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ABSTRACT

The development of a new tool (**IEQ**Compass) for holistic evaluation of indoor environmental quality (IEQ) is presented. The purpose of the new tool is to facilitate a broader understanding of IEQ, its importance for comfort, health and well-being, and to help and guide the building design process regarding IEQ. The tool evaluates the potential indoor air quality (IAQ), thermal, visual and acoustic IEQ, without considering user influence. The evaluation uses 16 parameters, four for each of the four areas of IEQ (IAQ, thermal, visual and acoustic IEQ). These are evaluated based on relevant criteria assessed from blueprints, existing building information modelling data or observations during building inspection. The criteria and parameters are weighted to obtain an overall IEQ label for the building, as well as partial labels for the four areas. The labelling scheme uses letter ranking and colour code similar to that used in energy performance certification. The results are also communicated through the newly developed "IEQ Design Compass", which is a detailed graphical visualisation at criteria level and helps identify potential IEQ problems that warrant attention.

1. Introduction

The indoor environmental quality (IEQ) of buildings has for many years been considered second to energy efficiency and at best a potential co-benefit when designing new buildings or renovating existing ones. This design strategy has often led to problems with e.g. overheating, glare due to large window areas, or poor air quality due to insufficient ventilation rates optimized towards low energy consumption [1–3]. The European Union's Energy Performance of Buildings Directive (EPBD) has increased the public's awareness of the importance of energy efficiency in the building sector through the use of the Energy Performance Certificates (EPC) [4]. Increasing public awareness of the importance of the indoor environment in the same manner would be a game-changer in the way the indoor environment is prioritized in buildings. The benefits would include increased comfort, improved health and well-being of building occupants, as well as economic consequences reflected in lower health care expenditures and increased productivity [5–10].

In order to increase the attention to IEQ, evaluation and labelling of IEQ should become available to both building users and building designers in an easily understandable and affordable manner, as has been the case for energy performance through EPC. Sustainability and building performance certification programs include the evaluation of the IEQ to a various degree [11]. Although there is a growing recognition of the importance of IEQ in these programs, there are opportunities for significant improvements [12]. In a study comparing the IEQ related content of major building certification schemes applicable for dwellings (DGNB, BREEAM, LEED, WELL and LBC - Living Building Challenge), Rohde et al. found that the overall weight of IEQ (defined as indoor air quality (IAQ), thermal IEQ, visual IEQ, acoustic IEQ and the availability for the users to control these parameters) ranged from 10% to 31% of the total scheme [13]. The study also showed large variations in the relative weights of the five IE areas. For example, LEED only includes IAQ and user's influence, LBC includes all except acoustics, whereas DGNB, BREEAM and WELL include all areas. DGNB was found to have the most balanced weights between the areas.

Other tools and evaluation schemes aim to more directly asses the

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IEQ [14,15]. These tend to assess the IAQ, thermal, visual and acoustic IEQ individually. However, not all tools include all four elements of IEQ. One reason for this may be that IAQ and thermal IEQ receive the most attention in the literature, whereas visual and acoustic IEQ are insufficiently understood and characterized [16]. Few studies investigated the combined effects of the different parameters on the perception of IEQ [17–19]. ASHRAE guideline *10–2016* [20] provides an overview of the combined effects by a systematic comparison of the parameters. The combined effects of the indoor environmental quality parameters are poorly understood and they have not been considered in earlier IEQ evaluation tools due to their complexity.

The inclusion of multiple indoor environmental areas in a single IEQ indicator requires their weighting. One of the challenges of this approach is to identify reasonable weights for the individual areas. Heinzerling et al. [21] compared several tools and evaluation methods that combined IAQ, thermal, visual and acoustic IEQ. The weights of the four areas varied between studies. Residovic [22] has developed the NABERS Indoor Environment tool for offices, which included thermal comfort, acoustic comfort, indoor air quality, lighting and office layout. Thermal IEQ and IAQ were found to be the most important parameters. The same prioritization was found by Ncube et al. [15]. In a study in residential buildings, Lai et al. [23] found the thermal and acoustic IEQ to be most important, while IAQ contributed the least to the overall IEQ. Humphreys [24] discussed the difficulties of establishing weights and suggested that instead of relying on a combined index, assessments should also include evaluations of the individual areas. Andargie et al. [16] suggested to establish the weights on a case-by-case basis, in order to address the large variability in buildings and their users.

The current study developed the **IEQ**Compass, a tool with the purpose to holistically evaluate and effectively communicate the potential IEQ in multifamily residential buildings at a national level in Denmark. However, the overall framework is versatile; the tool can be adapted for other building types, such as offices, schools and single-family homes, as well as for different regions. The tool is a product of the Danish REBUS project [25], which develops solutions for deep renovations in the social housing sector. However, the tool is applicable both in new and renovated buildings. It aims to facilitate a broader understanding of IEQ and its importance for comfort, health and well-being, and to promote IEQ considerations in renovation strategies in response to the growing need for deep renovations at a European level [26]. The project relies on a partnership between IEQ scientists, practitioners, developers and end-users. This paper describes the tool, its development and an example of its application.

2. Methodology

The described methodology addresses the approach applied to select the appropriate content and corresponding weighting for the tool that is intended to holistically evaluate the IEQ in multi-unit residential buildings.

2.1. Overall considerations

Assessment of the IEQ in multi-family buildings is often done through short-term measurements or surveys. Short-term measurements reflect the IEQ at the time of the measurements, while surveys rely on real-time subjective evaluations or the occupants' recall of their dwellings' IEQ. The application of these approaches in a nation-wide IEQ assessment program is not feasible. Moreover, the results of both methods are strongly influenced by occupant behaviour and thus do not reflect the *IEQ potential* of a building as such. For example, earlier works have identified IAQ problems as a result of insufficient window opening, overheating due to inappropriate use of existing solar shadings and a strong effect of kitchen exhaust fan use on air pollution after cooking [27–30]. Therefore, the present tool aims to assess the building's *potential* to provide good IEQ through building design and available technical solutions, without considering occupant behaviour, which can have unintended effects (e.g. effects of cooking on indoor air quality) or reflect personal preferences (e.g. temperature).

