was not the objective of the present work: our intention was to identify the IEQ indicators that are used at present by various certification schemes, standards and guidelines to characterize and rate IEQ in buildings, and their acceptable ranges. This work is thus an inventory of IEQ indicators and a comprehensive reference for future developments, revisions and supplements of certification schemes with respect to IEQ indicators.

The present work focused on parameters describing the thermal, acoustic and visual environment, and IAQ. They are important because they are used to assess the quality of indoor environment. However, as stipulated by different definitions of IEQ presented in the Supplementary Material, other factors should also be considered if high IEQ in buildings is to be achieved. These include views to the outside, electromagnetic fields, potable water, and ergonomic factors such as occupant control and functional aspects of indoor spaces. Many of these additional IEQ factors are not influenced by deep energy renovation, which is why they were not included in the present review, because it was assumed that energy renovation resulting in the upgrade of energy-efficient building components and HVAC systems will predominantly affect thermal conditions, acoustic environment, visual aspects and IAQ. The other parameters remain important and would have to be addressed separately if the full benefit of improved IEQ is to be obtained. Whichever methods are used it is worth noting that any improvement in IEQ is likely to result in economic benefits [34–36] such as increased safety, enhanced life quality, reduced stress and injuries, increased rental and resale value, and reduced liability.

The choice of building materials has a large influence on pollutant loads and consequently on IAQ, minimum ventilation rates and energy use. It is difficult to influence the selection of building materials and products during deep energy renovation unless some materials must be replaced. Selection of building materials has not been addressed in the present review but it should certainly be included in any IEQ certification. One way to achieve that goal could be to use the harmonized ‘lowest concentrations of interest’ values set by the EU LCI [28].

The integration of different IEQ indicators so that one index describes the IEQ in buildings presents an important challenge as it would address the expectations of the industry and practice. Few attempts have been made in the past to integrate different IEQ indicators [26], because the scientific data supporting such integration must be considered as insufficient at the moment. This is probably why in some cases IEQ indicators are not integrated. An example is the EN 16798 standard in which they are treated separately. Another example is the graphical indicators such as the one proposed by Teichman et al. [37].

The present review shows that all factors influencing IEQ are often considered to be equally important and are weighted more or less equally. This approach does not accord with the limited data from the seven studies summarized by Frontczak and Wargocki [33] on which environmental factors were important for building users. In these studies, building users were asked to rank the conditions according to their importance or to indicate their satisfaction with different environmental conditions or their overall satisfaction with IEQ, by means of questionnaires. Based on their responses the contribution of satisfaction with each parameter to overall satisfaction with indoor environmental quality was estimated. A summary of the results from these seven studies concluded that thermal comfort was considered to have slightly higher importance than acoustic comfort and satisfaction with air quality, and considerably higher importance compared with visual comfort.

The objective of present work was not to examine whether the IEQ indicators included in different certification schemes and standards are sufficient for ensuring comfort and health, but there is no reason to expect that this would not be the case (e.g., [38,39]). With respect to comfort it must be acknowledged that other parameters characterizing the environment in buildings must be taken into account, not just the four parameters discussed in the present work [33]. These parameters include building maintenance and cleanliness, ease of interaction, colours and textures and furniture adjustability. Existing comfort definitions listed in the Supplementary Material suggest that to achieve comfort, it is not enough to avoid negative sensations; it is also important that positive and rewarding emotions such as enjoyment and encouragement are evoked. These definitions indicate that comfort is not only a passive attribute, i.e. a given condition, but it is also an active adaptation, i.e. an opportunity to achieve preferences. Consequently, the IEQ indicators reviewed in the present work can only partially satisfy these definitions because they do not adequately address active adaptation. It would thus make sense to include IEQ indicators that are associated with positive emotions. In this way a holistic and integrated approach towards achieving high IEQ in buildings would be secured. With respect to health (definitions in the Supplementary Material), the IEQ indicators reviewed in the present work seem adequate. This applies especially to the IAQ indicators that generally match the WHO guidelines with regard to both ambient [30] and indoor pollutants [27,29]. Mental health, stress and cognitive performance should also be addressed because they are important determinants of general well-being and productivity [40].

The present work was initiated to provide input to the ALDREN project. Since the intention of ALDREN is not to propose new indicators to characterize IEQ in buildings undergoing deep energy renovation but rather to harmonize existing standards and certification schemes, the present results can be considered as directly applicable to ALDREN. Selecting the IEQ indicators to be used by ALDREN procedures among the IEQ indicators reviewed in the present work will thus not supersede the indicators used in the certification schemes. In fact, by using IEQ indicators that are already in use in GB schemes, ALDREN procedures may be more readily adopted so that they become part of the certification processes already in use.

5. CONCLUSIONS

The present work is an inventory of the indicators that are currently used to describe IEQ in GB schemes and standards. Many indicators are proposed in the green building certification schemes and standards to describe the quality of thermal, acoustic and visual environment, and IAQ. Several IEQ indicators are common to most of these documents. For thermal environment, the common indicators are PMV, PPD, operative temperature, air temperature, relative humidity and air speed. For acoustic environment, the common indicators are ambient noise and reverberation time. For visual environment, the common indicators are illuminance level, daylight factor and spatial daylight autonomy. For IAQ, the common indicators are ventilation rate and the concentrations of TVOC, formaldehyde, CO_2, CO, PM_{10}, $PM_{2.5}$, ozone, benzene and radon. Attempts have been made to weight the indicators for thermal, acoustic and visual environment and IAQ against one another but generally their impact has been regarded as equally important for overall IEQ. Further works is required to validate this assumption. It should also focus on developing a standard minimum protocol for assessing IEQ in buildings. The procedure that will be proposed by the ALDREN project is an attempt in this direction.

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TABLES

Table 1. Green Building certification schemes and research projects retrieved for review

Title	Region	Document	Website
Certifications			
Level(s)	EU	A common EU framework of core sustainability indicators for office and residential buildings – Part 3: How to make performance assessments using Level(s). Beta v1.0. August 2017.	http://ec.europa.eu/environment/eussd/buildings.htm
OsmoZ	France	Technical reference. Version 1.0. March 2018.	https://osmoz.certivea.fr
HQE	France	Practical guide of the benchmark for assessing the environmental performance of non-residential building under construction. September 2013. HQE reference – green building v2 – office and hotel sectors. January 2018.	https://www.certivea.fr
BREEAM	UK	BREEAM UK new construction – Non-domestic buildings – Technical manual. SD5076: 2.0. 2014.	https://www.breeam.com
KLIMA	Austria	Active building and renovation – Category: new office building. Version 2.0. March 2014.	https://www.klimaaktiv.at
DGNB	Germany	DGNB criteria: Environmental quality. 2012.	https://www.dgnb-system.de/de
ITACA	Italy	National ITACA protocol 2011 – Office. July 2012.	http://itaca.org/index.asp
LiderA	Portugal	Voluntary system for the sustainability of built environments. Version 2.0. 2011.	http://www.lidera.info/?p=apresenta&RegionId=3
IVE-BES	Spain	IVE health & wellbeing indicators – B.E.S guide prescriptions. 2018.	http://www.five.es/certificacion-edificios/oficinas/
CASBEE	Japan	CASBEE for building (new construction) – Technical manual (2014 edition). 2014.	http://www.ibec.or.jp/CASBEE/english
LEED	USA	LEED v4 for interior design and construction – Includes: commercial interiors, retail, hospitality. October 2014.	https://new.usgbc.org/leed
WELL	USA	The WELL building standard v1. January 2017.	https://www.wellcertified.com
NABERS	Australia	A guide to the NABERS indoor environment rating tool for building owners, managers & tenants. November 2015.	https://www.nabers.gov.au
Projects			
Buildings 2030	Europe	White paper – Building 4 people: people-centric buildings for European citizens. November 2017.	https://www.buildings2030.com

Title	Region	Document	Website
COMBI	Europe	WP5 social welfare – Quantification of productivity impacts – D5.4a final report. May 2018.	https://combi-project.eu
Eurofound	EU	Inadequate housing in Europe: costs and consequences. 2016.	https://www.eurofound.europa.eu
EVIA	Europe	Energy Performance of Buildings Directive: achieving both high indoor air quality and low energy consumption in European buildings. April 2017.	https://www.evia.eu
IAIAQ	EU	Promoting actions for healthy indoor air (IAIAQ). 2011.	https://publications.europa.eu/en/publication-detail/-/publication/4beb6973-83f8-49a9-a6c8-d31a6d75a247
SB Alliance	Europe	Research project: Sustainability thresholds generating value. 2015.	http://www.buildup.eu/en/explore/links/sustainable-building-alliance-sb-alliance
RESTORE	EU	Sustainability, restorative to regenerative – An exploration in progressing a paradigm shift in built environment thinking, from sustainability to restorative sustainability and on to regenerative sustainability – Working group one report: restorative sustainability. 2018.	http://www.eurestore.eu

