Energy & Buildings 209 (2020) 109683

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enbuild

Review of parameters used to assess the quality of the indoor environment in Green Building certification schemes for offices and hotels

Wenjuan Wei[a], Pawel Wargocki[b,*], Johann Zirngibl[a], Jana Bendžalová[c], Corinne Mandin[a]

[a] University of Paris-Est, Scientific and Technical Centre for Building (CSTB), Health and Comfort Department, French Indoor Air Quality Observatory (OQAI), 84 Avenue Jean Jaurès, Champs sur Marne, 77447 Marne la Vallée Cedex 2, France

[b] International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark, Nils Koppels Alle, Building 402, DK-2800 Kongens Lyngby, Denmark

[c] Environment and Building Energy Efficiency (ENBEE), Palkovicova 5, 82108 Bratislava, Slovakia

ARTICLE INFO

Article history:
Received 19 September 2019
Revised 13 November 2019
Accepted 8 December 2019
Available online 9 December 2019

Keywords:
Temperature
IAQ
sound
light
comfort
ALDREN project

ABSTRACT

Fourteen Green Building (GB) certification schemes were reviewed to examine the parameters they used to assess indoor environmental quality (IEQ). Ninety different parameters were identified. They were classified into four major IEQ components defining the thermal, acoustic and visual environments, and indoor air quality (IAQ). For the thermal environment, the most commonly used parameters were PMV, PPD, room operative temperature, room air temperature, room air relative humidity, and air speed. For the acoustic environment, the most commonly used parameters were ambient noise and reverberation time. For the visual environment, the most commonly used parameters were illuminance level, daylight factor, and spatial daylight autonomy. For IAQ, the most commonly used parameters were ventilation rate (outdoor air supply rate), TVOC, formaldehyde, CO_2, CO, PM_{10}, $PM_{2.5}$, ozone, benzene, and radon. Credits are used to rate the importance of different parameters for the overall level of IEQ in the reviewed schemes. Using these credits and the figures published in peer-reviewed papers, it was found out that the average contribution of the thermal, acoustic, luminous environment and air quality parameters to the overall IEQ rating of a building was respectively 27%, 17%, 22%, and 34%. The present work can be regarded as a reference for selecting parameters that are commonly used to characterize IEQ.

1. Introduction

The deep energy renovations of existing buildings in Europe will have to be carried out at a much higher rate to decarbonize European building stock in time to achieve the ambitious goals for significant reductions in energy use that have now been set by the European Commission. To this end, the European Commission launched many projects that would provide tools, methods and incentives for securing a higher rate of transformation of existing building stock into one with low energy use. One of these projects is the ALDREN project which was launched in November 2017. It brought together several partners from different European Union member states (http://aldren.eu/). ALDREN stands for "ALliance for Deep RENovation in buildings". The primary aim of this project was to extensively consolidate, promote, and implement harmonized procedures to overcome market barriers and support deep building renovation operations.

One important task within the scope of the ALDREN project was to provide methods for determining whether deep energy renovation has any effects on the health and well-being of building occupants. One reason for this was to address one of the conditions set by EPBD [1,2], which requires that building IEQ should not be degraded in the process of energy renovation. Specifically, EPBD stipulates that "*Member States should support energy performance upgrades of existing buildings that contribute to achieving a healthy indoor environment*" and that each long-term renovation strategy shall encompass "*an evidence-based estimate of expected energy savings and wider benefits such as those related to health, safety and air quality*". The ALDREN project therefore planned to develop a measurement protocol and a systematic method for rating IEQ that could also be used to estimate any non-energy benefits associated with improved IEQ that can add financial value. To meet these goals, the parameters that describe IEQ and their levels had to be defined to serve as a verification tool that could be used to

* Corresponding author.
E-mail address: paw@byg.dtu.dk (P. Wargocki).

https://doi.org/10.1016/j.enbuild.2019.109683
0378-7788/

document that no health risks are introduced and that the well-being of building occupants is not reduced as a result of an energy renovation. Although the definitions of IEQ agree as to what constitutes the quality of indoor environment (see Supplementary Material), there is no common definition or agreed standard set of parameters that should be measured to characterize IEQ and there is no standard IEQ metric.

It is generally agreed that IEQ consists of four major components: thermal environment, indoor air quality (IAQ), acoustic environment, and visual environment. According to the US Green Building Council, IEQ concerns the conditions inside a building and their effects on the occupants [3] (see Supplementary Material). IEQ is an important aspect of existing GB schemes worldwide [4,5]: A review of the credits assigned in BREEAM and Green Star NZ GB certification schemes has revealed that about 10% to 20% of all credits that can be assigned to the different parameters certified by these schemes are associated with IEQ [6]. GB schemes include many parameters that are used to assess IEQ and prescribe their ranges to ensure that IEQ conditions in buildings are acceptable, with zero or low health risks and high occupant well-being. Consequently, GB schemes can be regarded as a useful source of reference and guidance for the selection of parameters that should be used to assess IEQ in buildings undergoing energy renovation. However, there have been no reviews performed so far that summarize the parameters included in GB schemes to characterize IEQ and discuss their relevance and accuracy.

The present work, initiated within the ALDREN project as a way to reach its objectives, was consequently performed to review and systematize parameters used in GB schemes for assessing the IEQ to create a proper reference that can be used broadly for any future research and development activities that require the rating of IEQ in buildings. The focus was on offices and hotels, as these were the target buildings in the ALDREN project. The reference created by reviewing GB schemes was additionally expected to provide information that can specifically be used within the ALDREN project for selection of parameters for rating IEQ in buildings undergoing energy renovation.

2. Methods

GB schemes were reviewed to identify and summarize the parameters that are currently used to assess IEQ in buildings with the focus on offices and hotels. The recommended ranges of these parameters that prescribe conditions ensuring the health and well-being of building occupants were also retrieved. IEQ components including the thermal environment, IAQ, the acoustic environment, and the visual (luminous) environment were studied in order to address overall IEQ. The survey of GB schemes was extended by examining peer-reviewed articles, reports of European projects, and a major EU standard on IEQ (EN 16798:2018) [8] to verify and supplement the information collected from GB schemes. Previously completed and on-going European projects were found by an online search and by interviewing ALDREN partners and IEQ specialists.

