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To cite this article: Sergio Altomonte, Stefano Schiavon, Michael G. Kent & Gail Brager (2017): Indoor environmental quality and occupant satisfaction in green-certified buildings, Building Research & Information, DOI: [10.1080/09613218.2018.1383715](https://doi.org/10.1080/09613218.2018.1383715)

To link to this article: <https://doi.org/10.1080/09613218.2018.1383715>



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Published online: 01 Nov 2017.



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Indoor environmental quality and occupant satisfaction in green-certified buildings

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ABSTRACT

Green-building certification systems aim at improving the design and operation of buildings. However, few detailed studies have investigated whether a green rating leads to higher occupant satisfaction with indoor environmental quality (IEQ). This research builds on previous work to address this. Based on the analysis of a subset of the Center for the Built Environment Occupant Indoor Environmental Quality survey database featuring 11,243 responses from 93 Leadership in Energy and Environmental Design (LEED)-rated office buildings, this study explores the relationships between the points earned in the IEQ category and the satisfaction expressed by occupants with the qualities of their indoor environment. It was found that the achievement of a specific IEQ credit did not substantively increase satisfaction with the corresponding IEQ factor, while the rating level, and the product and version under which certification had been awarded, did not affect workplace satisfaction. There could be several reasons for this, some of which are outside the control of designers and beyond the scope of rating systems based primarily on design intent. The challenges and priorities facing building professionals, researchers and green building certification systems are discussed for the creation of more comfortable, higher performing and healthier green-rated buildings.

KEYWORDS

certification; environmental assessment; green buildings; indoor environmental quality (IEQ); Leadership in Energy and Environmental Design (LEED); occupant satisfaction; occupants; post-occupancy evaluation

Introduction

Green-building certification systems – such as Leadership in Energy and Environmental Design (LEED) in the US, the Building Research Establishment Environmental Assessment Method (BREEAM) in the UK, Green Mark in Singapore, and Green Star in Australia – are assuming a prominent role to promote the sustainability agenda in the design and operation of buildings. However, although rating systems certify buildings under several categories (*e.g.* energy, water efficiency, sustainable sites, materials and resources, *etc.*), their role towards enhancing occupant satisfaction with indoor environmental quality (IEQ) – *i.e.* the thermal, acoustic, luminous and air-quality parameters that create the perceived internal ‘ambient environmental conditions’ (Hedge, 2000) – has been debated for a long time, but is still not fully characterized.

Particularly in the workplace, the satisfaction of building occupants with the qualities of their indoor

environment has been associated with their health and wellbeing (Institute of Medicine, 2011; Bluyssen, 2014), self-assessed job performance (Huang, Zhu, Ouyang, & Cao, 2012; Lamb & Kwok, 2016; Lan, Lian, & Pan, 2010; Lan, Wargocki, & Lian, 2014; Wargocki & Seppänen, 2006), and behaviour (Frontczak et al., 2012; Frontczak & Wargocki, 2011). Some of these can also have a significant influence on buildings’ energy requirements (Janda, 2011) due to the adaptive actions (*e.g.* on thermostats, blinds, lights, *etc.*) that users exercise in response to changes in environmental conditions (Haldi & Robinson, 2011; Humphreys & Nicol, 1998).

In this context, an awareness that people spend almost 90% of their time indoors (Klepeis et al., 2001), and that salary costs in commercial buildings largely exceed investment and operational expenses (RMI, 2014), has triggered substantial interest in the potential contribution of green rating systems towards improved workplace experience.

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 Supplemental data for this article can be accessed <https://doi.org/10.1080/09613218.2018.1383715>.

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The paper is structured as follows. The remainder of this section summarizes the literature in this area, and illustrates the aim and structure of this paper. Next, the methods are described for a rigorous statistical analysis of occupant satisfaction in LEED-rated buildings, whose results are presented in the third section. Then, supported by the information and feedback received from an industry focus group with building professionals and researchers, the findings are examined and discussed in the fourth section, and contextualized within the relevant scientific literature.

Green certification and occupant satisfaction

Various studies have investigated the energy performance of green-rated offices against the general building stock (Newsham, Mancini, & Birt, 2009; Scofield, 2009, 2013), and have compared occupant IEQ satisfaction in green-certified and in conventional buildings (Newsham et al., 2012). However, despite the general assumption that a certified building leads to improved IEQ (USGBC, 2017a), the empirical evidence has often been inconsistent, sometimes also due to differences in the metrics utilized and the methods employed for data collection and analysis.

Among recent research reporting the positive effects of better IEQ in certified buildings, MacNaughton et al. (2017) found higher occupants' cognitive performance in green-rated offices ($n = 69$) than in non-certified but high-performing buildings ($n = 40$). Allen et al. (2016) also reported higher cognitive function scores under controlled air-quality conditions that would be expected in green-rated buildings compared with conventional ones ($n = 24$), supporting the results of earlier studies that suggested direct benefits of green rating to self-reported health (Allen et al., 2015; Macnaughton et al., 2016). Performing a meta-analysis on data from two field studies – Cost-effective Open-Plan Environments (COPE) project ($n = 779$) (Veitch, Farley, & Newsham, 2002) and Green-POE ($n = 230$) (Newsham et al., 2012) – Leder, Newsham, Veitch, Mancini, and Charles (2016) found that users of certified offices tended to rate all aspects of environmental satisfaction more highly than occupants of conventional buildings, although working in a green-rated office was not necessarily associated with higher job satisfaction. This study also suggested that users of green buildings might be more 'forgiving' of indoor conditions, as already proposed by Leaman and Bordass (2007). Liang et al. (2014) reported higher IEQ satisfaction in three buildings certified by Taiwan's Ecological Energy saving Waste reduction Health (EEWH) system ($n = 134$) compared with two non-rated buildings ($n = 99$). Satisfaction with thermal comfort, lighting, furniture

and cleanliness was found to be higher in two Korean-certified buildings than in two non-rated offices ($n = 222$) (Sediso & Lee, 2016). Hedge, Miller, and Dorsey (2014) compared user satisfaction in two LEED-certified buildings ($n = 249$) with one conventional building ($n = 70$) in Canada, showing that working in a green-rated office was mostly considered a healthier and more satisfying experience. However, certified buildings were not necessarily perceived as more comfortable and productive workplaces, with significant variability particularly on aspects that are not mandatory for LEED certification (e.g. acoustics, privacy and ergonomics). In a longitudinal study of two groups of bank employees in South Africa, one moving to a Green Star-rated building ($n = 98, 80$ and 59 , corresponding to three periods of analysis) and one staying in their non-certified office ($n = 114, 41$ and 52), self-reported measures of physical wellbeing and productivity revealed higher ratings in the new certified building, although IEQ perceptions were not always more positive (Thatcher & Milner, 2014). Similar results of improved self-assessed performance, wellbeing and enjoyment at work after moving into a newly refurbished BREEAM-rated office in UK were reported by Agha-Hosseini, El-Jouzi, Elmualim, Ellis, and Williams (2013).