Table 2. Thermal environment indicators

Thermal comfort indicator	Occurrence	Reference
Predicted mean vote (PMV)	8	Level(s), OsmoZ, BREEAM, KLIMA, ITACA, WELL, NABERS, EN 16798
Room air relative humidity	7	KLIMA, DGNB, LiderA, IVE-BES, CASBEE, NABERS, [15]
Room operative temperature	7	Level(s), KLIMA, DGNB, IVE-BES, WELL, EN 16798, [14]
Predicted percentage dissatisfied (PPD)	6	Level(s), OsmoZ, BREEAM, KLIMA, WELL, EN 16798
Air speed	6	HQE, KLIMA, LiderA, IVE-BES, NABERS, EN 16798
Room air temperature	5	HQE, LiderA, CASBEE, NABERS, [15]
Radiant temperature asymmetry	3	KLIMA, DGNB, EN 16798
Percentage dissatisfied for draught		
Vertical air temperature difference	2	KLIMA, EN 16798
Percentage dissatisfied for vertical air temperature differences		
Floor surface temperature		
Percentage dissatisfied for floor surface temperature		
Percentage dissatisfied for radiant temperature asymmetry	1	EN 16798
Wet-bulb globe temperature	1	OsmoZ
Adaptive comfort		
Perimeter performance	1	CASBEE
Percentage dissatisfied for asymmetric radiation	1	KLIMA
Difference between the room and ideal temperatures in summer	1	ITACA
Mean radiant temperature	1	NABERS

Table 3. Prescribed ranges for some common thermal environment indicators

Thermal environment indicator	EN 16798	Level(s)
Predicted Mean Vote (PMV)	Category 1: -0.2 < PMV < 0.2 Category 2: -0.5 < PMV < 0.5 Category 3: -0.7 < PMV < 0.7 Category 4: -1.0 < PMV < 1.0	Category 1: -0.2 ≤ PMV ≤ 0.2 Category 2: -0.5 ≤ PMV ≤ 0.5 Category 3: -0.7 ≤ PMV ≤ 0.7 Category 4: PMV < -0.7 and PMV > 0.7
Predicted Percentage Dissatisfied (PPD)	Category 1: < 6% Category 2: < 10% Category 3: < 15% Category 4: < 25%	Category 1: ≤ 6% Category 2: ≤ 10% Category 3: ≤ 15% Category 4: > 15%
Room operative temperature (°C)	For offices: Category 1: 21 – 25.5 Category 2: 20 – 26 Category 3: 19 – 27 Category 4: 18 – 28	In accordance with EN 15251
Air speed (m/s)	Category 1: ≤ 0.1 (winter), ≤ 0.12 (summer) Category 2: ≤ 0.16 (winter), ≤ 0.19 (summer) Category 3: ≤ 0.21 (winter), ≤ 0.24 (summer)	Not included

Table 4. Indoor air quality indicators

IAQ indicator	Occurrence	Reference
Ventilation rate	12	Level(s), OsmoZ, HQE, BREEAM, DGNB, ITACA, IVE-BES, CASBEE, LEED, WELL, NABERS, EN 16798
TVOC	11	OsmoZ, HQE, BREEAM, KLIMA, DGNB, IVE-BES, LEED, WELL, NABERS, [14,15]
Formaldehyde	11	Level(s), OsmoZ, HQE, BREEAM, KLIMA, DGNB, IVE-BES, LEED, WELL, NABERS, EN 16798
CO_2	11	Level(s), OsmoZ, KLIMA, IVE-BES, LEED, WELL, NABERS, EN 16798, [14,15,21]
Source emission level	9	Level(s), OsmoZ, HQE, BREEAM, DGNB, IVE-BES, CASBEE, LEED, EN 16798
CO	7	OsmoZ, HQE, IVE-BES, LEED, WELL, NABERS, EN 16798
PM_{10}	7	Level(s), OsmoZ, HQE, LEED, WELL, NABERS, EN 16798
$PM_{2.5}$	7	Level(s), OsmoZ, HQE, LEED, WELL, EN 16798, [14]
Ozone	6	OsmoZ, HQE, IVE-BES, LEED, WELL, EN 16798
Benzene	5	Level(s), OsmoZ, HQE, WELL, EN 16798
Radon	5	Level(s), HQE, IVE-BES, WELL, EN 16798
NO_2	4	OsmoZ, HQE, WELL, EN 16798
Room air relative humidity	4	Level(s), KLIMA, WELL, EN 16798
SO_2	3	HQE, IVE-BES, EN 16798
Visible mould	2	Level(s), WELL
Trichloroethylene Tetrachloroethene	2	WELL, EN 16798
Naphthalene Polyaromatic hydrocarbons	1	EN 16798
Airborne bacteria Airborne fungal spores Airborne fibers NO_x	1	IVE-BES
CS_2 CCl_4 Chlorobenzene Chloroform Dichlorobenzene (1,4-) Dichlorobenzene (1,1) Ethylbenzene	1	WELL

IAQ indicator	Occurrence	Reference
Hexane (n-)		
Isopropyl alcohol		
Methyl chloroform		
Methylene chloride		
Methyl tert-butyl ether		
Styrene		
Toluene		
Vinyl acetate		
Xylene (m, o, p combined)		

Table 5. Prescribed ranges for some common indoor air quality indicators

IAQ indicator	EN 16798	Level(s)
Ventilation rate	1. Design based on perceived air quality: Category 1: 10 l/(s per person), 0.5 l/(s m^2) for LPB-1, 1 l/(s m^2) for LPB-2, 2 l/(s m^2) for LPB-3 Category 2: 7 l/(s per person), 0.35 l/(s m^2) for LPB-1, 0.7 l/(s m^2) for LPB-2, 1.4 l/(s m^2) for LPB-3 Category 3: 4 l/(s per person), 0.2 l/(s m^2) for LPB-1, 0.4 l/(s m^2) for LPB-2, 0.8 l/(s m^2) for LPB-3 Category 4: 2.5 l/(s per person), 0.15 l/(s m^2) for LPB-1, 0.3 l/(s m^2) for LPB-2, 0.6 l/(s m^2) for LPB-3 2. Design based on CO$_2$ concentration: See CO$_2$ concentration 3. Design based on predefined ventilation rate: Category 1: 20 l/(s per person), 2 l/(s m^2) Category 2: 14 l/(s per person), 1.4 l/(s m^2) Category 3: 8 l/(s per person), 0.8 l/(s m^2) Category 4: 5.5 l/(s per person), 0.55 l/(s m^2)	In accordance with EN 16798
CO$_2$	Design CO$_2$ concentration above outdoors in ppm for non-adapted persons Category 1: 550 Category 2: 800 Category 3: 1350 Category 4: 1350	In accordance with EN 16798
CO	WHO guideline value (indoor): 15 min. mean: 100 mg/m^3 1 h mean: 35 mg/m^3 8 h mean: 10 mg/m^3 24 h mean: 7 mg/m^3	Not included
Formaldehyde	WHO guideline value (indoor): 30 min. mean: 100 µg/m^3	In accordance with the WHO guideline value
Benzene	No safe level determined	No safe level determined
PM$_{10}$	WHO guideline value (outdoor): 24 h mean: 50 µg/m^3 Annual mean: 20 µg/m^3	50 µg/m^3 (8 h mean)
PM$_{2.5}$	WHO guideline value (outdoor): 24 h mean: 25 µg/m^3 Annual mean: 10 µg/m^3	15 µg/m^3 (8 h mean)
Ozone	WHO guideline value (outdoor): 8 h mean: 100 µg/m^3	Not included
Radon	WHO guideline value (indoor): 100 Bq/m^3 (sometimes 300 mg/m^3,	In accordance with WHO guideline value

IAQ indicator	EN 16798	Level(s)
	country-specific)	

LPB-1: very low polluting building where predominantly very low-emitting materials and furniture are used, activities with emission of pollutants are prohibited and no previous emitting sources (such as tobacco smoke or emission from cleaning) were present. LPB-2: low polluting building where predominantly low emitting materials are used and materials and activities with emission of pollutants are limited. LPB-3: non low-polluting building where no effort has been done to select low-emitting materials and where activities with emission of pollutants are not limited or prohibited.