The following seven fundamental criteria were set for the tool:

- It must evaluate the building's potential to provide good IEQ, without being biased by occupant behaviour or taking it into consideration
- It must evaluate the occupants' possibilities to adjust and interact with the IEQ in their dwelling according to their own preferences (personal control)
- It must include the assessment of IAQ, thermal, visual and acoustic IEQ in relation to comfort, health and well-being
- It must be independent of physical measurements
- It must be based on existing regulations and standards whenever possible
- The assessment by the tool must be sufficiently detailed and at the same time easy and fast to use both regarding input data and output results
- The tool must be applicable for existing buildings (to evaluate present status), renovation projects (to evaluate before and after renovation) and new buildings (to be used for design and benchmarking).

2.2. Selection of parameters and criteria

Before selecting the parameters to be included in the tool, various evaluation schemes were studied (DGNB, BREEAM, LEED, WELL and LBC). The schemes for sustainable building design vary in their coverage of social sustainability aspects. WELL, for example, contains a comprehensive list of criteria that impact occupants including nourishment, drinking water, fitness and mind. The **IEQ**Compass was developed as a tool with focus on the indoor environment and deliberately does not cover other aspects of social sustainability. The reason for this decision was to make a distinct counterpart to building energy consumption, which receives much more attention. This is intended to be done by communicating IEQ in a similar manner.

In order to define the parameters included in the tool, gross lists of parameters relevant for acoustic IEQ (ACOU), Indoor Air Quality (IAQ), thermal IEQ (THER) and visual IEQ (VIS) were made. The lists were developed based on a literature survey and consultation with experts in each of the four areas. For each parameter included on the list, the sources (where applicable), the recommended or mandated limit values in Denmark and in the EU, impact on humans (comfort, symptoms, performance, health effects), occurrence including typical levels and variation over time, measurability/documentation and its challenges, and other issues relevant for inclusion in the tool, were described.

The extensive gross lists were then reduced to a number of parameters reasonable for an operational tool. For this purpose a set of rules was established:

- Each of the four areas (ACOU, IAQ, THER, VIS) were considered equally important
- Obtaining evaluation data for the parameters should not require measurements
- The final parameters should be selected based on their impact on building occupants' comfort and health. This was done by subjectively assigning them a value from 1 (lowest impact) to 5 (highest impact) for both comfort and health individually. The values were assigned by an appointed panel of 12 experts. The final selection of parameters followed a consensus-based approach within this panel, as suggested by Chew & Das [31], through several successive rounds of agreement, similar to the DELPHI technique [32].

Three quantitative parameters were selected for each of the four main areas (12 parameters in total). For each main area a fourth parameter describing the users' possibility to adjust and interact with the IEQ according to their own preferences (availability of personal control), was added. Thus, 16 parameters were included in the tool (the parameters are listed in section 3.1). Even though the tool disregards specific impact of occupant behaviour, the users' possibilities to adjust and interact with the indoor environment, as given by the building design and operation (e.g. individual control), was judged to be an essential part of the evaluation. This is to acknowledge the literature indicating a clear relationship between individual control of the indoor environment and occupant satisfaction [30,33].

In order to assess the parameters in the tool, between one and six relevant descriptive criteria were defined for each parameter. Each criterion can obtain a score between 0 (worst) and 10 (best). The assessment of the criteria is based on blueprints and existing Building Information Modelling (BIM) data, or observations during building inspection in existing buildings. Blueprints and BIM data are used when available. This is the case for most new buildings. Lack of documentation is common however in the case of old buildings and renovation projects. The criteria scores are assessed with the help of either checklists (e.g. questions with yes/no answers, as well as more detailed observations) or calculations (e.g. indoor sound levels calculated based on traffic-related outdoor sound levels provided by the national noise map [34], type of wall construction, windows and vents).

For checklists, the maximum score of 10 per criterion is distributed across the corresponding checklist entries (observations) (see example under Acoustic IE in section *3. Results*). The relative importance of each observation (score corresponding to an observation) was subjectively decided by a group of experts in each of the four areas [35]. The required calculations are performed automatically by the tool, upon entering the necessary input data. The calculated criteria (continuous variables) are assigned a score between 0 and 10 in a linear fashion (see section *3. Results* for an example). Linear interpolation was selected over a stepwise approach in order to prevent users from aiming to achieve the poorest condition within a specific step. For example, an identical score for CO_2 levels between 1000 ppm and 1499 ppm does not motivate to improve ventilation and reduce CO_2 concentration below 1499 ppm, which is easier to obtain. The calculations are made at "room level" or "apartment level". Data obtained at room level are combined into a single score for the apartment. These calculations aim to determine either the worst-case scenario (e.g. time with overheating), best-case scenario (e.g. direct sunlight hours) or average conditions (e.g. daylight across the apartment). Criteria calculated at "apartment level" are those anticipated not to vary significantly between rooms (e.g. ventilation/infiltration).

2.3. Weighting of criteria and parameters

Weighting the parameters and criteria is necessary in order to make a holistic evaluation of IEQ. The weights can either be adjustable based on values from occupants or building owners, as suggested by Gade et al. [36], or they can be a fixed set of values. The latter approach was selected for the **IEQ**Compass, in order to allow for benchmarking of multi-family residential buildings at a national level. The weights in the **IEQ**Compass are those described in Rohde et al. [35], which was a preliminary study (using the tool's Danish prototype name IV20) for the final tool presented here. It describes in detail the determination of the weights between the criteria and parameters used in the tool. Briefly, the weights were determined based on a questionnaire answered by 67 Danish building professionals and experts (BPE) within the four specific areas. By asking only building professionals, potential bias from asking occupants was avoided. Building occupants tend to be influenced by their current living conditions when answering a questionnaire. Moreover, we believe occupants have the tendency to provide comfort-based responses, whereas building professionals are more likely to consider both comfort and health implications of the IEQ. Each BPE judged his/her knowledge level within each of the four areas by selecting one of four categories (Expert, Comprehensive knowledge, Limited knowledge and No knowledge). Only responses in the questionnaire obtained from BPE in "Expert" and "Comprehensive knowledge" categories were used for analyses. See table 1 in Rohde et al. [35] for the distribution of self-reported knowledge level in the four IE areas. Data for the final weighting was used from 25, 47, 55 and 37 BPEs for acoustic IE, IAQ, thermal IE and visual IE, respectively.

