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

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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.

Keywords

Indoor Environmental Quality (IEQ); IEQ model; IEQ index; IEQ measurement; Occupant satisfaction; Performance Measurement Protocols (PMP)

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 Wargoeki [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 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.

Figure 1 - Figure 11 show pictures of IEQ measurement carts and desktop devices. The sensors associated with each device are provided in Table 1.



Figure 1: SCATs instrumented cart [33]



Figure 2: Instrumented chair-like cart [34]

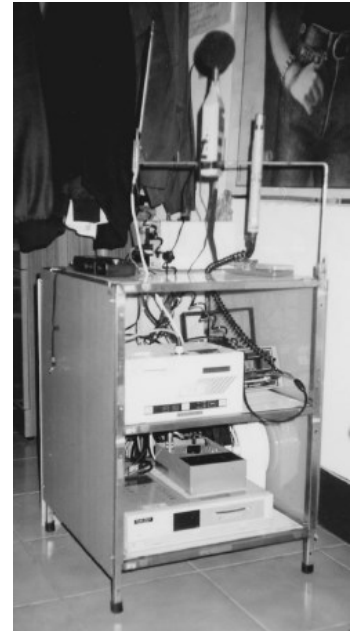


Figure 3: IEQ cart [18]

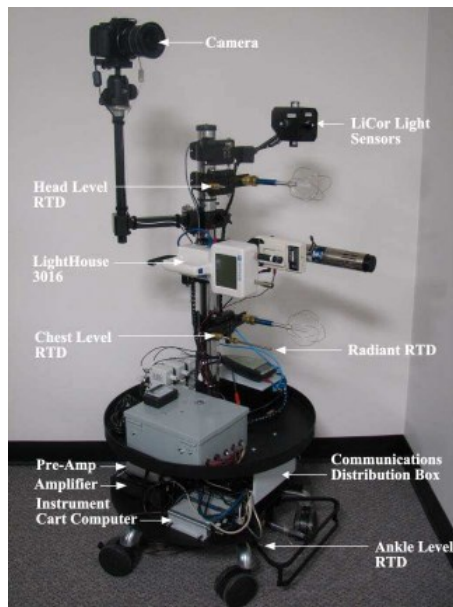


Figure 4: NICE instrumented cart part 1 [35]

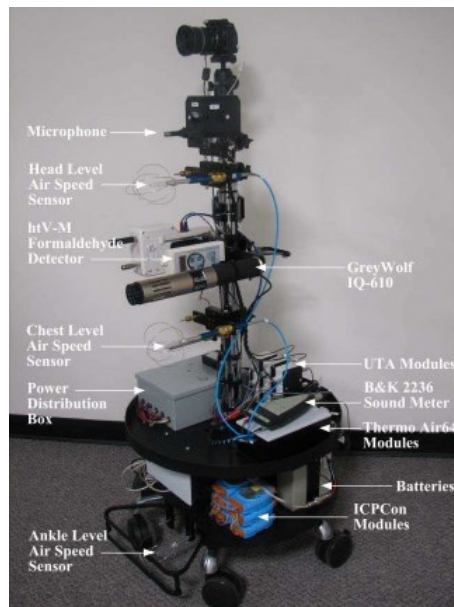


Figure 5: NICE instrumented cart part 2 [35]



Figure 6: IEQ logger [22]



Figure 7: EnviroBot [36]



Figure 8: Comprehensive IEQ monitoring cart [37,38]



Figure 9: UFAD commissioning cart [39]

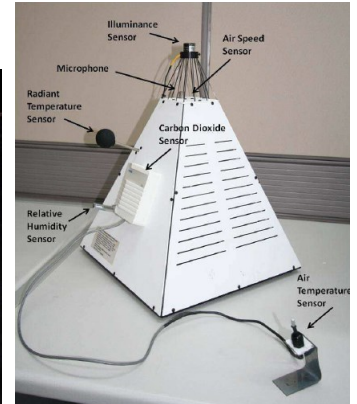


Figure 10: Pyramid desktop device [35]



Figure 11: Indoor climate monitor desktop device [40]

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, 1.1m; dewpoint temperature and chair surface temperature at 0.6m, radiant asymmetry at 1.1m
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} ,	Illuminance, camera for HDR	Air temperature at 0.1, 0.6, 1.1m; RH; hand-held air speed and radiant temperature

		TVOCs	luminance	
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, 1.7m; 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, 3.3m, 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

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 CO₂ 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 CO₂ 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.

