# Indoor environmental quality assessment models: A literature review and a proposed weighting and classification scheme

CrossMark

David Heinzerling*, Stefano Schiavon, Tom Webster, Ed Arens

*The Center for the Built Environment, Berkeley, CA, USA*

## ARTICLE INFO

## ABSTRACT

This paper explores the existing literature on indoor environmental quality (IEQ) evaluation models and proposes a new weighting and classification scheme. Studies that attempt to provide IEQ assessment of commercial buildings through a scoring system are reviewed and critiqued. Objective and subjective evaluation methods and correlations are discussed. The use of assessment categories (classes) in IEQ models is critiqued and an argument is proposed against their adoption. IEQ weighting schemes are summarized and compared against a newly developed scheme based on 52,980 occupant responses in office buildings. A binary assessment classification scheme is proposed in alignment with the ASHRAE/CIBSE/USGBC Performance Measurement Protocols for Commercial Buildings.

© 2013 Elsevier Ltd. All rights reserved.

## 1. Introduction

The indoor environmental quality (IEQ) performance of buildings affects the health, productivity and well-being of building occupants, as well as lifecycle costs, and energy consumption. Poor indoor air quality (IAQ) is related to sick-building-syndrome (SBS) [1–3], and high IEQ is associated with company and employee productivity gains and employee retention though this area of research is contentious and in need of additional studies [1,4–7]. In commercial buildings, green building advocates and indoor environmental quality researchers argue that occupants represent the largest share of the operational costs of a building, which suggests that high IEQ could have economic benefits [8–11]. IEQ parameters have a strong influence over energy consumption, both through design related decisions and in the operation of the building [12,13]. Therefore it is important to evaluate IEQ performance at a whole-building level in order to ensure high IEQ as efficiency measures are ratcheted up in the face of more stringent energy regulations. According to ASHRAE TC 1.6 (Terminology) Indoor Environmental Quality is a perceived indoor experience about the building indoor environment that includes aspects of design, analysis, and operation of energy efficient, healthy, and comfortable buildings. Fields of specialization include architecture, HVAC design, thermal comfort, indoor air quality (IAQ), lighting, acoustics, and control systems.

We found eight studies that have proposed methods for evaluating indoor environmental quality in commercial buildings using a scoring/rating system [14–22]. The method used for selecting these papers is discussed in Section 2. While many of the methods presented in these studies overlap, there are important differences that highlight multiple issues with such scoring systems. While Frontczak and Wargocki [23] discussed the comfort-related conclusions of many of these studies, there has not been a literature review conducted on the specifics of these IEQ model scoring systems. The literature on this subject uses many different terms to describe a similar goal, including IEQ model, IEQ index, rating system, and scoring system. While there are subtle differences in these terms that will be discussed in this paper, the most general term "IEQ model" is used here to refer to any system that takes IEQ performance data and produces an evaluative numerical summary of the data.

IEQ models require aggregating data to provide a summary picture of how well a space or building is performing. These summary evaluations may be completed using objective physical measurements (e.g., measurement of noise level, air temperature, illuminance, etc.), subjective occupant surveys (e.g., how satisfied are you with the noise level in your workstation?) or both. The purpose of an IEQ model is to distill the data contained in these

---

* Corresponding author. UC Berkeley, 390 Wurster Hall, Berkeley, CA 94720, USA. Tel.: +1 281 755 2525; fax: +1 510 643 5571.
*E-mail address:* dheinzerling@gmail.com (D. Heinzerling).

objective and subjective measurements into a rating or score. The accuracy, relevance and applicability of such scoring systems depend heavily on the quality of the objective and subjective assessment data that is collected. Therefore, before diving into IEQ models that use this data, this paper will briefly review the current state of subjective and objective measurement methods.

The aim of this paper is to provide: (1) an overview of subjective and objective IEQ evaluation methods and tools, (2) a literature review of IEQ models, (3) a discussion of the weaknesses of IEQ models and assessment class schemes, and (4) a proposal for a new weighting and assessment class scheme.

## 2. Overview of subjective and objective measurement methods and tools

In the past few years, documents to standardize and eventually codify IEQ measurement and performance have been written. In the United States, the ASHRAE/CIBSE/USGBC Performance Measurement Protocols for Commercial Buildings [24] and the Performance Measurement Protocols Best Practices Guide [25] add to the scope of the European standard EN15251 (2007), which provides guidance on IEQ measurement, standards, and input values to use in energy simulation software. This standard was created largely as guidance for architects and engineers tasked to follow European Council and Parliament directive on the energy performance of buildings (EPDB), which mandated energy performance certificates, among other items [26]. The focus of EN15251 is largely on defining and subsequently ensuring good IEQ while making design decisions to lower building energy use. Because EN15251 is a standard and is primarily used for energy simulation, there are few included practical guidelines on how to accurately and efficiently measure IEQ performance. In the last few years, multiple papers have been written to help fill this gap [14,15,27], though recently the publication of the REHVA Indoor Climate Quality Assessment guidebook (ICQ) has addressed the need for guidelines for thermal comfort and indoor air quality [13]. However, a single source guidebook for all IEQ parameters, like the Performance Measurement Protocols (discussed below), does not have a European equivalent at this time.

The Performance Measurement Protocols (PMP) provides a set of protocols that facilitate the appropriate and accurate comparison of measured energy, water, and indoor environmental quality performance of commercial buildings [24]. The protocols are provided in three different levels that represent a range of accuracy and cost: Basic, Intermediate, and Advanced. Additionally, the protocols provide guidance on issues of temporal and spatial resolution.

While the PMP and to some extent the ICQ offer guidance on appropriate subjective and objective measurement methods and tools, the specifics of exactly how to implement these methods and tools are largely left up to user. The next two sections briefly review major implementations of subjective and objective measurement methods and tools that are available in the literature.

### 2.1. Subjective measurement methods and tools

Surveying is often the simplest and least-expensive method for evaluating IEQ concerns in a building [24]. Occupant satisfaction is ultimately the primary interest of the building owner/operator regardless of physical IEQ conditions. There are many survey tools available for studying IEQ satisfaction among occupants. Schiavon and Peretti's review of IEQ surveys [28] provides a historical account of IEQ surveys. The two most widely used survey methods are the Building Use Studies Ltd. (BUS) [29] and the Center for the Built Environment (CBE) survey [30].

The subjective nature of surveys and range of opinions for similar IEQ physical conditions complicate the use of surveys as the only tool for evaluating building IEQ performance. Additionally, surveys do not always capture IEQ issues that may have energy implications (e.g. over-lighting or economizer operation) and have incomplete diagnostic capability. Nicol and Wilson [31] discuss other issues associated with surveys, including: (1) difficulty finding a representative period for surveying; (2) interpreting the results; and (3) which questions should be asked?

The first critique can be partially addressed by doing "right-now" surveys at different times of the day/week/month/year, though this can potentially lead to "survey fatigue" [32]. "Right-now" surveys ask about conditions at the moment the survey is given, as opposed to long-term surveys that ask occupants to summarize their overall satisfaction for the past week, month or year. The second critique refers to the lack of clear guidelines for practitioners on how to transform subjective measures into standardized limits of environmental parameters. For example, how should visual comfort satisfaction scores be interpreted in terms of light levels and glare ratios? The IEQ models discussed in Section 3 of this paper aim to address this limitation of surveys. However, interpretation issues remain, including how to relate whole building satisfaction and individual IEQ category satisfaction results. The third critique refers to the complicated nature of survey questions. The phrasing of survey questions can greatly affect the answers received, which can lead to biased or otherwise inaccurate results which complicates comparisons between surveys. Other factors, such as psychological and physiological states, and cultural and economic differences, are not typically accounted for in surveys. Benchmarking requires the static nature of the two most widely used occupant survey databases (CBE and BUS), making it difficult to edit existing questions or implement new questions that decrease bias and improve accuracy.

### 2.2. Objective measurement methods and tools

The first two critiques discussed concerning surveys above (finding a representative period and interpreting the results) also apply to objective measurements. There are also the additional issues of sensor accuracy/calibration and cost. There are complex and often expensive methods for keeping instruments calibrated, and while the sensors themselves are often expensive, the labor associated with deploying sensors across a large building and then analyzing the vast amount of data can quickly become impractical. The next two sections discuss the major published efforts to use objective measurements to evaluate IEQ in commercial buildings. This section is meant to provide an overview of common methods and tools, but is not meant to be an exhaustive review of objective IEQ measurement methods and tools.