In contrast, other studies have shown occupants of green buildings seldom having consistently higher satisfaction with their indoor working environment, emphasizing that the criteria for green certification might not yet be informed by a complete characterization of how physical conditions influence user perception. For example, Tham, Wargocki, and Tan (2015) compared the IEQ perception and prevalence of sick building syndrome (SBS) symptoms and sick leave in a Green Mark Platinum-certified building ($n = 31$) against a conventional office in Singapore ($n = 33$). Although the Green Mark building was perceived as cooler, and as having fresher and cleaner air, it did not have different (physical, chemical and biological) measured IEQ parameters, nor was any association detected between certification and lower SBS symptoms or sick-leave records. Menadue, Soebarto, and Williamson (2013) compared surveys in four Green Star-rated buildings against four conventional offices in South Australia ($n = 600$). The data showed that green-certified buildings provided slightly higher satisfaction with thermal comfort and perceived health, but lower satisfaction with lighting, noise and self-assessed productivity. A follow-up study, which also included indoor monitoring, detected similar IEQ metrics and occupants' perceptions in the two groups of buildings, although satisfaction with environmental conditions was in some cases lower in the Green Star offices (Menadue, Soebarto, & Williamson, 2014).

Aim and structure

Common limitations of most previous research include: (1) relying on relatively small sample sizes (at the level either of the number of buildings or of individual occupant responses), hence increasing the chances of type II errors (*i.e.* low statistical power); and (2) being based primarily on null-hypothesis significance testing of differences in mean satisfaction scores. These are methodological constraints that might severely limit the practical relevance of conclusions (Cumming, 2014; Kirk, 2003). The present authors addressed both these limitations in earlier work where we investigated if LEED certification leads to higher, equal or lower occupant satisfaction (Altomonte & Schiavon, 2013; Schiavon & Altomonte, 2014). In these studies, we analysed a large subset of the Center for the Built Environment (CBE) survey database featuring 21,477 responses from 144 office buildings, of which 65 were LEED rated. Different from previous research, we based the inferential analysis on the estimation of *effect sizes*, a standardized measure of the magnitude of differences detected and not just their statistical significance (Field, Miles, & Field, 2012). The results showed equal satisfaction with the building, workspace and several parameters of IEQ, between occupants of certified and non-certified offices, independent of *spatial factors* such as building size, office type, workspace layout and distance from windows, and of *personal characteristics* such as gender, age, work type and working hours. However, LEED buildings were found to be more effective in delivering occupant satisfaction in open spaces rather than in enclosed offices, and in small rather than in large buildings. In addition, results suggested that users of LEED offices may be more satisfied with air quality but less satisfied with the amount of light, and that the positive value of certification might decrease with time. In further research, we reached similar conclusions in a selection of BREEAM-rated office buildings in UK (Altomonte, Saadouni, Kent, & Schiavon, 2017).

These studies, however, did not include a detailed analysis of the associations between occupant satisfaction and the specific credits obtained by buildings under the IEQ category. To our knowledge, there is no research to date that has used a large sample of users' surveys to study their satisfaction with IEQ in green-rated buildings at the individual credit level. In response, this paper investigates occupant satisfaction in buildings certified by the LEED green rating system, considering: (1) the individual credits obtained under the IEQ category; (2) the total IEQ points earned and the LEED product and version under which certification was awarded; and (3) the final level of LEED rating attained.

Methods

LEED rating system and the IEQ category

LEED is a voluntary, consensus-based, market-driven programme providing third-party verification for green buildings (USGBC, 2017b). Since its inception in 1998, all LEED products – *e.g.* LEED for New Construction (NC), LEED for Existing Buildings (EB), LEED for Commercial Interiors (CI) – have gone through many releases (USGBC, 2014). For example, LEED NC – now featured within LEED: Building Design + Construction (BD + C) (USGBC, 2017c) – has evolved from version v2.0 in 2000, to v2.1 in 2002, v2.2 in 2005, v3 in 2009 and v4 in 2013. LEED uses a credit-based structure through which points can be earned across several categories: Location and Transportation, Sustainable Sites, Water Efficiency, Energy and Atmosphere, Material and Resources, Indoor Environmental Quality (IEQ), Innovation, and Regional Priority (USGBC, 2017c). Every category features various credits, some being mandatory prerequisites, each evaluating a project's performance and awarding points accordingly. Based on the number of points earned, a project can attain the following rating levels: Certified (40–49), Silver (50–59), Gold (60–79) and Platinum (≥ 80 points).

The current paper is particularly focused on the IEQ category, which features credits related to indoor air quality, thermal comfort, interior lighting, daylight, views, controllability of systems, acoustic performance, *etc.* The distributions of IEQ credits, and the number of points awarded, differ according to the LEED product and version under which certification is sought. Table 1 provides a comparison of the IEQ credits awarded by LEED NC/BD + C under v2.0, v3 and v4. The area-related credits are presented in rows, with an indication of the number of points that can be earned in each. Although the name of credits might have remained substantially unchanged across versions, the criteria for their attainment have progressively evolved.