Fifty-five schemes from 31 certifications obtained during a study of IAQ requirements in GB certifications were included in the survey [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 study of IAQ requirements mentioned above had been completed. The former included the European Level(s) scheme, which will be officially launched in 2020 [9], and the French OsmoZ scheme [10]. Only information included in documents available at the official websites of GB schemes was used in the present work.

Because the work was initiated by the ALDREN project whose focus was on the European building stock, priority was given to schemes developed in European countries. These schemes are expected to accord with EU regulations, standards, climate and with European traditions for construction, building culture and heritage. Some schemes developed outside Europe such as LEED, WELL, NABERS and CASBEE were also included because they are used globally and in Europe.

Schemes that defined the criteria for non-residential buildings (e.g., offices, hotels, and commercial buildings) were chosen for a detailed study. Within each scheme, the IEQ parameters 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, and the information contained in such schemes was also included. However, only IEQ indicators applicable to offices and hotels were retained, to match the ALDREN scope for which the present review was undertaken.

IEQ parameters prescribed by the EN 16798:2019 standard [8] for non-residential buildings superseding the standard EN 15251 [11] were included, to supplement information collected through the survey of GB schemes. The reason is that this standard is one of the many standards that have been developed to support the adoption and implementation of EPBD [2]. The standard provides input for the calculation and modeling of the energy performance of buildings by defining specific conditions of IEQ for different seasons, building types and classes of IEQ in buildings.

The peer-review literature search supplementing the survey of GB schemes was carried out to identify articles providing additional information on the contribution of the specific IEQ components to the overall rating of IEQ in buildings or proposing how different IEQ parameters can be integrated for this purpose; the GB schemes simply list IEQ parameters and their credits and do not integrate them into one metric. The Google Scholar and Science Direct search engines were used to identify relevant papers 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).

3. Results

3.1. Overview

Fourteen schemes, among which ten were European and four non-European, were selected for the detailed review (Table 1). Among these schemes, Level(s) is not a typical GB scheme but a common EU reporting framework for core sustainability indicators. Some schemes, such as HQE and BREEAM, were 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 other schemes focus on non-residential buildings or multi-purpose buildings. With regard to the main objective of the building certification, OsmoZ, BES and WELL address primarily or exclusively the health and well-being of building occupants or the quality of life in a built environment, while the other schemes are the classic rating tools providing assessments of various building aspects such as energy, water and use of materials, in addition to IEQ.

The GB schemes assign credits to different IEQ parameters, and both these and the total credits received for all IEQ parameters are compared to the credits available and used to classify the IEQ in a given building (Table 2). 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. In other schemes, the number of credits assigned to each of the four IEQ components could not be

Table 1
Green Building certification schemes and research projects examined in the present work.

Title	Region	Document	Applicable building type	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.	Office and residential	http://ec.europa.eu/environment/eussd/buildings.htm
OsmoZ	France	Technical reference. Version 1.0. March 2018.	Office	https://osmoz.certivea.fr
HQE	France	A practical guide of the benchmark for assessing the environmental performance of non-residential building under construction. September 2013.	Non-residential (in the world outside France)	https://www.certivea.fr
HQE	France	HQE reference – green building v2 – office and hotel sectors. January 2018.	Office and hotel	https://www.certivea.fr
BREEAM	UK	BREEAM UK new construction – Non-domestic buildings – Technical manual. SD5076: 2.0. 2014.	Non-residential	https://www.breeam.com
KLIMA	Austria	Active building and renovation – Category: new office building. Version 2.0. March 2014.	Office	https://www.klimaaktiv.at
DGNB	Germany	DGNB criteria: Environmental quality. 2012.	Non-residential	https://www.dgnb-system.de/de
ITACA	Italy	National ITACA protocol 2011 – Office. July 2012.	Office	http://itaca.org/index.asp
LiderA	Portugal	Voluntary system for the sustainability of built environments. Version 2.0. 2011.	Not specified	http://www.lidera.info/?p=apresenta&RegionId=3
BES	Spain	IVE health & wellbeing indicators – B.E.S guide prescriptions. 2018.	Office	http://www.five.es/certificacion-edificios/oficinas/
CASBEE	Japan	CASBEE for building (new construction) – Technical manual (2014 edition). 2014.	All building types except detached houses	http://www.ibec.or.jp/CASBEE/english
LEED	USA	LEED v4 for interior design and construction – Includes commercial interiors, retail, hospitality. October 2014.	Commercial interiors, retail and hotel	https://new.usgbc.org/leed
WELL	USA	The WELL building standard v1. January 2017.	Not specified	https://www.wellcertified.com
NABERS	Australia	A guide to the NABERS indoor environment rating tool for building owners, managers & tenants. November 2015.	Office	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
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
Credits assigned to indoor environmental quality in the Green Building certification schemes.

	BREEAM	KLIMA	DGNB	ITACA	LiderA	LEED	NABERS
Thermal comfort	3	120	10	5	5	1	30
IAQ	5	100	10	5	5	8	30
Acoustic comfort	4	0	10	5	2.5	2	15
Visual comfort	6	0	10	5	2.5	6	15
IEQ	18	220	40	20	15	17	90
Total credits of the scheme	150	1000	610	Not obtained	100	110	Not obtained

Table 3
Parameters used to assess the quality of the thermal environment in the examined GB certification schemes.