#### 2.2.1. Tools

Finding accurate, easy-to-use, and inexpensive measurement equipment is one of the major hurdles in IEQ performance evaluation. With the explosion of wireless monitoring equipment in recent years, measuring various building parameters has become a much less labor-intensive process. However, there are still a number of operational hurdles that still make measurement a cumbersome process. While sensor and logging device manufacturers have made products that are increasingly accurate and easy-to-use (e.g., wireless), the work of creating devices with multiple sensors is still largely in the hands of the users. IEQ measurement requires a combination of devices and individual sensors to capture the state of IEQ in a space. This section provides a brief review of devices that have been described in the literature.

Fig. 1 show pictures of IEQ measurement carts and desktop devices. The sensors associated with each device are provided in Table 1.
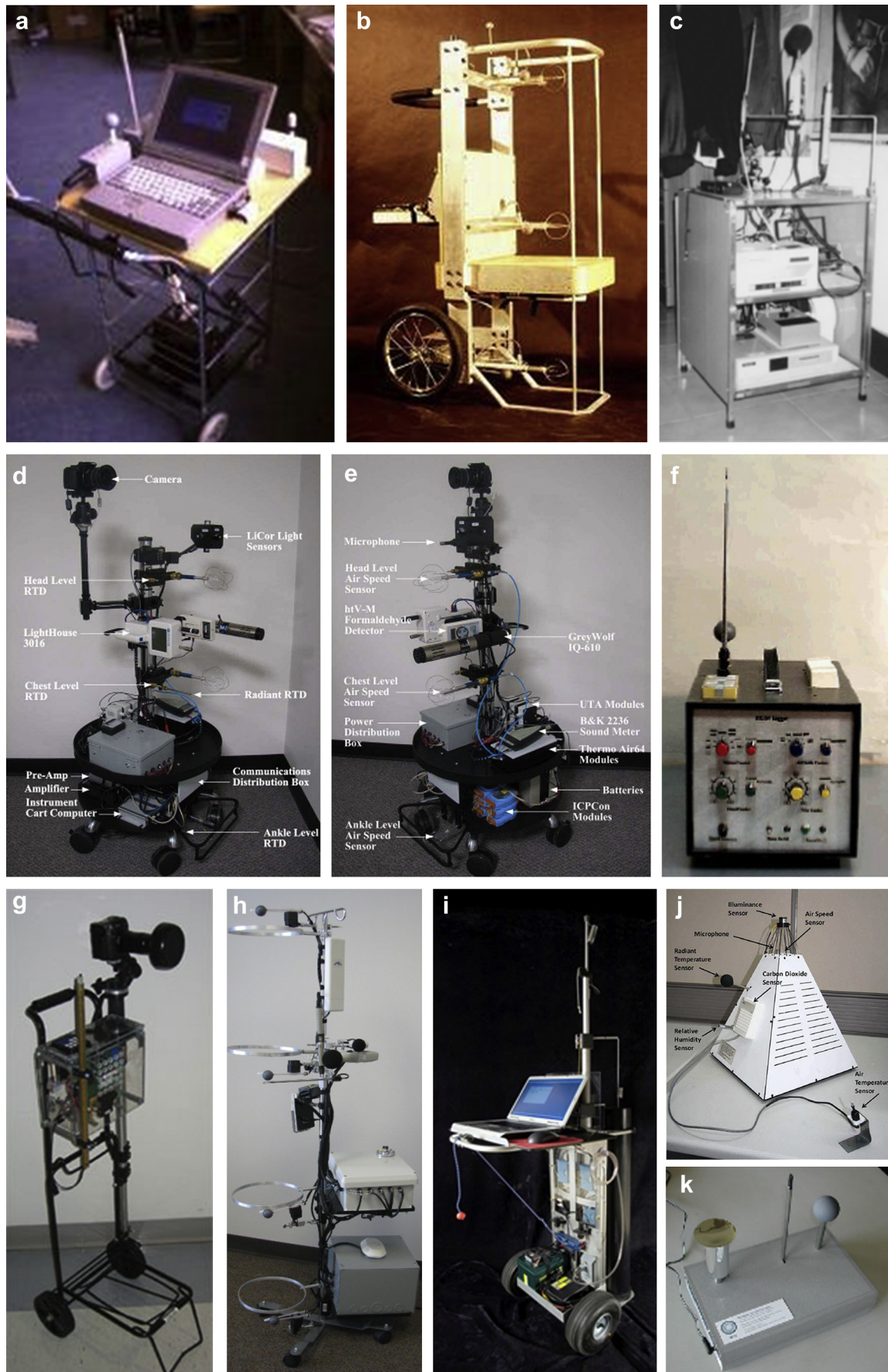
**Fig. 1.** (a) SCATs instrumented cart [33]. (b) Instrumented chair-like cart [34]. (c) IEQ cart [18]. (d) NICE instrumented cart part 1 [35]. (e) NICE instrumented cart part 2 [35]. (f) IEQ logger [22]. (g) EnviroBot [36]. (h) Comprehensive IEQ monitoring cart [37,38]. (i) UFAD commissioning cart [39]. (j) Pyramid desktop device [35]. (k) Indoor climate monitor desktop device [40].

These devices represent a wide range of abilities and size. Carts are primarily useful for their ability to move multiple sensors around a space, to have multiple wired sensors log to one location, and to keep sensors steady for the measurement period. With the advent of wireless sensors, this restriction of keeping sensors together is lifted. While there are still some practical advantages to having multiple sensors on one cart, the bulkiness of carts makes them difficult to move around spaces, travel with, and get measurements directly in the workspace while the occupant is present. In these studies, there is significant overlap in the types of sensors used to evaluate different IEQ parameters, though IAQ is often minimally measured with $CO_2$ and lighting is minimally measured with illuminance. The sensors chosen for these studies (as determined by cost, accuracy, and availability) provide a limited picture of the indoor environment and necessarily limit the interpretation of the IEQ models discussed later in this paper. There is extensive literature surrounding the problems and limitations of different sensor types (e.g. for $CO_2$ and outdoor airflow rate [41–43]) and such limitations are important to keep in mind when relying on objective measurements to interpret the quality of the indoor environment.

### 2.2.2. Methods

Measurement procedures describe the details of how a set of sensors are used to collect data. These details include temporal and spatial resolution as well as special instructions on the placement of the sensors, the presence of occupants, and other indoor conditions. Because IEQ models attempt to summarize overall IEQ performance, the details of data collection are important. To the authors' knowledge, there is no study that has systematically evaluated different levels of temporal and spatial resolutions needed for accurate assessment of whole-building level IEQ performance. Table 2 provides a summary of the spatial and temporal procedural variables for the studies reviewed in this paper that specified temporal and spatial procedures. Additionally, the EPA BASE protocol [44] and the ASHRAE/CIBSE/USGBC Performance Measurement Protocols for Commercial Buildings (PMP) [24] are included.

There is a wide range of temporal and spatial resolution used in these IEQ studies, though each study represents only a temporal and spatial snapshot of a building. There is little guidance from the literature on how many hours of data needs to be collected in order to provide a representative sample. The studies in Table 2 ranged from 1-day to 5 years in length. With improved technology and cheap storage, continuous measurement is more common practice today. With continuous measurement comes the need for analysis tools to breakdown the data into meaningful summaries of performance. The literature contains little discussion of custom analysis tools and procedures.

Metadata is "data about data," which in the context of building performance evaluation field studies is the data describing location, time, and sensors of measurements taken. Handling metadata is one of the most time consuming aspects of field studies. Much of this time spent is unavoidable; the time it takes to familiarize oneself with the building being studied (layout, systems, control sequences). However, some of the time dedicated to metadata is avoidable through efficient procedures. Existing literature on this issue is sparse, though there has been effort at the Center for Building Performance and Diagnostics (CBPD) to develop and document efficient metadata collection and handling procedures [36,45].

## 3. IEQ models literature review

Indoor environmental quality models combine multiple IEQ parameters into a single number and attempt to relate occupant satisfaction with objective measurements. An IEQ index, i.e. a numerical rating, is the result of an IEQ model. This combination is often used for rating or ranking an existing building according to its IEQ, though there is also potential for predicting IEQ in new design using IEQ models tied to simulation results [46]. One relevant motivating factor behind recent research on IEQ models is the European standard EN15251 (2007). An important feature of EN15251 is the breakdown of IEQ categories as shown in Table 3. There is some debate about the interpretation of these categories as aligned with levels of quality [27,31,47–50]. The categories are intended to express levels of expectation from occupants (category I being the highest expectation), though the highest category is not necessarily the highest IEQ and can be associated with negative energy consequences [31,47,48]. The categories presented in Table 3 provide the foundation for many of the IEQ models reviewed in this paper because they provide a straightforward method for breaking down data into performance categories that can be used for evaluation purposes. The critiques of this category breakdown will be discussed in the Discussion section of this paper.