The responses from the BPE were compared to the weights originally assigned by the researchers, building engineers and architects developing the tool. The final weights were based on careful consideration of both weights (from BPE and the developing team) for each criteria and parameter, and were rounded to the nearest 5%. The two approaches agreed reasonably well for most endpoints. Where this was not the case, additional information was gathered in order to explain the difference and determine the final weight. For example the BPE assigned an average weight of 22% for the occupants' possibility to adjust the acoustic IE, one of the four parameters in the acoustic IE (ACOU4, see below), while the developing team assigned 5%. Since good acoustic IEQ primarily depends on building design, the possibilities to make adjustments are limited and only a single criterion (opening the window towards silent side) is part of this parameter in the tool. On these grounds it was judged that a 5% weight for occupant control of acoustic IE was appropriate.

3. Results

The evaluation of the 16 selected parameters and their corresponding criteria are described in the following sections. The communication of the results and an illustration of application of the tool using a case study, are presented.

3.1. Parameters and criteria in the tool

3.1.1. Acoustic indoor environment (ACOU)

The evaluation of the acoustic IEQ considers the effect of sound from outdoors, from neighbours, from technical installations within the dwelling and the occupants' possibilities to adjust these (Table 1).

The potential noise levels in parameters ACOU1 and ACOU2 are evaluated based on information on the wall construction, type of windows and load-carrying structure. ACOU1 evaluates the level of noise indoors originating from outdoor noise caused by traffic or industry. The

Table 1
Parameters, criteria and their weights for the assessment of acoustic IEQ (ACOU).

Parameter		Parameter weights	Criteria		Criterion weights
ACOU1	Noise from surroundings	35%	1.1	Low impact of external noise (e.g. traffic noise, industry)	80%
			1.2	Possibility to open windows towards a silent side	20%
ACOU2	Noise from neighbouring dwellings	35%	2.1	Low impact of noise from other dwellings - airborne noise	50%
			2.2	Low impact of noise from other dwellings - impact noise	50%
ACOU3	Noise from within the dwelling	25%	3.1	Technical installations	60%
			3.2	Reverberation time	40%
ACOU4	Occupants' possibilities to adjust the acoustic IEQ	5%	4.1	Possibility to open windows in multiple directions	100%

average outdoor noise level from traffic can be found, for any given address in the noise exposed areas of Denmark, in the Danish national noise map (Fig. 1). The average noise level from industrial sources is calculated separately and added when relevant. The score is then calculated from the calculated indoor noise level, where the maximum score (10 points) is obtained for a day-evening-night equivalent sound level, $L_{den} \leq 23$ dB(A), corresponding to sound class A in the Danish standard for sound classification of dwellings [37]. The lowest score (0 points) corresponds to class D in the standard ($L_{den} \geq 38$ dB(A)). L_{den} between these values are scored linearly between 10 and 0 points (Fig. 2).

ACOU2 estimates the level of airborne noise (ACOU2.1) and impact noise (ACOU2.2). Class A defined in the standard on sound classification corresponds again to the maximum score. For ACOU2.1 this corresponds to an airborne sound insulation, R'w, of minimum 63 dB between apartments, while for ACOU2.2 the impact noise, $L'_{n,W}$, must be below 43 dB.

ACOU3 is evaluated based on noise from technical installations and reverberation time. The noise from technical installations (ACOU3.1) is evaluated using the checklist in Table 2, which serves as an example of score distribution across the respective checklist entries. The reverberation time (ACOU3.2) is estimated using Sabine's formula [37], which considers the presence of standard sound absorbents (table, two chairs, a desk and a closet) in a standard lightly furnished room (floor area of 12 m^2 and height of 2.5 m). The assumed light furnishing corresponds to an absorptions area of 2 m^2 (17% of the floor area) [38]. The actual furnishing in a dwelling is not considered in order to avoid penalization for the occupants' furnishing preferences. In order to apply this calculation for all room sizes, the absorptions area in the tool is fixed at 17% of the floor area. Evaluation of reverberation time is not a requirement for Danish dwellings and no standard values therefore exist. A reverberation time of 0.4 s was chosen to obtain the highest score (10), 0.8 s

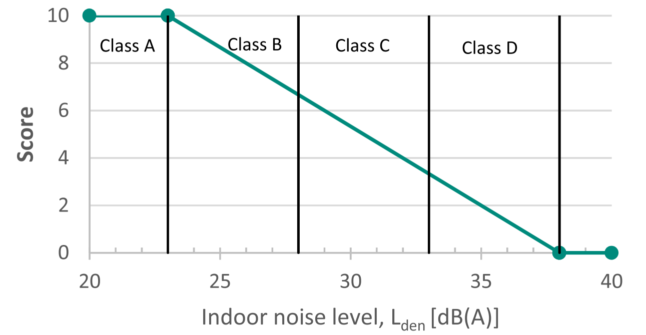

Fig. 2. Score chart for criterion ACOU1.1 (impact of external noise) as a function of day-evening-night equivalent sound level (L_{den}). Classes A-D indicate sound classes in the Danish standard for sound classification of dwellings [37].

gives the lowest score (0).

The occupants' possibilities to adjust the acoustic IEQ (ACOU4) are limited, since it largely depends on the building design. This is reflected in the weight of this parameter, which constitutes only 5% of the total score for the acoustic IEQ.

3.1.2. Indoor air quality (IAQ)

The evaluation of the indoor air quality (IAQ) considers the effect of outdoor air quality, building ventilation and building materials, household activities and the occupants' possibilities to adjust these (Table 3).

The evaluation of the impact of outdoor air (IAQ1) is based on the annual average concentration of $PM_{2.5}$ at a given address, reported by the Danish national particle map [39]. The final score is obtained after adjustment for the presence of air filtration in the ventilation system and