Table 2: Objective measurement procedural variables summary

Protocol / Study		Acoustics	IAQ	Lighting	Thermal Comfort
PMP (Intermediate level) [24]	Temporal	Background noise: 30 seconds 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: 0.76m above floor at regular grid spacing = ¼ space between luminaires Luminance: 11 specific locations (see PMP pgs 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-minute averages on mobile cart (20 locations) VOCs, PM, HCHO: one 9-hour integrated sample	Continuous measurement for 3 days	Continuous measurement for 3 days and 5-minute 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 hour continuous measurements during summer, winter, and swing seasons over 5 year period (unknown how long per building); Cart measurements made for 15 minutes with 15 second 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 minute logging intervals			
	Spatial	Unknown			
[18]	Temporal	24 hours 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 minutes for measurement period; 1 minute intervals; mean of 20 minute interval used for analysis			
	Spatial	Workstations of the occupants that were surveyed while occupant was present			
[35]	Temporal	NICE: 10-15 minutes for measurement period; unknown sampling rate; during occupied hours; Pyramid: 15 minute sampling rate, continuous measurement for several days			
	Spatial	NICE: balance of space types (open plan, enclosed, perimeter, interior); Pyramid: up to 6 fixed locations			

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 break down 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.

Table 3: Categories for IEQ (EN 15251, 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)

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 (Figure 12a): 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 (Figure 12b): 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.