Some studies choose to define their own quality categories (based on subjective/objective regression equations) while others use existing standards. To avoid confusion of whether such categories should be interpreted as "quality categories," this study uses the term "assessment classes," where it is left up to the specific model of what is being assessed (e.g. quality, occupant satisfaction, or tightness of control).

### 3.1. Literature review method

A literature search was performed in Google Scholar using key terms "IEQ model", "IEQ index", "building index", "IEQ + commercial + model". Thirteen peer reviewed papers were found. Eight were selected based on the following criteria: (1) the primary purpose of the paper is to describe an IEQ model or index, where IEQ includes at least acoustics, IAQ, lighting, and thermal comfort; and (2) the model pertains to commercial buildings. The IEQ models we found fall into two basic categories: Subjective–objective and objective-criteria:

> *Subjective–objective (Fig. 2a)*: Studies that attempt to correlate subjective and objective measures, providing equations that predict occupant satisfaction for each IEQ category based on objective measurements and overall IEQ as a combination of each sub-index [15,16,19,20,22]. This overall IEQ index is then compared to a fixed set of ranges that define the level of IEQ in the space or building.
>
> *Objective-criteria (Fig. 2b)*: Studies in which objective measurements are made and compared against a fixed set of criteria that determine what assessment class the measurement falls into. This discretization of measurements creates a breakdown of time-spent in each assessment class, which can then be used to determine single value indexes for each IEQ category and overall IEQ [14,17,18]. These studies may or may not include subjective measurements, but the subjective measurements are not included as part of the overall IEQ index. However, the objective criteria themselves were derived from previous subjective–objective type studies.

The studies were summarized using the following variables: (1) Objective measures: which IEQ parameters were measured with instruments? (2) Subjective measures: were occupants or professionals surveyed? (3) Subjective/Objective relationship: what sort of relationship was reported between the two measures (e.g. linear, nonlinear)? (4) Assessment classes: does the study include a breakdown into assessment classes, if so, how are they defined? (5) IEQ category weights: does the study attempt to apply weights to different IEQ categories, if so, what are the weights?

**Table 1**
Summary of IEQ cart instrumentation.

| Cart | Acoustics | IAQ | Lighting | Thermal Comfort |
|---|---|---|---|---|
| SCATs instrumented cart [33] | Sound level meter | $CO_2$ | Illuminance | Air temperature; globe temperature; air speed; RH. Instruments tethered to cart and placed on occupant desktops when in use. |
| Instrumented chair-like cart [34] | – | – | Illuminance | Air temperature, air speed, and globe temperature at 0.1, 0.6, 1.1 m; dewpoint temperature and chair surface temperature at 0.6 m, radiant asymmetry at 1.1 m |
| IEQ cart [18] | Sound level meter | $CO_2$, CO, $PM_{tot}$ | Illuminance | Air temperature; air speed; RH |
| NRC indoor climate evaluator (NICE) [35] | Sound level meter | $CO_2$, HCHO, CO, VOCs, PM(0.3–10 μm), | Illuminance, camera for HDR luminance | Air temperature, globe temperature, RH, air speed |
| IEQ logger [22] | Sound level meter | $CO_2$ | Horizontal and vertical illuminance | Air temperature, globe temperature, radiant temperature |
| EnviroBot[36] | – | $CO_2$, CO, $PM_{tot}$, TVOCs | Illuminance, camera for HDR luminance | Air temperature at 0.1, 0.6, 1.1 m; RH; hand-held air speed and radiant temperature |
| Comprehensive IEQ monitoring cart [37,38] | Sound level meter | $CO_2$, CO, $PM_{tot}$, TVOCs | Horizontal and vertical illuminance, camera for HDR luminance | Air temperature and globe temperature at 0.1, 0.6, 1.1, 1.7 m; air speed; RH |
| UFAD commissioning cart [39] | – | – | – | Air temperature at 0.1, 0.23, 0.49, 0.73, 0.98, 1.2, 1.5, 1.7, 2.1, 2.5, 2.8, 3.3 m, underfloor temperature and pressure, floor and ceiling infrared surface temperature (IRT) |
| Pyramid desktop device [35] | Sound level meter | $CO_2$ | Illuminance | Air temperature, radiant temperature, RH, air speed |
| Indoor climate monitor [40] | – | – | – | Air temperature, globe temperature, RH, air speed |

**Table 2**
Objective measurement procedural variables summary.

| Protocol/study | | Acoustics | IAQ | Lighting | Thermal comfort |
|---|---|---|---|---|---|
| PMP (intermediate level) [24] | Temporal | Background noise: 30 s minimum per measurement | Continuous for at least 1 week | Unknown | Continuous for unknown length of time |
| | Spatial | Background noise: at any valid measurement point where occupants are and at least 4 locations per room | Spaces with unusual or atypical activities; omit sparsely occupied and unoccupied areas | Illuminance: 0.76 m above floor at regular grid spacing = ¼ space between luminaires Luminance: 11 specific locations (see PMP pp. 145–146) | At typical workstations; Close to locations where occupants identified issues; In relevant areas of control system (diffusers, radiators, windows) |
| EPA base [44] | Temporal | Background noise: continuous measurement for 3 days | CO, $CO_2$: continuous for 3 days and 5-min averages on mobile cart (20 locations) VOCs, PM, HCHO: one 9-h integrated sample | Continuous measurement for 3 days | Continuous measurement for 3 days and 5-min averages on mobile cart (20 locations) |
| | Spatial | 3 fixed locations | 3 fixed locations and 20 mobile cart locations | 3 fixed locations | 3 fixed locations and 20 mobile cart locations |
| [36] | Temporal | Spot measurements and 24 h continuous measurements during summer, winter, and swing seasons over 5 year period (unknown how long per building); Cart measurements made for 15 min with 15 s interval data and averaged | | | |
| | Spatial | 10–15% of workstations per floor; Cart placed in the position of the occupant's chair | | | |
| [37] | Temporal | One week of measurements per building; Continuous measurement at 1, 5, 15 min logging intervals | | | |
| | Spatial | Unknown | | | |
| [18] | Temporal | 24 h of continuous measurement | | | |
| | Spatial | Sensors installed in breathing zone but in a fixed location that minimizes influence on living behavior of elders in study. Unknown density of measurement locations. | | | |
| [16] | Temporal | 20 min for measurement period; 1 min intervals; mean of 20 min interval used for analysis | | | |
| | Spatial | Workstations of the occupants that were surveyed while occupant was present | | | |
| [35] | Temporal | NICE: 10–15 min for measurement period; unknown sampling rate; during occupied hours; Pyramid: 15 min sampling rate, continuous measurement for several days | | | |
| | Spatial | NICE: balance of space types (open plan, enclosed, perimeter, interior); Pyramid: up to 6 fixed locations | | | |

**Table 3**
Categories for IEQ (EN15251, 2007).

| Category | Explanation |
|---|---|
| I | High level of expectation only used for spaces occupied by very sensitive and fragile persons |
| II | Normal expectation for new buildings and renovations |
| III | A moderate expectation (used for existing buildings) |
| IV | Values outside the criteria for the above categories (only acceptable for limited periods) |

### 3.2. Literature review results

Table 4 summarizes the papers found in this literature review and the characteristics of IEQ models. The papers are ordered by publication year. Most IEQ model studies also weight the IEQ categories when determining overall IEQ in order to apply a factor of relative importance. This weighting of IEQ categories is based on occupant survey results or determined through regression analysis. Humphreys outlines the pitfalls associated with combining IEQ categories into one index [48]. Frontczak and Wargocki [23] summarized much of the literature available on IEQ category weighting, two of which are included in Table 4. Kim and De Dear [51], using the Center for the Built Environment IEQ survey database described in Ref. [52], looked at relationships between IEQ categories and overall workspace satisfaction. Rather than apply a weighting scheme to IEQ categories to obtain overall IEQ, Kim and De Dear used Kano's model of customer satisfaction to breakdown IEQ category performance into more detailed relationships with satisfaction (Basic Factors, Bonus Factors, and Proportional Factors). Frontczak et al. [52] using a mixed model logistic regression provide adetailed analysis of the relative importance of IEQ categories and building characteristics (office type, distance from windows, etc.) to workplace and overall building satisfaction. Weighting factors can be obtained from the odds ratio reported in the paper. These three studies offer clear guidance on the relationship between satisfaction with IEQ categories and building features and overall occupant satisfaction, though the details are beyond the scope of this paper, which focuses on existing IEQ models. For the papers that included weighting factors, we have reported them in Table 4 as they are described in the original papers. Further discussion of weighting factors is included in Section 5 of this paper, and the subset of papers for which it was possible to compare weighting factors was chosen for further analysis.