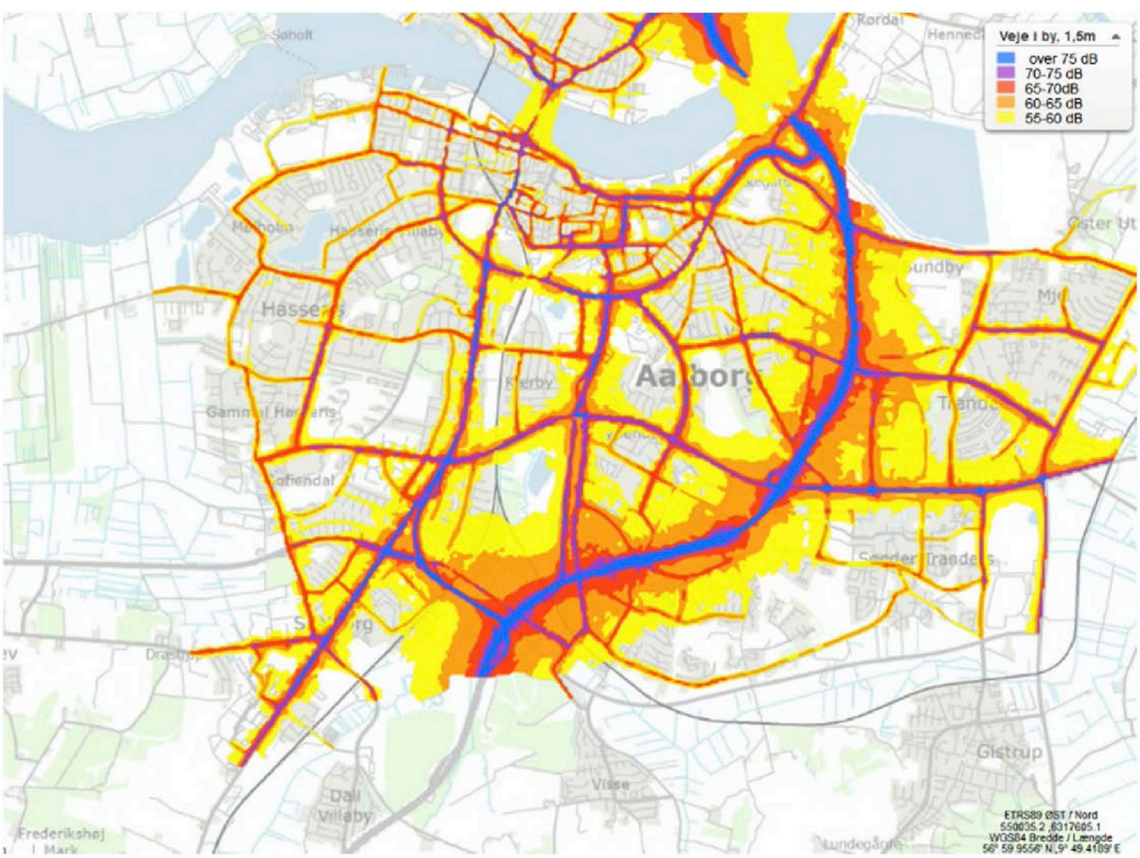

Fig. 1. The average outdoor noise level from traffic as shown in the Danish national noise map [34].

Table 2
Scores for criterion ACOU3.1 – noise from the building's technical installations. Conditions promoting a low noise level result in a high score. The final score is the sum of scores for three sub-criteria (maximum score is 10).

Score	0	1	2	3	4	6
Ventilation	Mechanical ventilation without silencing		No mechanical ventilation, only natural ventilation		Silencers are present, one central ventilation unit	Silencers are implemented locally for all rooms
Elevator in staircases	Yes		Yes, with silencing measures taken into account	No		
Visible drains	Yes	No				

Table 3
Parameters, criteria and their weights for the assessment of indoor air quality (IAQ).

Parameter		Parameter weights	Criteria		Criterion weights
IAQ1	Impact of outdoor air	15%	1.1	Outdoor air quality and filtration	100%
IAQ2	Building ventilation and materials	35%	2.1a	Mechanical ventilation (and commissioning)	70%
			2.3	Emission from materials	30%
			2.1b	Natural ventilation (potential ACR)	35%
			2.2	Bathroom exhaust fan	35%
			2.3	Emission from materials	30%
IAQ3	Impact of household activities	30%	3.1	Options for drying clothes	30%
			3.2	Stove exhaust hood	50%
			3.3	Stove type (electricity or gas)	20%
IAQ4	Occupants' possibilities to adjust the IAQ	20%	4.1	Ventilation boost, natural ventilation	35%
			4.2	Ventilation boost, mechanical ventilation	30%
			4.3	Automatic control of ventilation rate	35%

its efficiency. IAQ2 is evaluated differently for mechanically ventilated buildings and naturally ventilated buildings, acknowledging the fact that mechanical ventilation can ensure a more stable minimum air change rate (ACR) across the dwelling compared to natural ventilation [40,41]. For the same reason, the presence of a bathroom exhaust fan (IAQ2.2) is scored in addition to the potential natural ventilation (infiltration) rate (IAQ2.1b), which is estimated using the method described by ASHRAE [42]. IAQ2 also considers emissions from materials. Scores are given if documentation is provided that no changes to surface materials have been made during the past two years or certified low emitting materials have been applied to at least 75% of all surfaces. A list of approved certifications and labels are included in the tool manual.

IAQ3 scores source control solutions related to occupant activities (clothes drying, stove and exhaust hood). Although occupant behaviour and furnishing are not considered in the tool, these technical solutions, which influence moisture and pollutant levels in the dwelling, are considered an integral part of the building. The users' possibilities to adjust the indoor air quality (IAQ4) include the options to manually boost the ACR by i) opening windows (single-sided or cross ventilation) (IAQ4.1), ii) boosting the mechanical ventilation system (IAQ4.2), or iii) turning on automatic control of the ACR based on measurements of CO_2 and humidity (IAQ4.3).

3.1.3. Thermal indoor environment (THER)

The thermal IEQ is evaluated based on the summer and winter indoor temperature conditions, draught in the dwelling and the occupants' possibilities to adjust these conditions (Table 4).

The indoor temperature conditions in the summer and winter (THER1 and THER2) are scored based on the results of detailed calculations performed by the tool with the relevant input parameters set for Danish climate conditions. Thus, the tool requires adjustments before its application for different climates. The parameter THER1 evaluates the summer conditions. The criterion THER1.1 scores the number of hours above 27 °C in the dwelling during a standard year. A maximum of 30 h per year results in maximum score. THER1.2 scores the availability of technical solutions used to avoid discomfort from cold surfaces during cooling (e.g. cooling by ceiling elements combined with mechanical ventilation). THER2 evaluates the winter conditions. THER2.1 scores the type of temperature control, where the presence of thermostats in each room yields the highest score. THER2.2 evaluates possible discomfort due to low radiant temperatures caused by window and wall

Table 4
Parameters, criteria and their weights for the assessment of thermal IEQ (THER).

