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TAIL, a new scheme for rating indoor environmental quality in offices and hotels undergoing deep energy renovation (EU ALDREN project)

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ABSTRACT

To avoid health risks and discomfort, the European Energy Performance for Building Directive (EPBD) mandates that "Member States should support energy performance upgrades of existing buildings that contribute to achieving a healthy indoor environment." There is, however, no widely accepted method for rating the overall level of indoor environmental quality (IEQ), although several different approaches are proposed by standards, guidelines, and certification schemes. To fill this void, a new classification rating scheme called TAIL was developed to rate IEQ in offices and hotels undergoing deep energy renovation during their normal use; the scheme is a part of the energy certification method developed by the EU ALDREN project. The TAIL scheme standardizes rating of the quality of the thermal (T) environment, acoustic (A) environment, indoor air (I), and luminous (L) environment, and by using these ratings, it provides a rating of the overall level of IEQ. Twelve parameters are rated by measurements, modelling, and observation to provide the input to the overall rating of IEQ. Their quality levels are determined primarily using Standard EN-16798-1 and World Health Organization (WHO) air quality guidelines and are expressed by colours and Roman numerals to improve communication. The TAIL rating was shown to discriminate IEQ levels when its feasibility was examined in eleven buildings across Europe to provide support for its applicability and input for further modifications. Opportunities for using the scheme in other types of buildings and for its further development and application are discussed.

1. Introduction

Several policies and actions have been put forward by the European Union (EU) to mitigate and reduce the impact of climate change. One such action is the modernization and renovation of the European building stock, which is responsible for 40% of energy use and 36% of carbon dioxide (CO_2) emissions [14]. The European Commission created instruments to initiate changes in how buildings are constructed, operated, and maintained to achieve significant reductions in energy use. The framework was established by the Energy Performance of Building Directive (EPBD), which was launched in 2003 [13], re-cast in 2010 [14], and amended in 2018 [10]. The main purpose of this Directive is to promote improvements in the energy performance of buildings. This applies both to new construction and existing buildings, of which 25% are commercial buildings, 75% are considered to be inefficient, and about 35% are at least 50 years old.

Despite these high ambitions and good intentions, the implementation of EPBD failed somewhat concerning renovation of the existing building stock. Renovation rates that followed EPBD recommendations have not exceeded 1% to 2% [49], although it is estimated that renovation accounts for 57% of all construction activity, and many renovations do not reach the full amount of energy savings that could be achieved [41]. Renovation rates following EPBD recommendations should reach at least 3% to guarantee that minimum energy reduction goals will be met [41]. One reason for this shortfall could be that renovations, even those leading to reductions in energy

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use, have not been sufficiently economically attractive because of the costs involved and the subsequently long pay-back times. The focus in recent years has therefore been to promote other benefits that can be achieved with deep energy renovation. Several research projects were launched to create incentives and tools to facilitate and enhance renovation rates in this context. One of them was the ALDREN project (ALliance for Deep RENovation in buildings, November 2017 – October 2020, https://aldren.eu/). The overall aim of ALDREN was to overcome market barriers and promote the deep renovation of buildings (DER); the focus was on office buildings and hotels. The main goal of ALDREN was that parameters describing indoor environmental quality (IEQ) would become part of assessments of energy performance. This was expected to make energy renovations more attainable and attractive in a much higher proportion of the building market.

Although different parameters have been used to describe IEQ [44], no standard set of the parameters used to characterize IEQ in buildings has yet been agreed, and no set of parameters has been very broadly used. Furthermore, there is no supporting scheme allowing standard and repeatable rating of IEQ during energy renovations even though some attempts have been made in the past. Some of them are summarized in the following, but none has been accepted as a normative rating scheme.

Devitofrancesco et al. [8] developed an IEQ assessment tool for offices that can be used under real working conditions. It was based on the measuring protocols of IEQ indicators stipulated in several European and international standards. Weighting was assigned to aggregate the IEQ components, i.e., thermal environment, indoor air quality, acoustic environment, and luminous environment, to reflect the policy-making context and certain indoor environmental characteristics. Different weights were also assigned to the indicators within each IEQ component to reflect the technical choices. These were based on the experience of experts, the choice of weighting being thus subjective. Danza et al. [6] assessed the IEQ of two rooms subjectively in an occupant survey and objectively using measurements of some IEQ indicators stipulated in the EN 16798-1 standard. The relationship between the perceived IEQ level and the measured IEQ indicators was analysed using Multiple Linear Regression, which determined the regression coefficients for the IEQ components. The coefficients were different between the two rooms that were studied (-0.125 to 0.059 for the thermal environment, -0.06 to -0.043 for the luminous environment, 0.085 to 0.102 for the acoustic environment, and 0.374 to 0.379 for the IAQ). Park et al. [36] and Cochran Hameen et al. [5] developed protocols for post-occupancy evaluation and measurements of IEQ in offices and schools using online instrumentation (National Environmental Assessment Toolkit, NEAT). Their approach, however, did not provide a method for aggregation of the IEQ component parameters and did not include some relevant pollutants, such as volatile organic compounds (VOCs) or radon. Piasecki et al. [37] developed an IEQ index by calculating the percentage of occupants dissatisfied with IEQ as a function of measurements of different parameters, e.g., air temperature and CO_2 concentration. Although the index considers both occupants' perception and objective measurements of IEQ parameters, the relationship is based on empirical evidence, and no practical application of them is available. Mui et al. [33] developed an IEQ index consisting of five indicators: air temperature, relative humidity, CO_2 concentration, horizontal illumination level, and sound pressure level; the focus was on air-conditioned buildings. Finally, Larsen et al. [32] proposed IEQ-Compass, a method for assessing IEQ during the energy renovation of dwellings. IEQ-Compass is an asset rating as it provides a method for assessing the quality of the indoor environment at the design stage that would result from design decisions that would achieve energy savings, so no actual verification and measurements can be made during its use, although a check is made by asking building occupants to rate the parameters defining IEQ. Another labelling scheme for residential buildings was proposed by the TripleA-reno project [50], which combines energy performance, indoor environmental indicators, and well-being indicators, and stipulates the IEQ parameters that should be measured, including operative temperature, relative humidity, and concentrations of CO_2, formaldehyde, $PM_{2.5}$, PM_{10} and total volatile organic compounds (TVOCs).

Since none of the above-proposed procedures has been adopted as a standard method or describes the actual performance of a building in terms of the overall level of IEQ and IEQ during regular use, one of the intentions of the ALDREN project was to define a scheme for rating IEQ parameters and overall IEQ. This is the scheme described in the present paper; it is called the TAIL rating scheme. It was intended to assist the process of deep energy renovation, to ensure that the renovation process does not degrade the building's IEQ and that IEQ in the renovated building meets the health and well-being requirements prescribed by the applicable international standards and guidelines. The premise was that the new method should comply with existing standards and Green Building (GB) schemes that address IEQ, particularly in office and hotel buildings, which were the focus of the ALDREN project. It was additionally proposed that the method should be based on objective measurements because occupant surveys, although valuable and useful, may not be easy to implement and do not have the repeatability and rigour achieved by measurements of physical and chemical parameters. In addition to defining the scheme, pilot feasibility studies in eleven buildings are described to examine its applicability and provide input for further modifications.

2. TAIL rating scheme

The present section describes the methodology to be used to rate IEQ using TAIL. It starts with a definition of the scheme (2.1) and continues with a description of the parameters selected for inclusion in the scheme (2.2), a description of the scheme (2.3), and an assessment protocol (2.4).