Description of the dataset

The data for this study originate from the CBE Occupant Indoor Environmental Quality survey database. The CBE survey is a web-based benchmarking and evaluation tool that can be applied to investigate the factors that drive satisfaction in buildings from the perspective of their occupants (Altomonte & Schiavon, 2013; Zagreus, Huizenga, Arens, & Lehrer, 2004). Satisfaction votes are measured on an ordered seven-point Likert scale, ranging from 'very satisfied' (+3) to 'very

Table 1. Distribution of indoor environmental quality (IEQ) credits for Leadership in Energy and Environmental Design (LEED) for New Construction v2.0, v3 and v4.

| LEED NC v2.0 (2000) | | LEED NC v3 (2009) | | LEED BD + C: NC v4 (2013) |
|--|--|--|---|---|
| Minimum IAQ Performance (R) | | Minimum IAQ Performance (R) | | Minimum IAQ Performance (R) |
| Environmental Tobacco Smoke Control (R) | | Environmental Tobacco Smoke Control (R) | | Environmental Tobacco Smoke Control (R) |
| Carbon Dioxide (CO ₂) Monitoring (1) | | Outdoor Air Delivery Monitoring (1) | | Enhanced IAQ Strategies (2) |
| Increased Ventilation Effectiveness (1) | | Increased Ventilation (1) | | |
| Indoor Chemical and Pollutant Source Control (1) | | Indoor Chemical and Pollutant Source Control (1) | | |
| Low-Emitting Materials | Adhesive and Sealants (1) Paints and Coatings (1) Carpet Systems (1) Composite Wood (1) | Low-Emitting Materials | Adhesive and Sealants (1) Paints and Coatings (1) Flooring Systems (1) Composite Wood and Agrifiber Products (1) | Low-Emitting Materials (3) |
| Construction IAQ Management Plan – During Construction (1) | | Construction IAQ Management Plan – During Construction (1) | | Construction IAQ Management Plan (1) |
| Construction IAQ Management Plan – After Construction (1) | | Construction IAQ Management Plan – Before Occupancy (1) | | IAQ Assessment (2) |
| Controllability of Systems – Thermal Comfort (1) | | Controllability of Systems – Non-Perimeter Spaces (1) | | Thermal Comfort (1) |
| Thermal Comfort – Design (1) | | Thermal Comfort – Compliance with ASHRAE 55-1992 (1) | | |
| Thermal Comfort – Verification (1) | | Thermal Comfort – Permanent Monitoring System (1) | | |
| Controllability of Systems – Perimeter Spaces (1) | | Controllability of Systems – Lighting (1) | | Interior Lighting (2) |
| Daylight and Views – Daylight 75% of spaces (1) | | Daylight and Views – Daylight (1) | | Daylight (3) |
| Daylight and Views – Views 90% of spaces (1) | | Daylight and Views – Views (1) | | Quality Views (1) |
| – | | – | | Acoustic Performance (1) |

Notes: IAQ = indoor air quality; R = required credits that are prerequisite for certification.

dissatisfied' (–3), with a neutral midpoint (0). The full database currently features over 100,000 user responses collected from over 1200 buildings around the world (CBE, 2017). The dataset for this analysis includes 11,243 occupant responses from 93 office buildings located in the US (83) and Canada (10). All buildings administered the CBE survey within two years of receiving their LEED certification and were rated under: LEED for New Constructions & Major Renovations (NC); LEED for Existing Buildings, Operation & Maintenance (EB/EBOM); or LEED for Commercial Interiors (CI).

The distribution of buildings and occupant responses by LEED product, version and rating level are reported in Tables 2 and 3. Separate from our own dataset, the last column of Table 2 provides a percentage distribution of LEED ratings and versions for the buildings certified by LEED NC, EB/EBOM and CI currently featured in the USGBC public project directory (USGBC, 2017d). Compared with the USGBC data, the buildings in our dataset are skewed towards the highest levels of certification (Gold and Platinum) and older LEED versions (v1.0/v2.2). Table 4 provides the distribution of occupant responses based on buildings' spatial factors and personal characteristics (Frontczak & Wargocki, 2011; Schiavon & Altomonte, 2014).

Data analysis

This study is structured on a rigorous statistical analysis of occupant satisfaction in LEED-rated buildings, whose results are presented below in the next section.

The statistical analysis was based on a subset of the CBE survey centred on 12 categories. Of these, emphasis was given to: satisfaction with the building, workspace and features of the indoor environment related to air quality, temperature, lighting, visual comfort,

Table 2. Distribution of buildings in the dataset.

| | LEED product | | | Total | USGBC ^a |
|---------------------|--------------|------------|------------|------------|--------------------|
| | NC | EB/EBOM | CI | | |
| LEED rating | | | | | |
| Platinum | 16 | 4 | 5 | 25 (26.9%) | 7.9% |
| Gold | 29 | 7 | 7 | 43 (46.2%) | 40.5% |
| Silver | 8 | 2 | 6 | 16 (17.2%) | 32.9% |
| Certified | 5 | 0 | 4 | 9 (9.7%) | 18.7% |
| LEED version | | | | | |
| v1.0 or Pilot | 3 | 1 | 7 | 11 (11.8%) | 0.4% |
| v2.0 | 15 | 2 | 9 | 26 (28.0%) | 9.0% |
| v2.1/v2.2 | 37 | 0 | 0 | 37 (39.8%) | 31.0% |
| 2008 | 0 | 2 | 0 | 2 (2.2%) | 3.2% |
| v3 (2009) | 3 | 8 | 6 | 17 (18.3%) | 56.0% |
| Total | 58 (62.4%) | 13 (14.0%) | 22 (23.6%) | 93 | 23,094 |

Note: ^aUpdated in June 2017 from <http://www.usgbc.org/projects> considering a total of 23,094 buildings certified by LEED NC, LEED EB/EBOM and LEED CI (this also includes 76 buildings certified by LEED v4, corresponding to 0.4% of the total).

Table 3. Distribution of occupants' responses in the dataset.

| | LEED product | | | Total |
|---------------------|--------------|--------------|--------------|--------------|
| | NC | EB/EBOM | CI | |
| LEED rating | | | | |
| Platinum | 1186 (22.3%) | 848 (29.7%) | 291 (9.5%) | 2325 (20.7%) |
| Gold | 3472 (65.1%) | 1456 (50.9%) | 1746 (57.2%) | 6674 (59.4%) |
| Silver | 524 (9.8%) | 556 (19.4%) | 425 (13.9%) | 1505 (13.4%) |
| Certified | 148 (2.8%) | 0 | 591 (19.4%) | 739 (6.6%) |
| LEED version | | | | |
| v1.0 or Pilot | 284 (5.3%) | 80 (2.8%) | 1602 (52.5%) | 1966 (17.5%) |
| v2.0 | 1371 (25.7%) | 164 (5.7%) | 899 (29.4%) | 2434 (21.6%) |
| v2.1/v2.2 | 3523 (66.1%) | 0 | 0 | 3523 (31.3%) |
| 2008 | 0 | 491 (17.2%) | 0 | 491 (4.4%) |
| v3 (2009) | 152 (2.9%) | 2125 (74.3%) | 552 (18.1%) | 2829 (25.2%) |
| Total | 5330 (47.4%) | 2860 (25.4%) | 3053 (27.2%) | 11,243 |