Parameter		Parameter weights	Criteria		Criterion weights
THER1	Temperature, summer	30%	1.1	Overheating of critical rooms	90%
			1.2	Discomfort due to cold surfaces	10%
THER2	Temperature, winter	25%	2.1	Heat source controls	50%
			2.2	Surface temperatures	50%
THER3	Draught risk	20%	3.1	Draught from leaky openings	40%
			3.2	Downdraught from surfaces	25%
			3.3	Draught from ventilation	35%
THER4	Occupants' possibilities to adjust the thermal IEQ	25%	4.1	Ventilation boost, natural ventilation	25%
			4.2	Ventilation boost, mechanical ventilation	10%
			4.3	Automatic control of ventilation rate	15%
			4.4	External shading	20%
			4.5	Cooling system	5%
			4.6	Temperature regulation at room level	25%

constructions. The given score decreases with the increasing number of hours where the radiant temperature asymmetry is above 10.5 °C. This is rarely the case in new buildings, where the maximum score will often be achieved. The criterion may, however, identify construction problems in older buildings.

THER3 evaluates the risk of draught caused by leaky windows and external doors (THER3.1, based on visual inspection), downdraught (THER3.2 based on thermal transmittance and U-values of window surfaces) and mechanical ventilation and air supply (THER3.3, based on e.g. type of mechanical ventilation, presence of preheating, type of inlet).

The first three criteria scoring the occupants' possibilities to adjust the thermal IEQ (THER4.1-THER4.3) are related to ventilation and thus similar to those used for indoor air quality (IAQ4.1-IAQ4.3). However, in THER4.1-THER4.3, the evaluation is entirely related to the thermal conditions in the dwelling. The strict focus on thermal IEQ is also applied in THER4.4, where the possibility to control external shading is considered positive regardless of the potential visual discomfort (reduced view), which is addressed under the visual IEQ. Similarly, the possibility of personal control of mechanical cooling (THER4.5) results in additional scores despite the possible increase in energy consumption. When external shading and cooling (THER4.4 and THER4.5) are not present, these are removed from the evaluation and the criterion weights under THER4 are changed, while maintaining the relative weights of the remaining criteria (THER4.1 33.33%; THER4.2 13.33%; THER4.3 20.00%; THER4.6 33.33%). The same adjustment is made when only one of the two criteria is absent. THER4.6 scores the possibility to control the temperature at room level, in combination with the speed of the system's response to a change. The thermal indoor environment is the area with the most possibilities for occupant control (THER4), which is reflected in the parameter weight of 25%.

3.1.4. Visual indoor environment (VIS)

The evaluation of the visual IEQ (VIS) considers the supply of daylight (amount and quality), direct sunlight, view (in and out) and the occupants' options to adjust some of these (Table 5).

The amount and quality of daylight and direct sunlight (VIS1 and VIS2) are assessed through calculations performed by the tool on a 3D model of the building, upon providing the window area, glass type, direction, position and other relevant input parameters. VIS1 also scores the colour rendering caused by the selected type of glass (VIS1.2). Colour-neutral glass with a colour rendering index above 97 yields maximum score. VIS2 calculates the number of direct sunlight hours per day in the dwelling for 1 February, according to standard EN 17037 [43]. More direct sunlight results in a higher score in Danish dwellings. This parameter should, however, be adapted to other climates and building typologies. It should be noted that the tool only evaluates natural daylight conditions, since light fixtures are not an integral part of the residential building design. Adoption of the tool for other building types (e.g. office buildings) may require the inclusion of the effects of lighting installations.

The parameter scoring the view in and view out (VIS3) takes into consideration the positive effects of a good view from the dwelling and the negative effects of compromised privacy (view-in) [44]. VIS3 thus scores qualitative elements of the visual IEQ and supports the equal role of comfort, health and well-being in the consideration of IEQ, as defined by Rohde et al. [45]. VIS3 is aimed to promote the design of buildings that ensures a balance between providing a pleasant view for the occupants and protecting their privacy (limited view-in from passers-by). A model for the evaluation of view-in and privacy was therefore developed and incorporated in the tool.

VIS4.1 evaluates the occupants' possibility to adjust the solar shading (no possibility (lowest score), manual or by remote control (highest score)). VIS4.2 scores whether the shading can be activated and adjusted for each window individually. As is the case for the acoustic IEQ, the potential occupant control is limited, because the solutions responsible for the visual IEQ are often decided during the design process. This is reflected in the relatively low weight of the parameter VIS4 (10%).

3.2. Criteria and parameters weights

Three levels of weighting are applied in the tool (Fig. 3). The weighting between all criteria within a given parameter provides a parameter score (first level of weighting). The four parameters in each area are weighted to obtain an overall area score (second level of weighting). Finally, the overall IEQ score is obtained after weighting the four areas (ACOU, IAQ, THER, VIS) equally (25% each; third level of weighting).

The first and second level weightings are based on the weights identified by Rohde et al. [35]. These are included in Tables 1 and 3–5. The four main areas are equally weighted because of the lack of sufficient data on their relative perceived importance.

3.3. Communication of results

One of the objectives of the **IEQ**Compass tool is to provide an intuitive communication of a dwelling's potential IEQ to both professionals and a broader audience. The results are communicated in two ways. The tool provides an overall "IEQ label", as well as a deeper insight into the criteria scores through the "IEQ Design Compass". Both use labelling by a letter ranking and colour code, similar to energy labels for buildings used in European energy performance certificates [46] (Table 6). The tool labels the building with an overall class, but partial classes for the four individual IEQ areas are also reported. This allows the identification of the most critical areas that should be addressed during the design process of new buildings, in existing buildings or in renovation projects.

The "IEQ label" must be applicable for all buildings. Class C, therefore, corresponds to the minimum IEQ conditions set for new buildings by the 2018 Danish Building Regulation. In order to obtain classes A and B, the building must perform, at least under some parameters, better than the building regulation's minimum requirements for IEQ. The overall class is obtained based on a (weighted) average of the scores for the four areas (ACOU, IAQ, VIS, THER). However, the overall class cannot be more than two classes above the lowest class obtained for the four individual areas. For example, class B can only be obtained if all

Table 5
Parameters, criteria and their weights for the assessment of visual IE.