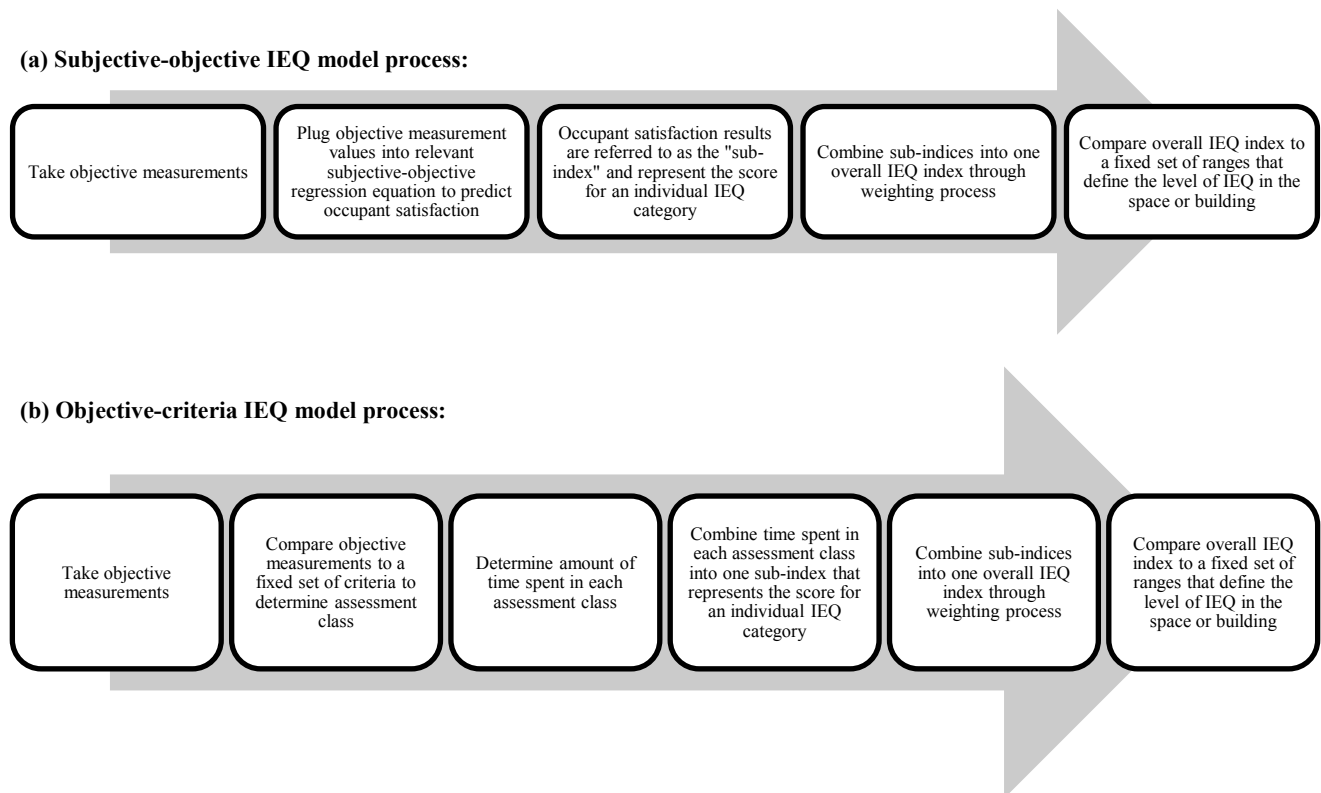


Figure 12: (a) Subjective-objective IEQ model process; (b) Objective-criteria IEQ model process

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?

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 quality 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 [52], looked at relationships between IEQ categories and overall workspace satisfaction. Rather than apply a weighting scheme to IEQ categories to obtain overall IEQ quality, Kim and de Dear used Kano's model of customer satisfaction to break down 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 a detailed 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 Chapter 5 of this paper, and the subset of papers for which it was possible to compare weighting factors was chosen for further analysis.

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	Acoustics: 0.18 IAQ: 0.36 Lighting: 0.16 TC: 0.30

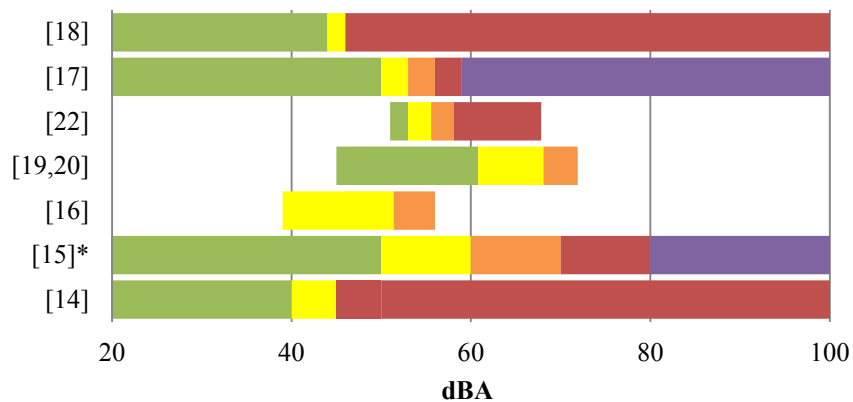
				V: $0 \leq \text{IEQ} \leq 20$; Very low quality IEQ
[14]	Acoustics: sound level pressure (dBA) IAQ: CO ₂ Lighting: illuminance TC: operative temperature	-	-	EN15251: I, II, II, IV Acoustics: 0.16 IAQ: 0.15 Lighting: 0.146 Summer TC: 0.189 Winter TC: 0.173

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 CO ₂ < 550 ppm PM ₁₀ < 0.09 mg/m ³	lx > 110	18.5 ≤ air temp ≤ 24.5 °C 43 ≤ RH ≤ 67 % air speed < 0.45 m/s
	Uncertain	44 ≤ dBA ≤ 46	8 ≤ CO ≤ 10 ppm 550 ≤ CO ₂ ≤ 650 ppm 0.09 ≤ PM ₁₀ ≤ 0.11 mg/m ³	90 ≤ lx ≤ 110	17.5 ≤ air temp ≤ 18.5 °C 24.5 ≤ air temp ≤ 25.5 °C 37 ≤ RH ≤ 43 % 67 ≤ RH ≤ 73 % 0.45 ≤ air speed ≤ 0.55 m/s
	Non-healthy	dBA > 46	CO > 10 ppm CO ₂ > 650 ppm PM ₁₀ > 0.11 mg/m ³	lx < 90	air temp < 17.5 °C air temp > 25.5 °C RH < 37 % RH > 73 % air speed > 0.55 m/s
[17]	100	dBA ≤ 50	CO < 2 ppm CO ₂ < 600 ppm PM ₁₀ < 0.025 mg/m ³ VOCs < 0.05 mg/m ³ HCHO < 8 ppb	lx > 500	0 ≤ PMV < 0.5
	80	50 < dBA ≤ 53	2 ≤ CO ≤ 4.5 ppm 600 ≤ CO ₂ ≤ 800 ppm 0.025 ≤ PM ₁₀ ≤ 0.05 mg/m ³ 0.05 ≤ VOCs ≤ 0.1 mg/m ³ 8 ≤ HCHO ≤ 16 ppb	300 ≤ lx ≤ 500	0.5 ≤ PMV ≤ 1
	60	53 < dBA ≤ 56	4.5 ≤ CO ≤ 9 ppm 800 ≤ CO ₂ ≤ 1000 ppm 0.05 ≤ PM ₁₀ ≤ 0.15 mg/m ³ 0.1 ≤ VOCs ≤ 0.3 mg/m ³	150 ≤ lx ≤ 350	1 ≤ PMV ≤ 1.5