Parameter	No.*	Reference
Predicted mean vote (PMV)	8	Level(s), OsmoZ, BREEAM, KLIMA, ITACA, WELL, NABERS, EN 16798
Room air relative humidity	7	KLIMA, DGNB, LiderA, BES, CASBEE, NABERS, [21]
Room operative temperature	7	Level(s), KLIMA, DGNB, BES, WELL, EN 16798, [20]
Predicted percentage dissatisfied (PPD)	6	Level(s), OsmoZ, BREEAM, KLIMA, WELL, EN 16798
Air speed	6	HQE, KLIMA, LiderA, BES, NABERS, EN 16798
Room air temperature	5	HQE, LiderA, CASBEE, NABERS, [21]
Radiant temperature asymmetry	3	KLIMA, DGNB, EN 16798
Percentage dissatisfied for draught		
Vertical air temperature difference	2	KLIMA,
Percentage dissatisfied for vertical air temperature differences		EN
Floor surface temperature		16798
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

* Number of surveyed documents that include the parameter.

Table 4
Prescribed ranges for some common parameters used to assess the thermal environment recommended by EN 16798 [8] and Level(s) [9].

Parameter	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

determined because this information is not made available on public web pages.

Fourteen research articles and seven reports of European projects were also consulted to supplement the information collected by examining GB schemes. With respect to the selected European projects providing information relevant to the present work (Table 1), their objectives varied considerably and included aspects such as sustainability, building energy performance, and social welfare; only the Buildings 2030 project proposed IEQ indicators. In the other projects, IEQ was not the primary objective, so IEQ indicators were either not taken into account or not discussed.

3.2. Thermal environment

Table 3 summarizes the 19 parameters used to assess the quality of the thermal environment in buildings in the documents examined in the present work. Six parameters assessing 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 work. They are Predicted Mean Vote (PMV), Predicted Percentage Dissatisfied (PPD), operative temperature, air temperature, relative humidity, and air speed. Among them, PMV and PPD are to be derived from other parameters and are an integral part of standards related to the thermal environment, such as Standard EN 16798 and the European Level(s) framework, while the other four are indoor environmental parameters that can be directly measured by instruments and are actually 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. The six thermal parameters described above are also included in ASHRAE Standard 55 [12] and the ISO 7730 standard [13]. These two international standards address only the thermal environmental conditions, so they list more parameters that can be used to assess the quality of thermal environment such as radiant temperature asymmetry, draft, and vertical air temperature difference. As shown in the present work, these parameters are rarely used in GB schemes. The standards referenced by the selected GB schemes that are relevant for the assessment of the quality of the thermal environment are listed in Table S1 in the Supplementary Material.

Table 4 shows the ranges of 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 defined in terms of the quality of the indoor environment, and the prescribed ranges are consistent in both documents. Operative temperature is also classified by EN 16798 into four categories. The recommended range for the lowest category (Category IV) is 18 to 28°C for offices and other comparable spaces 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 lowest 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 them.

Table S1 in the Supplementary Material summarizes the ranges of PMV, PPD, operative temperature, air temperature, relative humidity, and airspeed prescribed by the specific GB schemes. It is worth noting that these ranges are quite similar to ranges defined by EN 16798 [8]. Moreover, the Level(s) framework [9] defines maximum allowable hours (% time) with temperatures outside the specific range rather than a range of temperatures or other parameters defining the thermal environment. It recommends that reporting thermal comfort indicators can be based both on calculation and measurement, as well as during the design stage (in simulations) and after completion (as measurements) to check how the building actually performs.

3.3. Indoor air quality

Table 5 shows the 39 parameters that are used to assess the IAQ in buildings in the documents examined in the present work. Thirty-five parameters are concentrations of indoor air pollutants, of which 29 are gaseous pollutants and mainly volatile organic compounds (VOCs). Indoor air pollutants included in different GB schemes vary widely, and no rationale for their choice and inclusion was found. Few biological pollutants are considered, the reason being the difficulty of their quantitative assessment and the lack of credible reference levels [15].

Ten parameters for assessing IAQ have been used in more than five of the documents examined in the present study. They are ventilation rate, TVOC, CO_2, CO, formaldehyde, PM_{10}, $PM_{2.5}$, ozone, benzene, and radon; the last seven of these ten listed parameters are included in the WHO air quality guidelines [14,15]. 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 are not listed by Level(s). TVOC is used only in some national GB schemes. For this parameter, the LEED scheme refers to the ISO 16000-6 standard which considers TVOC concentration as the entire area of the chromatogram between n-hexane (C6) and n-hexadecane (C16) and uses the toluene response factor to determine the TVOC concentration [16,17].

The premise for using ventilation rates as the IAQ indicator is that they are strongly linked to indoor pollutant concentrations, and it is assumed that the higher the ventilation rate, the lower the pollutant concentrations. This assumption is valid only when the air supplied into the building is clean and for pollutants that can be diluted and/or removed by ventilation. As 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 at present as the most reasonable proxy for IAQ. Likewise, the CO_2 concentration is also commonly used to assess IAQ

Table 5
Parameters used to assess indoor air quality in the examined Green Building certification schemes.

Parameter	No.*	Reference
Ventilation rate	12	Level(s), OsmoZ, HQE, BREEAM, DGNB, ITACA, BES, CASBEE, LEED, WELL, NABERS, EN 16798
TVOC	11	OsmoZ, HQE, BREEAM, KLIMA, DGNB, BES, LEED, WELL, NABERS, [20,21]
Formaldehyde	11	Level(s), OsmoZ, HQE, BREEAM, KLIMA, DGNB, BES, LEED, WELL, NABERS, EN 16798
CO_2	11	Level(s), OsmoZ, KLIMA, BES, LEED, WELL, NABERS, EN 16798, [20,21,29]
Source emission level	9	Level(s), OsmoZ, HQE, BREEAM, DGNB, BES, CASBEE, LEED, EN 16798
CO	7	OsmoZ, HQE, 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, [20]
Ozone	6	OsmoZ, HQE, BES, LEED, WELL, EN 16798
Benzene	5	Level(s), OsmoZ, HQE, WELL, EN 16798
Radon	5	Level(s), HQE, 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, BES, EN 16798
Visible mould	2	Level(s), WELL
Trichloroethylene	2	WELL, EN 16798
Tetrachloroethene		
Naphthalene	1	EN 16798
Polyaromatic hydrocarbons		
Airborne bacteria	1	BES
Airborne fungal spores		
Airborne fibres		
NO_x		
CS_2	1	WELL
CCl_4		
Chlorobenzene		
Chloroform		
Dichlorobenzene (1,4-)		
Dichlorobenzene (1,1)		
Ethylbenzene		
Hexane (n-)		
Isopropyl alcohol		
Methyl chloroform		
Methylene chloride		
Methyl tert-butyl ether		
Styrene		
Toluene		
Vinyl acetate		
Xylene (m, o, p combined)		

* Number of surveyed documents that include the parameter.