Table 6. Acoustic environment indicators

Acoustic comfort indicator	Occurrence	Reference
Ambient noise	9	OsmoZ, HQE, BREEAM, KLIMA, IVE-BES, LEED, WELL, NABERS, EN 16798
Reverberation time	8	Level(s)*, OsmoZ, HQE, BREEAM, DGNB, IVE-BES, LEED, WELL
Background noise	3	OsmoZ, CASBEE, WELL
Equivalent absorption area	2	OsmoZ, HQE
Acoustic insulation of spaces concerning the noise outdoors	2	HQE, IVE-BES
Intelligibility	2	HQE, IVE-BES
Noise masking sound level	2	IVE-BES, WELL
Facade acoustic performance	1	Levels(s)*
Impact noise		
Airborne noise		
Sound insulation of openings	1	CASBEE
Sound insulation of partition walls		
Sound insulation performance of floor slabs		
Sound insulation performance of floor slabs (heavy-weight impact source)		
Composite sound transmission class	1	LEED
Weighted pressure level of the standardized shock noise transmitted in the spaces	1	HQE
Acoustic insulation of indoor spaces (in reception) concerning the noise from other indoor spaces for activities		
Acoustic class	1	ITACA
Sound insulation of interior partitions	1	IVE-BES
Screens location		

*The current version of Level(s) does not include indicators defining acoustic performance, but they are planned for inclusion in future versions.

Table 7. Prescribed ranges for some common acoustic environment indicators

Acoustic environment indicator	EN 16798	Level(s)
Ambient noise (Equivalent continuous sound level, $L_{eq,nT,A}$, unit: dB(A))	Hotel rooms: Category 1: ≤ 25 Category 2: ≤ 30 Category 3: ≤ 35 Hotel reception, lobbies, small offices, conference rooms: Category 1: ≤ 30 Category 2: ≤ 35 Category 3: ≤ 40 Landscaped offices: Category 1: ≤ 35 Category 2: ≤ 40 Category 3: ≤ 45	Not included
Reverberation time	Not included	No prescribed range determined

Table 8. Visual environment indicators

Visual comfort indicator	Occurrence	Reference
Illuminance level	10	Level(s)*, BREEAM, LiderA, IVE-BES, CASBEE, LEED, WELL, EN 16798, [14,15]
Daylight factor	8	Level(s)*, OsmoZ, HQE, BREEAM, DGNB, ITACA, CASBEE, EN 16798
Spatial daylight autonomy	5	Level(s)*, OsmoZ, HQE, LEED, WELL
Artificial illuminance level	4	Level(s)*, OsmoZ, BREEAM, IVE-BES,
Discomfort glare in artificial lighting	4	HQE, DGNB, IVE-BES, WELL
Colour rendering index	3	HQE, DGNB, WELL
Useful daylight illuminance	2	Level(s)*, [21]
Annual sun exposure	2	Level(s)*, BREEAM
Proximity of natural light	2	OsmoZ, HQE
Daylight uniformity	2	HQE, BREEAM
Annual relative lighting percentage	1	DGNB
Electric light flicker	1	WELL

*The current version of Level(s) does not include indicators defining visual environment, but they are planned for inclusion in future versions.

Table 9. Prescribed ranges for some visual environment indicators

Visual comfort indicator	EN 16798	Level(s)
Illuminance level (IL)	Average maintained illumination in offices: 500 Lux	$300 \leq IL \leq 3000$ Lux at desk height
Daylight factor	Category 1: $D_{Ca,j} \geq 6\%$, $7\% < D_{SNA} \leq 10\%$ Category 2: $4\% \leq D_{Ca,j} < 6\%$, $4\% \leq D_{SNA} < 7\%$ Category 3: $2\% \leq D_{Ca,j} < 4\%$, $2\% \leq D_{SNA} < 4\%$ Category 4: $D_{Ca,j} < 2\%$, $0\% \leq D_{SNA} < 2\%$	$\geq 2\%$
Spatial daylight autonomy	Not included	> 300 Lux at desk height for a stipulated percentage of the year

$D_{Ca,j}$: Daylight factor for vertical facades. D_{SNA}: Daylight factor for roof lights.