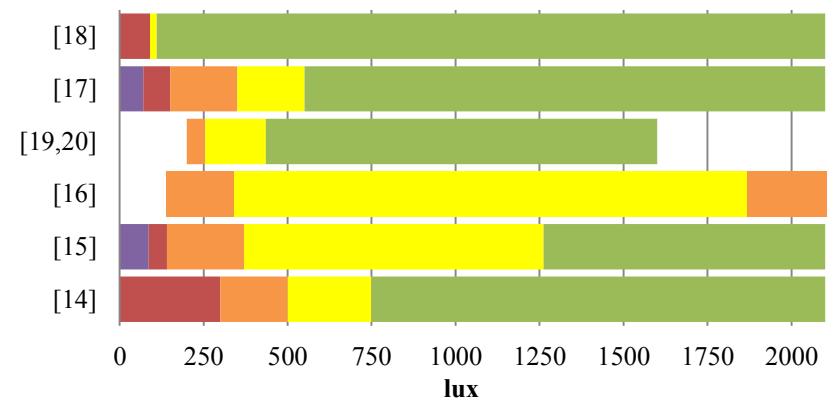
Study	Assessment Class	Acoustics	IAQ	Lighting	Thermal Comfort
			16 ≤ HCHO ≤ 100 ppb		
	40	56 < dBA ≤ 59	9 ≤ CO ≤ 15 ppm 1000 ≤ CO ₂ ≤ 2500 ppm 0.15 ≤ PM ₁₀ ≤ 0.35 mg/m ³ 0.3 ≤ VOCs ≤ 3 mg/m ³ 100 ≤ HCHO ≤ 1000 ppb	70 ≤ lx ≤ 150	1.5 ≤ PMV ≤ 2
	20	dBA > 59	CO > 15 ppm CO ₂ > 2500 ppm PM ₁₀ > 0.35 mg/m ³ VOCs > 3 mg/m ³ HCHO > 1000 ppb	lx < 70	PMV > 2
[22]	Percent dissatisfied (0-100); regression model for each IEQ category and overall IEQ	$[0.0389 * dBA - 1.9652] * 100\%$	$[0.28 \ln CO_2 - 1.68] * 100\%$	-	$[0.021t_o^2 - 0.919t_o + 10.225] * 100\%$
[19,20]	Level of acceptance (0-1); regression model for each IEQ category and overall IEQ	$1 - \left(\frac{1}{1 + e^{(9.54 - 0.134 * dBA)}} \right)$ where 45 ≤ dBA ≤ 72	$1 - \frac{1}{2} \left(\frac{\frac{1}{1 + e^{(3.118 - 0.00215 * CO_2)}}}{\frac{1}{1 + e^{3.23 - 0.00117 * CO_2}}} \right)$ where 500 ≤ CO ₂ ≤ 1800	$1 - \left(\frac{1}{1 + e^{(-1.017 + 0.00558 * lx)}} \right)$ where 200 ≤ lx ≤ 1600	$1 - \left(\frac{PPD}{100} \right)$
[16]	Occupant satisfaction (-1 - 1); regression model for each IEQ category and overall IEQ, where -1 = dissatisfied and 1 = satisfied	$-0.0230 * dBA + 1.382$ where 39 ≤ dBA ≤ 56	$-0.0002 * CO_2 + 0.244$ where 275 ≤ CO ₂ ≤ 2360	$-5 \times 10^{-7} lx^2 - 0.0011lx - 0.106$ where 140 ≤ lx ≤ 2150	$-0.0063t_o^2 + 0.287t_o - 2.934$ where 16.6 ≤ t _o ≤ 30.3 °C; 15 ≤ RH ≤ 75 %; 0.01 ≤ air speed ≤ 0.44 m/s
[15]	Sub-index for each IEQ category (0-100); apply sub-index to overall IEQ index; apply	$100 - 2 \left(\frac{\text{Actual dBA}}{\text{Design dBA}} \right)$	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	$-176.16X^2 + 738.4X - 690.29$ where X = {ln(ln(lux))}	100 - PPD