Table 4. Distribution of occupants' responses based on spatial factors and personal characteristics.

| Spatial and personal factors | Occupants' responses |
|-----------------------------------|----------------------|
| Office type | |
| Enclosed | 2592 (23.1%) |
| Open space | 7597 (67.6%) |
| Other | 329 (2.9%) |
| Not available (n.a.) | 725 (6.4%) |
| Spatial layout | |
| Private office | 2592 (23.1%) |
| Shared office | 461 (4.1%) |
| Cubicles with high partitions | 3143 (28.0%) |
| Cubicles with low partitions | 3258 (29.0%) |
| Open (few or no partitions) | 735 (6.5%) |
| Other | 329 (2.9%) |
| n.a. | 725 (6.4%) |
| Distance from window | |
| Within 4.6 m (15 feet) | 7324 (65.1%) |
| Further than 4.6 m (15 feet) | 3011 (26.8%) |
| n.a. | 908 (8.1%) |
| Gender | |
| Female | 5221 (46.4%) |
| Male | 3829 (34.1%) |
| n.a. | 2193 (19.5%) |
| Age group (years) | |
| 30 or under | 1810 (16.1%) |
| 31–50 | 4006 (35.6%) |
| Over 50 | 2168 (19.3%) |
| n.a. | 3259 (29.0%) |
| Time at workspace (months) | |
| < 3 | 645 (5.7%) |
| 4–6 | 968 (8.6%) |
| 7–12 | 1869 (16.6%) |
| > 12 months | 4942 (44.0%) |
| n.a. | 2819 (25.1%) |
| Weekly working hours | |
| ≤ 10 | 511 (4.5%) |
| 11–30 | 1739 (15.5%) |
| > 30 | 7076 (62.9%) |
| n.a. | 1917 (17.1%) |
| Total | 11,243 |

noise and cleanliness; and to self-assessed conditions for productivity. This selection aimed to focus on the CBE survey categories most relevant to the IEQ credits featured in the LEED products and versions under which buildings in this dataset were certified. The only exceptions were the CBE questions about acoustic quality (noise level and sound privacy), which were not addressed in LEED credits until v4 (not included in this research). However, these categories were still included in this study due to the relevance that the acoustic environment has for overall occupant satisfaction.

The first part of our analysis investigated the relationships between the individual IEQ credits obtained and occupant satisfaction with the survey categories that might be influenced by the design strategies related to their achievement. For this, a series of pairings (Table 5) was developed from which 72 comparisons were analyzed.

Calculations were made of the descriptive statistics (mean, standard deviation, median, first and third quartiles) and the differences between the means and medians of satisfaction scores by organizing occupant responses in two independent groups, corresponding to the buildings that had obtained a specific IEQ credit (x_1) and buildings that had not (x_0). Initial exploratory inspection of the data, performed by Shapiro–Wilk (Shapiro & Wilk, 1965) and Kolmogorov–Smirnov (Smirnov, 1948) tests, revealed consistent non-normal distributions for all comparisons (tests were all highly significant). Since the assumption of homogeneity of variance (Ansari–Bradley tests) was also frequently violated (Ansari & Bradley, 1960), and data had an ordinal character, we tested the statistical significance of differences between satisfaction scores with a two-tailed non-parametric Wilcoxon rank-sum test. This test looks for differences between two independent groups and calculates the associated p -value using a Monte Carlo method (Field et al., 2012). For all tests, the results were considered statistically significant when $p \leq 0.05$. Whereas some LEED credits allowed earning more than one point (*i.e.* EQc2, EQc2.4, EQc.8.1), the related occupant responses were excluded from the analysis since their very small number resulted in comparisons between independent groups of a strongly inhomogeneous sample size, hence limiting the robustness of inferences (*e.g.* higher risk of type II errors, particularly when the assumption of homogeneity of variance was violated). Due to the large size of the samples considered, which may confound statistical and practical significance, for each comparison we calculated the effect size to quantify the practical relevance of statistically significant differences (Schiavon & Altomonte, 2014). Consistent with

Table 5. Pairings between Leadership in Energy and Environmental Design (LEED) indoor environmental quality (IEQ) credits (and sub-credits) and Center for the Built Environment (CBE) survey categories.

| LEED IEQ credit (and sub-credit) | CBE survey category |
|--|--|
| EQc1 – CO ₂ Monitoring | Air Quality |
| EQc1 – Outdoor Air Delivery | Air Quality |
| EQc1.1 and c1.2 – IAQ Management, Outdoor Air & Ventilation | Air Quality, Conditions for Productivity |
| EQc1.3 and c1.4 – IAQ Management, Particulates & Additions | Air Quality |
| EQc2 – Increased Ventilation | Air Quality, Temperature, Noise |
| EQc2 – Ventilation Effectiveness | Air Quality, Temperature, Noise |
| EQc2.2 – Controllability of Systems, Lighting | Amount of Light |
| EQc2.3 – Occupant Comfort, Thermal Comfort Monitor | Visual Comfort, Temperature |
| EQc2.4 – Daylight and Views | Amount of Light, Ability Light ^a , Conditions for Productivity |
| EQc3.1 – Construction IAQ Management, During Construction | Air Quality |
| EQc3.1 – High Performance Green Cleaning Program | Air Quality |
| EQc3.2 – Construction IAQ Management, Before Occupancy | Air Quality |
| EQc4.1 – Low-Emitting Materials, Adhesive & Sealants | Air Quality |
| EQc4.2 – Low-Emitting Materials, Paints | Air Quality |
| EQc4.3 – Low-Emitting Materials, Carpets | Air Quality |
| EQc4.4 – Low-Emitting Materials, Composite Wood | Air Quality |
| EQc4.5 – Low-Emitting Materials, Furniture and Seating | Air Quality |
| EQc5 – Indoor Chemical and Pollutant Source Control | Air Quality, Building Cleanliness, Workspace Cleanliness |
| EQc6.1 – Controllability of Systems, Lighting | Amount of Light, Ability Light ^a , Visual Comfort |
| EQc6.1 – Controllability of Systems, Perimeter | Amount of Light, Visual Comfort, Temperature, Conditions for Productivity |
| EQc6.2 – Controllability of Systems, Non-Perimeter | Amount of Light, Visual Comfort, Temperature |
| EQc6.2 – Controllability of Systems, Thermal Comfort | Temperature |
| EQc6.2 – Controllability of Systems, Temperature and Ventilation | Temperature |
| EQc7.1 – Thermal Comfort, Comply ASHRAE 55 | Temperature |
| EQc7.1 – Thermal Comfort, Compliance | Temperature |
| EQc7.2 – Thermal Comfort, Permanent Monitoring System | Air Quality, Temperature |
| EQc7.2 – Thermal Comfort, Verification | Air Quality, Temperature |
| EQc7.2 – Thermal Comfort Monitoring | Air Quality, Temperature |
| EQc8.1 – Daylight and Views, Daylight | Air Quality, Noise |
| EQc8.1 – Daylight and Views, Daylight 75% of Spaces | Amount of Light, Visual Comfort, Ability Light ^a , Noise |
| EQc8.2 – Daylight and Views, Views | Air Quality, Amount of Light, Visual Comfort, Ability Light ^a , Noise, Visual Privacy |
| EQc8.2 – Daylight and Views, Views 90% of Spaces | Amount of Light, Visual Comfort, Ability Light ^a , Visual Privacy |