FIGURES

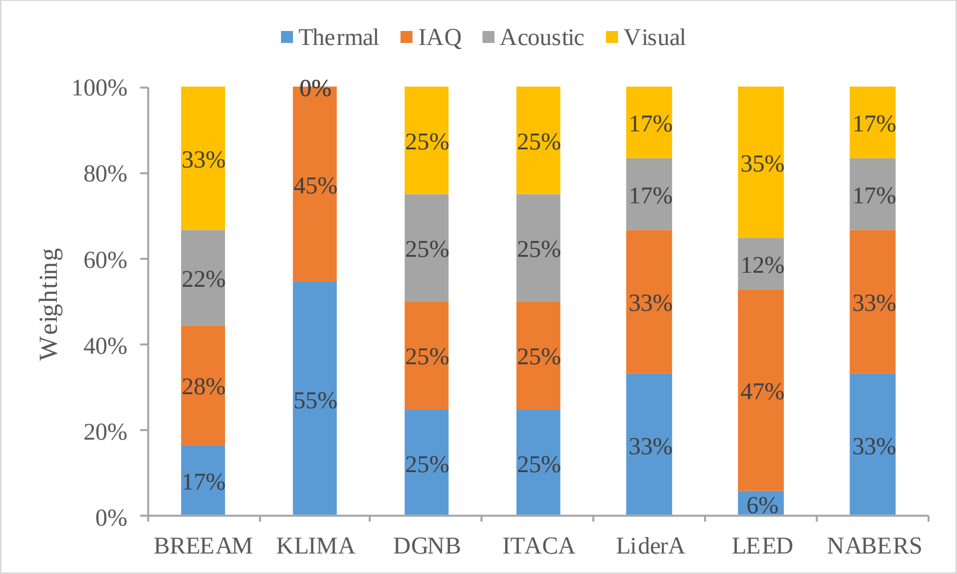

Fig. 1. Weightings of the IEQ components in different Green Building schemes

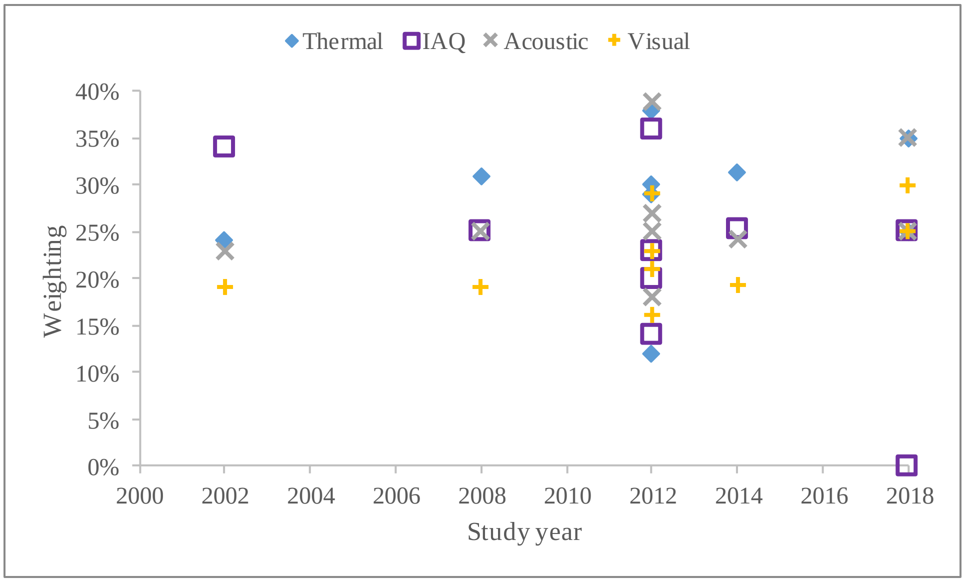

Fig. 2. Weightings of the IEQ components in research articles

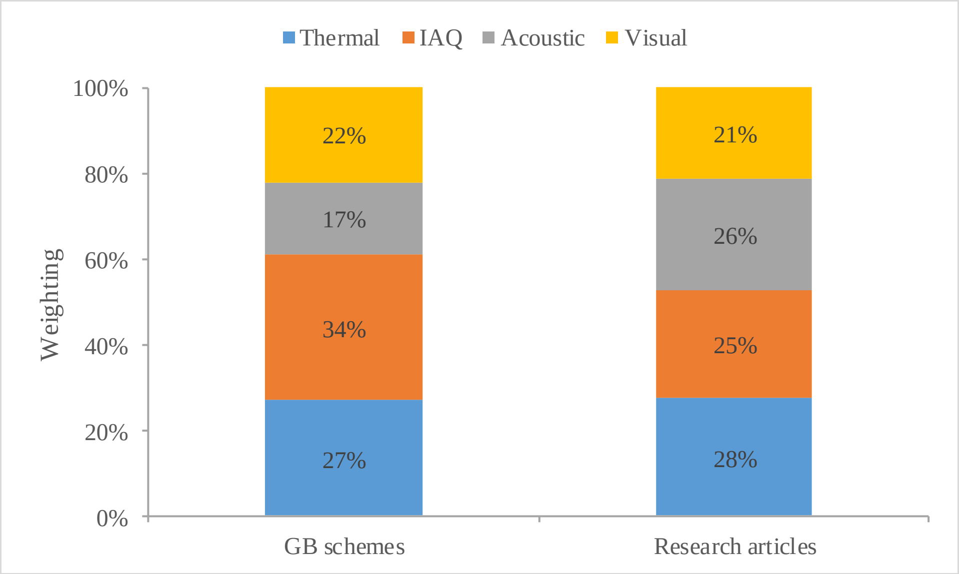

Fig. 3. Comparison of the average IEQ weightings in GB schemes and research articles

SUPPLEMENTARY MATERIAL

Selected definitions of indoor environmental quality (IEQ)

IEQ is a broad concept embracing IAQ, thermal, acoustical and visual environment, as well as ergonomic features. There are several definitions of IEQ. Some of them are listed in the following:

- According to the US Green Building Council (US GBC), IEQ encompasses the conditions inside a building—air quality, lighting, thermal conditions, ergonomics—and their effects on occupants or residents. Strategies for addressing IEQ include those that protect human health, improve quality of life and reduce stress and potential injuries. Better IEQ can enhance the lives of building occupants, increase the rental and resale value of the building, and reduce liability for building owners.

- According to the US Center for Disease Control (CDC) and the National Institute for Occupational Safety and Health (NIOSH), IEQ refers to the quality of a building's environment in relation to the health and well-being of those who occupy space within it.

- According to Sustainable Facilities Tools, IEQ is most simply described as the conditions inside the building. It includes air quality, but also access to daylight and views, pleasant acoustic conditions, and occupant control over lighting and thermal comfort. It may also include the functional aspects of a space such as whether the layout provides easy access to tools and people when needed and whether there is sufficient space for occupants.

- According to the National Institute of Building Sciences in the US, IEQ encompasses IAQ, which focuses on airborne contaminants, as well as other health, safety, and comfort issues such as aesthetics, potable water, ergonomics, acoustics, lighting, and electromagnetic frequency levels.

- According to the Dictionary of Construction, IEQ is an important criterion for green, or sustainable, building design, which refers to general overall building occupant comfort. It includes humidity, ventilation and air circulation, acoustics, and lighting.

In conclusion, IEQ should include all physical, chemical and biological parameters that define IEQ and have been documented to affect health and comfort. Furthermore, IEQ should include the factors that affect building functionality and user-friendliness in fulfilling the requirements and preferences pertaining to IEQ.

Selected definitions of indoor air quality (IAQ)

World Health Organization regards the quality of air inside homes, offices, schools, day care centres, public buildings, health care facilities or other private and public buildings where people spend a large part of their life as an essential determinant of a healthy life and well-being. Indoor air quality (IAQ) is consequently described by parameters of indoor air that may affect an occupant's health and well-being. These parameters are listed in several definitions of IAQ, some of which are listed in the following:

- According to the US Environmental Protection Agency (US-EPA), IAQ corresponds to temperature, humidity, ventilation and chemical or biological contaminants of the air inside a building. It refers to the air quality within and around buildings and structures, especially as it relates to the health and comfort of building occupants.

- According to the Glossary of Indoor Air produced by the International Society for Indoor Air Quality and Climate (ISIAQ), air quality is an indicator of the types and amounts of pollutants in the air that might cause discomfort or risk of adverse effects on human or animal health, or damage to vegetation.

- The Indoor Air Quality Association (IAQA) defines IAQ as the physical characteristics (temperature and relative humidity), chemical characteristics (gaseous contaminants) and airborne constituents (particles suspended in the air, mould, bacteria, inorganic pollutants) of air in buildings with a special concern for their impact on occupant health and comfort.

- According to the Organization for Economic Cooperation and Development (OECD), indoor air pollution refers to the chemical, biological and physical contamination of indoor air. It may result in adverse health effects. In developing countries, the main source of indoor air pollution is biomass smoke which contains suspended particulate matter (PM), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO), formaldehyde and Polycyclic Aromatic Hydrocarbons (PAHs). In industrialized countries, in addition to NO_2, CO, and formaldehyde, radon, asbestos, mercury, human-made mineral fibres, volatile organic compounds, allergens, tobacco smoke, bacteria and viruses are the main contributors to indoor air pollution.

All definitions agree that indoor air quality refers to pollutants inside the occupied buildings that can have their origin indoors or outdoors, i.e. the pollutants that are within and around buildings both be considered when indoor air quality is defined. All definitions also agree that pollutants comprise physical, chemical and biological species, particularly the types and levels that have adverse effects on human health and comfort. Work and rest (sleep) are not addressed, the latter being probably considered as an implicit determinant of health and comfort. Some definitions besides the pollutants include physical parameters of the environment such as temperature and relative humidity although they are normally associated with the thermal conditions rather than with indoor air quality.

Selected definitions of comfort

Throughout history, comfort has been considered to provide mental and physical strength, encouragement and consolation, and to ensure a happy, hygienic, orderly and convenient life. There are several definitions of comfort that are in agreement with this point of view. For example, according to the Meriam Webster Dictionary, comfort is not only the absence of negative sensations but also the presence of positive and rewarding (enriching) emotions such as enjoyment and encouragement. Comfort is consequently defined as:

- a state or feeling of being less worried, upset, frightened, etc.;
- a state or situation, in which a person is relaxed and does not have any physically unpleasant feelings caused by pain, heat, cold, etc.;
- a feeling of relief and encouragement – a contented well-being;
- a satisfying or enjoyable experience.

These elements can be found in other definitions of comfort summarized in the report with the title “Making Indoor Climate” edited by Jacob Buur and published in 2012 by the University of Southern Denmark. Some of which are listed in the following:

- in engineering, comfort is defined as the optimum range for physical parameters associated with occupants’ experienced levels of comfort such as daylight, noise, temperature and air quality. It is a condition, in which a person can maintain a normal balance between somatic (bodily) responses and the environment, although other parameters than physical are also considered, especially if an adaptive approach is considered, in which occupants not passively affected by the indoor environment but can affect it;
- in architecture, comfort is considered as heat and light contributing to psychological feelings of security, domesticity, practicality, and aesthetic value. Comfort also means that adaptive opportunities are provided and relations between indoor and outdoor climate are maintained;
- in anthropology, comfort is considered as the ability of human beings to adapt their immediate environment and create conditions (shelter) that is not only practical but also comfortable;
- in psychology, comfort is associated with a limited set of behaviours and environments which a person experiences without becoming anxious (uneasy, troubled, bothered). It is thus more related to cognition, perception and mood. In other words, comfort requirements include those under which a person can control the environment according to their preferences, avoiding stress and anxiety;

- in sociology, comfort is understood as the conditions and environment that humans establish within their surroundings rather than an attribute of a certain technological product or system;

- in philosophy, comfort is defined as a complete automatic control of conditions, challenged by reduced or absent individual autonomy, passiveness reducing interaction with nature;

- from the design and policy perspective being comfortable refers to smart (intelligently automated) solutions that are in parallel conducive to pre-existing practices as well as technically appropriate and cost-effective.

In conclusion, a condition of comfort is thus a condition with no negative aspects, creating positive sensations. If the condition of comfort can be provided to an individual, it is a passive attribute, but it can also be an opportunity to achieve preferences through active adaptation of the environment.