2.1. Definition of the rating scheme

There are four major components of the indoor environment: thermal environment, acoustic environment, luminous (visual) environment, and indoor air quality [31,40]. A deep energy retrofit may alter any or all of these four components. The thermal environment may be affected by improving the properties of the building envelope by adding insulation and changing the windows, the heating/cooling systems, or the thermal controls. Indoor air quality may be influenced by a reduction of the rate of supply of outside air caused by tightening the building envelope to reduce heat losses due to uncontrolled infiltration and leakages in the building envelope [51]. As a result, the concentration of pollutants emitted by indoor sources may increase. At the same time, the concentration of any contaminants originating outdoors may be reduced. The energy renovation process may also include installing a mechanical ventilation system, which will impact the concentration of pollutants indoors but may also increase the risk of noise and draft. The installation of new building and furnishing materials may additionally increase the indoor air concentration of the pollutants they emit. Regarding acoustics, an improvement of the thermal insulation of the building envelope and new tight windows may reduce noise from outdoor sources but may also enhance the perception of indoor noise from mechanical systems [51] The deep energy renovation process may include the installation of smaller windows to reduce heat loss, which, as a consequence, will reduce daylighting levels and necessitate the increased use of artificial lighting. The spectral selectivity of glazing material [52] is often determined based on their energy reduction properties, and this may affect the amount and quality of the daylight penetrating indoors. The installation of energy-efficient lighting may also affect the quality of the light delivered indoors [53] .

A rating classification scheme is consequently proposed that addresses the four major components of IEQ to assess the influence of deep energy renovation on the quality of the indoor environment. The proposed scheme is called ALDREN-TAIL, in short, TAIL, where T stands for the thermal environment, A for the acoustic environment, I for indoor air quality, and L for the luminous (visual) environment; a graphical presentation of the TAIL rating is shown in Fig. 1. The quality of each of the four components of TAIL is indicated by using one of the four colours: green denotes a high (desired) quality level, yellow a medium (refined) quality level, orange a moderate (ordinary) quality level, and red a low (undesirable) quality level. Based on the quality levels of the four TAIL components, the overall (integrated) quality level of the indoor environment is determined and indicated by a Roman numeral in the centre of graphical presentation of the TAIL rating (Fig. 1), where I denotes a high (desired) quality level, II a medium (refined) quality level, III a moderate (ordinary) quality level, and IV a low (undesirable) quality level. The Roman numerals and levels of quality of the indoor environment are aligned with the EN 16798-1 standard [17], one of the many standards supporting EPBD by defining indoor environmental input parameters for the design and assessment of the energy performance of buildings and thus highly relevant in the context of the TAIL rating scheme; in this way, the applicability and connection of TAIL to energy renovations and EPBD is ensured.

2.2. Selection of parameters included in the rating scheme

The quality level of each of the components included in the TAIL rating scheme is determined based on the quality levels of the parameters characterizing each of them. The following criteria were used to select these parameters:

(1) The parameters that are likely to change in the process of deep energy renovation even when it has included no deliberate action concerning IEQ.
(2) The parameters that are included in the existing building certification schemes and standards prescribing conditions of the indoor environment in buildings and are recommended by guidelines concerning the health and comfort of building occupants.
(3) The parameters that can be measured using accessible and validated methods.
(4) The parameters that have been demonstrated to have an impact on occupants' health, well-being, comfort, work performance, or sleep quality.

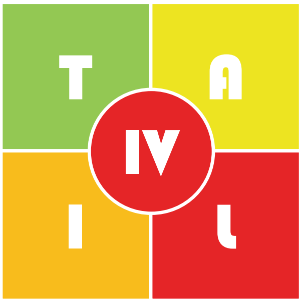


Fig. 1. The TAIL rating scheme with four colours representing the quality levels of each IEQ component and the overall IEQ level; the colours are just examples of the quality levels, and each of the TAIL components can have any of the four quality levels represented by four colours. The Roman numeral in the centre shows the integrated overall quality level determined based on the quality level of the four components of TAIL.

The first criterion, (1), connects the parameters defining IEQ in the TAIL rating scheme with the energy renovation process. The selection process was based on the results of a Danish project (https://byggeriogenergi.dk/vaerktoejer/energiloesninger-oversigt/) that created a catalogue of energy renovation actions and linked them to their impact on parameters defining IEQ (Table S1 in the Supplementary Information (SI) provides a summary in English); the results were confirmed in the review by Ortiz et al. [51].

The second criterion, (2), connects the parameters defining IEQ in the TAIL rating scheme with the protocols for measuring IEQ that are already in use to support its adoption in practical applications and to ensure its alignment with the methods currently used for the characterization of IEQ in buildings. The selection was based on the results of a review of IEQ indicators in fourteen GB schemes [44], including the EU Level(s) framework for core sustainability indicators [15] and on relevant peer-reviewed articles, reports of European projects, and the EN 16798-1 standard [17] (Table S2 in SI provides a summary).

The third criterion, (3), ensures that the use of the rating scheme is not restricted by access to sophisticated and advanced measuring instrumentation or unusually high measurement costs.

The last criterion, (4), ensures the inclusion of parameters that have been demonstrated to impact comfort, well-being, human health, cognitive performance, and sleep and thus have been monetized as far as possible. This will make it possible to estimate the potential benefits of deep energy renovation in addition to the intended reduction in energy use; these benefits are frequently called non-energy benefits. The selection was supported by identifying and examining different reviews and research papers on these topics (e.g., [54]; [20]; [55]; [56]; [1,28], as well as several air quality guidelines [45–47].

2.3. Description of the rating scheme

Twelve parameters are used to determine the quality of the four TAIL components (Table 1). Following Wei et al.'s [44] results, Table S3 in SI shows which parameters are included in different standards and green building certification schemes.

2.3.1. Parameters used for rating the quality of the thermal environment (T)

The indoor air temperature was selected to describe the quality of the thermal environment (T) in the TAIL rating scheme. Standard EN 16798-1[17] specifies use of the operative temperature to characterize the thermal environment. However, in low-energy buildings, the difference between air temperature and operative temperature is relatively small [30,7], and the former was therefore selected as simpler to measure. Temperature is one of the five parameters defining how the thermal environment affects human thermal comfort. It is used to estimate two thermal comfort indicators, predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD); it is also used to determine thermal comfort classes when the adaptive thermal comfort model is used [17,20]. Elevated air temperatures can cause thermal discomfort and exacerbate the acute non-clinical health symptoms known as Sick-Building Syndrome (SBS) symptoms [59]; [60]; [61]. Elevated temperatures can also reduce air quality as perceived by building occupants [59]. Studies show that too high and too low temperatures can reduce work performance ([62]; [63]) and affect sleep quality [64] . Temperatures can also affect the chemical processes

Table 1
TAIL indicators.

TAIL component	Indicator	The possible influence of renovation operations
Thermal environment (T)	Air temperature	(1) Thermal rehabilitation (insulation) of an envelope, roof, ground floor, etc. (2) New low-energy windows (3) Installation of low-temperature heating and high-temperature cooling hydronic systems (4) Air-based cooling and heating systems (5) Improved control of heating/cooling systems (6) Installation of sunscreens
Acoustic environment (A)	Sound pressure level	(1) New windows (2) Tightening of the envelope and thermal rehabilitation of envelope
Indoor air quality (I)	Ventilation rate	(1) New ventilation system
	Carbon dioxide concentration	(1) New ventilation system (2) Tightening of the envelope
	Formaldehyde concentration	(1) New ventilation system (2) Tightening of the envelope (3) New materials
	Benzene concentration	(1) Tightening of envelope (2) Thermal rehabilitation of envelope and new windows (3) New ventilation system
	Particle ($PM_{2.5}$) concentration	(1) Tightening of envelope (2) Thermal rehabilitation of envelope and new windows (3) New ventilation system
	Radon concentration	(1) Tightening of envelope (2) Thermal rehabilitation (3) New ventilation system
	Air relative humidity	(1) New ventilation system
	Visible mould area	(1) Thermal rehabilitation (reduced cold bridges) (2) New ventilation system
Visual (luminous) environment (L)	Illuminance	(1) Renovation of a low-energy artificial lighting system
	Daylight factor	(1) Skylights (2) New windows

occurring in buildings, such as the air and surface reactions that affect exposures and physical processes affecting emissions from building and furnishing materials [65].