Note: ^aThe category Ability Light refers to satisfaction with light for task performance in response to the following question: 'Overall, does the lighting quality in your workspace enhance or interfere with your ability to get your job done?'

our previous research, we calculated the effect size using the Spearman rho (ρ) rank-correlation coefficient. The interpretation of the outcome was based on the thresholds given by Ferguson (2009): $\rho < 0.20$ = negligible; $0.20 \leq \rho < 0.50$ = small; $0.50 \leq \rho < 0.80$ = moderate; and $\rho \geq 0.80$ = large; $\rho < 0.20$ was considered non-*substantive*, hence denoting non-practically relevant differences. In reporting the results of the inferential analysis, we also included Cliff's delta (δ) coefficient as a further measure of effect size due to its more intuitive interpretation. Cliff's δ – which is very strongly correlated to Spearman ρ – provides an estimation of the 'probability' that individual observations in a group are larger (or smaller) than

those in another group, representing the degree of 'overlap' between two distributions. It ranges from -1 (if all observations in group 1 are larger than group 2) to $+1$ (if all observations in group 1 are smaller than group 2), and takes the value 0 if the two distributions are identical (Cliff, 1996).

For the second part of the analysis investigating the relationship between the total IEQ points earned by buildings and occupant satisfaction, we considered only the CBE survey categories focusing on satisfaction with the building and the workspace. The analysis was conducted on the full dataset of responses, while also taking into account the different LEED products and

versions under which certification was awarded. Initially, linear regressions were used to explore and highlight any observable association between the variables. Ordinal logistic regression was then performed, since this is an inferential statistical method that is suitable to treat single-response ordinal or categorical-scaled outcome variables – that is, occupant satisfaction – and continuous-scaled predictor variables – that is, total IEQ points earned (McCullagh, 1980; Winship & Mare, 1984). To examine the influence of LEED product and version on the outcome variable, a third variable system was used by separately specifying them as interaction terms in the ordinal logistic regression model (*i.e.* Total IEQ Points*LEED Product and Total IEQ Points*LEED Version). Only one covariate was included in the original model at one time. The proportion of variance explained by the predictor variables in the model is expressed in terms of pseudo- R^2 , with larger values indicating that more of the variation was accounted for by the model, to a maximum of 1 (Cox & Snell, 1989). The interpretation of the outcome was informed by the thresholds provided by Ferguson (2009).

Finally, in the third part of the analysis, a Kruskal-Wallis analysis of variance (ANOVA) was used to study the relationships between the final level of LEED rating attained and occupant satisfaction with the building and the workspace (Kruskal & Wallis, 1952). A non-parametric Fligner-Killeen test of homogeneity of variance was used to examine the variances across the independent groups (Fligner & Killeen, 1976), and *post-hoc* Wilcoxon rank sum tests were used to determine where the differences detected in the ANOVA were (Field, 2016). Again, Spearman ρ was used as a measure of the effect size (Ferguson, 2009) to infer the magnitude and practical relevance of the influences detected.

All statistical analysis was performed using R software version 3.3.1 (R Team, 2017).

The interpretation of the results obtained was supported by expert feedback gathered in the context of an industry focus group comprising some 20 building professionals who were invited to contribute based on their direct experience with the development, education, design and practice of LEED certification (Krueger, 2009). The discussions generated within the focus group, corroborated by an extensive literature review, were used as a framework to interpret and explain the patterns emerging from the data (Berg & Lune, 2011). These methods contributed different perspectives to help contextualize the findings from the statistical analysis, discuss the features that may contribute to improved IEQ, and frame the complex design and construction processes underlying the dynamic nature of building operations.

Results

Occupant satisfaction and individual IEQ credits

For each of the 72 comparisons between the CBE survey responses and the relevant LEED IEQ credit, homogeneous samples were drawn only from buildings that were certified by the LEED product and version featuring that specific IEQ credit. The grouping of buildings is reported in Table 6.

Table 7 and Figure 1 present, respectively, the results of the analysis and a graphic visualization of the descriptive and inferential statistics for a selection of comparisons focused on satisfaction with air quality, temperature, amount of light and visual comfort. The box plots and full descriptive and inferential statistics for all 72 comparisons are provided in Appendices A and B in the supplemental data online. The supplemental data provided also include the test statistic (AB) and two-tailed statistical significance (p -AB) for the Ansari-Bradley tests, and the test statistic (W) and Z-score for the Wilcoxon tests.

The Wilcoxon rank-sum tests detected statistically significant differences in 49 of 72 cases. However, 71 of 72 comparisons had an effect size of negligible magnitude ($\rho < 0.20$). A reasonable hypothesis would have been that there was higher satisfaction with a specific IEQ attribute in buildings having earned the associated IEQ point. Instead, the results in Table 7 and Figure 1 reveal that the achievement of an individual IEQ credit *does not* have a practically relevant influence on occupant satisfaction with the corresponding IEQ parameter. The only exception is seen in the comparison between credit IEQc3.1 – High Performance Green Cleaning Program and satisfaction with air quality ($\Delta\text{Mdn} = -1.0$, $W = 205,000$, $p < 0.001^{***}$, $\rho = 0.27$). This small but substantive effect size indicates, in this case, a better

Table 6. Building groups based on Leadership in Energy and Environmental Design (LEED) product and version.

| Building group | LEED product and version |
|----------------|---------------------------|
| B | LEED NC 2.0, LEED NC 2.1 |
| C | LEED NC 2.2, LEED NC 2009 |
| C1 | LEED CI 2.0 |
| C2 | LEED CI 2009 |
| C3 | LEED Canada CI 1.0 |
| C4 | LEED CI 1.0 |
| E | LEED EB 1.0 |
| F | LEED EB 2.0 |
| G | LEED EBOM 2008 |
| G1 | LEED EBOM Canada |

Note: LEED NC = New Construction; LEED EB = Existing Buildings; LEED EBOM = Existing Buildings: Operations & Maintenance; LEED CI = Commercial Interiors.