Selected definitions of health

The World Health Organization defines health very broadly as a state of complete physical, mental and social well-being and not merely the absence of disease. This implies that comfort and well-being are important attributes of health and is in agreement with the definition of health provided by the Meriam Webster Dictionary, which defines health as the condition of being sound in body, mind or spirit. This definition also states that health should be also considered as the condition in which one is well and free from illness and disease. Illness is understood as the condition that prevents body or mind from working normally, while disease is a condition of the living animal or one of its parts that impairs normal functioning and is normally manifested by distinct signs and symptoms. This part of the definition matches the medical description of health in which adverse health is defined as the causation, promotion, facilitation and/or exacerbation of a structural and/or functional abnormality, shown by the following manifestations: responses in biomarkers, physiological impact, symptoms including pain, and clinical outcomes that lead potentially to reduced quality of life and contribute to disability or premature death [1].

Selected definitions of work performance and productivity

Work performance is assessed in terms of human abilities to perform certain tasks. It includes cognitive performance tasks such as thinking, understanding, learning and remembering. Some of these abilities are innate and some are acquired through learning and experience. When these abilities can be used to their full extent, work performance is high. When they cannot be used fully under certain conditions, work performance is reduced. There may be different reasons why these abilities cannot be fully used, but it is well documented that these reasons include inadequate IAQ or IEQ at that causes discomfort and dissatisfaction, distraction or physiological changes manifested by health symptoms or even disease.

In contrast to work performance, productivity is an economic term, which is affected by work performance but is also strongly affected by the investment or costs that were incurred to achieve a certain level of work performance (Business Dictionary). Productivity thus defines the ratio between the output (work performance) and the input (capital costs and investments). Since it includes the cost of each man -hour, productivity can also be considered as a measure of the efficiency of a company.

Sometimes the terms labour productivity or workforce productivity are used. They measure the hourly output of a country's economy by quantifying the average amount of real gross domestic product (GDP) produced by each hour of labour.

Table S1. Methods and prescribed ranges to assess common thermal environment indicators in Green Building schemes

Thermal comfort indicator	Standard	Threshold
PPD	ISO 7730, EN 15215, ASHRAE 55	KLIMA: Category A: < 6% Category B: < 10% WELL: Points A: ≤ 10% Points B: ≤ 6%
PMV	ISO 7730, EN 15215, ASHRAE 55	KLIMA: Category A: -0.2 < PMV < 0.2 Category B: -0.5 < PMV < 0.5 ITACA: -1 point: > 0.7 or < -0.7 0 point: -0.7 ≤ PMV ≤ 0.7 3 points: -0.4 ≤ PMV ≤ 0.4 5 points: -0.2 ≤ PMV ≤ 0.2 WELL: Points A: -0.5 ≤ PMV ≤ 0.5 Points B: -0.2 ≤ PMV ≤ 0.2
Room air temperature	ISO 7726	HQE: Office: < 28 °C Hotel: < 26 °C LiderA: 18 – 26 °C CASBEE: Office: Level 1: Not adequate for Level 2 Level 2: 20 °C in winter, 28 °C in summer Level 3: 22 °C in winter, 26 °C in summer Level 4: Not available Level 5: 24 °C in winter and summer. Hotel: Level 1: 20 °C in winter, 28 °C in summer Level 2: Not available Level 3: 22 °C in winter, 26 °C in summer Level 4: Not available Level 5: 24°C in winter and summer NABERS: 21 – 24.9 °C
Room operative temperature	EN 15251	KLIMA: Category A: 24.5 +/- 1.0 °C Category B: 24.5 +/- 1.5 °C Category C: 24.5 +/- 2.5 °C DGNB: Winter: Category 1: 21 – 25 °C Category 2: 20 – 25 °C

Thermal comfort indicator	Standard	Threshold
		Category 3: 19 – 25 °C Summer: Category 1: 19 – 25.5 °C Category 2: 19 – 26 °C Category 3: 19 – 27 °C IVE-BES: Category 1: Winter: 21 – 23 °C Summer: 23.5 – 25.5 °C Category 2: Winter: 20 – 24 °C Summer: 23 – 26 °C
Room air relative humidity	Not referenced	KLIMA: ≤ 60% DGNB: ≥ 25%, absolute humidity < 12 g/kg LiderA: 35% – 60% IVE-BES: Winter: 40% – 50% Summer: 45% – 60% CASBEE: Level 1: Not adequate for Level 3 Level 2: Not available Level 3: 50% in summer 40% winter Level 4: Not available Level 5: 45% – 55% NABERS: 35% – 65%
Air speed	EN 13779	HQE: < 0.15 m/s KLIMA: Category A: ≤ 0.12 m/s Category B: ≤ 0.19 m/s Category C: ≤ 0.24 m/s LiderA: ≤ 0.2 m/s in winter, ≤ 0.5 m/s in summer IVE-BES: Category 1: ≤ 0.1 m/s in winter, ≤ 0.12 m/s in summer Category 2: ≤ 0.16 m/s in winter, ≤ 0.19 m/s in summer

Table S2. Methods and prescribed ranges to assess common IAQ indicators in Green Building schemes

IAQ indicator	Standard	Threshold
Ventilation rate	EN 16798, EN 12599, EN 15251, ISO 16000, ISO 12569, EN 13779, EN 12521, ASHRAE 62.1	OsmoZ: ≥ 25 m^3/h/pers. in offices ≥ 30 m^3/h/pers. in restaurants and meeting rooms. CASBEE: Level 1: Not adequate for Level 3 Level 2: Not available Level 3: ≥ 25 m^3/h Level 4: ≥ 30 m^3/h Level 5: ≥ 35 m^3/h NABERS: ≥ 10 l/s
TVOC	Not referenced	OsmoZ: Level 1: ≤ 1500 µg/m^3 Level 2: ≤ 500 µg/m^3 HQE: Level A: < 500 µg/m^3 Level B: 500 ≤ TVOC ≤ 1000 µg/m^3 Level C: 1000 < TVOC ≤ 1500 µg/m^3 Level D: 1500 < TVOC ≤ 2000 µg/m^3 Level E: 2000 < TVOC ≤ 3000 µg/m^3 Level F: > 3000 µg/m^3 BREEAM: < 300 µg/m^3 (8-h average) KLIMA: 0 point: 1000 < TVOC ≤ 3000 µg/m^3 10 points: 500 < TVOC ≤ 1000 µg/m^3 20 points: 300 < TVOC ≤ 500 µg/m^3 30 points: ≤ 300 µg/m^3 DGNB: 0 point: > 3000 µg/m^3 10 points: ≤ 3000 µg/m^3 25 points: ≤ 1000 µg/m^3 50 points: ≤ 500 µg/m^3 IVE-BES: ≤ 200 µg/m^3 LEED: ≤ 500 µg/m^3 WELL: All spaces except commercial kitchen spaces: < 500 µg/m^3 Enhanced: < 200 µg/m^3
Formaldehyde	ISO 16000-3	OsmoZ: Level 1: ≤ 50 µg/m^3 Level 2: ≤ 10 µg/m^3 HQE: Level A: < 10 µg/m^3 Level B: 10 ≤ HCHO ≤ 30 µg/m^3

IAQ indicator	Standard	Threshold
		Level C: 30 < HCHO ≤ 50 µg/m^3 Level D: 50 < HCHO ≤ 70 µg/m^3 Level E: 70 < HCHO ≤ 100 µg/m^3 Level F: > 100 µg/m^3 BREEAM: ≲ 100 µg/m^3 (30-min average) KLIMA: 0 point: > 0.12 mg/m^3 10 points: 0.1 < HCHO ≤ 0.12 mg/m^3 20 points: 0.06 < HCHO ≤ 0.1 mg/m^3 30 points: ≤ 0.06 mg/m^3 DGNB: 0 point: > 120 µg/m^3 10 points: ≤ 120 µg/m^3 25 points: ≤ 60 µg/m^3 IVE-BES: ≤ 0.12 mg/m^3 LEED: ≤ 27 ppb WELL: All spaces except commercial kitchen spaces: < 27 ppb Enhanced: < 13.4 ppb
CO$_2$	EN 15251, ASHRAE 62.1, Australian Standard 1668.2	OsmoZ: ≤ 1000 ppm or indoor/outdoor difference < 600 ppm KLIMA: ≤ 1500 ppm
PM$_{10}$	ISO 7708	OsmoZ: ≤ 50 µg/m^3 HQE: < 50 µg/m^3 (24-h average), < 20 µg/m^3 (long term) LEED: < 50 µg/m^3 WELL: < 50 µg/m^3
CO	Not referenced	OsmoZ: ≤ 10 ppm HQE: ≤ 10 µg/m^3 for 8-h exposure ≤ 30 µg/m^3 for 1-h exposure ≤ 60 µg/m^3 for 30-min exposure ≤ 100 µg/m^3 for 15-min exposure IVE-BES: ≤ 5 ppm LEED: ≤ 9 ppm WELL: < 9 ppm, Enhanced: < 6 ppm
PM$_{2.5}$	ISO 7708	OsmoZ: Level 1: ≤ 35 µg/m^3 Level 2: ≤ 10 µg/m^3 HQE: Level A: < 2 µg/m^3 Level B: 2 ≤ PM 2.5 ≤ 5 µg/m^3 Level C: 5 < PM 2.5 ≤ 10 µg/m^3 Level D: 10 < PM 2.5 ≤ 20 µg/m^3 Level E: 20 < PM 2.5 ≤ 30 µg/m^3