The quality level of the thermal environment (T) is determined by calculating the percentage of time the temperatures are outside the ranges shown in Table 2, according to the season and the presence of mechanical cooling. These ranges are aligned with the EN 16798–1 standard [17], assuming typical clothing and activity levels for building occupants, and they lead to different levels of discomfort caused by the thermal environment. To be classified in each category, the temperatures can exceed the indicated range by 1 °C for no more than 5%, and by 2 °C for no more than 1% of the occupancy time during which the measurements were performed (during the working hours in offices and night-time sleeping hours in hotels). The approach using the % of the time during occupancy for which temperatures are higher than the recommended ranges is similar to the method proposed by Level(s) [15].

2.3.2. Parameters used for rating the quality of the acoustic environment (A)

The sound pressure level was selected to describe the quality of the acoustic environment (A) in the TAIL rating scheme. The sound pressure level is the most commonly used method to characterize airborne noise. Other parameters characterizing the acoustic environment are often used. These include impact noise both within and between rooms, reverberation time, and the acoustic insulation of the building façade. Because the measurements of these parameters are non-trivial and there are no standard reference performance criteria relating them to human comfort for many of them, these parameters were not selected to characterize the acoustic environment in the present scheme. For sound pressure level, relationships have been established between the sound pressure level and subjectively reported noise discomfort [24] and to predict when work performance is likely to be reduced [22]. Only elevated levels of the sound pressure level (>55 dB(A)) that seldom occur indoors have been shown to have a negative effect on performance, and 85 dB(A) is used as a maximum permitted level for occupational environments (https://www.cdc.gov/niosh/topics/noise/; https://www.osha.gov/noise). However, keeping the noise level indoors low is important, especially for ensuring good sleep quality [34].

Acoustic quality levels (A) as characterized by the sound pressure levels are shown in Table 3. They correspond to those in the EN 16798–1 standard [17]. To be classified in each quality level, the average measured sound pressure levels should not exceed the ranges defined by the indicated quality level. Average sound pressure levels should preferably be determined with no occupants present, but the 5th percentile of the continuously measured sound pressure levels in occupied spaces may be used if measurements made with no occupants present are not available.

2.3.3. Parameters used for rating indoor air quality (I)

Eight parameters were selected to describe indoor air quality in the TAIL rating scheme. As there is no single parameter describing indoor air quality, several different types of indoor air pollutants (chemical, biological and physical) must be considered [39]. These parameters are ventilation rate, relative humidity (RH), carbon dioxide concentrations (CO_2), benzene, formaldehyde, $PM_{2.5}$, radon, and visible mould. Ventilation rate and CO_2 concentration are the most frequently used parameters of indoor air quality ([66]; [67]; [68]; [69]; [70], [79]). However, they may not provide sufficient information to accurately determine the indoor air quality in a building ([72]; [71]; [39]. Additional parameters were therefore included to improve the quality of the rating. The list of possibly relevant indoor air pollutants is quite long [43], but not all of them were included, mainly for practical reasons and the high cost of measuring them all. Another selection criterion was the availability of IAQ guidelines values and relevant permissible exposure levels.

The quality levels of parameters describing indoor air quality (I) are shown in Table 4. The reference values are either from the EN 16798-1 standard [17], from guidelines published by World Health Organization [45–47], or from Level(s) [15]. The quality levels for CO_2 and RH were determined by calculating the percentage of time the different parameters are within the ranges presented in Table 4; to be classified in each quality level, the measurements shall not exceed the range defined by the indicated quality level and the lower quality level for more than 5% of the time, and the range defined by the next lowest quality level for more than 1% of the time during occupancy hours (during the working hours in offices and the night, sleeping hours, in hotels). The quality levels shall be determined for other parameters by checking their compliance with the permissible concentrations presented in Table 4. These permissible concentrations must be exceeded as they are enforced or recommended by cognizant authorities.

2.3.4. Parameters used for rating the quality of the luminous (visual) environment (L)

Illuminance and daylight factor were selected to describe the quality of the visual environment in the TAIL rating scheme. Ade-

Table 2
Ranges of the indoor air temperature (EN 16798-1 [17]).

Quality of the thermal environment (T)	Buildings with mechanical cooling		Buildings without mechanical cooling	
	Heating season[1]	Non-heating[2] (cooling) season	Heating season[1]	Non-heating[3,4] (+cooling season)
Green	22 ± 1 °C	24.5 ± 1 °C	22 ± 1 °C	upper limit $0.33\Theta_{rm} + 18.8 + 2$ °C lower limit $0.33\Theta_{rm} + 18.8 - 3$ °C
Yellow	22 ± 2 °C	24.5 ± 1.5 °C	22 ± 2 °C	upper limit $0.33\Theta_{rm} + 18.8 + 3$ °C lower limit $0.33\Theta_{rm} + 18.8 - 4$ °C
Orange	22 ± 3 °C	24.5 ± 2.5 °C	22 ± 3 °C	upper limit $0.33\Theta_{rm} + 18.8 + 4$ °C lower limit $0.33\Theta_{rm} + 18.8 - 5$ °C
Red	If other quality levels cannot be achieved		If other quality levels cannot be achieved	

$\Theta_{rm} = (1-\alpha)\{\Theta_{ed-1} + \alpha\,\Theta_{ed-2} + \alpha^2\,\Theta_{ed-3}\}$.
where:
Θ_{rm} = outdoor running mean temperature for that day (°C).
Θ_{ed-1} = daily mean outdoor air temperature for the previous day.
α = constant between 0 and 1 (recommended value is 0.8).
Θ_{ed-i} = daily mean outdoor air temperature for the i-th previous day.
Alternatively, using the following approximate formula (when records of daily running mean outdoor temperature are not available: $Qm = (Q_{ed-1} + 0.8\,Q_{ed-2} + 0.6\,Q_{ed-3} + 0.5\,Q_{ed-4} + 0.4\,Q_{ed-5} + 0.3\,Q_{ed-6} + 0.2\,Q_{ed-7}) / 3.8$.

[1] Assuming clo = 1.0, office work and RH = 50%.

[2] Assuming clo = 0.5, office work, and RH = 50%.

[3] Summer and shoulder seasons; Θ_{rm} is the running mean outdoor temperature that can be calculated as follows:

[4] Daily mean outdoor air temperature for the previous day obtained from measurements or from the nearest meteorological station.

quate lighting is essential for performing work [19], and proper room darkening is important for sleep quality [42,35,4]. Access to daylight is equally essential, and many studies indicate that it affects both overall well-being ([73,74]) and cognitive performance ([75]). Moreover, exposure to daylight while awake has been shown to positively affect sleep quality ([76,77,78]).

The quality levels of the luminous environment (L) characterized by illuminance and daylight factor are presented in Table 5. They correspond to those in the EN 16798-1 [17], EN 17037 [18], and ISO 15469 [25] standards. They are to be determined by calculating the percentage of the time with illuminance within the indicated range and comparing calculated daylight factors with the proposed levels; only working hours in offices and sleeping hours in hotels are taken into account.

Table 3
Ranges of the sound pressure level.

Quality of the acoustic environment (A)	Offices[1]		Hotel rooms[1]
	Small office	Landscape office	
Green	≤30 dB(A)	≤35 dB(A)	≤25 dB(A)
Yellow	≤35 dB(A)	≤40 dB(A)	≤30 dB(A)
Orange	≤40 dB(A)	≤45 dB(A)	≤35 dB(A)
Red	If other quality levels cannot be achieved	If other quality levels cannot be achieved	If other quality levels cannot be achieved

[1] According to EN16798-1 [17]; in a small office, i.e., individual office, the nominal occupation density is 0.1 person per m^2 floor, and in the landscape office, it is 0.07 person per m^2 floor.