Fig. 3 shows a graphical representation of the major overlapping conditions that make up the assessment class breakdowns given in Table 5. Not all components of each study are represented and not all of the studies were meant to be broken down into these distinct classes so some interpretation was required. The legend for the figures helps explain how each of the studies treats the categories slightly differently. While some studies refer directly to occupant satisfaction, others refer to classes, categories, or health levels. However, for those studies that do not define classes directly in terms of occupant satisfaction, their classes can be traced back to occupant satisfaction studies. In order to use Cao et al. [16], which used a regression scale from −1 to 1 (dissatisfied to satisfied), we chose to break that range evenly into five categories. Interestingly, because the satisfaction regression equations in this study resulted in low maximum satisfactions and high minimum satisfactions, there is actually never a score higher than 0.6 or a score lower than −0.6, meaning no one is ever quite "satisfied" or "dissatisfied" according to their definition of 1 as satisfied and −1 as dissatisfied. Thus, there are no green or purple bars for the Cao et al. study. Their study was also the only one to suggest a negative satisfaction consequence for higher light levels, resulting in the symmetrical assessment class breakdown for lighting.

**(a)**



**(b)**
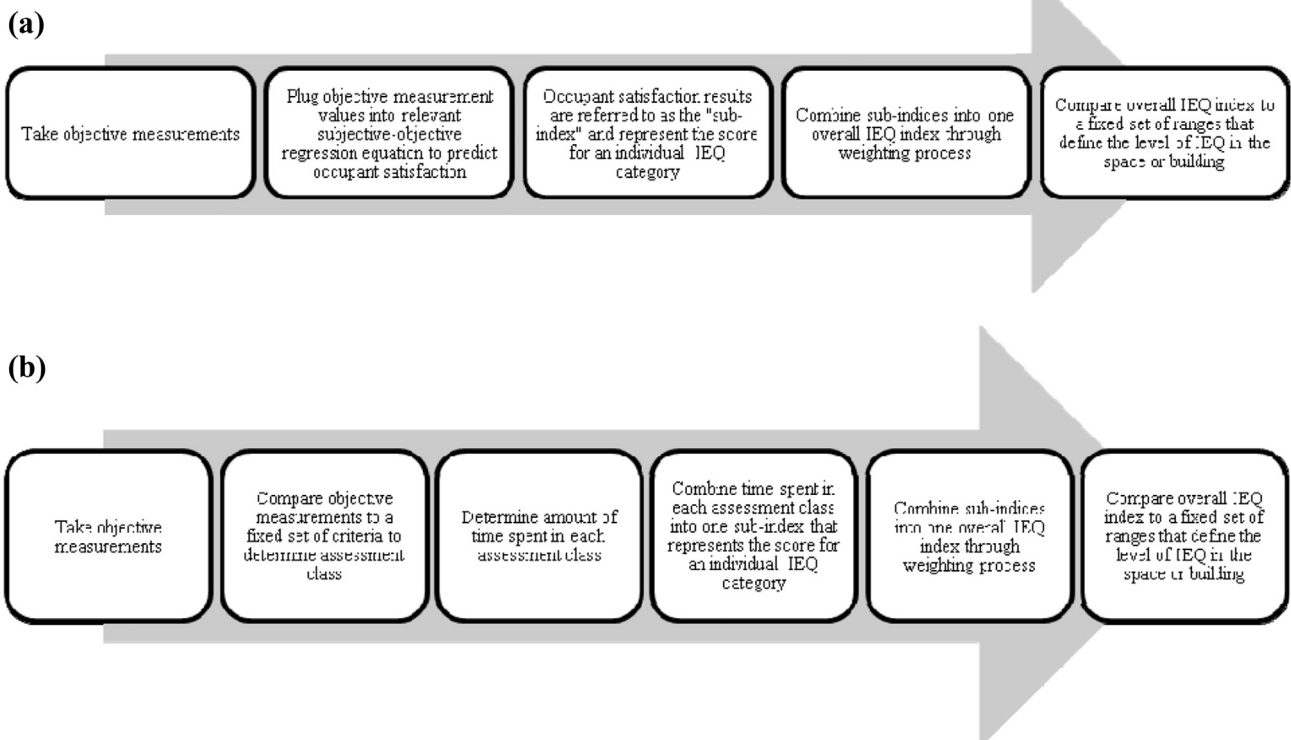


**Fig. 2.** (a) Subjective−objective IEQ model process; (b) objective-criteria IEQ model process.

**Table 4**
Summary of IEQ models in literature.

| Study | Objective measures | Subjective measures | Subjective/objective relationship | Assessment categories | IEQ category weights |
|---|---|---|---|---|---|
| [18] | Acoustics: sound level pressure (dBA) IAQ: CO, $CO_2$, $PM_{tot}$ Lighting: illuminance TC: air speed, air temperature, relative humidity | Simultaneous right-now survey | Linear regression | Healthy range (HR) Uncertain range (UR) Non-healthy range (NR) | – |
| [17] | Acoustics: sound level pressure (dBA) IAQ: CO, $CO_2$, $PM_{tot}$, HCHO, VOCs Lighting: illuminance, illuminance uniformity at face, daylight-use ratio TC: air speed, air temperature, relative humidity, PMV | Expert survey to determine category weightings | – | 20, 40, 60, 80, 100 <60 means "sanitary risk" | Acoustics: 0.203 IAQ: 0.209 Lighting: 0.164 TC: 0.208 EMF[*]: 0.135 [*]Electro-magnetic field |
| [22] | Acoustics: sound level pressure (dBA) IAQ: $CO_2$ Lighting: horizontal and vertical illuminance TC: air temperature, globe temperature, radiant temperature | Simultaneous right-now survey | Single-variable regression (per category) Multivariate regression (overall IEQ) | Level I: 10% dissatisfied Level II: 20% dissatisfied Level III: 30% dissatisfied | Acoustics: 0.28 IAQ: 0.09 TC: 0.42 |
| [19,20] | Acoustics: sound level pressure (dBA) IAQ: $CO_2$ Lighting: illuminance TC: operative temperature | One-time survey of 293 occupants | Single-variable regression (per category) Multivariate regression (overall IEQ) | – | Regression constants; higher = greater importance: Acoustics: 4.74 IAQ: 4.88 Lighting: 3.7 TC: 6.09 |
| [16] | Acoustics: sound level pressure (dBA) IAQ: $CO_2$ Lighting: illuminance TC: operative temperature | Simultaneous right-now survey | Single-variable regression (per category) Multivariate regression (overall IEQ) | – | Regression constants; higher = greater importance: Acoustics: 0.224 IAQ: 0.118 Lighting: 0.171 TC: 0.316 |
| [15] | Acoustics: sound level pressure (dBA) IAQ: $CO_2$ Lighting: illuminance TC: PPD | Simultaneous right-now survey | Multivariate regression (overall IEQ) | I: 80 < IEQ ≤ 100; Very high quality IEQ II: 60 < IEQ ≤ 80; High quality IEQ III: 40 < IEQ ≤ 60; Medium quality IEQ IV: 20 < IEQ ≤ 40; Low quality IEQ V: 0 ≤ IEQ ≤ 20; Very low quality IEQ | Acoustics: 0.18 IAQ: 0.36 Lighting: 0.16 TC: 0.30 |
| [14] | Acoustics: sound level pressure (dBA) IAQ: $CO_2$ Lighting: illuminance TC: operative temperature | – | – | EN15251: I, II, II, IV | Acoustics: 0.16 IAQ: 0.15 Lighting: 0.146 Summer TC: 0.189 Winter TC: 0.173 |

As an example of how to read these charts, for the acoustic assessment classes shown in Fig. 3a, the background sound level measurement (dBA) required for the highest assessment class (green bar) ranges from 20 to 61 dBA between the studies. This result suggests a high level of disagreement between studies on what background sound level should represent the highest assessment class. There is clear variation and disagreement between the studies on the appropriate breakdown of assessment classes except for PMV, which does not include all studies (and as its own index, is fairly straightforward to categorize).

## 4. Discussion

There are four main concerns with IEQ models as they have been presented in the literature:

1. There are limited guidelines on how to use the IEQ models along with a lack of consensus on measuring protocols and in particular on temporal and spatial resolution and sensor accuracy. Moreover, there is a lack of consensus on how the results should be interpreted and if buildings can be compared based on model results.

2. Assessment class limits are controversial and justification for certain limits is weak. Additionally, these limits are not always aligned with differences in occupant satisfaction.
3. Space-type differences are not implemented in most of the models. Marino et al. [14] includes a space-type weighting factor though offers no guidance on how such factors may be determined.
4. Inter-category relationships (interaction effect [53]) are not considered in the IEQ model framework. None of the models presented here discuss the interaction between IEQ categories, for example, higher thermal comfort is often associated with higher indoor air quality [54].

The first two concerns are discussed in more detail in the next two sections. The third and fourth concerns are discussed in further detail in Ref. [55] and contribute to the design of the proposed weighting and classification scheme presented in Section 5.