IAQ indicator	Standard	Threshold
		Level F: > 30 µg/m^3 LEED: ≤ 15 µg/m^3 WELL: < 15 µg/m^3
Ozone	Not referenced	OsmoZ: ≤ 100 µg/m^3 IVE-BES: ≤ 0.1 ppm LEED: ≤ 0.075 ppm WELL: < 51 ppb, Enhanced: < 25 ppb
Benzene	ISO 16017-2	OsmoZ: Level 1: ≤ 10 µg/m^3 Level 2: ≤ 2 µg/m^3 HQE: Level A: < 10 µg/m^3 Level B: 10 ≤ Benzene ≤ 25 µg/m^3 Level C: 25 < Benzene ≤ 35 µg/m^3 Level D: 35 < Benzene ≤ 45 µg/m^3 Level E: 45 < Benzene ≤ 50 µg/m^3 Level F: > 50 µg/m^3 WELL: For all spaces except commercial kitchen spaces: ≤ 30 µg/m^3
Radon	Not referenced	HQE: Below 400 Bq/m^3, the situation does not justify any particular corrective action Between 400 and 1000 Bq/m^3, it is necessary to undertake simple corrective actions. Above 1000 Bq/m^3, corrective actions, possibly of a large scale, must be carried out at short delays. IVE-BES: ≤ 200 Bq/m^3 WELL: < 0.148 Bq/L, Enhanced: < 0.037 Bq/L

Table S3. Methods and prescribed ranges to assess common acoustic environment indicators in Green Building schemes

Acoustic comfort indicator	Standard	Threshold
Ambient noise	NF S31-199, BS 8233	OsmoZ: < 52 dB HQE: ≤ 40 dB(A) in individual and collective offices ≤ 45 dB(A) in open office spaces ≤ 43 dB(A) in modular office spaces KLIMA: ≤ 40 dB(A) IVE-BES: Office Noise Index < 58 NABERS: ≤ 45 dB
Reverberation time	ISO 19488, ISO 354, BS 8233	OsmoZ: < 1.2 s HQE: Individual office: Level A: ≤ 0.6 s Level B: 0.6 < RT ≤ 0.7 s Level C: > 0.7 s Level D: > 0.7 s Level E: > 0.7 s Level F: > 0.7 s DGNB: Individual office: 0 point: > 1.5 s 10 points: ≤ 1.5 s 25 points: ≤ 1 s 50 points: ≤ 0.8 s IVE-BES: ≤ 0.9 s (volume ≤ 350 m^3, general purpose) ≤ 1.2 s (volume > 350 m^3, general purpose)

Table S4. Methods and prescribed ranges to assess common visual environment indicators in Green Building schemes

Visual comfort indicator	Standard	Threshold
Illuminance level (IL)	EN 12464-1, ISO 8995-1, GB50034	BREEAM: ≥ 300 Lux for 2000 hours per year LiderA: 350 – 400 Lux IVE-BES: Low: ≥ 100 Lux Moderate: ≥ 200 Lux High: ≥ 500 Lux Very High: ≥ 1000 Lux Temporary use: ≥ 50 Lux Regular use: ≥ 100 Lux Temporary communication: ≥ 25 Lux Regular communication: ≥ 50 Lux CASBEE: Office: Level 1: Not available Level 2: IL < 300 or ≥ 1000 Lux Level 3: 300 ≤ IL < 500 Lux Level 4: 500 ≤ IL < 1000 Lux Level 5: 500 < IL < 1000 Lux Hotel: Level 1: < 100 Lux Level 2: Not available Level 3: ≥ 100 Lux Level 4: Not available Level 5: Not available
Daylight factor (DF)	Not referenced	OsmoZ: Level 1: > 0.7% Level 2: > 1.5% Level 3: > 2% HQE: > 0.7% – >2.5% BREEAM: > 2% (80% area) DGNB: 50% of the usable area has a DF >: 0 point: < 1% 8 points: 1% 12 points: 1.5% 16 points: 2% ITACA: -1 point: < 2% 0 point: 2% 3 points: 2.6% 5 points: 3% CASBEE: Level 1: < 1%

Visual comfort indicator	Standard	Threshold
		Level 2: 1% ≤ DF < 1.5%, Level 3: 1.5% ≤ DF < 2%, Level 4: 2% ≤ DFS < 2.5%, Level 5: ≥ 2.5%
Spatial daylight autonomy (SDA)	EN 12464-1	OsmoZ: Level 1: 10% ≤ SDA < 45% Level 2: 45% ≤ SDA < 65% Level 3: 65% ≤ SDA ≤ 100% LEED: 2 Points: 55% 3 Point: 75% WELL: SDA (200, 40%) is achieved for at least 30% of regularly occupied space. OR SDA (300, 50%) is achieved for at least 70% of the space. Enhanced: Points A: SDA (300, 50%) is achieved for greater than 55% of regularly occupied floor area Points B: SDA (300, 50%) achieved for greater than 75% of regularly occupied floor area

Annex 3: IEQ parameters impacted by energy renovation actions

IEQ parameters impacted by energy renovation actions

- **General and local thermal environment** (air temperature, mean radiant temperature, radiant assymetry, reduced cold draft, reduced risk of overheating/overcooling and free cooling): thermal rehabilitation (insulation) of envelope, roof, ground floor, etc., new low-energy windows, installation of low temperature heating and high temperature cooling hydronic systems, air-based cooling and heating systems, improved control of heating/cooling systems, installation of sunscreens
- **Mold**: thermal rehabilitation (reduced cold bridges), installation of ventilation system
- **Moisture levels**: installation of ventilation system
- **Radon**: thermal rehabilitation of ground floor and cellars
- **Ventilation and air quality**: installation of ventilation system, low-emitting materials
- **Penetration of ambient pollution, airtightness:** tightening of envelope, thermal rehabilitation of enevelope and new windows, installation of ventilation system
- **Ambient noise penetration**: new windows, tightening of enevelope and thermal rehabilitation of envelope
- **Daylight**: skylights, new windows
- **Visual environment, illuminance**: renovation of low-energy artificial lighting system
- **Glare**: installation of sunscreens

- **No impact on IEQ**: use of renewable energy sources, heat pumps, more effective boilers, connection to district heating, etc

Annex 4: Methodology related to data collection in existing buildings

THERMAL Environment

Parameter	*Rationale for inclusion*	*Assessment method*
Air temperature (°C)	Avoiding **discomfort** related to overheating and overcooling Included in Level(s) and EN16798 Included in the following certification schemes: HQE, LiderA, NABERS and CASBEE	**Modeling – simulations (prior to and after renovation)**[1,2] Modeling period 1 year Climatic data: test reference year and/or the local representative weather data Follow Level(s) 4.2.1.1 (details of modeling need to be provided by Task 2.2) **On-line measurements (prior to and after renovation)**[1,2] Calibrated sensors with accuracy of at least ±0.5ºC shall log temperatures. Measuring one month. Time-interval: from 1 min to 10 min. In offices, only data for the period corresponding to working hours from Monday to Friday will be used. An additional measurement of outdoor temperature is recommended both in offices and hotels; the hourly data from the near ambient measuring station can be used instead. Reports shall provide information on the % of working hours in offices and % of hours weekly in hotels with temperatures outside any specified range for each of the measuring location. To be classified in each category the temperatures can exceed the indicated range by 1ºC no more than 5% and by 2ºC no more than 1% of time. To be representative it is recommended (not compulsory) that measurements shall be carried out in the most critical periods of the year with respect to outdoor temperatures. For heating season, it will be the coldest week according to the statistical reference year and for the non-heating season it will be the hottest week according to statistical reference year. Shoulder periods may be critical as well due to position and altitude of the sun, especially in Nordic countries, and they can be considered as well.