Table 4
Ranges of the indoor air quality indicators.

Quality of indoor air quality (I)	Green	Yellow	Orange	Red
Carbon dioxide (concentration above outdoors)[1,2]	≤550 ppm	≤800 ppm	≤1350 ppm	If other quality levels cannot be achieved
Ventilation rate[3,7]	≥(10 L/s/p + 2.0 L/s/m^2floor)	≥(7 L/s/p + 1.4 L/s/m^2floor) and <(10 L/s/p + 2.0 L/s/m^2floor)	≥(4 L/s/p + 0.8 L/s/m^2floor) and <(7 L/s/p + 1.4 L/s/m^2floor)	If other quality levels cannot be achieved
Relative humidity offices[2,4] hotel rooms[2,4,5]	≥30%≤50%≥30% and ≤50%	≥25%≤60%≥25% and ≤60%	≥20%≤70%≥20% and ≤60%	If other quality levels cannot be achieved
Visible mold[6,7]	No visible mould	Minor moisture damage, minor areas with visible mould (<400 cm^2)	Damaged interior structural component, larger areas with visible mould (<2500 cm^2)	Large areas with visible mould (≥2500 cm^2)
Benzene[7]	<2 μg/m^3	≥2 μg/m^3	no criteria	≥5 μg/m^3
Formaldehyde[7]	<30 μg/m^3	≥30 μg/m^3	no criteria	≥100 μg/m^3
Particles $PM_{2.5}$ (gravimetric)[7]	<10 μg/m^3	≥10 μg/m^3	no criteria	≥25 μg/m^3
Particles $PM_{2.5}$ (optical)[7]	<10 μg/m^3	≥10 μg/m^3	no criteria	≥25 μg/m^3
Radon[7,8]	<100 Bq/m^3	≥100 Bq/m^3	no criteria	≥300 Bq/m^3

[1] Outdoor CO_2 should be measured or assumed using https://www.co2.earth/; indoor CO_2 according to EN 16798-1 [17].

[2] To be classified in each quality level, the measurements shall not exceed the range defined by the indicated quality level and the lower quality level for more than 5% of the time, and the range defined by the next lowest quality level for more than 1% of the time.

[3] For non-low polluting buildings according to EN 16798-1 [17], because no information on pollution load; the measured ventilation rates (average values of the two measurements) shall be compared with the nominal ventilation rate for that area according to design.

[4] The levels match EN 16798-1 in terms of the humidification requirements [17]

[5] The higher levels selected to avoid house dust mite infestation (survival and reproduction).

[6] According to the Nordic classification system and Level(s); observations in the instrumented rooms should be supplemented by observations in locations where the risk of mould is likely (e.g., those identified by using simulations of surface relative humidity).

[7] The permissible levels that cannot be exceeded: benzene ([45]; [12]), formaldehyde [29]; [45]) and $PM_{2.5}$ [47].

[8] Two-month average value measured in winter [45;11]).

Table 5
Ranges of the visual environmental indicators.

Quality of the luminous environment (L)	Offices		Hotel rooms
	Daylight factor[1]	% of the time with measured illuminance between 300 and 500 Lux[2]	% of the time with measured illuminance ≥100 Lux[3]
Green	≥5.0%	≥60% and ≤100%	0%
Yellow	≥3.3%	≥40% and <60%	>0% to ≤ 50%
Orange	≥2.0%	≥10% and <40%	>50% to ≤90%
Red	If other quality levels cannot be achieved	If other quality levels cannot be achieved	If other quality levels cannot be achieved

[1] The lowest daylight factor to reach respectively ≥750 Lux, ≥500 Lux, ≥300 Lux and ≥100 Lux; the daylight factor values are taken according to Standard EN 17037 [18] for Brussels.

[2] Following the requirements of the HQE green building certification scheme [23].

[3] Following the requirements of CASBEE [3]; CASBEE requirement is only for the illuminance level and not for the frequency of occurrence..

2.3.5. Rating of the overall quality of the indoor environment

A two-step process is used to determine the overall quality of the indoor environment.

First, the quality of the twelve parameters is determined. If some parameters are assessed during different seasons, only the least favourable result is considered when calculating the overall quality of the indoor environment, following a precautionary approach. Then, based on their levels, the overall quality of the indoor environment is determined. The quality levels of the twelve parameters are determined based on the categories defined in Tables 2–5. The quality level of each parameter is obtained by calculating the interim rating using the levels obtained in different locations in a building, as follows:

$$\text{Interim rating} = \frac{\sum_1^k R_k * O_k}{n} \qquad (1)$$

where k is the number of quality levels; R is the rank for the specific quality level k ($R = 1$ for green level, $R = 2$ for yellow level, $R = 3$ for orange level, and $R = 4$ for red level); O is the number of observations (measurements) for the specific quality level k; n is the total number of observations (measurements) where the quality of the parameter was determined.

The interim rating defines the quality levels: green when the rating is between 1 and 1.4; yellow when it is between 1.5 and 2.4; orange for a rating between 2.5 and 3.4; and red when it is between 3.5 and 4. The ranges of interim ratings were decided arbitrarily to guarantee that the actual quality level matches the majority of the quality levels determined in a building.

Secondly, once the quality level of each parameter has been determined, the quality level of the four major components included in the scheme is estimated by taking the lowest quality level among the parameters defining each component of TAIL. The lowest interim rating will always determine the quality level of the TAIL components, even when the quality levels of parameters defining TAIL were made in several different seasons of the year.

Once the quality levels for all four TAIL components have been separately determined, the overall quality level for the building is determined by selecting the lowest quality level among the four TAIL components. Selecting the lowest quality level creates an incentive to improve the IEQ; this topic is discussed below.

2.4. Assessment protocol

2.4.1. Overall assessment protocol

The parameters defining TAIL are assessed by measuring ten parameters, by simulation of the daylight factor, and from observations performed by a qualified expert for mould; for daylighting and mould, no simple on-site assessment methods exist. The measurements are performed in a building and outside the building (outdoors) to create a reference.

The assessment of parameters defining TAIL is performed before and after renovation in the same season and during the same months (and weather if possible), to avoid seasonal bias. The assessments are ideally performed in both heating and non-heating (or cooling) seasons to capture seasonal differences, but assessments are also acceptable during one season. Inclusion of shoulder periods (spring and autumn) could be useful as a supplement to assessments made during either heating or non-heating season but are not required. Radon measurements are only performed during the winter months and only in radon-prone areas. The daylight factor, as it is simulated, is determined only once. This also applies to the observation of mould. During the on-site measurements, the building should be operated and occupied as usual to capture typical conditions; the operating mode of the building (e.g., ventilation airflows, set-points, use of energy, etc.) and occupation density should be reported.