### 4.1. Limited guidance on appropriate use of IEQ models

An important component in appropriate use of IEQ models is the establishment of a set of consensus based measurement protocols.
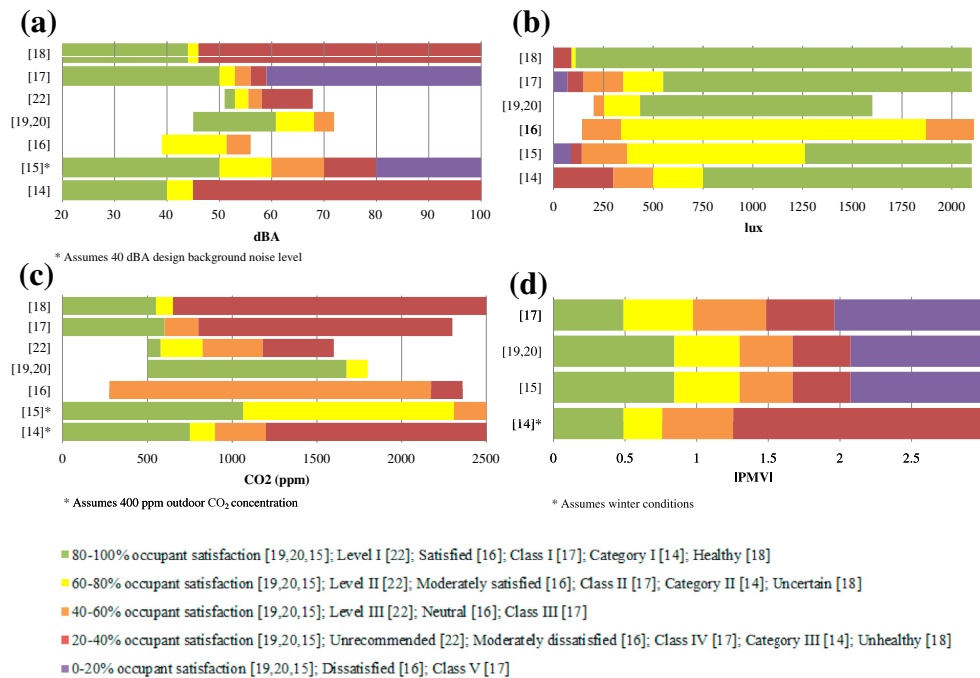
**Fig. 3.** (a) Comparison of background noise level assessment class breakdowns; (b) comparison of illuminance level assessment class breakdowns; (c) comparison of $CO_2$ level assessment class breakdowns; (d) comparison of PPD assessment class breakdowns.

The Performance Measurement Protocols for Commercial Buildings (PMP) has provided a strong starting point for such protocols in the United States and the United Kingdom because it is the result of a consensus process among the main organizations in the field of IEQ (ASHRAE, CISBE, USGBC). However, in its current state, there are large holes when looked at from the perspective of a cohesive set of protocols for the purposes of strict evaluation of IEQ via a model approach such as those explored in this paper. Many of these holes are detailed in Ref. [55], and Kim provides an extensive critique of the PMP, highlighting many of the same issues we discovered [37,38].

One of the goals of IEQ models is to be able to create a database of scores that can be benchmarked against, like the EnergyStar program [56] does with the CBECS database [57]. In order to achieve this goal, clear and consistent temporal and spatial measurement resolutions need to be established and proceduralized in order to ensure representative datasets are used for analysis through IEQ models—a step that has not been completed in the PMP. These procedures will require development over time through large, long-term studies of IEQ parameters that are matched to occupant survey data. In the PMP, summary tables of instrumentation accuracy and calibration requirements should be developed in order to ensure high quality instrumentation. Such information is available in each corresponding section of the PMP, though there is not a quick way of obtaining this information without going through the entire book. Without a cohesive set of measurement protocols, IEQ models cannot be appropriately compared between buildings. While IEQ models are still useful for providing an overall evaluative picture of a building, they cannot yet be reliably used as a true scorecard, rating, or to build a database for benchmarking.

### 4.2. Assessment class limits are controversial

The assessment class limits summarized in Table 5 vary widely between studies. Additionally, as discussed earlier in Section 3.2, there is disagreement concerning appropriate interpretation of the

EN15251-2007 categories [27,31,47—50], which serve as the basis for the assessment class limits of two of the studies [14,15]. According to Nicol and Wilson, the categories were designed not to penalize buildings with a wider band of control by referring to occupant expectations rather than levels of tightness of control [31]. We agree with Nicol and Wilson's assertion that the EN15251-2007 categories have been and will continue to be interpreted as levels of quality (e.g. category I = best, category IV = worst). Marino et al. [14] refer to quality and color (I — green, II — yellow, III — orange, IV — red) of each category, which stems from the color scheme provided in EN15251-2007 (I — white, II — green, III — yellow, IV — red). Regardless of whether the categories refer outright to levels of quality, the primary interpretation of occupant expectations is to equate a high level of expectation with a high tightness level. The primary danger associated with such assessment class limits is that tighter parameter bounds will be associated with higher quality buildings and designers will strive for these narrow bounds rather than less-energy intensive but equally satisfactory wider bounds [58,59]. Similarly, on the operational end, building operators may strive to maintain narrow conditions with the mistaken belief that such narrow bands represent higher quality and greater occupant satisfaction. Arens et al. suggest that the EN15251-2007 categories for thermal comfort do not align with perceptible changes in occupant satisfaction and may lead to more energy intensive buildings [47]. Extensive research has shown that at least for thermal comfort and lighting, occupants can be satisfied over a wide range of conditions (thermal comfort: [60—62]; lighting: [63,64]). Additionally, there are potential economic implications associated with tighter levels of control, both in design and operation.

There have been multiple papers defending the rationale behind the EN15251-2007 categories [27,49,50], in which there are three main arguments: (1) the categories provide greater choices for designers, building types, and countries; (2) higher categories do not necessarily result in increased energy consumption because energy consumption is limited by a different standard; (3) the

**Table 5**
Summary of assessment class conditions for IEQ models in literature.

| Study | Assessment class | Acoustics | IAQ | Lighting | Thermal comfort |
|---|---|---|---|---|---|
| [18] | Healthy | dBA < 44 | CO < 8 ppm<br>$CO_2$ < 550 ppm<br>$PM_{10}$ < 0.09 mg/m³ | lx > 110 | 18.5 ≤ air temp ≤ 24.5 °C<br>43 ≤ RH ≤ 67%<br>air speed < 0.45 m/s |
| | Uncertain | 44 ≤ dBA ≤ 46 | 8 ≤ CO ≤ 10 ppm<br>550 ≤ $CO_2$ ≤ 650 ppm<br>0.09 ≤ $PM_{10}$ ≤ 0.11 mg/m³ | 90 ≤ lx ≤ 110 | 17.5 ≤ air temp ≤ 18.5 °C<br>24.5 ≤ air temp ≤ 25.5 °C<br>37 ≤ RH ≤ 43%<br>67 ≤ RH ≤ 73%<br>0.45 ≤ air speed ≤ 0.55 m/s |
| | Non-healthy | dBA > 46 | CO > 10 ppm<br>$CO_2$ > 650 ppm<br>$PM_{10}$ > 0.11 mg/m³ | lx < 90 | air temp < 17.5 °C<br>air temp > 25.5 °C<br>RH < 37%<br>RH > 73%<br>air speed > 0.55 m/s |
| [17] | 100 | dBA ≤ 50 | CO < 2 ppm<br>$CO_2$ < 600 ppm<br>$PM_{10}$ < 0.025 mg/m³<br>VOCs < 0.05 mg/m³<br>HCHO < 8 ppb | lx > 500 | 0 ≤ \|PMV\| < 0.5 |
| | 80 | 50 < dBA ≤ 53 | 2 ≤ CO ≤ 4.5 ppm<br>600 ≤ $CO_2$ ≤ 800 ppm<br>0.025 ≤ $PM_{10}$ ≤ 0.05 mg/m³<br>0.05 ≤ VOCs ≤ 0.1 mg/m³<br>8 ≤ HCHO ≤ 16 ppb | 300 ≤ lx ≤ 500 | 0.5 ≤ \|PMV\| ≤ 1 |
| | 60 | 53 < dBA ≤ 56 | 4.5 ≤ CO ≤ 9 ppm<br>800 ≤ $CO_2$ ≤ 1000 ppm<br>0.05 ≤ $PM_{10}$ ≤ 0.15 mg/m³<br>0.1 ≤ VOCs ≤ 0.3 mg/m³<br>16 ≤ HCHO ≤ 100 ppb | 150 ≤ lx ≤ 350 | 1 ≤ \|PMV\| ≤ 1.5 |
| | 40 | 56 < dBA ≤ 59 | 9 ≤ CO ≤ 15 ppm<br>1000 ≤ $CO_2$ ≤ 2500 ppm<br>0.15 ≤ $PM_{10}$ ≤ 0.35 mg/m³<br>0.3 ≤ VOCs ≤ 3 mg/m³<br>100 ≤ HCHO ≤ 1000 ppb | 70 ≤ lx ≤ 150 | 1.5 ≤ \|PMV\| ≤ 2 |
| | 20 | dBA > 59 | CO > 15 ppm<br>$CO_2$ > 2500 ppm<br>$PM_{10}$ > 0.35 mg/m³<br>VOCs > 3 mg/m³<br>HCHO > 1000 ppb | lx < 70 | \|PMV\| > 2 |
| [22] | Percent dissatisfied (0–100); regression model for each IEQ category and overall IEQ | [0.0389*dBA − 1.9652]*100% | [0.28ln $CO_2$ − 1.68]*100% | − | $[0.021t_0^2 - 0.919t_0 + 10.225]*100\%$ |
| [19,20] | Level of acceptance (0–1); regression model for each IEQ category and overall IEQ | $1 - \left(\dfrac{1}{1+e^{(9.54-0.134*dBA)}}\right)$<br>where 45 ≤ dBA ≤ 72 | $1 - \dfrac{1}{2}\left(\dfrac{1}{1+e^{(3.118-0.00215*CO_2)}} - \dfrac{1}{1+e^{3.23-0.00117*CO_2}}\right)$<br>where 500 ≤ $CO_2$ ≤ 1800 | $1 - \left(\dfrac{1}{1+e^{(-1.017+0.00558*lx)}}\right)$<br>where 200 ≤ lx ≤ 1600 | $1 - \left(\dfrac{PPD}{100}\right)$ |
| [16] | Occupant satisfaction (−1 −1); regression model for each IEQ category and overall IEQ, where −1 = dissatisfied and 1 = satisfied | −0.0230*dBA + 1.382<br>where 39 ≤ dBA ≤ 56 | −0.0002*$CO_2$ + 0.244<br>where 275 ≤ $CO_2$ ≤ 2360 | $-5 \times 10^{-7}\ lx^2 - 0.0011\ lx - 0.106$<br>where 140 ≤ lx ≤ 2150 | $-0.0063t_0^2 + 0.287t_0 - 2.934$<br>where 16.6 ≤ $t_0$ ≤ 30.3 °C;<br>15 ≤ RH ≤ 75%;<br>0.01 ≤ air speed ≤ 0.44 m/s |