Parameter		Parameter weights	Criteria		Criterion weights
VIS1	Daylight	35%	1.1	Daylight intensity and distribution	80%
			1.2	Colour rendering of windows	20%
VIS2	Direct sunlight	25%	2.1	Sunlight exposure (hours/day)	100%
VIS3	View	30%	3.1	View out (access and quality)	40%
			3.2	View-in (exposure to passers-by)	35%
			3.3	Influence of view by external shading	25%
VIS4	Occupants' possibilities to adjust the visual IEQ	10%	4.1	External solar shading, adjustment	50%
			4.2	External solar shading, window-by-window activation	50%

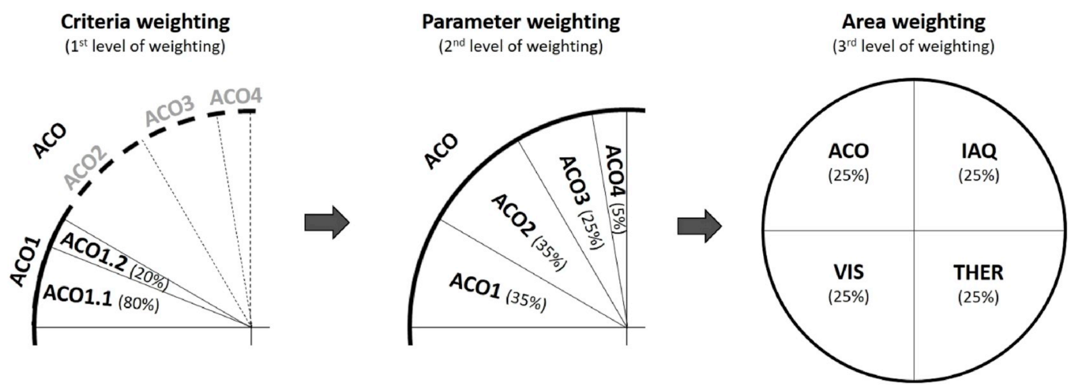

Fig. 3. 1st, 2nd and 3rd level of weightings applied in the **IEQ**Compass.

Table 6
Scores corresponding to the letter ranking and colour codes on the **IEQ**Compass labels.

Letter rank on the IEQCompass labels	Scores (fraction of the maximum achievable score)
A	85% ≤ score ≤ 100%
B	75% ≤ score < 85%
C	65% ≤ score < 75%
D	55% ≤ score < 65%
E	45% ≤ score < 55%
F	35% ≤ score < 45%
G	0% ≤ score < 35%

individual area classes are D or higher. Table 6 shows the ranges of scores corresponding to the seven classes. These scores are applicable both for the individual classes and for the overall class based on the average of the four area scores.

The “IEQ Design Compass” (see next section for example) provides the results with an additional level of detail by illustrating the scores (0-10) for all criteria under each parameter. The purpose of the “IEQ Design Compass” is to help identify potential IEQ problems and aid designers in decision making regarding the IEQ in an early stage of the design process. It can be used both for new buildings and for renovations. In the latter case, the Compass illustrates how the different parameters may change under different renovation scenarios and where the largest improvements can be found. The tool allows specific criteria in the Compass to be locked, in order to illustrate that these criteria cannot be changed during renovation (e.g. the quality of view out will often be unchanged after renovation).

3.4. Example of application

To illustrate the application of the tool, a case study is presented. Fig. 4 shows the case study building before and after its extensive renovation.

One apartment in the building block is used to illustrate the application of the tool. It is situated on the first floor of the 2-storey apartment building and has an area of 92 m^2 (Fig. 5). Three rooms are facing south and do not have solar shading. The common room and the kitchen face north and have overhangs above the window (balcony above).

Fig. 4. The Case study building before and after renovation. After renovation the building features larger windows and shallow balconies to provide more daylight in the dwellings.

The apartment was constructed in 1972, which is reflected in the insulation levels and type of ventilation. The U-value for the external walls was 0.4 W/m^2K, the U-value for the windows was 1.5 W/m^2K (solar heat gain transfer coefficient, g-value = 0.63; light transmittance, LT-value = 0.7). The hybrid ventilation included mechanical exhaust in the kitchen, lavatory and bathroom, combined with natural ventilation (outdoor air inlet through vents in the windows, lack of heat recovery or preheating).

Fig. 6 shows the “IEQ label” with the overall class and the four partial classes generated by the tool for the apartment. The potential IEQ in the apartment was classified as class E. The thermal IEQ, indoor air quality and visual IEQ were rated as class E, the acoustic IEQ obtained class D. The classification indicated a potential for improvements in all areas. The “IEQ Design Compass” for the apartment is shown in Fig. 7.

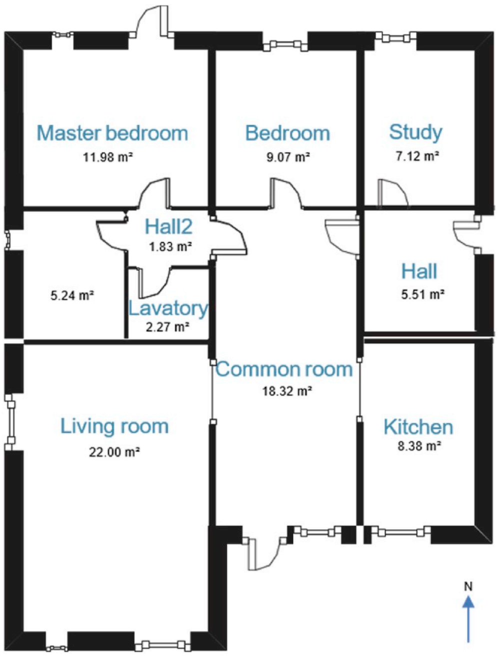

Fig. 5. Floor plan of the apartment used in the case-study.

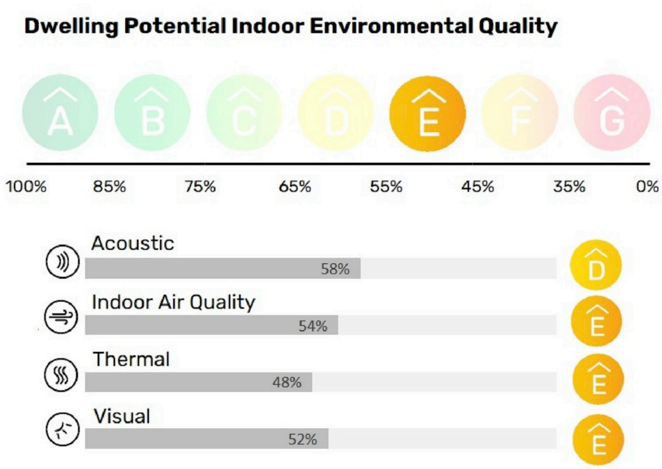

Fig. 6. "IEQ label" for the apartment before renovation.