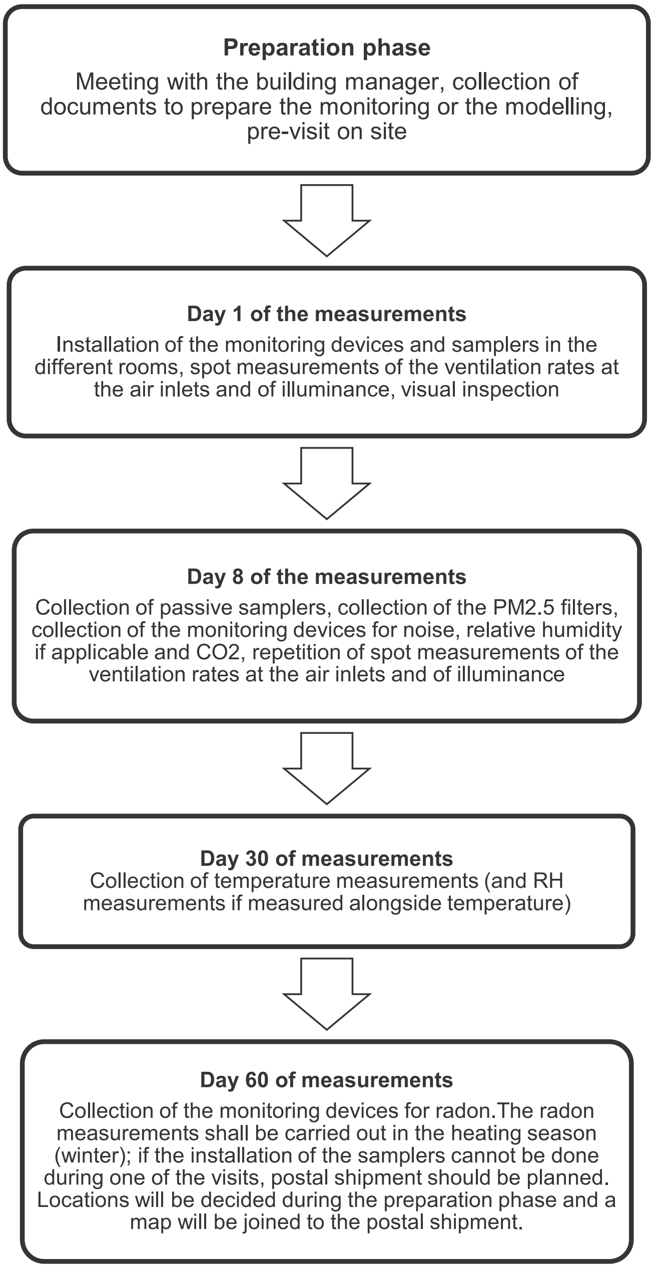
It is proposed that assessment of the parameters defining the TAIL values be made a few months before the planned deep energy renovation to capture the typical conditions that occur in a building, but not earlier than one year before the energy renovation. It is proposed that the measurements after renovation should be made after the building has been in regular operation for not less than three months but not later than one year after renovation, to ensure that observed quality levels can be attributed to the actual renovation and not to other factors. These periods may have to be adjusted once more experience of using the scheme in actual buildings has been gained.

In some cases, it is permissible to replace the assessment before renovation with the data retrieved from previous monitoring campaigns performed in the building. This waiver can be granted if measuring protocols match the protocols recommended for the present rating scheme and if measurements were performed not earlier than two years before the date of planned deep energy renovation. Measurements of some parameters retrieved from the Building Management Energy System may also be used if they are available.

The overall process of assessing the parameters included in the present rating scheme for a given building before and after deep energy renovation is shown in Fig. 2.

In each building, the assessment of parameters should be made in several locations. The number of locations is a compromise between the need to ensure that the assessment represents the whole building and its technical and economic feasibility. The costs include measurement/sampling with one or two operators and the time it takes to analyse the data. The following principles are proposed regarding the selection of locations where the TAIL parameters are assessed:

- The rooms with the lowest and the highest occupation density should be selected.
- Rooms with different geographic orientations should be selected.
- Rooms facing both street/road, garden should be selected.
- Rooms with different typologies should be selected. These should include:
  - Rooms built or retrofitted (during any previous renovation) at the same time.



Preparation phase

Meeting with the building manager, collection of documents to prepare the monitoring or the modelling, 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 PM2.5 filters, collection of the monitoring devices for noise, relative humidity if applicable and CO2, repetition of spot measurements of the ventilation rates at the air inlets and of illuminance

Day 30 of measurements

Collection of temperature measurements (and RH measurements if measured alongside temperature)

Day 60 of measurements

Collection of the monitoring devices for radon.The radon measurements shall be carried out in the heating season (winter); if the installation of the samplers cannot be done during one of the visits, postal shipment should be planned. Locations will be decided during the preparation phase and a map will be joined to the postal shipment.

Fig. 2. The process of assessment of the parameters used to derive the level of TAIL.

  - Rooms that share the same air handling unit and ventilation/air conditioning zone.
  - Rooms with similar building materials, furniture, etc.
  - Rooms with similar types of solar shading devices.
- Single and open-plan offices in office buildings and rooms of different sizes in hotels.
- Rooms that are occupied.

The assessments are only carried out in office rooms in the case of office buildings and guest rooms in the case of hotels; the lobby, service rooms, meeting or conference rooms, corridors, etc. are not considered because they are not designed for permanent occupation and have very variable schedules of use. The sum of the areas represented by the measuring locations should correspond to about 10% of the total office floor area in office buildings and the total guest room floor areas in a hotel. Depending on the building's size, a minimum of two locations should be selected. If feasible and to improve the quality of the assessment of IEQ, the number of locations should be higher, e.g., at least one per floor. Before the assessment, the different areas of the building sharing common features must be identified by the building manager or technical staff to facilitate the choice of the measurement locations.

In each location, the assessments should ideally be performed in the centre of the room, not closer than 1 m from the wall, about 0.8 to 1 m above the floor or on a table/desk or the bedside table. For thermal environment measurements, a height of 0.6 m is considered to represent what is experienced by a seated person. Placing instruments in ventilation channels or close to heating sources, including direct sunshine, must be avoided.

In each season, the assessments are performed during at least one working week (Monday to Friday, but only during working hours) for office buildings and a full week (Monday to Monday, Tuesday to Tuesday, etc. but only during sleeping hours) for hotels, except for temperature for which the measurements should continue for one month, and for radon, for which the measurements should continue for two months.

Table 6 summarizes the different assessment protocols.

2.4.2. Assessment of the thermal environment (T)

The temperature is measured according to the ISO 7730 [27] and ISO 7726 [26] standards: calibrated sensors with an accuracy of ± 0.5 °C or better are used. The suggested logging interval is from 1 to 10 min. The temperature outdoors should be recorded simultaneously or obtained from the nearest meteorological station.

2.4.3. Assessment of the acoustic environment (A)

The sound pressure level is measured according to the standards EN ISO 10052 [87] and EN ISO 16032 [86]. The measurements are made with calibrated sensors with an accuracy of ±1 dB(A) or better. The measurements are made with all systems in operation to adhere to the reference criteria. They are made with typical levels of background (ambient) noise and with windows closed. Continuous measurements are preferable, and if so, it is recommended that a 1 to 10 min logging interval should be used. If measurements are made in occupied offices, the 5th percentile of the measured sound pressure levels during working hours is used: it is assumed that people will leave the office rooms from time to time during the day, and the 5th percentile was selected as representative of unoccupied conditions. In unoccupied offices, the mean measured sound pressure level is used.

2.4.4. Assessment of indoor air quality (I)

Except for mould, which is assessed by observation, all parameters defining indoor air quality in the scheme are to be measured. Different measuring protocols and different standards should be followed, as listed in Table 6. Passive samplers, when used, should be suspended so that they are not located on a surface; any adhesive should be strictly avoided when mounting the samplers, as they could be a source of airborne pollution. In the case of mould, the size of any visible patch of mould is to be estimated. This assessment can only be made by a person trained to perform such observations.

The time-integrated measurements are made 24/7. This applies to gravimetric $PM_{2.5}$, benzene, formaldehyde, and radon measured using passive samplers. Mould observations and ventilation rates are spot assessments. The measurements of CO_2, relative humidity, and $PM_{2.5}$ using optical counters are to be performed during working hours in offices and during the night (sleeping) hours in hotel rooms.

2.4.5. Assessment of the luminous environment (L)

The light intensity is determined by performing measurements of illuminance [16] and by simulation of the daylight factor.

Illuminance refers to the total light delivered on a horizontal surface at desk height (0.85 m above the floor) by either an artificial lighting system or through windows (daylight); at the same time,

Table 6
Measurement protocols of the TAIL indicators.