| Ref | | | | | |
|---|---|---|---|---|---|
| [15] | Sub-index for each IEQ category (0–100); apply sub-index to overall IEQ index; apply overall IEQ index to quality categories listed in Table 4 | *Choice 1:* $100 - \{395 \times \exp(-1.83q^{0.25})\}$ where $q$ is ventilation rate (l/s) *Choice 2:* $100 - \{395 \times \exp(-15.15CO_2^{-0.25})\}$ where $CO_2$ is concentration above outdoor concentration *Choice 3:* $100 - \{\exp[5.98 + (\frac{c_i}{-1.12})^4]\}$ where $c_i$ is perceived air quality measured in decipol | | $-176.16X^2 + 738.4X - 690.29$ where $X = (\ln(\ln(\text{lux})))$ | $100 - PPD$ |
| [14] | I | $dBA < 40$ | $CO_2$ above outdoor concentration $CO_2 < 350$ ppm | $\text{lx} > 750$ | (Operative temperature) Winter: $21 \leq t_0 \leq 25$ °C Summer: $23.5 \leq t_0 \leq 25.5$ °C air speed $< 0.15$ m/s |
| | II | $40 \leq dBA \leq 45$ | $350 \leq CO_2 < 500$ ppm | $500 \leq \text{lx} \leq 750$ | Winter: $20 \leq t_0 \leq 21$ °C $25 \leq t_0 \leq 26$ °C Summer: $23 \leq t_0 \leq 23.5$ °C $25.5 \leq t_0 \leq 26$ °C $0.15 \leq$ air speed $\leq 0.18$ m/s |
| | III | $45 \leq dBA \leq 50$ | $500 \leq CO_2 < 800$ ppm | $300 \leq \text{lx} \leq 500$ | Winter: $18 \leq t_0 \leq 20$ °C $26 \leq t_0 \leq 28$ °C Summer: $22 \leq t_0 \leq 23$ °C $26 \leq t_0 \leq 27$ °C $0.18 \leq$ air speed $\leq 0.21$ m/s |
| | IV | $dBA > 50$ | $CO_2 > 800$ ppm | $\text{lx} < 300$ | Winter: $t_0 < 18$ °C $t_0 > 28$ °C Summer: $t_0 < 22$ °C $t_0 > 27$ °C air speed $> 0.21$ m/s |

categories are helpful for evaluating the performance of a building over a year (primarily for design, but also for operation when used with fixed clo/met values). The first argument suggests that the existence of the EN15251 categories allows for greater flexibility in design decisions (e.g. we would like to build a Category I building, rather than a Category II building; or country A specifies category I as standard and country B specifies category II as standard), though we are not sure why the existence of the categories allows for any more flexibility than one larger category of compliance. This argument also suggests that there are clear situations in which occupant expectations would be reasonably different based on the building context (e.g. building type, building age, occupancy type) and that these different expectations correspond to measurable differences in environmental parameters. However, we feel that without research that defines such building context related expectations as affecting occupant satisfaction, the danger associated with making that assumption outweighs the utility of the categories. The second argument suggests that the requirements of energy standards will take care of any potential increases in energy consumption related to more tightly controlled buildings. It is not clear from their argument how an energy standard would counteract the negative effect of tighter temperature control. Moreover, energy standards specify the minimum energy performance that a building can legally provide—we hope designers aspire to go beyond the standard requirements, which is often most easily done by decreasing tightness of control. The third argument suggests analytical utility in the assessment categories. Raimondo et al. [49] and Olesen [50] suggest that the categories are not intended to force the operation of a building into certain class limits, but rather to evaluate how the distribution of performance among classes changes over the course of a year. Regardless of the intention, binning data raises the problem of the decisions involved in defining the bins and the conclusions that will be drawn from those decisions. While there may be analytical value in breaking yearly design or operation data into time-percentage bins, we do not agree that standardizing the boundaries of these bins is necessary or helpful. At this point, not enough guidance exists in the IEQ standards/guidelines or research community to justify the definition of precise boundaries for assessment classes except as two bins: compliance and non-compliance.

In understanding that conditions that are acceptable to occupants will encompass a range of values for most environmental parameters, there seems to be more value in industry agreement on the division of acceptable and unacceptable conditions rather than gradations of both. Such thinking informed the decision to propose an assessment class scheme based solely on compliance with the relative standards or guidelines outlined in the PMP, which is discussed in the next section.

## 5. Proposed weighting and classification scheme

We propose only two assessment classes: (1) compliance with the standards and guidelines outlined in the PMP, (2) non-compliance with the standards and guidelines outlined in the PMP. Additionally, different space-types are included for the lighting and acoustics categories. Inter-category relationships have not been addressed in this model. Table 6 outlines the conditions for each IEQ category for compliance. This proposal is only valid for commercial spaces, though could be adapted to other building types. The "″" symbol (ditto) in Table 6 means that the condition is not different from the condition specified in the "Default" space-type row.

For this proposal, thermal comfort is defined as compliance with ASHRAE Standard 55 − 2010 [65], which includes multiple methods for compliance (PMV, elevated air speed, and adaptive

**Table 6**
IEQ model based on assessment of occupant satisfaction.

| Space-type | Acoustics | IAQ | Lighting | Thermal comfort |
|---|---|---|---|---|
| Default (open plan office with intensive computer use and no sound masking) | dBA ≤ 40 | $CO_2$ ≤ 700 ppm above outdoor $CO_2$ | 300 ≤ lx ≤ 2500 | ASHRAE Standard 55 − 2010 |
| Open plan office with intensive computer use and sound masking | dBA ≤ 45 | " | " | " |
| Open plan office with intermittent computer use and no sound masking | " | " | 500 ≤ lx ≤ 2500 | " |
| Open plan office with intermittent computer use and sound masking | dBA ≤ 45 | " | 500 ≤ lx ≤ 2500 | " |
| Conference room − televideo conference | dBA ≤ 30 | " | 500 ≤ lx ≤ 2500 | " |
| Lobby/stairway | dBA ≤ 50 | " | 100 ≤ lx ≤ 2500 | " |
| Private office | " | " | 500 ≤ lx ≤ 2500 | " |

comfort). The PMP does not include a maximum recommended lighting level for illuminance, but we feel that over-lighting is an issue that needs to be addressed. Lindelöf and Morel have shown through Bayesian estimation based on lab studies that 2500 lx is the upper illuminance level at which the probability of occupant discomfort jumps up [66]. While an upper illuminance level is important to consider for occupant visual comfort, ideally the electric light contribution toward illuminance (including both task and general lighting) in an office environment should be zero when sufficient daylight exists or kept at or slightly above the recommended minimums outlined in the PMP when sufficient daylight is not available.