Table 7. Descriptive and inferential statistics for comparisons between occupant satisfaction and Leadership in Energy and Environmental Design (LEED) indoor environmental quality (IEQ) credits.

| Credit | Credit name | Building Groups | N_0 | N_1 | M_0 | M_1 | SD_0 | SD_1 | ΔM | Mdn_0 | Mdn_1 | IQR_0 | IQR_1 | ΔMdn | p | δ | ρ |
|--|---|----------------------|-------|-------|-------|-------|--------|--------|------------|---------|---------|---------|---------|--------------|---------|----------|--------|
| <i>Satisfaction with air quality</i> | | | | | | | | | | | | | | | | | |
| EQc2 | Increased Ventilation & Ventilation Effectiveness | C, C1, C2, C3, C4, F | 2143 | 2417 | 1.24 | 1.44 | 1.54 | 1.49 | -0.20 | 2.0 | 2.0 | 2.0 | 2.0 | 0.0 | < 0.001 | 0.08 | 0.07 |
| EQc3.1 | High Performance Green Cleaning Program | G, G1 | 368 | 1877 | -0.02 | 1.16 | 1.64 | 1.46 | -1.19 | 0.0 | 1.0 | 2.0 | 2.0 | -1.0 | < 0.001 | 0.41 | 0.27 |
| <i>Satisfaction with temperature</i> | | | | | | | | | | | | | | | | | |
| EQc6.2 | Controllability of Systems, Thermal | C, C1, C2, C3 | 2396 | 1854 | 0.51 | 0.67 | 1.76 | 1.80 | -0.16 | 1.0 | 1.0 | 3.0 | 3.0 | 0.0 | < 0.001 | 0.06 | 0.05 |
| EQc7.2 | Thermal Comfort Monitoring & Verification | C3, C4 | 723 | 857 | 0.39 | 0.90 | 1.71 | 1.75 | -0.51 | 1.0 | 1.0 | 3.0 | 2.0 | 0.0 | < 0.001 | 0.18 | 0.16 |
| <i>Satisfaction with amount of light</i> | | | | | | | | | | | | | | | | | |
| EQc8.1 | Daylight and Views, Daylight | B, C1, C3 | 3850 | 1721 | 1.19 | 1.42 | 1.72 | 1.55 | -0.23 | 2.0 | 2.0 | 3.0 | 2.0 | 0.0 | < 0.001 | 0.06 | 0.05 |
| EQc8.2 | Daylight and Views, Views | B, C1, C3 | 3283 | 2288 | 1.36 | 1.11 | 1.64 | 1.72 | 0.25 | 2.0 | 2.0 | 3.0 | 2.0 | 0.0 | < 0.001 | -0.09 | -0.07 |
| <i>Satisfaction with visual comfort</i> | | | | | | | | | | | | | | | | | |
| EQc8.1 | Daylight and Views, Daylight | C, C2 | 982 | 891 | 1.47 | 1.22 | 1.57 | 1.62 | 0.25 | 2.0 | 2.0 | 2.0 | 2.0 | 0.0 | < 0.001 | -0.10 | -0.09 |
| EQc8.2 | Daylight and Views, Views | C, C2 | 1004 | 907 | 1.46 | 1.23 | 1.56 | 1.63 | 0.23 | 2.0 | 2.0 | 2.0 | 2.5 | 0.0 | 0.001 | -0.08 | -0.07 |

Notes: Presented are the coding and name of each credit, the building groups from where responses were drawn, the sizes of independent groups (N_0 corresponding to satisfaction votes expressed in buildings that had not earned a point in the specific LEED IEQ credit; and N_1 to buildings that had), the means of satisfaction scores in each group (M_0 and M_1), the standard deviations (SD_0 and SD_1), the differences in means (ΔM), the medians (Mdn_0 and Mdn_1), the interquartile ranges (IQR_0 and IQR_1), the difference in medians (ΔMdn), the statistical significance (p) for the Wilcoxon tests, and the effect sizes (Cliff's δ and Spearman ρ).

$p \leq 0.001$ = highly significant; $0.001 < p \leq 0.01$ = significant; $0.01 < p \leq 0.05$ = weakly significant; $p > 0.05$ = not significant;
 $\rho < 0.20$ = negligible; $0.20 \leq \rho < 0.50$ = small; $0.50 \leq \rho < 0.80$ = moderate; $\rho \geq 0.80$ = large.