The acoustic IEQ obtained 58% of the maximum score. Relatively low scores were obtained for ACOU2.1 and ACOU2.2, which evaluate airborne noise and impact noise from neighbours, respectively. ACOU3.2 had a very low score due to long reverberation time and thus acoustic discomfort. Improvements of the acoustic indoor environment often require extensive constructional changes, which were not part of this project due to budget restrictions.

The indoor air quality obtained 54% of the possible top score. The lack of filtration of the outdoor air resulted in a reduced score for IAQ1. Low air change rates achieved by natural ventilation resulted in a low score for IAQ2.1. Both of these parameters were improved after renovation by installing balanced mechanical ventilation with heat recovery and preheating. This caused the parameter IAQ2 to be re-evaluated through two criteria (IAQ2a) instead of three (IAQ2b). IAQ3.2 revealed the need for an upgrade of the kitchen exhaust hood (from recirculation unit to one that exhausts to the outdoor), however this was not carried out during the renovation. The lack of user control of ventilation (IAQ4) further reduced the score and the corresponding class for indoor air quality. This remained the same after renovation.

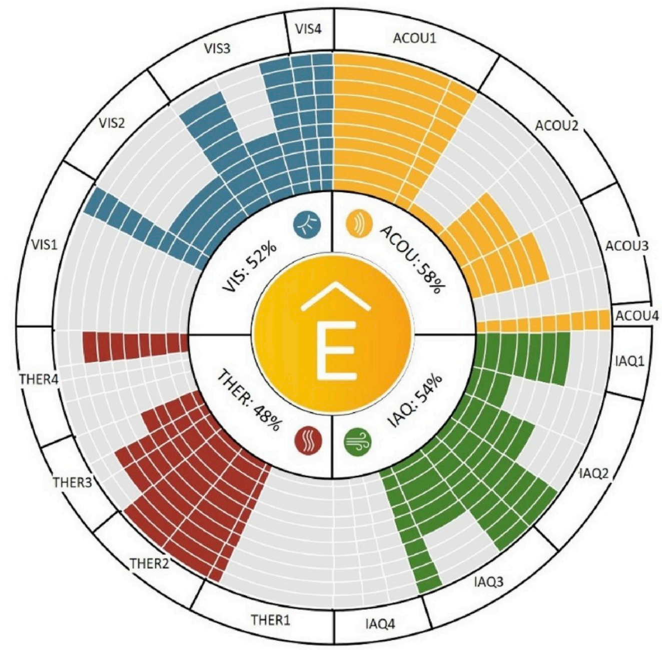

Fig. 7. The "IEQ Design Compass" before renovation of the apartment.

The rating of the thermal IEQ (48% of maximum score) identified problems during summer conditions when high indoor temperatures could be reached (THER1.1). This was solved by improving the g-value of the windows (from 0.63 to 0.53) and with additional ventilation. During winter, the natural ventilation caused the risk of draught (THER3.3), which was eliminated by adding mechanical ventilation that supplies preheated air to the apartment. The apartment lacked external shading or any cooling system, which reduces THER4 into 4 criteria in this evaluation. The lack of possibilities for the occupants to manually increase ventilation leads to a low score for THER4. This remained the same after renovation.

The visual IEQ obtained 52%, especially due to the low amount of daylight caused by deep rooms with small windows (VIS1.1) and lack of direct sunlight (VIS2). During renovation the window area was increased, thereby improving both criteria. The discomfort caused by the risk of view-in by passers-by (VIS3.2) remained the same before and after renovation.

The tool has revealed the need to improve ventilation (including personal control), façade (including shading) and windows (size and quality) and that these improvements would lead to a significantly improved IEQ. The U-value of the external walls was improved to 0.16 W/m^{2}K, the U-value of the windows to 0.52 W/m^{2}K (g-value = 0.53, LT-value = 0.74). Following renovation, the potential IEQ in the apartment improved to class C, with the four individual area classes being C (ACOU), D (IAQ), B (THER), and B (VIS) (Fig. 8).

4. Discussion

The ambition behind developing the **IEQ**Compass was to increase the overall focus on indoor environmental quality when designing new buildings or renovating existing ones, and thereby guiding designers towards designing healthier and more comfortable buildings. The tool is easy and fast to apply already in the early stages of a design process. It provides an IEQ labelling system, which can be implemented at a national level to complement the existing building energy certification program.

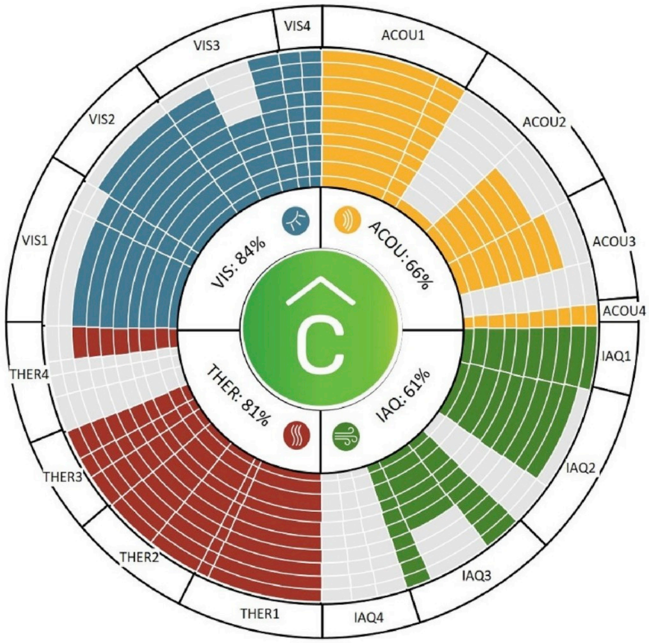

Fig. 8. The “IEQ Design Compass” after renovation of the apartment.

4.1. Limitations of the tool and its applicability

The **IEQ**Compass evaluates the *building's potential* to provide a comfortable and healthy indoor environment, without considering occupant influence. Although occupant behaviour is a strong driver of indoor environmental quality, the individual differences can be difficult to measure or predict. Measurements and surveys are often an important and trusted part of IEQ evaluations, but they also pose substantial practical and economic challenges. The labelling system needs to be widely affordable. Measurements and surveys are therefore not part of the tool.