Study	Assessment Class	Acoustics	IAQ	Lighting	Thermal Comfort
	overall IEQ index to quality categories listed in Table 4		above outdoor concentration Choice 3: $100 - \left\{ \exp \left[5.98 + \left(\frac{C_i}{-112} \right)^4 \right] \right\}$ where C_i is perceived air quality measured in decipol		
[14]	I	dBA < 40	CO ₂ above outdoor concentration CO ₂ < 350 ppm	lx > 750	(Operative temperature) Winter: 21 ≤ t _o ≤ 25 °C Summer: 23.5 ≤ t _o ≤ 25.5 °C air speed < 0.15 m/s
	II	40 ≤ dBA ≤ 45	350 ≤ CO ₂ < 500 ppm	500 ≤ lx ≤ 750	Winter: 20 ≤ t _o ≤ 21 °C 25 ≤ t _o ≤ 26 °C Summer: 23 ≤ t _o ≤ 23.5 °C 25.5 ≤ t _o ≤ 26 °C 0.15 ≤ air speed ≤ 0.18 m/s
	III	45 ≤ dBA ≤ 50	500 ≤ CO ₂ < 800 ppm	300 ≤ lx ≤ 500	Winter: 18 ≤ t _o ≤ 20 °C 26 ≤ t _o ≤ 28 °C Summer: 22 ≤ t _o ≤ 23 °C 26 ≤ t _o ≤ 27 °C 0.18 ≤ air speed ≤ 0.21 m/s
	IV	dBA > 50	CO ₂ > 800 ppm	lx < 300	Winter: t _o < 18 °C t _o > 28 °C Summer: t _o < 22 °C t _o > 27 °C air speed > 0.21 m/s