Indicator	Measurements
Air temperature	Online measurements. Calibrated sensors with an accuracy of at least 0.5 °C shall log temperatures. Measurement duration: one month. Time-interval: from 1 min to 10 min. An additional measurement of outdoor relative humidity is recommended both in offices and hotels; data from the near-ambient measuring station can be used instead.
Sound pressure level	Online measurements. Measuring period from Monday to Friday in offices and seven consecutive days in hotels. Time-interval: 1 min. Calibrated sensors with an accuracy of at least 1 dB(A) shall be used to log noise levels.
Ventilation rate	Two measurements shall be performed at the onset and towards the end of continuous measurements carried out for other parameters in buildings with mechanical supply and/or exhaust. In naturally ventilated buildings, infiltration rates can be measured. Calibrated flow hood (capture hood) shall be used to measure airflow on all inlets and exhausts in the rooms selected for measurements.
Carbon dioxide concentration	Online measurements. Calibrated Fourier Transform infrared (FTIR) sensors with an accuracy of at least ±50 ppm of reading shall be used to log carbon dioxide. Measuring period from Monday to Friday in offices and seven consecutive days in hotels. Time-interval: from 1 min to 10 min. An additional measurement of CO_2 concentration outdoors is recommended both in offices and hotels, but 400 ppm can otherwise be assumed.
Formaldehyde concentration	Passive measurements from Monday to Friday in offices and seven consecutive days in hotels. To be representative, it is recommended (not compulsory) that measurements should be carried out twice in the most critical periods of the year in terms of the outdoor temperature, i.e., in winter and summer. In this case, the average concentration is used for the ranking. Measurements must comply with ISO 16000-4:2011 [82].
Benzene concentration	Passive measurements from Monday to Friday in offices and seven consecutive days in hotels. An additional measurement of the outdoor concentration is recommended, but data from the nearest ambient air quality monitoring station can be used instead. To be representative, it is recommended (not compulsory) that measurements should be carried out twice in the most critical periods of the year in terms of the outdoor temperature, i.e., in winter and summer. In this case, the average concentration is used for the ranking. Measurements must comply with ISO 16017-2:2003 standard [83].
Particle ($PM_{2.5}$) concentration	Gravimetric (preferable) or measurements with calibrated optical counters shall be performed. Measurements must be performed from Monday to Friday in offices and on seven consecutive days in hotels. An additional measurement of outdoor concentration is recommended, but data from the nearest 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 in terms of the outdoor temperature, i.e., in winter and summer. In this case, the average concentration is used for the ranking. Gravimetric measurements must comply with standard CEN – EN 12341:2014 [84].
Radon concentration	Passive measurements. The measuring period is two months during winter only. Passive dosimeters must be installed in 2 locations on 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 [85].
Air relative humidity	Online measurements. Calibrated sensors with an accuracy of at least 5% shall log indoor air relative humidity. Measuring should be for one month in the case of temperature monitoring with the same instrument, otherwise, the measurement period should be from Monday to Friday in offices and seven consecutive days in hotels. Time-interval: from 1 min to 10 min. An additional measurement of outdoor relative humidity is recommended both in offices and hotels, but data from the nearest ambient measuring station can be used instead.
Visible mould area	Observations in the instrumented rooms. In addition, other locations should be included where a mould risk is present according to surface relative humidity simulations.
Illuminance	Spot measurements the first day (morning + midday + afternoon) of the monitoring and the last day (morning + midday + afternoon) at 5 locations per room (averaging measurements in the middle of the room + 4 corners). Calibrated sensors with an accuracy of at least 3 lx (or 3% of the measured value with the resolution of 1 lx) shall log illuminance. An additional measurement of outdoor illuminance level is recommended.
Daylight factor	Dynamic daylight simulations should be performed according to EN 15193-1 [81] (no standard simulation tools are available, the one recommended is based on radiance) for one year.

it must be ensured that the lighting system is providing a sufficient illuminance level. The measurements are made with calibrated sensors having an accuracy of ±3 Lux (or ±3% of the measured value with the resolution of 1 Lux) or better. The measurements of illuminance shall encompass the task light illuminance and the background lighting level; for both, the requirements are the same. Spot measurements and continuous measurements can be made; in the latter case, a logging interval of 1–10 min is recommended. The measurements shall be repeated on at least two days and three times per day in the case of the spot measurements.

The daylight factor assumes a constant ratio between the illuminance levels outside and illuminance levels inside. This ratio is not constant ([80]), so EN 17037 [18] recommends using dynamic daylight simulations if possible. The amount of daylight in a room using daylight factors is calculated (not measured) on a horizontal work plane divided into a grid with a height above the floor level of 0.85 m. The sky type assumed should be TYPE 1 or TYPE 16 from ISO 15469 standard [25], and it should be stated what type was used in the calculations. A specialized simulation tool for estimating daylight factor can also be used.

3. Feasibility study in eleven pilot buildings

The TAIL rating scheme was trialed in six office buildings (Offices #1 to #6) and five hotel buildings (Hotels #1 to #5) located in Southern, Central, and Northern Europe, in different climatic zones and countries. The purpose was to examine the feasibility of TAIL and identify the need for any immediate modifications. The eleven buildings were planed to be retrofitted, and the TAIL scheme was used only before the buildings underwent an energy retrofit. The measurements in office buildings were performed in the heating season between April 2019 and March 2020. The measurements in three hotel buildings (Hotels #3 to #5) were made between May and June 2019 when the heating and cooling systems were both out of service. The measurements in Hotel #1 were performed in April 2019 with the heating system on, and Hotel #2 in May 2019 with the cooling system on. Apart from Office #6, between two and eight rooms in each building were selected for the measurements to represent different room types, floors, and building orientations, as described in section 2.4.1. Although only one room was measured in Office #6, the results were kept as the purpose of the measurements was to examine the feasibility of the TAIL rating scheme rather than the building's IEQ. The measurements in office rooms were made when they were occupied and during working hours, while the measurements in the hotel rooms were made when unoccupied during the night.

Fig. 3 shows the classification of IEQ in buildings using the TAIL rating scheme. The overall IEQ in these buildings was somewhat inferior because it was rated to be moderate (orange level) or poor (red level) since at least one of the TAIL components was rated to have this quality level, although other TAIL components did reach higher quality levels.

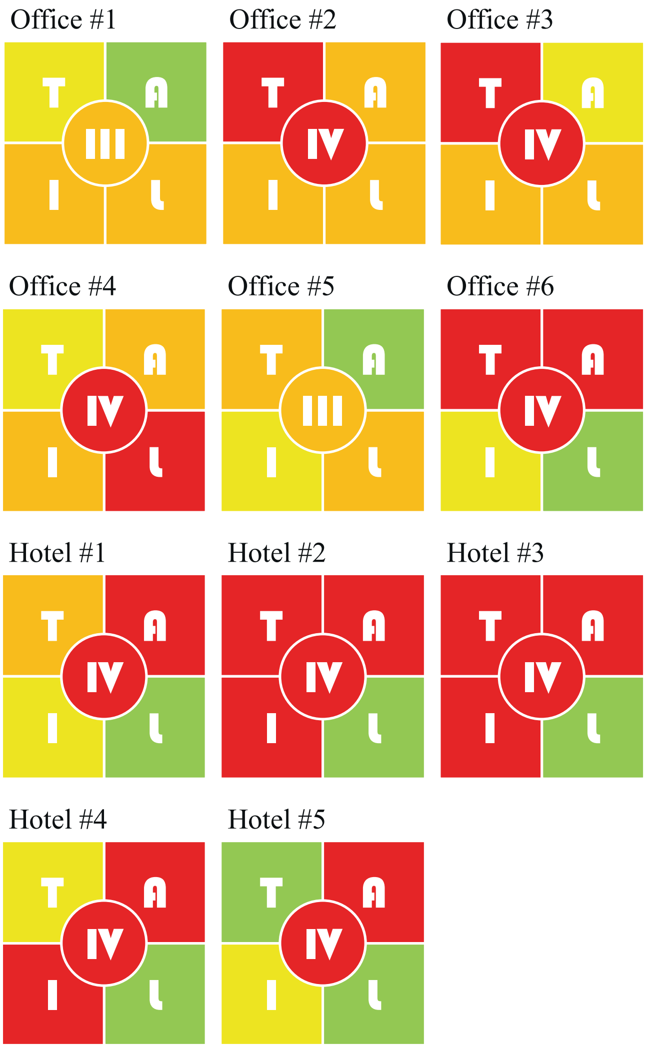


Fig. 3. Classification of pilot buildings using TAIL.