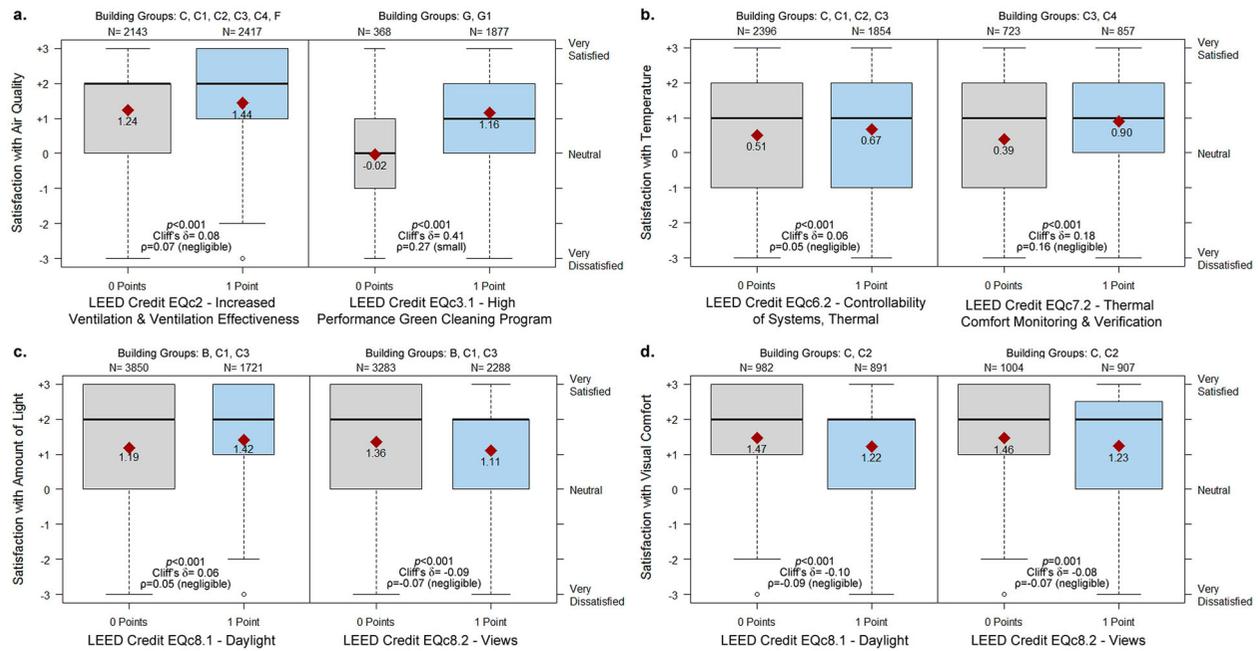


Figure 1. Selected box plots for Leadership in Energy and Environmental Design (LEED) credits and satisfaction with: (a) air quality; (b) temperature; (c) amount of light; and (d) visual comfort. The box plots provide the sizes of the independent sample groups, the mean (red diamond), the median (solid horizontal bar), the first and third quartiles, the minimum and maximum of satisfaction scores, and the results of the inferential analysis.

Note: $p \leq 0.001$ = highly significant; $0.001 < p \leq 0.01$ = significant; $0.01 < p \leq 0.05$ = weakly significant; $p > 0.05$ = not significant; $p < 0.20$ = negligible; $0.20 \leq p < 0.50$ = small; $0.50 \leq p < 0.80$ = moderate; $p \geq 0.80$ = large.

perception of air quality reported by occupants of buildings certified by LEED EBOM 2008 and LEED EBOM Canada that have earned a point in the IEQ credit 3.1 (Figure 1(a)). However, this result should be treated with caution since the assumption of homogeneity of variance was violated (p -AB $< 0.001^{***}$). Although the hypothesis of equal variances is not crucial when testing samples of equal, or nearly equal (and relatively large), sizes (Field et al., 2012), this comparison was based on very different numbers of responses in each independent group ($N_0 = 368$; $N_1 = 1877$).

Occupant satisfaction and total IEQ points

Table 8 presents the sample sizes of buildings and occupants' responses based on the total number of IEQ points earned by the buildings featured in the dataset, ranging from a minimum of five to a maximum of 16 points. Figure 2 presents the linear regressions for the total LEED IEQ points and satisfaction with the workspace.

Figure 2(a) unexpectedly shows a tendency for satisfaction with the workspace to decrease slightly as the number of IEQ points earned increases (negative slope; regression coefficient = -0.03). Figure 2(b) plots the same relationship but now broken up by LEED product, showing that this negative relationship came primarily from buildings certified by LEED NC, while the

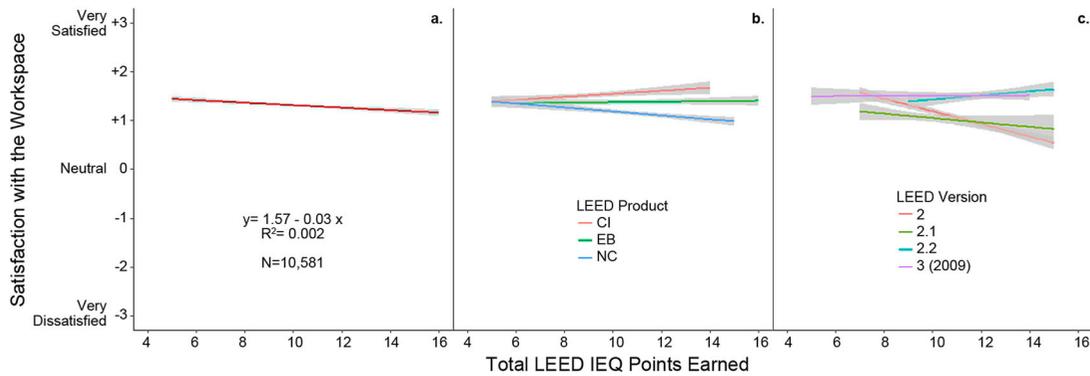
regression line was flat for LEED EB, and there was a positive slope for LEED CI (all regression coefficients are provided in the supplemental data online). Figure 2(c) shows that buildings certified by newer versions of LEED (*i.e.* v3 (2009) and 2.2) performed slightly better in terms of mean workspace satisfaction as the total IEQ points increase. The linear regressions related to individual LEED products, included in Appendix C, also online, provide further context to these tendencies.

Ordinal logistic regression was employed to explore whether the total number of IEQ points earned could predict occupant satisfaction with the workspace. In addition, consideration was also given to LEED product and version, separately treating them as covariates that interact with the predictor variable (total IEQ points) to study their effect on the outcome variable (occupant satisfaction). The results of the ordinal logistic regression are presented in Table 9.

As one might have expected from a visual inspection of Figure 2, Table 9 shows that the total number of IEQ points earned by a building *does not* affect satisfaction with the workspace (pseudo- $R^2 = 0.01$). Adding as a covariate the LEED product (Total IEQ Points*LEED Product) provides negligible improvement to the predicting capacity of the model (pseudo- $R^2 = 0.02$). Conversely, the proportion of variance accounted for by the predictor variables achieves a benchmark of practical relevance –

Table 8. Sample sizes based on total Leadership in Energy and Environmental Design (LEED) indoor environmental quality (IEQ) points earned.

| Total LEED IEQ points | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|-----------------------|-----|-----|------|-----|-----|------|-----|------|------|-----|-----|----|
| Number of buildings | 4 | 3 | 12 | 8 | 9 | 12 | 9 | 11 | 9 | 10 | 5 | 1 |
| Occupants' responses | 165 | 856 | 1537 | 916 | 746 | 2357 | 644 | 1208 | 1679 | 910 | 207 | 18 |

**Figure 2.** Linear regressions for satisfaction with the workspace based on total Leadership in Energy and Environmental Design (LEED) indoor environmental quality (IEQ) points earned for: (a) the full dataset; (b) the LEED product; and (c) the LEED version.