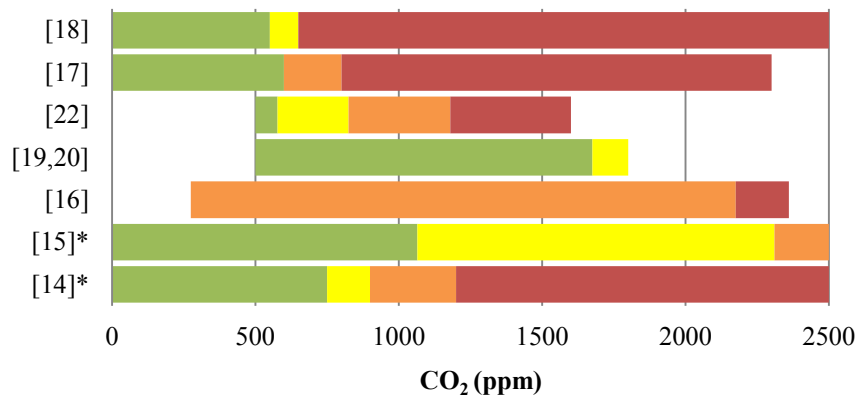


(a) Comparison of background noise level assessment class breakdowns

* Assumes 40 dBA design background noise level

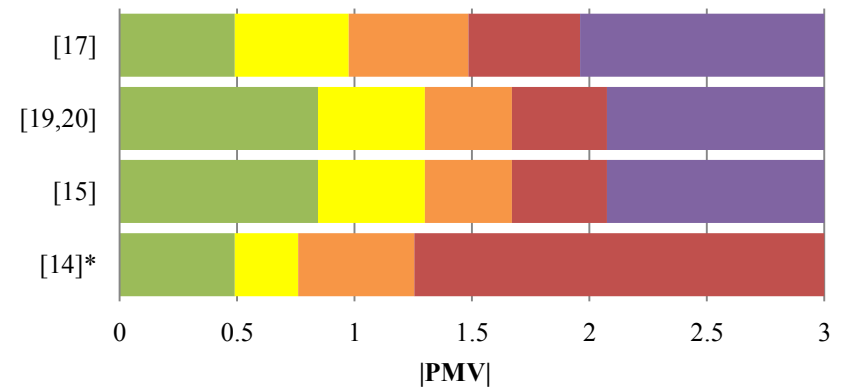


(b) Comparison of illuminance level assessment class breakdowns



(c) Comparison of CO₂ level assessment class breakdowns

* Assumes 400 ppm outdoor CO₂ concentration



(d) Comparison of PPD assessment class breakdowns

* Assumes winter conditions

- 80-100% occupant satisfaction [19,20,15]; Level I [22]; Satisfied [16]; Class I [17]; Category I [14]; Healthy [18]
- 60-80% occupant satisfaction [19,20,15]; Level II [22]; Moderately satisfied [16]; Class II [17]; Category II [14]; Uncertain [18]
- 40-60% occupant satisfaction [19,20,15]; Level III [22]; Neutral [16]; Class III [17]
- 20-40% occupant satisfaction [19,20,15]; Unrecommended [22]; Moderately dissatisfied [16]; Class IV [17]; Category III [14]; Unhealthy [18]
- 0-20% occupant satisfaction [19,20,15]; Dissatisfied [16]; Class V [17]

Figure 13: (a) Comparison of background noise level assessment class breakdowns; (b) Comparison of illuminance level assessment class breakdowns; (c) Comparison of CO₂ level assessment class breakdowns; (d) Comparison of PPD assessment class breakdowns

Figure 13 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.

As an example of how to read these charts, for the acoustic assessment classes shown in Figure 13a, the background sound level measurement (dBA) required for the highest assessment class (green bar) ranges from 20-61 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 [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. 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 [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 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, (II) 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.

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)	$\text{dBA} \leq 40$	$\text{CO}_2 \leq 700 \text{ ppm}$ above outdoor CO_2	$300 \leq \text{lx} \leq 2500$	ASHRAE Standard 55 - 2010
Open plan office with intensive computer use and sound masking	$\text{dBA} \leq 45$	"	"	"
Open plan office with intermittent computer use and no sound masking	"	"	$500 \leq \text{lx} \leq 2500$	"
Open plan office with intermittent computer use and sound masking	$\text{dBA} \leq 45$	"	$500 \leq \text{lx} \leq 2500$	"
Conference room - televideo conference	$\text{dBA} \leq 30$	"	$500 \leq \text{lx} \leq 2500$	"
Lobby / stairway	$\text{dBA} \leq 50$	"	$100 \leq \text{lx} \leq 2500$	"
Private office	"	"	$500 \leq \text{lx} \leq 2500$	"

For this proposal, thermal comfort is defined as compliance with ASHRAE Standard 55 – 2010 [65], which includes multiple methods for compliance (PMV, elevated airspeed, and adaptive 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 et al. 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 et al. [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 Bluysen et al. [67]; however, we are unable to identify which data in Bluysen et al. that Marino et al. uses. The conclusions of Bluysen 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 Figure 14. Further details on the implementation of this proposal, including a case study, are provided in [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 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 [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.

Table 7: Summary of IEQ category weighting schemes

Study	Number of occupants surveyed	Acoustics	IAQ	Lighting	Thermal Comfort
1. [17]*	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]*	-	0.25	0.23	0.23	0.29
6. Proposed PMP-based	52,980	0.39	0.2	0.29	0.12

* Adjusted weights

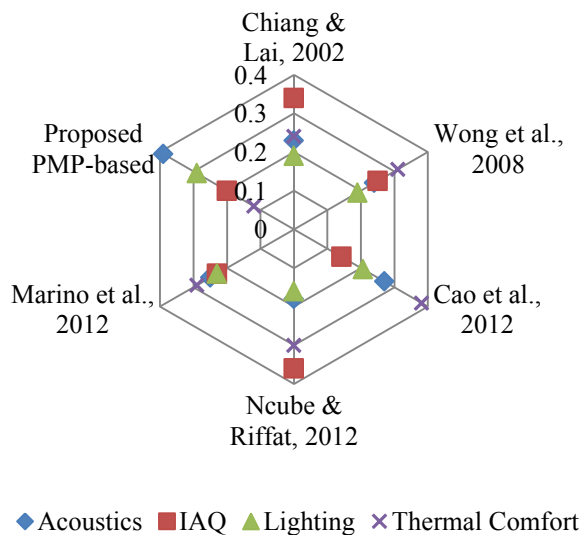


Figure 14: Summary plot of IEQ category weighting schemes

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.

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