Table 6
Prescribed ranges for some common parameters used to assess indoor air quality recommended by EN 16798 [8] and Level(s) [9].

Parameter	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 ppm Category 2: 800 ppm Category 3: 1350 ppm Category 4: 1350 ppm	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, country-specific)	In accordance with WHO guideline value

LPB-1: very low polluting building where predominantly very low-emitting materials and furniture are used, activities with the 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 made to select low-emitting materials and where activities with emission of pollutants are not limited or prohibited.

in buildings because it is an indicator of the effectiveness of ventilation in an occupied building.

Table 6 shows the prescribed ranges for ventilation rates, 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 when prescribing the acceptable concentrations of pollutants [14,15]. WHO guideline values are available for CO, formaldehyde, benzene, and radon [14], and for ozone, $PM_{2.5,}$ and PM_{10} [15]. For ventilation rates, the prescribed ranges vary 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 pollutant load in a given space. According to EN 16798, ventilation rates can be set to achieve prescribed levels of perceived air quality (the % of persons dissatisfied with air quality upon entering a room), to limit the concentrations of target pollutants to prescribed levels, or by using the ventilation rates prescribed in the standard.

Table S2 in the Supplementary Material lists the ten most common parameters used to assess IAQ that are included in different GB schemes, together with their prescribed ranges, and the standards referenced by the GB schemes that are relevant for their assessment.

3.4. Acoustic environment

Table 7 shows 20 parameters that are used in the documents examined in the present work to assess the quality of the acoustic environment in buildings. Two parameters, i.e., ambient noise and reverberation time, are used by more than five documents examined in the present study.

Table 8 shows their ranges as prescribed by EN 16798 and Level(s). It should be noted that the current version of Level(s) does not include parameters defining acoustic performance and the parameters referred to in Table 7 are mentioned by Level(s) as potential future indicators of the quality of acoustic environment (see Part III of Level(s)). The 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 a 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 parameters used to assess ambient noise levels and reverberation times in GB schemes, their prescribed ranges, and the standards relevant for the evaluation of acoustic environment and referred to in GB schemes.

3.5. Visual environment

Table 9 shows 12 parameters that are used to assess the quality of the visual environment in the documents examined

Table 7
Parameters used to assess the quality of the acoustic environment in the Green Building certification schemes examined.

Parameter	No.*	Reference
Ambient noise	9	OsmoZ, HQE, BREEAM, KLIMA, BES, LEED, WELL, NABERS, EN 16798
Reverberation time	8	Level(s)**, OsmoZ, HQE, BREEAM, DGNB, 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, BES
Speech Intelligibility	2	HQE, BES
Noise masking sound level	2	BES, WELL
Facade acoustic performance	1	Level(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	BES
Screens location		

*Number of surveyed documents that include the indicated parameter. **The current version of Level(s) does not include parameters describing acoustic performance, but they are planned for inclusion in future versions.

Table 8
Prescribed ranges for some common parameters used to assess the quality of the acoustic environment recommended by EN 16798 [8] and Level(s) [9].

Parameter	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 9
Parameters used to assess the quality of the visual (luminous) environment in the examined Green Building certification schemes.

Parameter	No.*	Reference
Illuminance level	10	Level(s)**, BREEAM, LiderA, BES, CASBEE, LEED, WELL, EN 16798, [20,21]
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, BES
Discomfort glare in artificial lighting	4	HQE, DGNB, BES, WELL
Colour rendering index	3	HQE, DGNB, WELL
Useful daylight illuminance	2	Level(s)**, [29]
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

*Number of surveyed documents that include the indicated parameter. **The current version of Level(s) does not include parameters describing the visual environment, but they are planned for inclusion in future versions.

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

Table 10 shows the ranges of the three parameters commonly used to describe the visual environment as they are prescribed by EN 16798 and Level(s). Level(s) recommends that the illuminance level should be between 300 and 3000 Lux (useful daylight illuminance should be 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 value of the daylight factor should be 2%, and EN 16798 suggests that the maximum value of the daylight factor for roof lights should be 10% to avoid overheating.

Table 10
Prescribed ranges for some common parameters used to assess the quality of visual (luminous) environment recommended by EN 16798 [8] and Level(s) [9].

Parameter	EN 16798	Level(s)
Illuminance level (IL)	Average maintained illumination in offices: 500 Lux	$300 \le IL \le 3000$ Lux at desk height
Daylight factor	Category 1: $D_{Ca,j} \ge 6\%$, $7\% < D_{SNA} \le 10\%$ Category 2: $4\% \le D_{Ca,j} < 6\%$, $4\% \le D_{SNA} < 7\%$ Category 3: $2\% \le D_{Ca,j} < 4\%$, $2\% \le D_{SNA} < 4\%$ Category 4: $D_{Ca,j} < 2\%$, $0\% \le D_{SNA} < 2\%$	$\ge 2\%$
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.

Table S4 in the Supplementary Material presents three common parameters that are used to assess the quality of the visual environment in GB schemes, their prescribed ranges and the standards relevant for the evaluation of visual environment and referred to by the GB schemes.