In addition to the assessment class limits, the proposed model suggests a new IEQ category weighting scheme. Table 7 provides a summary of IEQ category weighting schemes from the literature reviewed in this paper (Table 4), as well as a new proposed scheme. Mui and Chan was not included because they determined that their lighting regression coefficient was nonsensical [22]. Not all models from the literature used the same four IEQ categories ([14,17] had extra categories). For these two studies, we adjusted the categories weights by dividing the original weights by the sum of the weights with the extra categories removed. Our adjustment may not be a completely accurate representation of the data because without original datasets new regression coefficients could not be computed. The datasets used in each study varied in size and quality. Chiang et al. [18] used an analytic hierarchy process (AHP) method which sampled 12 professionals to determine the appropriate weights. Wong et al. [19], Cao et al. [16], and Ncube and Riffat [15] all used multivariate linear regression of occupant responses to determine category weights. Each of these studies regressed IEQ category comfort response against an overall comfort survey response. Marino et al. suggested computed weightings from Bluyssen et al. [67]; however, we are unable to identify which data in Bluyssen et al. that Marino et al. uses. The conclusions of Bluyssen et al. suggest that providing a 'short-cut' to relative importance factors of IEQ categories would

not be valid for the dataset (5732 occupant responses from the HOPE project).

The weights proposed here were computed using a subset of the CBE survey database that was created for use in Frontczak et al. [52]. This subset database only included office buildings—further details of the database are included in Frontczak et al. Occupant responses to satisfaction questions concerning the following variables were regressed against overall workplace satisfaction: (1) Acoustics: average of noise and sound privacy; (2) IAQ: air quality; (3) Lighting: average of visual comfort and amount of light; and (4) Thermal comfort: temperature. The multivariate linear regression coefficients were normalized to sum to 1. The results of this regression model suggest that lighting and acoustics are considerably more important than IAQ and thermal comfort. There are many reasons that boiling down an entire database of results into one linear regression is problematic. However, for the purposes of this study, the validity of the specific IEQ category weighting scheme is less important than the comparisons between the models. A spider plot of the weighting schemes is shown in Fig. 4. Further details on the implementation of this proposal, including a case study, are provided in Ref. [55].

The weighting schemes presented here attempt to combine interrelated IEQ categories into one satisfaction/performance model. While there may be value in combined indices for benchmarking and rating purposes, there is also a loss of information and consequently a danger of misinterpretation. Many factors influence the relative importance of IEQ categories and devising a universal weighting scheme that applies to all buildings at all times is unlikely. However, we do not feel that further research on weighting schemes is fruitless, as insight can be gained from studying the interrelatedness of environmental

**Table 7**
Summary of IEQ category weighting schemes.

| Study | Number of occupants surveyed | Acoustics | IAQ | Lighting | Thermal comfort |
|---|---|---|---|---|---|
| 1. [17][a] | 12 professionals | 0.23 | 0.34 | 0.19 | 0.24 |
| 2. [19] | 293 | 0.24 | 0.25 | 0.19 | 0.31 |
| 3. [16] | 500 | 0.27 | 0.14 | 0.21 | 0.38 |
| 4. [15] | 68 | 0.18 | 0.36 | 0.16 | 0.30 |
| 5. [14][a] | – | 0.25 | 0.23 | 0.23 | 0.29 |
| 6. Proposed PMP-based | 52,980 | 0.39 | 0.2 | 0.29 | 0.12 |

[a] Adjusted weights.
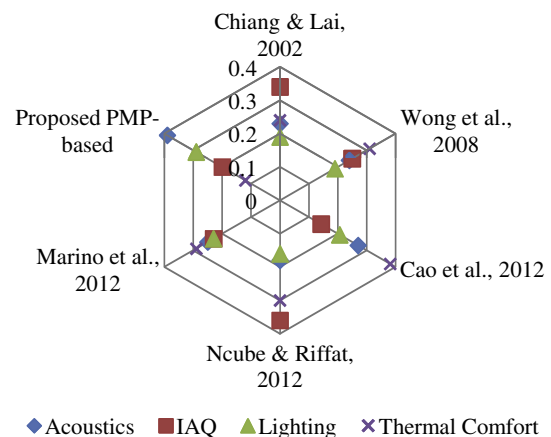


**Fig. 4.** Summary plot of IEQ category weighting schemes.

parameters and occupant satisfaction. We agree with Humphreys [48] that one-to-one comparisons of individual environmental parameters provide more information and are less likely to result in a conclusion that is inconsistent with occupant responses. With this in mind, the scorecard proposal presented in Ref. [55] emphasizes individual IEQ category scores and a separation between objective and subjective measurement scores. Physical measurements will continue to be limited to sensors that are relatively inexpensive, accurate, and widely available, which provides a very limited and necessarily different picture of the indoor environment than occupant surveys. Such limited physical measurements also lead to misuse of current industry standard models (e.g. assuming still air when computing PMV) which can result in erroneous ratings or predicted occupant satisfaction. With these thoughts in mind, we present our weighting scheme for the purposes of comparison and discussion. Further research involving large case studies is needed to highlight the dangers and/or usefulness of such weighting schemes used in combined IEQ indices.

## 6. Conclusion

We summarize the results of this study with the following conclusions:

- There is a lack of consensus on measuring protocols (temporal and spatial resolution and sensor accuracy), IEQ category weighting schemes and assessment class limits. Consequently, the same building could have different performance interpretations, which prevents benchmarking.
- None of the models reviewed in this paper accounted for inter-category relationships and only one model accounted for different space-types.
- Assessment classes/categories should be limited to two classes: compliance and non-compliance. We proposed numerical definitions of the compliance and non-compliance ranges based on ASHRAE/CIBSE/USGBC Performance Measurement Protocols.
- IEQ category weighting schemes require additional research and should be used with caution. We presented a newly developed weighting scheme based on 52,980 occupant responses in office buildings as another model for future review and discussion.

In addition to the above conclusions we offer the following recommendations for future research:

- Standardized measurement protocols (especially temporal and spatial resolution requirements) need to be established through long-term IEQ studies in order to create a benchmarking database of standard IEQ data.
- More research should be conducted to improve the robustness of IEQ weighting schemes and to verify the efficacy of proposed methods. Research on inter-category relationships should continue and be accounted for in future IEQ assessment models.
- Research and organization aimed at the goal of standardizing methods of IEQ assessment should be encouraged and promoted (i.e., a standards committee, or industry association).

We feel that Indoor Environmental Quality (IEQ) models have potential to be a market driver and a motivator for designers, operators, and building owners. IEQ measurement can help discover and correct problems, but when such measurements are implemented in a standardized fashion, IEQ models have the power to transform the measurements into scores that can be used in ratings and standards. Such standardized procedures that would enable potentially more appropriate use of IEQ models are not necessarily far off with improved revisions to the Performance Measurement Protocols guidebooks, and future research into the avenues presented above.