[1] "Design stage" according to Level(s)

[2] After renovation is "Post-completion" stage according to Level(s)

ACOUSTIC Environment

Parameter	***Rationale for inclusion***	***Assessment method***
Noise level (from installed equipment)	Avoiding **discomfort** Included in EN16798. Planned for inclusion in Level(s) Included in the following certification schemes: HQE, BREEAM, OsmoZ, KLIMA, IVE, LEED, WELL and NABERS	**On-line measurements (prior to and after renovation in unoccupied building)[1,2]** Measuring period from Monday to Friday in offices and 7 consecutive days in hotels. Time-interval: 1 min. Calibrated sensors with accuracy of at least ±1dB(A) shall log noise level. The measurements shall be made in unoccupied spaces or measured values without occupants must be used. The data from sensors shall be extracted to present number of hours exceeding different categories indicated the criteria for ranking. To be classified in each category the measured levels shall comply with categories specified by the criteria for the ranking.

[1] "Design stage" according to Level(s)

[2] After renovation is "Post-completion" stage according to Level(s)

INDOOR AIR QUALITY

Parameter	*Rationale for inclusion*	*Assessment method*
Carbon dioxide (CO_2)	Avoiding **discomfort** Included in EN16798 and Level(s). Included in the following certification schemes: OsmoZ, KLIMA, IVE, LEED, WELL and NABERS	**Modeling – simulations (prior to and after renovation)**[1,2] Modeling period 1 year **On-line measurements (prior to and after renovation in occupied building)**[1,2] Calibrated Fourier Transform infrared (FTIR) sensors with accuracy of at least ±50 ppm of reading shall log carbon dioxide. Measuring period from Monday to Friday in offices and 7 consecutive days in hotels. Time-interval: from 1 min to 10 min. In offices, only data for the period corresponding to working hours shall be used. By default, measurements between 9 am and 5 pm can be considered. In hotels, only data during room occupancy shall be used. By default, measurements between midnight and 6 am can be considered. An additional measurement of CO_2 concentration outdoors is recommended both in offices and hotels; else 400 ppm can be considered. Reports shall include the % of working hours in offices and % of sleeping hours in hotels when carbon dioxide concentration is outside any given range for each of the measuring location. To be classified in each category the CO_2 concentration shall not exceed the indicated range by no more than 5% of time with regard to concentration levels set by the next higher category and 1% of time with regard to concentrations set by the following higher category.
Ventilation rate (outdoor air supply rate)	Avoiding **discomfort** Included in EN16798 and Level(s). Included in the following certification schemes: OsmoZ, HQE, BREEAM, DGNB, ITACA, IVE, LEED, WELL, NABERS and CASBEE	**Measurements (prior to and after renovation in occupied building)**[1,2]: Two measurements shall be performed at the onset and towards the end of continuous measurements carried out for other parameters (temperature, RH, CO_2, etc.) in buildings with mechanical supply and/or exhaust. No measurements are to be performed in naturally ventilated buildings. Calibrated flow hood (capture hood) shall be used to measure airflow on all inlets and exhausts in the rooms selected for measurements. The measured ventilation rates (average values of the two measurements) shall be compared with the nominal ventilation rate for that area according to design.
Air relative humidity (%)	Avoiding **health risk** Included in Level(s). Included in the following certification schemes: KLIMA and WELL	**Modeling – simulations**[1,2] Modeling period 1 year. **On-line measurements (prior to and after renovation in occupied building)**[1,2] Calibrated sensors with accuracy of at least ±5% shall log indoor air relative humidity.

		Measuring one month in case of temperature monitoring with the same instrument, otherwise measurement period from Monday to Friday in offices and 7 consecutive days in hotels. Time-interval: from 1 min to 10 min. In offices, only data for the period corresponding to working hours will be used. An additional measurement of outdoor relative humidity is recommended both in offices and hotels; the hourly data from the near ambient measuring station can be used instead. Reports should include % hours relative humidity is outside any given range for each of the measuring location. To be classified in each category the relative humidity can exceed the indicated range by 5% no more than 5% and by 10% no more than 1% of time.
Visible mold	Avoiding **health risks** Included in Level(s) and dealt with by WHO (with no recommendation on the level) Included in WELL	**Visual assessment by a qualified expert (walk-through prior to and after renovation in occupied building)** Observations in the instrumented rooms. In addition, locations should be included where the risk of mold is present according to simulations of surface relative humidity.
Benzene	Avoiding **health risks** Included in WHO IAQ guidelines and Level(s) Included in the following certification schemes: HQE, OsmoZ and WELL	**Passive measurements (prior to and after renovation in occupied building)**[1,2] Passive measurements from Monday to Friday in offices and 7 consecutive days in hotels. An additional measurement of outdoor concentration is recommended; the data from the nearby ambient air quality monitoring station can be used instead. To be representative it is recommended (not compulsory) that measurements are carried out twice in the most critical periods of the year with respect to outdoor temperatures, i.e. in winter and in summer. In this case, the average concentration is used for the ranking. Measurements must comply with ISO 16017-2:2003 standard (Indoor, ambient and workplace air -- Sampling and analysis of volatile organic compounds by sorbent tube/thermal desorption/capillary gas chromatography -- Part 2: Diffusive sampling).
Formaldehyde	Avoiding **health risks** (strong airway irritant, carcinogen) Included in WHO IAQ guidelines and Level(s) Included in the following certification schemes: HQE, BREEAM, OsmoZ, KLIMA, DGNB, IVE, LEED, WELL and NABERS	**Passive measurements (prior to and after renovation in occupied building)**[1,2] Passive measurements from Monday to Friday in offices and 7 consecutive days in hotels. To be representative it is recommended (not compulsory) that measurements are carried out twice in the most critical periods of the year with respect to outdoor temperatures, i.e. in winter and in summer. In this case, the average concentration is used for the ranking. Measurements must comply with ISO 16000-4:2011 (Indoor air -- Part 4: Determination of formaldehyde -- Diffusive sampling method).

Particles ($PM_{2.5}$)	Avoiding **health risks** Included in WHO IAQ guidelines and Level(s) Included in the following certification schemes: HQE, OsmoZ, LEED and WELL	**Measurements (prior to and after renovation in occupied building)**[1,2] Gravimetric (preferable) or measurements with calibrated optical counters shall be performed. Measurements must be performed from Monday to Friday in offices and 7 consecutive days in hotels. In offices, the pump must be programmed to sample air only during working hours (by default from 9 am to 5 pm). An additional measurement of outdoor concentration is recommended; the data from the nearby ambient air quality monitoring station can be used instead. To be representative it is recommended (not compulsory) that measurements are carried out twice in the most critical periods of the year with respect to outdoor temperatures, i.e. in winter and in summer. In this case, the average concentration is used for the ranking. Gravimetric measurements must comply with standard CEN - EN 12341:2014 (Ambient air - Standard gravimetric measurement method for the determination of the PM10 or PM2,5 mass concentration of suspended particulate matter).
Radon (relevant only for the radon-prone areas and office and hotel areas with ground floor)	Avoiding **health risks** Included in WHO IAQ guidelines and Level(s) Included in the following certification schemes: HQE, IVE and WELL	**Passive measurements (prior to and after renovation in occupied building)**[1,2] Measuring period is 2 months during winter only. Passive dosimeters must be installed in 2 locations the ground floor (if there are offices in office buildings and rooms in hotels at the ground level). Measurements must comply with ISO 11665-8:2013 (Measurement of radioactivity in the environment - air: radon-222 - Part 8: Methodologies for initial and additional investigations in buildings).