3.6. Overall rating of IEQ

The GB schemes that were examined did not provide information describing the contribution of the four components of IEQ to the overall IEQ rating in a building, as they do not assess or credit the overall IEQ – instead, they separately assess the quality of thermal, acoustic and visual environment and IAQ as it is outlined in Sections 3.2 to 3.5. The credits used to assess the parameters describing these components were grouped, and the proportion of credits attributed to each of the four components of IEQ were calculated as a proportion of the overall number of credits available for assessing the quality of IEQ. These proportions are illustrated in Fig. 1. The LEED scheme gives proportionally more credits to IAQ and visual environment, 47% and 35% respectively, than the other schemes. In BREEAM, DGNB, ITACA, LiderA, and NABERS, the credits assigned to different IEQ components are quite similar: 25% to 33% of all credits assigned to IEQ are given to parameters assessing IAQ, 17% to 33% to thermal environment, 17% to 33% to visual environment, and 17% to 22% to the acoustic environment.

Since GB schemes did not provide direct information on the overall IEQ assessment, 14 research articles were reviewed for this information [18–31]. These articles provided information on how to aggregate the components of IEQ to determine the overall IEQ level. The equations proposed to aggregate the components of IEQ were presented using more or less the following format [22].

$$IEQ = w_1 \times TEI + w_2 \times AEI + w_3 \times IAQI + w_4 \times LEI \quad (1)$$

where *TEI, AEI, IAQI, LEI* describe the quality of the four IEQ components, i.e., thermal environment, acoustic environment, IAQ, and luminous (visual) environment on the same scale (e.g., from 0 to 100 [22]) so that their aggregation is possible when deriving an overall IEQ index, while w_i (i = 1, …, 4) are the weightings ($\sum_i w_i = 100\%$) attributed to each component depending on its importance and contribution to the overall rating of IEQ. TEI, AEI, IAQI, LEI are derived by aggregation of different parameters describing their quality, e.g. an, IAQI may depend on the levels of carbon dioxide (CO_2), volatile organic compounds (VOCs), particulate matter and fungi [32]. The level of aggregation is made by simple addition, weighted addition or, by other methods [23,32] but was not the objective of the present work and the relevant information for this aggregation was not examined. The focus was on the weighting factors w_1 to w_4. Fig. 2 summarizes the weighting factors used in the studies identified during the present work [18,19,24–30]. As may be seen, these weightings vary between 12% and 38% for thermal environment, 14% and 36% for IAQ, 16% and 25% for visual environment, and 18% and 39% for the acoustic environment. If these weightings are averaged, the quality of the thermal environment receives on average the highest weighting in the overall rating of IEQ, 28%, while the quality of the acoustic environment, IAQ and the visual environment receive average weightings of 26%, 25%, and 21% respectively.

Fig. 3 compares the average weightings for each IEQ component proposed in the literature with the average proportion of credits attributed to each IEQ component in GB schemes. It appears that

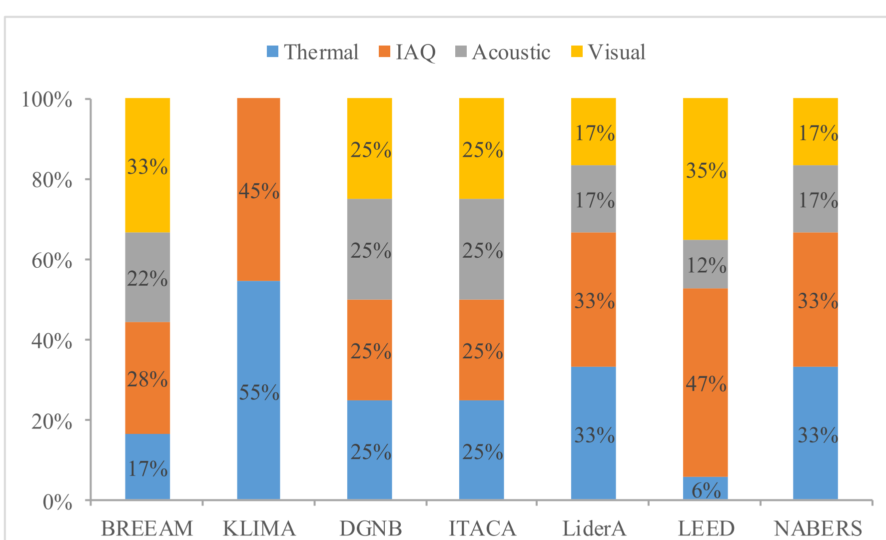

Fig. 1. Percentages of the total number of credits that are assigned to parameters describing four components of IEQ in different GB certification schemes examined in the present work.

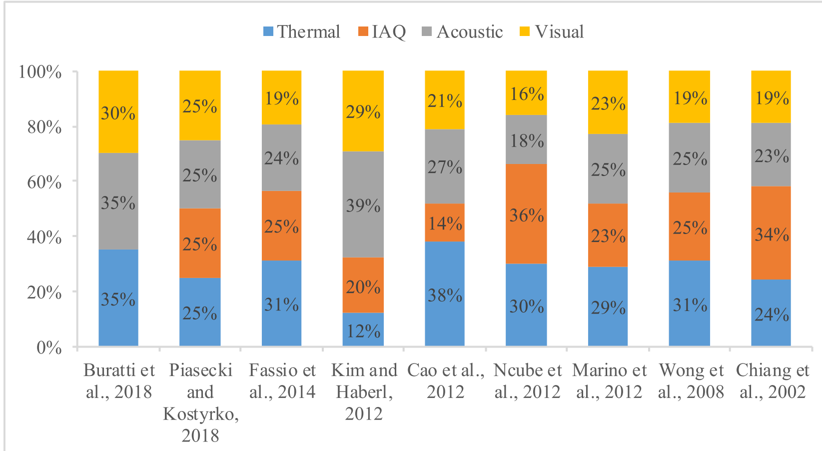

Fig. 2. Weightings proposed in the examined research papers when aggregating the four components of IEQ to derive the overall rating of IEQ.