## References

[1] Fisk WJ. Health and productivity gains from better indoor environments and their relationship with building energy efficiency. Annual Review of Energy and the Environment 2000;25:537—66.
[2] Jones AP. Indoor air quality and health. Atmospheric Environment 1999;33: 4535—64.
[3] Wargocki P, Wyon DP, Sundell J, Clausen G, Fanger PO. The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity. Indoor Air 2000;10:222—36.
[4] Humphreys MA, Nicol JF. Self-assessed productivity and the office environment: monthly surveys in five European countries. ASHRAE Transactions 2007;113:606.
[5] Leaman A, Bordass B. Are users more tolerant of "green" buildings? Building Research & Information 2007;35:662—73.
[6] Lorsch HG, Abdou OA. The impact of the building indoor environment on occupant productivity — part 1: recent studies, measures, and costs. ASHRAE Transactions 1994;100:741.
[7] Singh A, Syal M, Grady SC, Korkmaz S. Effects of green buildings on employee health and productivity. American Journal of Public Health 2010;100:1665—8.
[8] Kats G, Alevantis L, Berman A, Mills E, Perlman J. The costs and financial benefits of green buildings: a report to California's sustainable building task force; 2003.
[9] Pyke C, McMahon S, Dietsche T. Green building & human experience testing green building strategies with volunteered geographic information. US Green Building Council Research Program White Paper; 2010.
[10] Wilson A. Productivity and green buildings — EBN:13:10. Environmental Building News 2004.
[11] Wargocki P, Seppänen O. Indoor climate and productivity in offices. REHVA Guidebook 2006.
[12] Olesen BW. Revision of EN 15251: indoor environmental criteria. REHVA European HVAC Journal 2012:6—12.
[13] REHVA. Indoor climate quality assessment. Brussels: Federation of European Heating, Ventilation and Air-conditioning Associations; 2011.
[14] Marino C, Nucara A, Pietrafesa M. Proposal of comfort classification indexes suitable for both single environments and whole buildings. Building and Environment 2012;57:58—67.
[15] Ncube M, Riffat S. Developing an indoor environment quality tool for assessment of mechanically ventilated office buildings in the UK — a preliminary study. Building and Environment 2012;53:26—33.
[16] Cao B, Ouyang Q, Zhu Y, Huang L, Hu H, Deng G. Development of a multivariate regression model for overall satisfaction in public buildings based on field studies in Beijing and Shanghai. Building and Environment 2012;47:394—9.
[17] Chiang CM, Lai CM. A study on the comprehensive indicator of indoor environment assessment for occupants' health in Taiwan. Building and Environment 2002;37:387—92.
[18] Chiang CM, Chou PC, Lai CM, Li YY. A methodology to assess the indoor environment in care centers for senior citizens. Building and Environment 2001;36:561—8.
[19] Wong LT, Mui KW, Hui PS. A multivariate-logistic model for acceptance of indoor environmental quality (IEQ) in offices. Building and Environment 2008;43:1—6.
[20] Lai CK, Mui KW, Wong LT, Law LY. An evaluation model for indoor environmental quality (IEQ) acceptance in residential buildings. Energy and Buildings 2009;41:930—6.
[21] Roulet C, Flourentzou F, Labben H, Santamouris M, Koronaki I, Dascalaki E, et al. ORME: a multicriteria rating methodology for buildings. Building and Environment 2002;37:579—86.
[22] Mui KW, Chan WT. A new indoor environmental quality equation for air-conditioned buildings. Architectural Science Review 2005;48:41—6.
[23] Frontczak M, Wargocki P. Literature survey on how different factors influence human comfort in indoor environments. Building and Environment 2011;46: 922—37.
[24] ASHRAE/CIBSE/USGBC. Performance measurement protocols for commercial buildings. Atlanta: American Society of Heating, Refrigeration, and Air Conditioning Engineers; 2010.
[25] ASHRAE. Performance measurement protocols: best practices guide. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers; 2012.
[26] European Parliament and Council. Energy performance of buildings directive (EPBD) 2003;2002/91/EC.
[27] Olesen BW. The philosophy behind EN15251: indoor environmental criteria for design and calculation of energy performance of buildings. Energy and Buildings 2007;39:740—9.

[28] Peretti C, Schiavon S. Indoor environmental quality surveys. A brief literature review. In: Proceedings of indoor air, Austin 2011.

[29] Cohen R, Standeven M, Bordass B, Leaman A. Assessing building performance in use 1: the probe process. Building Research & Information 2001;29:85–102.

[30] CBE. Occupant Indoor Environmental Quality (IEQ) Survey; 2008.

[31] Nicol JF, Wilson M. A critique of European Standard EN 15251: strengths, weaknesses and lessons for future standards. Building Research & Information 2011;39:183–93.

[32] Porter SR, Whitcomb ME, Weitzer WH. Multiple surveys of students and survey fatigue. New Directions for Institutional Research 2004;2004:63–73.

[33] Nicol JF, McCartney K. Smart controls and thermal comfort project. SCATs final report, Oxford; 2000.

[34] Benton C, Bauman F, Fountain M. A field measurement system for the study of thermal comfort. ASHRAE Transactions 1990;96:623–33.

[35] Newsham G, Birt B, Arsenault C. Do green buildings outperform conventional buildings? Indoor environment and energy performance in North American offices; 2012.

[36] Choi J-H, Loftness V, Aziz A. Post-occupancy evaluation of 20 office buildings as basis for future IEQ standards and guidelines. Energy and Buildings 2012;46:167–75.

[37] Kim H, Haberl J. Field-test of the new ASHRAE/CIBSE/USGBC performance measurement protocols for commercial buildings: basic level. ASHRAE Transactions 2012:118.

[38] Kim H. Methodology for rating a building's overall performance based on the ASHRAE/CIBSE/USGBC performance measurement protocols for commercial buildings. Texas A&M University; 2012.

[39] Webster T, Bauman F, Anwar G. CBE portable wireless monitoring system (PWMS): UFAD systems commissioning cart design specifications and operating manual; 2007.

[40] Paliaga G. Operable windows, personal control and occupant comfort. Berkeley: University of California; 2004.

[41] Fisk W, Sullivan D. Sensors at louvers and downstream of airflow straighteners measuring outdoor air intake rates using electronic velocity sensors at louvers and downstream of airflow straighteners; 2008.

[42] Fisk W, Sullivan D, Faulkner D, Eliseeva E. $CO_2$ monitoring for demand controlled ventilation in commercial buildings. LBNL-3279E; 2010.

[43] Fisk W, Faulkner D. Measuring OA intake rates. ASHRAE Journal 2006;48:50–7.

[44] EPA. A standardized EPA protocol for characterizing indoor air quality in large office buildings. Washington, DC: Indoor Environment Division, US EPA; 2003.

[45] Azizan A, Kim SH, Viraj S. EnviroDB: applied database systems design for the national environmental assessment toolkit (NEAT). In: Proceedings of the fifth international conference for enhanced building operations 2005.

[46] Catalina T, Iordache V. IEQ assessment on schools in the design stage. Building and Environment 2012;49:129–40.

[47] Arens E, Humphreys MA, De Dear R, Zhang H. Are "class A" temperature requirements realistic or desirable? Building and Environment 2010;45:4–10.

[48] Humphreys MA. Quantifying occupant comfort: are combined indices of the indoor environment practicable? Building Research & Information 2005;33: 317–25.

[49] Raimondo D, Corgnati SP, Olesen BW. Evaluation methods for indoor environmental quality assessment. REHVA Journal 2012:14–9.

[50] Olesen B. Why specify indoor environmental criteria as categories?In Adapting to change: new thinking on comfort, vol. 7730. London: Network for Comfort and Energy Use in Buildings; 2010.

[51] Kim J, De Dear R. Nonlinear relationships between individual IEQ factors and overall workspace satisfaction. Building and Environment 2012;49: 33–40.

[52] Frontczak M, Schiavon S, Goins J, Arens E, Zhang H, Wargocki P. Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design. Indoor Air 2012;22:119–31.

[53] Dodge Y, editor. The oxford dictionary of statistical terms. Oxford University Press; 2003.

[54] Fang L, Clausen G, Fanger PO. Impact of temperature and humidity on the perception of indoor air quality. Indoor Air 1998;8:80–90.

[55] Heinzerling D. Commercial building indoor environmental quality evaluation: methods and tools. University of California Berkeley; 2012.

[56] EnergyStar.gov. ENERGY STAR Portfolio Manager n.d.

[57] U.S. Energy Information Administration (EIA). Commercial buildings energy consumption survey (CBECS); 2003.

[58] Hoyt T, Lee KH, Zhang H, Arens E, Webster T. Energy savings from extended air temperature setpoints and reductions in room air mixing. UC Berkeley; 2009.

[59] Schiavon S, Melikov AK. Energy saving and improved comfort by increased air movement. Energy and Buildings 2008;40:1954–60.

[60] Zhang H, Arens E, Pasut W. Air temperature thresholds for indoor comfort and perceived air quality. Building Research & Information 2011;39:134–44.

[61] De Dear R. Thermal comfort in practice. Indoor Air 2004;14(Suppl. 7):32–9.

[62] De Dear RJ, Brager GS. Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. Energy and Buildings 2002;34:549–61.

[63] Escuyer S, Fontoynont M. Testing in situ of automatic lighting plus manual controlled task lighting: office occupants reactions. In: Proceedings of the 9th European lighting conference (Lux Europa), Reykjavik, Iceland 2001. p. 70–5.

[64] Begemann SHA, Van den Beld GJ, Tenner AD. Daylight, artificial light and people in an office environment, overview of visual and biological responses. International Journal of Industrial Ergonomics 1997;20:231–9.

[65] ANSI/ASHRAE. ANSI/ASHRAE 55-2010: thermal environmental conditions for human occupancy. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers; 2010.

[66] Lindelöf D, Morel N. Bayesian estimation of visual discomfort. Building Research & Information 2008;36:83–96.

[67] Bluyssen PM, Aries M, Van Dommelen P. Comfort of workers in office buildings: the European HOPE project. Building and Environment 2011;46:280–8.