The quality levels of the thermal environment (the T component in the scheme) in the buildings are shown in Fig. S1 in SI. The quality levels of the thermal environment in Hotels #4 and #5 were rated as medium (yellow level) or high (green level), because the air temperatures in the selected rooms were between 21 °C and 24 °C during the night hours. Hotels #1 to #3 were rated as moderate (orange level) or poor (red level) because the air temperatures were often lower than those required for the green and yellow levels. A possible reason for the low temperatures in these hotel rooms is that it was impossible to make measurements in occupied guest rooms. As the measurements were intended to examine the measuring protocol, they were nevertheless executed in unoccupied hotel rooms. The thermal environments in four office buildings were designated as moderate (orange level) or poor (red level). The reasons were large temperature variations in time (Offices #2, #3, and #6) and space (Office #5) in the buildings so that the rooms were either overheated or insufficiently heated. The thermal environment in two office buildings (Offices #1 and #4) was designated as medium (yellow level). This represented the average quality level of the different rooms, which varied between the green and orange levels. Overall, the buildings had different thermal conditions, and the measurements of the T component in TAIL could discriminate between them.

The quality levels of the acoustic environment (the A component in the scheme) are shown in Fig. S2 in SI. The average sound pressure level (LAeq) during the night hours was higher than 35 dB (A) in all the hotel buildings where measurements were performed, and the variation in the sound pressure levels measured between 10 pm and 6 am was <3 dB(A). This suggests that the noise came from the building installations. The quality levels of the office buildings were high (green level) or medium (yellow level), except for Offices #2 and #6. These two office buildings were situated near roads, and the sound pressure levels were always high during the day. As in the case of the thermal environment, buildings had different acoustic conditions that are differentiated by the measurements of sound pressure level and result in differences between the quality of the A component in TAIL.

The levels of IAQ (the I component in the scheme) are shown in Figs. S3 and S4 in SI. Most of the measured concentrations were found to comply with the requirements corresponding to high (green level) and medium (yellow level) quality levels. In one office building (Office #1), the concentrations of CO_2 corresponded to a moderate (orange level) quality level. The reason was a malfunctioning ventilation system; thus, six of the seven measured rooms in this building were at the orange level. In two other office buildings (Offices #2 and #3), the quality level associated with the CO_2 concentration ranged from high-quality (green level) to poor (red level). In this case, the reason was that the occupant density was too high for the ventilation in some rooms. The relative humidity was below 25% in three office buildings (Offices #2, #3, and #4), so they were rated as moderate (orange level). The relative humidity was often higher than 60% in three hotel buildings (Hotels #2 to #4), which implies an increased risk of house dust mites. The measurements could show differences in the quality level of the I component in TAIL, although there were various reasons for them.

The quality levels of the visual (luminous) environment (L component I the scheme) are shown in Fig. S5 in SI. The overall luminous quality levels in the five office buildings were moderate (orange level) or poor (red level) for two possible reasons. First, the illuminance levels at desk height in some rooms were often higher than 500 lx, particularly at midday, and even more than 1000 lx because of malfunctioning or not accessible sun protection systems. This shows that TAIL is capable of identifying problems with such installations. Second, when the outdoor illuminance was low, the artificial lighting in some buildings (Office #3) could not provide sufficient light. All in all, the measurements of the L component in the scheme could detect differences in the luminous environment in the selected buildings.

The field measurements discussed above documented the feasibility of the TAIL rating scheme and confirmed its intended attributes. The measurements indicated which parameters could be improved during the retrofit to achieve a higher overall quality of the indoor environment. They also indicated which IEQ parameters had good quality levels and should be at least maintained during the retrofit. The TAIL rating scheme could also discriminate between buildings based on the indoor environment quality levels and classify them accordingly.

4. Discussion

In the absence of a widely used standard or an approved method for rating the overall IEQ in buildings, a rating scheme was developed within the ALDREN project called TAIL. TAIL is not just a reporting scheme but also a rating scheme for IEQ in buildings during their intended use. The scheme makes it possible to rate the four components describing IEQ and derives an integrated rating of IEQ based on the quality of these four components. TAIL is voluntary and does not supersede the national codes and regulations, but it is based on existing standards and guidelines. Reporting all indoor environmental quality components together, as is done in TAIL, has not previously been done in this form, and consequently, this could be considered as an important new contribution. The feasibility of the scheme was tested by carrying out measurements in eleven buildings. These measurements showed that using the scheme made it possible to identify several problems with IEQ that were caused by malfunctioning equipment or by other events. The measurements provided useful data and input, which were then used to make small renovations (not reported here). These measurements also confirmed that the protocol and the TAIL rating scheme concepts are operational and can be used in practice.

It is conventional to present the specific parameters describing the components of IEQ that are included in the existing standards and certification schemes dealing with the comfort, well-being, and health of building occupants [44]. The unique feature of TAIL is that it provides a quantitative rating of the quality of the components describing IEQ and an integrated overall quality rating of the indoor environment in a building; these assessments are made when a building is in normal use. The TAIL rating scheme can thus be considered to provide new and systematised information on the indoor environmental quality in a building. Following the original design intention, TAIL classifies and compares IEQ and its components before and after a renovation and provides some level of comparability between different renovation strategies. However, it cannot be ruled out that TAIL might evolve into a rating scheme that will make it possible to compare IEQ levels in different buildings, as is done in energy labelling.

The scheme can be regarded as a relatively crude yet robust method for rating components and the overall quality of indoor environments. The quality levels are based on the measurement, simulation, or observation of only twelve parameters characterizing IEQ, whereas as many as 90 parameters are used to characterize IEQ in different standards and certification schemes [44]. Many more parameters would have to be used to ensure a rigorous and accurate characterization of IEQ, but it should be noted that using additional parameters will make the measuring protocol more expensive to execute and require more effort when implemented in practice. The selection of 12 parameters was a compromise between what is absolutely minimum, practically achievable, pragmatic, and yet credible for rating IEQ in buildings. In the future, the effect of any proposed addition of new parameters on the precision of the overall rating will have to be investigated.

Air temperature is the only measurement used to characterize the thermal environment represented by the T component in the scheme. Usually, operative temperature is used to estimate the indoor thermal environment's impact on building occupants. However, continuous measurements that log operative temperature are not simple. New studies show that temperature and operative temperature are quite similar in low-energy houses, especially with radiant systems, while poorer agreement is found in buildings with mixing ventilation [30,7]. Air temperature is considered to represent the thermal environment reasonably well in most buildings. It should be emphasized that the requirements for the quality levels based on air temperature reflect the 16798-1 standard [17] for buildings with and without mechanical cooling. The TAIL rating scheme does not include parameters that characterize local discomfort caused by draft, thermal gradients, or thermal asymmetry, although draft is a widespread complaint among building occupants and office employees, and airspeed provides information on local cooling. They were omitted because the necessary instrumentation is expensive, and making the measurements required would be very time-consuming.

The acoustic environment (A) is characterized by the sound pressure level in the scheme. It was selected because a low noise level is essential for sleep quality [34] and because it is in accordance with the EN16798-1 standard [17]. The acoustic environment could also be characterized in terms of impact noise within and between rooms, by the reverberation time, and by the acoustic insulation of the building façade, but because the measurement of these parameters is non-trivial, and because there are no standardized performance criteria for many of these metrics, they were not included in the TAIL characterization of the acoustic environment. A further important quality of the acoustic environment is the distraction created by noise, and this is one of the major complaints made by office workers. However, no standard method for its measurement has yet been proposed.