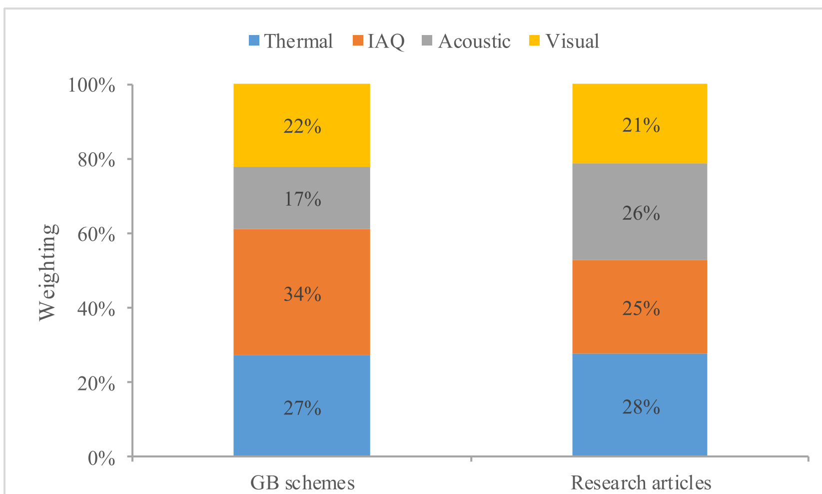

Fig. 3. Comparison of the average percentages of the total number of credits that are assigned to parameters describing four components of IEQ in different GB certification schemes derived from Fig. 2 and the average IEQ weightings in research articles derived from Fig. 1.

the weightings and proportions are close to 25% suggesting that each of the four components of IEQ is considered to contribute equally much or to be of similar importance when assessing the overall IEQ level in a building.

4. Discussion

The present paper provides information on what parameters are taken into account when IEQ is characterized using GB certification schemes, the ranges and levels of these parameters that are regarded as relevant for achieving indoor environments in buildings of a quality that is acceptable for building occupants, and finally how these parameters are rated and weighted against each other. The present work thus serves research and practice by creating a unique reference for current methods and rating schemes used to characterize IEQ in buildings that focus on office buildings and hotels. It also creates a reference for future development of IEQ rating schemes that use objectively measured parameters characterizing IEQ. Furthermore, it can be used as a reference for future revisions and supplements of existing GB schemes and for developing IEQ indicators.

The present work shows the complexity of characterizing the quality of indoor environments. If all parameters included in the schemes reviewed in this paper were to be measured to describe IEQ fully, the work of characterizing IEQ could be considered impractical - nearly 100 parameters would have to be measured. It is then relevant to ask whether all parameters need to be measured for proper characterization of IEQ in buildings. The present paper does not provide the answer to this question, but shows which parameters are common for different certification schemes. The commonality of parameters used to characterize IEQ in buildings can be used as a justification for their selection and inclusion in the metric of IEQ. It is clear from the definitions of indoor environmental quality, comfort and well-being, health, and performance presented in the Supplementary Material that parameters included in the GB certification schemes to characterize IEQ in buildings are adequately addressing them. Furthermore, there are numerous examples in the scientific literature that parameters included in the GB schemes and identified in the present work are pertinent and should be considered when IEQ in buildings is assessed.

It must be acknowledged that there are parameters that are not included in the GB schemes even though they are relevant for characterizing the quality of built environment. There can be many reasons why they are not included in GB schemes, and most likely some can be connected with measuring difficulties or lack of references defining what levels can be considered as acceptable. Among parameters not addressed are biocontaminants such as bacteria or virus, infectious disease transmission being also a key determinant of the quality of indoor environments [34, 35]. Other examples include views to the outside, electromagnetic fields, and ergonomic factors such as occupant control and the functional aspects of indoor spaces. These parameters are included in the definitions of IEQ (see Supplementary Material). They will therefore have to be addressed if the full benefit of improved IEQ is to be obtained and they should be included in any future set of IEQ indicators whose purpose is to rate the overall level of IEQ in any building type.

Existing comfort definitions listed in the Supplementary Material suggest that to achieve comfort, it is not sufficient to avoid negative sensations; it is also essential that positive and rewarding emotions such as enjoyment and encouragement are evinced. These definitions indicate that comfort is not just a passive attribute, i.e., a given condition, but is also an active adaptation, i.e., an opportunity to achieve preferences. The parameters used to assess IEQ that are summarized in the present work can only partially satisfy these definitions because they do not adequately address active adaptation. It would thus make sense to consider the inclusion of IEQ indicators that are associated with positive emotions when parameters that define IEQ are selected. In this way, a holistic and integrated approach towards achieving high IEQ in buildings would be ensured. With regard to assessment of effects on health (definitions of health can be found in the Supplementary Material), the parameters used to assess IEQ summarized in the present work seem adequate according to current knowledge and health guidelines. This applies especially to the IAQ indicators that generally match the WHO guidelines relating to the quality of both ambient [15] and indoor air [14,35]. A valuable addition would be IEQ indicators addressing mental health, stress, and cognitive performance because they are all determinants of general well-being and productivity [36].

Subjective ratings of IEQ were not included among parameters used to rate the quality of indoor environment. They provide useful information on the conditions in buildings that are experienced by building occupants (e.g. [37]). However, no standardized method exists that can be used to perform subjective evaluations of IEQ and many different survey protocols exist that have been used to obtain IEQ ratings from building occupants, e.g. [38]. This creates significant limitations regarding application of occupant surveys to characterize IEQ in buildings. Among the GB certification schemes examined in the present work, only OsmoZ, WELL, and NABERS propose to use subjective evaluations, but even in the case of these schemes no standard method for collecting the subjective ratings is stipulated. There is no reason to believe that measuring parameters identified in the present review will not predict the responses of building occupants. It will, however, provide information only for an average response or associated risk, or whether acceptable limits were exceeded. They will not provide information on the distribution and variation of ratings and responses among building occupants, may not protect the most sensitive, and will not provide information on the individual level of response. This information is necessary for advancing the technologies supporting IEQ and ensuring that requirements for all users in buildings are met.