[1] “Design stage” according to Level(s)

[2] After renovation is “Post-completion” stage according to Level(s)

VISUAL Environment

Parameter	***Rationale for inclusion***	***Method of assessment***
Daylight factor (building plan depth)	Avoiding **discomfort** Included in 16798, Proposed for inclusion in Level(s) Mandated by EPBD 2010/31/EU Included in the following certification schemes: HQE, BREEAM, OsmoZ, DGNB, ITACA and CASBEE	**Modeling – simulations (prior to and after renovation in occupied or unoccupied building)[1,2]** Dynamic daylight simulations should be performed according to EN 15193-1 (no standard simulation tools are available, the one that are recommended are based on radiance). 1-year long simulations
Illuminance (lux)	Avoiding **discomfort** Included in 16798 Proposed for inclusion in Level(s) Included in the following certification schemes: BREEAM, LiderA, IVE, LEED, WELL and CASBEE	**Modeling – simulations (prior to and after renovation)[1,2]:** 1-year long simulations **Spot measurements (prior to and after renovation in occupied building)[1,2]** Spot measurements the first day (morning + midday + afternoon) of the monitoring and the last day (morning + midday + afternoon), at 5 locations per room (middle of the room + 4 corners to average). Six measurements per room. Calibrated sensors with accuracy of at least ±3 lux (or ±3% of measured value with resolution of 1 lux) shall log illuminance. An additional measurement of outdoor illuminance level is recommended.

[1] “Design stage” according to Level(s)

[2] After renovation is “Post-completion” stage according to Level(s)

Annex 5: Assessment of the indoor environment quality before and after renovation

THERMAL Environment

Parameter	*Criteria for the ranking*
Air temperature (°C)	**Temperature during target hours:** Reported performance follows EN15251/EN16798 and is indicated below; the method of reporting can follow Level(s) Part 3, chapter 4.2.1.2. Performance criteria are defined by the level of operative temperature, PMV or PPD or hours outside any given range. Temperature range during occupied hours (working hours offices and any occupied hours hotels) shall be within the indicated range; any allowable departures are indicated in the “Assessment method”. **Buildings with mechanical cooling** Heating season (assuming clo 1.0, office work and RH=50%) Cat I. 22±1ºC Cat II. 22±2ºC Cat III. 22±3ºC Cat IV. All others Non-heating (cooling) season (assuming clo=0.5, office work and RH=50%) Cat I. 24.5±1ºC Cat II. 24.5±1.5ºC Cat III. 24.5±2.5ºC Cat IV. All others **Buildings without mechanical cooling** Heating season (assuming clo=1.0. office work and RH=50%) Cat I. 22±1ºC Cat II. 22±2ºC Cat III. 22±3ºC Cat IV. All others Non-heating season (summer and shoulder seasons) indoor temperature (Θo) depends on running mean outdoor temperature (Θrm) Cat I. upper limit Θo=0.33Θrm+18.8+2 lower limit Θo=0.33Θrm+18.8-3 Cat II. upper limit Θo=0.33Θrm+18.8+3

	lower limit $\Theta o=0.33\Theta rm+18.8-4$ Cat II. upper limit $\Theta o=0.33\Theta rm+18.8+4$ lower limit $\Theta o=0.33\Theta rm+18.8-5$ Cat IV. All other conditions Levels(s) allow another approach for adaptive method whereas (operative) temperature varies as follows: Cat. I ±2ºC Cat. II ±3ºC Cat. III ±4ºC Cat. IV not defined No specific criteria for hotels so the criteria indicated above should be followed depending on whether the hotel is with mechanical cooling or without it.

ACOUSTIC Environment

Parameter	***Criteria for the ranking***
Noise level (from installed equipment)	**Noise level** ($L_{eq,nT,A}$) in unoccupied spaces during working hours in offices and during waking and sleeping hours in hotels **SMALL OFFICES** Cat I. ≤30 dB(A) Cat II. ≤35 dB(A) Cat III. ≤40 dB(A) **LANDSCAPE OFFICES** Cat I. ≤35 dB(A) Cat II. ≤40 dB(A) Cat III. ≤45 dB(A **HOTEL ROOMS** Cat I. ≤25 dB(A) Cat II. ≤30 dB(A) Cat III. ≤35 dB(A)

INDOOR AIR QUALITY

Parameter	***Criteria for the ranking***
Carbon dioxide (CO_2)	**Maximum conc. above outdoors during full occupancy**; outdoor level can be assumed to 400 ppm or measured value should be used; determined based on comfort requirements (avoid the % people dissatisfied with air quality) Cat I. ≤550 ppm Cat II. >550 and ≤800 ppm Cat III. >800 ppm and ≤1350 ppm Cat IV. >1350 ppm
Ventilation rate (outdoor air supply rate)	**Design values for non-low polluting building (by default, as emissions are not known) and the occupation density (m^{2}floor/p**) Cat I. 10 L/s/p and 2.0 L/s/m^2 Cat II. 7 L/s/p and 1.4 L/s/m^2 Cat III. 4 L/s/p and 0.8 L/s/m^2 Cat IV. 2.5 L/s/p and 0.6 L/s/m^2
Air relative humidity (%)	**OFFICES** **RH to avoid health risk due to ocular dryness**: Cat I. No risk: ≥40% Cat II. Moderate risk: ≥30% and <40% Cat III. At risk: ≥10% and <30% Cat IV. High risk: <10% **HOTELS** **RH to avoid health risk due to house dust mites**: Cat I. No risk: ≤50% Cat II. Moderate risk: >50% and ≤60% No category III Cat IV. High risk: >60%

Visible mold	**Prevalence of mold:** Cat I. No visible mold Cat II. Minor moisture damage, minor areas with visible mold (<400 cm^2) Cat III. Damaged interior structural component, larger areas with visible mold (<2,500 cm^2) Cat IV. Large areas with visible mold (≥2,500 cm^2)
Benzene	**Benzene concentration (µg/m^3)** Cat I. < 2 µg/m^3 Cat II. and Cat III. [2 – 5] µg/m^3 Cat IV. ≥ 5 µg/m^3
Formaldehyde	**Formaldehyde concentration (µg/m^3)** Cat I. < 30 µg/m^3 Cat II. and cat. III [30 – 100] µg/m^3 Cat IV. ≥ 100 µg/m^3
Particles (PM$_{2.5}$)	**PM2.5 concentration (µg/m^3)** Cat I. < 10 µg/m^3 Cat II. and Cat III. [10 – 25] µg/m^3 Cat IV. ≥ 25 µg/m^3 In case of measurements with optical counters, concentrations on shorter time intervals can be calculated. **IN OFFICES** Cat I. The 8-hour average concentration never exceeds 15 µg/m^3 (Level(s)). Cat II. The 8-hour average concentration of 15 µg/m^3 is exceeded once (one day in the week). Cat III. The 8-hour average concentration of 15 µg/m^3 is exceeded two or three days in the week. Cat IV. The 8-hour average concentration of 15 µg/m^3 is exceeded four or five days in the week. **IN HOTELS** Cat I. The 24-hour rolling average concentration never exceeds 25 µg/m^3 (WHO Air Quality Guideline). Cat II. The 24-hour rolling average concentration of 25 µg/m^3 is exceeded <10% of the week.

	Cat III. The 24-hour rolling average concentration of 25 µg/m^3 is exceeded between 10 and 50% of the week. Cat IV. The 24-hour rolling average concentration of 25 µg/m^3 is exceeded half of the week or more.
Radon (relevant only for the radon-prone areas and office and hotel areas with ground floor)	**2-month average concentration (Bq/m^3)** Cat I. < 100 Bq/m^3 (WHO) Cat II. and Cat III. [100 – 300[Bq/m^3 Cat IV. ≥ 300 Bq/m^3

VISUAL Environment

Parameter	*Criteria for the ranking*
Daylight factor (building plan depth)	**Daylight factor (DF)** levels (2% is a minimum) Cat I. Strong: >7% Cat II. Medium: <7% and ≥4% Cat III. Low: <4% and ≥2% Cat IV. None: <2% **Useful Daylight Illuminance (UDI):** hours with insufficient daylight level (≤100 Lux) and hours when daylight causing visual discomfort - glare (≥2,000 Lux)
Illuminance (lux)	**OFFICES AND HOTELS DURING DAY (9 am to 5 pm):** % of time with illuminance between 300-500 lux at work desk height (ref. HQE) Cat I. [60 – 100%] Cat II. [40 – 60%[Cat III. [10 – 40%[Cat IV. <10% **HOTELS DURING NIGHT**, to avoid disturbance from light while sleeping (0-6 am); can only be assessed with modeling (ref. adapted from CASBEE) Cat I. 100% of time < 100 lux Cat II. 0-50% of time ≥ 100 lux Cat III. 51-90% ≥ 100 lux Cat IV. 90% of time ≥ 100 lux

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