The labelling system is based on a holistic approach, which includes the evaluation of IAQ, thermal, visual and acoustic IEQ. While this is considered an improvement compared to earlier efforts to create an evaluation system for the indoor environmental quality in buildings [14,15,22], it has its weaknesses. Classifying the IEQ of a dwelling or building into a single overall label requires weighting of parameters within the four areas. Individual classification of each parameter also relies on the weighting of the respective criteria. The weights at both levels have been determined based on subjective judgments of a group of experts. This approach may challenge the objectivity and reliability of the tool and its applicability for a national labelling system. However, great effort has been made to determine the weights that would produce a robust tool. This procedure was described in detail by Rohde et al. [35]. The four areas have been weighted equally, which may not reflect the occupant's true preferences between them [16,21,24]. Prioritization of the four areas is subjective and the scientific literature supporting a specific weighting between the areas is insufficient. As such data becomes available, the weighting in the tool may be updated.

As mentioned in the Introduction, data on the combined effects of the different areas and their parameters on IEQ is limited. Due to the complexity of the potential interactions and the uncertainty of their estimates, combined effects of the included parameters were not considered in the tool. However, the **IEQ**Compass indirectly addresses some elements of interactions. It identifies how alteration of one factor (e.g. installing new windows) may affect multiple parameters (e.g. temperature summer/winter, draught, air quality, reverberation time, daylight and view). As our understanding of the combined effects of the included parameters improves, they may be incorporated in future versions of the tool.

The tool has been developed, and the applied weights have been determined, with the Danish climate and building conditions in mind. Denmark has a temperate climate with relatively cool summers, moderately cold winters and large seasonal variations in daylight. The buildings have a relatively high standard in terms of energy consumption and overall design. Denmark has some of the most stringent energy performance requirements for new and renovated buildings. However, the building stock is ageing and due to the climate conditions and the often tightly built naturally ventilated residential buildings, indoor climate problems, especially those related to moisture and mould, are common. For application outside this region, the tool with its weights needs to be adapted to the local climate, buildings and perhaps even cultural conditions. Moreover, the **IEQ**Compass was developed for dwellings. Application in other building types, such as schools or offices, is relatively easily achievable after minor modifications of the criteria and weights. For example, the current tool does not consider artificial lighting, which is not covered by the Danish building code for dwellings. Future adaptations of the tool for buildings for which such regulation exists should include the evaluation of artificial lighting. Thereby, the tool is versatile regarding content, while its framework and structure (four areas, each consisting of three building-related parameters and one user-related parameter) are independent of building typology.

The tool does not differentiate between urban and rural areas. Dwellings in urban areas are often exposed to noise, air pollution and view-in from passers-by to a larger extent than dwellings in rural areas. Therefore the **IEQ**Compass may on average indicate poorer conditions and a larger need for improvement in urban areas, where better solutions may be necessary in order to provide a good IEQ for occupants.

4.2. Target groups

The **IEQ**Compass was developed to address two different target groups, which is reflected in the two different methods to display and communicate the results (“IEQ label” and “IEQ Design Compass”*)*. The “IEQ label” targets a broad audience familiar with similar labelling schemes used for building energy consumption as well as for certain consumer products. This should facilitate a nationwide adoption, application along with the existing energy certification, and consequently a potentially large societal impact.

The “IEQ Design Compass” addresses practitioners in the construction sector. Its purpose is to promote dialogue between consultants and building owners/developers, set targets for good indoor environments and thus facilitate the implementation of solutions that ensure them. This should ideally occur already in the early design phase, where the tool is applicable due to its simple input structure. Poor indoor environment can often be traced to decisions taken too late, when substantial changes are difficult and expensive to make. The “IEQ Design Compass” can also be useful during building renovation, where it helps identify problems that deserve attention in order to achieve an improved IEQ.

4.3. Role of the building industry in development and implementation

In order to make the tool viable for the building industry, leading companies in the Danish building industry and key stakeholders from relevant industrial organizations were consulted during the development of the tool. Several workshops with industrial participation were organized to obtain feedback on the tool's contents, user interface, presentation of results and application strategy. All participants of the workshops were invited to test the tool, which helped identify errors and ambiguities. Two test rounds were conducted during the development of the tool. The first round was conducted after the completion of the tool's first test version. It identified parts of the tool difficult to understand or use, such as the description of input variables and their entry into the tool. The test also collected information on the time required to complete an entire evaluation of a dwelling, which was compared between first-time users and repeat users. The required time for a complete test dropped significantly after only a few applications of the tool. However, entering input data for the visual IE remained cumbersome and was therefore further automatized. Additionally, the test identified the lack of some building constructions predefined in the tool and additional constructions were thus added. The second test round focused on the scoring and weighting. It attempted to compare the users' subjective evaluation of the IEQ with the outputs provided by the **IEQ**Compass. The test revealed, among others, that the score for acoustic IE was consistently too low, regardless of the actual conditions. A less stringent scoring was consequently adopted to achieve a more realistic distribution.

Experts and practitioners from the industry were also asked to fill in the questionnaire, which was used to determine the weighting factors for the different criteria and parameters in the tool. The active involvement of the industry in the development of the tool is anticipated to facilitate the tool's adoption by the intended end-users. The implementation of the tool will start on a voluntary basis, but it is envisioned to contribute to the Danish building regulation in the future.

5. Conclusion

The **IEQ**Compass demonstrates that developing a holistic tool for the evaluation of the indoor environmental quality, which considers indoor air quality, thermal, visual and acoustic indoor environmental quality, is feasible. Weighting of the parameters used for the evaluation of the four areas (IAQ, thermal, visual and acoustic IEQ) and their underlying criteria has been established. This has been done for dwellings only and the tool is therefore currently not applicable for other building typologies. The tool can however be relatively easily adapted to other types of building. Moreover, the four areas are currently weighted equally, due to the lack of data on their relative importance for the overall IEQ. If such data becomes available, the weighting may be updated in the tool.

The tool performs all simulations and calculations required for the evaluation of the IEQ. Its application is relatively straightforward; the typical time required to perform an evaluation for an apartment is under 3 h. The results from the tool target two different user groups, building professionals and a broader audience, including building users. The results are therefore presented at two different levels of detail. The "IEQ label" indicates the overall IEQ label for a dwelling, together with the partial labels obtained for the four individual areas. A 7-step letter ranking labelling system was developed for this purpose. This level informs building owners and occupants in a fashion similar to the building energy performance certification programs. The "IEQ Design Compass" is a more detailed graphical presentation of the results. It is intended to help designers and building professionals identify potential causes of IEQ problems and appropriate solutions during the design process.

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