The present review of GB schemes did not define or directly assess the impact of different parameters characterizing IEQ on the overall IEQ rating or how many of them would be needed to construct such a rating. The importance of major components of IEQ for the overall level of IEQ in a building is indirectly provided in the schemes by attributing credits to different IEQ parameters and components. With few exceptions (Fig. 1), the credits attributed to different components correspond to approximately one-quarter of all credits assigned for IEQ. This is similar to what has been reported in the scientific literature (Fig. 2). For example, Frontczak and Wargocki [33] summarized seven studies that examined 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 could be 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 than visual comfort. It is worth noting that the rationale for the weighting of IEQ components has rarely been discussed in the literature and apart from some evidence presented by Frontczak and Wargocki [33], there is no real scientific justification for it, 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. Piasecki and Kostyrko [22,29] examined the weighting of IEQ components by comparing different methods. They argued that although some methods, including the analytic hierarchy process, were developed to determine the weightings, their results cannot credibly be evaluated. They suggested additionally that the use of equal weightings would avoid the suspicion that the specific weightings would impact the overall rating IEQ. This proposal accords with the present findings. The integration of different IEQ indicators so that a single index can be used to describe the IEQ in buildings presents an important challenge; such an integrative index would respond to the expectations of the industry and practitioners, and its development must be regarded as one of the most urgent tasks for future research.

Besides the GB certification schemes summarized in the present work, there are several EU and international standards that are either referenced by GB schemes or provide information on a specific component of IEQ. They deal with measurement techniques, sampling, and analytical procedures. Since they do not provide information on all the components and parameters that should be used for rating IEQ in buildings, focusing only on one or two parameters, they were not examined in the present work, although they are listed for reference in the Supplementary Material.

Lastly, most of the documents examined in the present work can be accessed by browsing the Internet, and the information presented in this paper is based only on information included in documents available at the official websites of GB certification schemes. However, this information may not be complete since most of the GB certification schemes are commercial and some information in them is not available to the public such as, e.g., information on the methods used to certify IEQ as acceptable. Among the 14 Green Building schemes selected for the present work, only the Level(s), which is a common EU reporting framework of core sustainability indicators, is entirely accessible. Despite this, it is still believed that most of the important information regarding parameters used by GB certification schemes to assess IEQ has been accessed and that the results of the present study are consequently trustworthy and provide a good summary of the IEQ indicators included in these documents.

5. Conclusions

The survey was carried out as part of the project ALDREN (ALliance for Deep RENovation in buildings) whose aim is to develop a harmonized procedure for deep energy renovation operations in offices and hotels; the procedure is called the ALDREN method and requires the definition of a method for rating the effects of building energy renovation on the health and well-being of building occupants. The present work was undertaken to assist this goal and also to address the much broader aim of reviewing the parameters that are currently used to describe IEQ in GB schemes.

Nearly 100 parameters that are used in the GB schemes to describe IAQ and the quality of the thermal, acoustic, and visual (luminous) environment were identified. Several of them are common to most of these documents, and are also prescribed by standards, codes, and recommended by guidelines relevant for IEQ.

For the thermal environment, the common parameters are PMV, PPD, operative temperature, air temperature, relative humidity, and air speed. For the acoustic environment, the common parameters are ambient noise and reverberation time. For the visual environment, the common parameters are illuminance level, daylight factor, and spatial daylight autonomy. For IAQ, the common parameters are ventilation rate (outdoor air supply rate) and the concentrations of TVOC, formaldehyde, CO_2, CO, PM_{10}, $PM_{2.5}$, ozone, benzene, and radon.

Attempts have been made to differentially weight the quality levels of thermal, acoustic, and visual environment and IAQ to derive a combined index of IEQ, but in most GB schemes their impact has been regarded as equally important for the overall IEQ. Further work is needed to validate this assumption, as well as to decide on which parameters are necessary for proper characterization of IEQ in buildings.

A metric of IEQ would be useful for proper characterization of IEQ in buildings and can be considered a priority, as it would supplement an energy metric and allow full characterization of building performance, and would be likely to lead to technological advancements.

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.

Acknowledgments

The present work was supported by the coordination and support action on ALliance for Deep RENovation in buildings (ALDREN) supported through EC Horizon 2020 Programme, contract number 754159. We thank Professor David P. Wyon for his comments and revision of the manuscript.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.enbuild.2019.109683.