Indoor air quality (I) in the scheme is characterized by seven parameters. In the absence of an IAQ metric [39], a selection of relevant parameters was made, taking into account the standards and guidelines dealing with IAQ. The renovation process may result in the reappearance of toxic pollutants hidden in the building's structure, such as polychlorinated biphenyls (PCBs), asbestos, or other pollutants that have not been included because their measurements are non-trivial or because no IAQ guidelines have been proposed for some of them.

Illuminance on a horizontal surface, a parameter often used to characterize the luminous environment (L), is used as a simple measure to ensure adequate lighting [57]. The dynamics of daylight through lengthy measurements prescribed by EN 17037 standard [18] are relatively complicated, so the illuminance levels due to daylight penetration into buildings are to be derived not by measurement but by calculating the daylight factor. No other parameters describing visual quality are considered, not even glare or the colour temperature of artificial lighting, even though the latter is important for the use of energy-saving light sources, and glare is a frequent complaint in buildings. As in the case of other components of IEQ, the measurement of these parameters is too expensive and complicated to be feasible in the present context.

Rather than setting arbitrary quality levels, the TAIL rating scheme refers to the quality levels defined by Standard EN 16798-1 [17], so they can be assumed to be widely accepted and used; arbitrary credits are used in many certification schemes [44], and other methods to rate IEQ [32,37,38]. The principle of the approach is that the quality level of all components contributing to the overall rating of IEQ must be high if the indoor environmental quality is to be regarded as high. Consequently, no weighting or any other form of qualitative judgment of each component's importance has been proposed, instead, all aspects of IEQ are treated as being of equal importance. If one component is of poor quality, this is assumed to affect the overall quality of the indoor environment. The proposed method can be regarded as precautionary. It also protects against the trade-offs between different components of IEQ, creates an incentive for improvement, and encourages excellence and innovation. This approach is analogous to the derivation of different certification levels in the DGNB scheme [9] or the Green Mark scheme [2]; although in these schemes, a higher quality level or class is allowed even though some parameters or components of the scheme have not reached this class. The proposed approach is more similar to the method for determining the ambient pollution level (see air quality index in EU, https://www.eea.europa.eu/themes/air/air-quality-index or Pollutant Standards Index (PSI) in Singapore, https://www.haze.gov.sg/), where the highest concentration of any pollutant (which in the case of the TAIL rating scheme is the lowest quality level) determines the ambient (outdoor) air quality level. Averaging quality levels results in a loss of information and can lead to misinformation [48] so it was rejected. TAIL is a rating scheme, not a continuous metric in which each component is derived on the same scale. It would be useful to know the weighted impact of each component of IEQ on the overall rating of IEQ, but there is insufficient information on this matter in the current literature [20].

When determining the quality level of each of the parameters used to assess the components of IEQ, measurements, simulations, and observations in selected locations (rooms) within the building must be performed. All the selected locations should be representative of the entire building. Consequently, taking the lowest quality level as representative of the building would be too restrictive and unfairly penalizing. Therefore, in this particular case, an arbitrary interim rating was proposed by ranking the measurements depending on their quality level.

The current protocol for deriving the quality levels of parameters defining the TAIL components makes it possible to exceed the ranges defining the quality levels for some parameters and for some of the time, generally for no more than 5% of the time. The exceedance was allowed to compensate for measurement imprecision and temporary fluctuations in the measured parameters that may cause unexpectedly high peaks and changes in the measured parameters. The proposed exceedance time of 5% should be validated in future measurements, but it is the same as in other documents that allow exceedance, e.g., the Danish Building Regulations [58] and Level(s) [15] and was therefore selected.

TAIL is used to rate the IEQ in buildings during their normal use. It is therefore based predominantly on measurements performed in buildings during normal use and preferably in different seasons to capture seasonal variability; one parameter is simulated, and one is observed, as no standard measurements are available. Modelling can support the measurements, but it is unclear whether it can replace them as models may have a ''performance gap'' (may not exactly correspond to reality) and require underlying assumptions that may not exactly match the conditions when a building is in use.

The scheme is based on the objective measurement of parameters describing IEQ, but ratings made by building occupants provide useful information about the quality of the indoor environment that objective measurements cannot capture. There are many different methods for collecting occupant ratings, and they have not yet been standardized and are not fully validated as a tool that can provide repeatable results for making comparisons between different buildings. One reason is that they are affected by the personalities, preferences, etc., of the occupants providing the ratings. This is why they were not selected as an alternative or additional measurement method in the TAIL scheme.

Future developments of the scheme may also consider linking economic value with each TAIL component and the overall IEQ quality level of a building. It would allow economic assessment of a building that took account of its location, first cost, utility costs, and overall IEQ level, allowing better characterization of non-energy benefits. The use of the scheme to characterize and classify IEQ in buildings may additionally lead to innovation and overall improvement of IEQ at a reduced energy cost. The TAIL assessment value for IEQ could be reported together with an energy certificate and, in this way, would focus more attention on achieving high indoor environmental quality when the renovation is planned; the same may also apply to new construction. To support the measurement of the TAIL components, sensors that target the specific parameters that define indoor environmental quality can be pre-installed, reducing subsequent measurement costs. Modelling and simulation tools can be further developed to support the prediction of the TAIL rating at the design stage, either in full or partially, making it possible to choose the best renovation strategy, as suggested by Heibati et al. [21]. Regular and repeatable ratings (every 2–4 years) would be necessary to identify any irregularities in building performance and any need for changes to maintain the original IEQ quality levels. The TAIL rating scheme was developed specifically for offices and hotels, so future revisions and tests should examine its applicability to other building types.

TAIL is only one of several possible approaches to assessing indoor environmental quality. The overall goal of these schemes should be to satisfy the needs of buildings' occupants. These needs can be defined differently and can differ between different population groups. TAIL makes reference to European standard EN 16798-1 [17] describing the quality levels of the parameters defining indoor environmental quality, some of which but not all are based on perception, as well as to the air quality guidelines issued by WHO that are based on health criteria and are applicable worldwide. Reference criteria can be selected differently, e.g., if the burden of disease is a reference criterion for IEQ, Disability-Adjusted Life Years (DALYs) or Quality-Adjusted Life Years (QALYs) can be used instead.

5. Conclusions

A new IEQ rating scheme called ALDREN-TAIL, or in short, TAIL, was proposed, creating a framework for rating IEQ components and the overall IEQ level in a building during its normal use. The acronym TAIL stands for the thermal environment (T), acoustic environment (A), indoor air quality (I), and luminous (L) environment. Twelve parameters are used to assess the four IEQ components. These parameters were selected based on a comprehensive review of indicators that had been proposed previously to characterize indoor environmental quality. The quality levels of each parameter comply with the existing criteria in green building certifications, Standard EN 16798-1, the WHO guidelines for IAQ, and the European Level(s) framework. A strong feature of the TAIL rating scheme is that it does not use any arbitrary credits or weighting to determine the quality level of the indoor environment. The four major components of IEQ are equally important, so if one component is found to have a poor quality level, the overall level of IEQ is considered poor. A feasibility study of the TAIL rating scheme was executed by using TAIL to characterize the IEQ in six office and five hotel buildings that were about to be subjected to energy renovation. The results of these field measurements confirm that the scheme can discriminate between the IEQ in different buildings and can connect the measured levels with specific events. In the original design intention, TAIL was developed to classify and compare IEQ and its components before and after an energy renovation, to document the impact of energy renovation on IEQ, but it cannot be ruled out that TAIL might evolve into an overall rating scheme that will make it possible to compare the IEQ in different buildings as in energy labelling. The TAIL rating scheme should therefore be considered as the first step in developing a classification, and later an integrated index characterizing IEQ in buildings, and as a standardized approach at the EU level.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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