References

[1] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings, Off. J. Eur. Union. (2010) http://www.buildup.eu/sites/default/files/content/EPBD2010_31_EN.pdf.
[2] Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency, Off. J. Eur. Union (2018) https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32018L0844&from=EN.
[3] LEED, Green Building 101: What is indoor environmental quality?, (2018). https://www.usgbc.org/articles/green-building-101-what-indoor-environmental-quality.
[4] B. Mattoni, C. Guattari, L. Evangelisti, F. Bisegna, P. Gori, F. Asdrubali, Critical review and methodological approach to evaluate the differences among international green building rating tools, Renew. Sustain. Energy Rev. 82 (2018) 950–960, doi:10.1016/j.rser.2017.09.105.
[5] M. Shan, B. gang Hwang, Green building rating systems: Global reviews of practices and research efforts, Sustain. Cities Soc. 39 (2018) 172–180, doi:10.1016/j.scs.2018.02.034.
[6] D.T. Doan, A. Ghaffarianhoseini, N. Naismith, T. Zhang, A. Ghaffarianhoseini, J. Tookey, A critical comparison of green building rating systems, Build. Environ. 123 (2017) 243–260, doi:10.1016/j.buildenv.2017.07.007.
[7] W. Wei, O. Ramalho, C. Mandin, Indoor air quality requirements in green building certifications, Build. Environ. 92 (2015) 10–19, doi:10.1016/j.buildenv.2015.03.035.
[8] FprEN 16798-1:2018. Energy performance of buildings — Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics — Module M1-6, 2018.
[9] N. Dodd, M. Cordella, M. Traverso, S. Donatello, Level(s) – A common EU framework of core sustainability indicators for office and residential buildings, 2017. doi:10.2760/95143.
[10] Certivéa, OsmoZ référentiel technique détaillé version 1.0, 2018. https://osmoz.certivea.fr/referentiel.
[11] EN 15251:2007. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, 2007.
[12] ANSI/ASHRAE Standard 55-2010. Thermal environmental conditions for human occupancy, 2010.
[13] ISO 7730:2005. Ergonomics of the thermal environment - analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria., 2005.
[14] World Health Organization, WHO Guidelines for Indoor Air Quality: Selected Pollutants, Copenhagen, Denmark, 2010.
[15] World Health Organization, Air Quality Guidelines for Europe, 2nd ed., 2000. doi:10.1007/BF02986808.
[16] ISO 16000-6, Indoor air - Part 6: Determination of volatile organic compounds in indoor and test chamber air by active sampling on Tenax TA sorbent, thermal desorption and gas chromatography using MS-FID, 2011.
[17] U.S. Green Building Council, LEED v4 for interior design and construction, 2014. https://new.usgbc.org/leed.
[18] B. Cao, Q. Ouyang, Y. Zhu, L. Huang, H. Hu, G. Deng, Development of a multivariate regression model for overall satisfaction in public buildings based on field studies in Beijing and Shanghai, Build. Environ. 47 (2012) 394–399, doi:10.1016/j.buildenv.2011.06.022.
[19] C.-M. Chiang, C.-M. Lai, A study on the comprehensive indicator of indoor environment assessment for occupants' health in Taiwan, Build. Environ. 37 (2002) 387–392, doi:10.1016/S0360-1323(01)00034-8.
[20] M. Jin, S. Liu, S. Schiavon, C. Spanos, Automated mobile sensing: Towards high-granularity agile indoor environmental quality monitoring, Build. Environ. 127 (2018) 268–276, doi:10.1016/j.buildenv.2017.11.003.
[21] P. Kumar, C. Martani, L. Morawska, L. Norford, R. Choudhary, M. Bell, M. Leach, Indoor air quality and energy management through real-time sensing in commercial buildings, Energy Build. 111 (2016) 145–153, doi:10.1016/j.enbuild.2015.11.037.
[22] M. Piasecki, K. Kostyrko, S. Pykacz, Indoor environmental quality assessment: Part 1: Choice of the indoor environmental quality sub-component models, J. Build. Phys. 41 (2017) 264–289, doi:10.1177/1744259117702882.
[23] L.C.R. Salis, M. Abadie, P. Wargocki, C. Rode, Towards the definition of indicators for assessment of indoor air quality and energy performance in low-energy residential buildings, Energy Build. 152 (2017) 492–502, doi:10.1016/j.enbuild.2017.07.054.
[24] F. Fassio, A. Fanchiotti, R. Vollaro, Linear, non-linear and alternative algorithms in the correlation of IEQ factors with global comfort: a case study, Sustainability 6 (2014) 8113–8127, doi:10.3390/su6118113.
[25] H. Kim, J.S. Haberl, Field-test of the new ASHRAE/CIBSE/USGBC performance measurement protocols for commercial buildings: Basic level, ASHRAE Trans. 118 (2012) 135–142.
[26] M. Ncube, S. Riffat, Developing an indoor environment quality tool for assessment of mechanically ventilated office buildings in the UK – A preliminary study, Build. Environ 53 (2012) 26–33, doi:10.1016/j.buildenv.2012.01.003.
[27] L.T. Wong, K.W. Mui, P.S. Hui, A multivariate-logistic model for acceptance of indoor environmental quality (IEQ) in offices, Build. Environ 43 (2008) 1–6, doi:10.1016/j.buildenv.2007.01.001.
[28] C. Marino, A. Nucara, M. Pietrafesa, Proposal of comfort classification indexes suitable for both single environments and whole buildings, Build. Environ. 57 (2012) 58–67, doi:10.1016/j.buildenv.2012.04.012.
[29] M. Piasecki, K.B. Kostyrko, Indoor environmental quality assessment, part 2: Model reliability analysis, J. Build. Phys. 5 (2018) 1–28, doi:10.1177/1744259118754391.
[30] C. Buratti, E. Belloni, F. Merli, P. Ricciardi, A new index combining thermal, acoustic, and visual comfort of moderate environments in temperate climates, Build. Environ 139 (2018) 27–37, doi:10.1016/j.buildenv.2018.04.038.
[31] D. Heinzerling, S. Schiavon, T. Webster, E. Arens, Indoor environmental quality assessment models: A literature review and a proposed weighting and classification scheme, Build. Environ. 70 (2013) 210–222, doi:10.1016/j.buildenv.2013.08.027.
[32] W. Wei, O. Ramalho, M. Derbez, J. Ribéron, S. Kirchner, C. Mandin, Applicability and relevance of six indoor air quality indexes, Build. Environ. 109 (2016) 42–49, doi:10.1016/j.buildenv.2016.09.008.
[33] M. Frontczak, P. Wargocki, Literature survey on how different factors influence human comfort in indoor environments, Build. Environ. 46 (2011) 922–937, doi:10.1016/j.buildenv.2010.10.021.
[34] ASHRAE position document on airborne infectious diseases, 2014. https://www.ashrae.org/File Library/About/Position Documents/Airborne-Infectious-Diseases.pdf.

[35] World Health Organization, WHO Guidelines For Indoor Air Quality: Dampness and Mould, Copenhagen, Denmark, 2009.
[36] P. Wargocki, D.P. Wyon, Ten questions concerning thermal and indoor air quality effects on the performance of office work and schoolwork, Build. Environ. 112 (2017) 359–366, doi:10.1016/j.buildenv.2016.11.020.
[37] M. Frontczak, S. Schiavon, J. Goins, E. Arens, H. Zhang, P. Wargocki, Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design, Indoor Air 22 (2012) 119–131, doi:10.1111/j.1600-0668.2011.00745.x.
[38] S. Corgnati, M. Gameiro da Silva, R. Ansaldi, E. Asadi, J.J. Costa, M. Filippi, J Kaczmarczyk, A. Melikov, B.W. Olesen, Z. Popiloek, P. Wargocki, Indoor Climate Quality Assessment. REHVA Guidebook No. 14. Federation of European Heating, Vent. Air Condition. Assoc. (2011).