Note: Grey lines represent 95% confidence intervals. The regression coefficients for each LEED product are provided as supplemental data online.

yet, only marginally – once taking into account the LEED version (Total IEQ Points*LEED Version) under which the certification was awarded (pseudo- $R^2 = 0.04$).

The same methods of analysis were also repeated for occupant satisfaction with the building, and the results are reported in Appendices D–F in the supplemental data online. Consistent with previous research on the CBE database (Frontczak et al., 2012), the findings are similar, showing strong correlations between satisfaction with the building and with the workspace.

Occupant satisfaction and rating level

The Kruskal–Wallis ANOVA and the Fligner–Killeen tests of homogeneity of variance returned high statistical significance, hence supporting the need to adopt non-parametric post-hoc tests to explore the relationships between the final levels of LEED rating achieved and satisfaction with the building and with the workspace. The

detailed statistical data are reported in Appendix G in the supplemental data online. The summary results of the Wilcoxon rank-sum pairwise comparisons related to satisfaction with the workspace are provided in Table 10 (full inferential results are presented in, Table H2, also online).

Unexpectedly, the differences in mean (ΔM) were mostly positive, suggesting a trend for higher satisfaction with the workspace in buildings that had received a lower certification level. However, the tests detected statistical significance only in three of six comparisons, and effect sizes were consistently not practically relevant ($\rho < 0.20$). This leads us to conclude that the achievement of a higher rating level *does not* have a substantive influence on satisfaction with the workspace. The descriptive and inferential statistics related to satisfaction with the building – characterized by similar findings – are provided in Appendix H1 in the supplemental data online, and the full box plots for all comparisons between final

Table 9. Ordinal logistic regression model fits and pseudo- R^2 for satisfaction with the workspace.

| CBE category | Data | –Log-likelihood | χ^2 | d.f. | p | Pseudo- R^2 |
|---------------------------------|-------------------------------|-----------------|----------|------|---------|---------------|
| Satisfaction with the Workspace | Intercept | 699.2 | | | | 0.01 |
| | Total IEQ Points | 527.5 | 141.7 | 11 | < 0.001 | |
| | Intercept | 1602.1 | | | | 0.02 |
| | Total IEQ Points*LEED Product | 1403.6 | 198.5 | 11 | < 0.001 | |
| | Intercept | 1372.9 | | | | 0.04 |
| | Total IEQ Points*LEED Version | 1118.6 | 254.3 | 11 | < 0.001 | |

Notes: Presented are the data featured in the analysis, the –log-likelihood (i.e. a measure of the unexplained variation in the regression model), the test statistic (χ^2), the degrees of freedom (d.f.), the statistical significance (p), and the pseudo- R^2 (i.e. the proportion of variance accounted for by the predictor variable(s) in the model).

$p \leq 0.001$ = highly significant; $0.001 < p \leq 0.01$ = significant; $0.01 < p \leq 0.05$ = weakly significant; $p > 0.05$ = not significant;

pseudo- $R^2 < 0.04$ = negligible; $0.04 \leq R^2 < 0.25$ = small; $0.25 \leq R^2 < 0.64$ = moderate; $R^2 \geq 0.64$ = large.

CBE = Center for the Built Environment.

Table 10. Pairwise comparisons for satisfaction with the workspace and Leadership in Energy and Environmental Design (LEED) rating.

| Comparison | N_0 | N_1 | M_0 | M_1 | SD_0 | SD_1 | ΔM | Mdn_0 | Mdn_1 | IQR_0 | IQR_1 | ΔMdn | p | ρ |
|---------------------------|-------|-------|-------|-------|--------|--------|------------|---------|---------|---------|---------|--------------|---------|--------|
| Certified versus Platinum | 712 | 2142 | 1.51 | 1.38 | 1.31 | 1.38 | 0.12 | 2.00 | 2.00 | 1.00 | 1.00 | 0.00 | 0.055 | -0.04 |
| Certified versus Gold | 712 | 6271 | 1.51 | 1.23 | 1.31 | 1.43 | 0.28 | 2.00 | 2.00 | 1.00 | 2.00 | 0.00 | < 0.001 | -0.06 |
| Certified versus Silver | 712 | 1456 | 1.51 | 1.45 | 1.31 | 1.27 | 0.05 | 2.00 | 2.00 | 1.00 | 1.00 | 0.00 | 0.163 | -0.03 |
| Silver versus Platinum | 1456 | 2142 | 1.45 | 1.38 | 1.27 | 1.38 | 0.07 | 2.00 | 2.00 | 1.00 | 1.00 | 0.00 | 0.529 | -0.01 |
| Silver versus Gold | 1456 | 6271 | 1.45 | 1.23 | 1.27 | 1.43 | 0.22 | 2.00 | 2.00 | 1.00 | 2.00 | 0.00 | < 0.001 | -0.06 |
| Gold versus Platinum | 6271 | 2142 | 1.23 | 1.38 | 1.43 | 1.38 | -0.16 | 2.00 | 2.00 | 2.00 | 1.00 | 0.00 | < 0.001 | 0.05 |

Notes: Presented are the independent groups (e.g. Certified versus Platinum) and their sizes (N_0 and N_1), the descriptive statistics of satisfaction scores in each group (mean, standard deviation, median, interquartile range, difference in mean and median), the two-tailed statistical significance (p) for the Wilcoxon tests, and the effect size (Spearman ρ).

$p \leq 0.001$ = highly significant; $0.001 < p \leq 0.01$ = significant; $0.01 < p \leq 0.05$ = weakly significant; $p > 0.05$ = not significant; $\rho < 0.20$ = negligible; $0.20 \leq \rho < 0.50$ = small; $0.50 \leq \rho < 0.80$ = moderate; $\rho \geq 0.80$ = large.

LEED rating levels and satisfaction with the building and the workspace are reported, respectively, in Appendices I and L, also online. Since no practically relevant differences in occupant satisfaction were detected when comparing buildings with different rating levels – and considering that, in the previous analysis, the interaction terms in the ordinal logistic regression (i.e. Total IEQ Points*LEED Product and Total IEQ Points*LEED Version) did not substantively increase the prediction capability of the model – no further testing was conducted also to take into account the different product and version under which buildings had achieved their final certification.

Discussion

Although the presented analysis produced results inconsistent with the hopes and expectations that many stakeholders may have about LEED and IEQ, there are still valuable lessons that the building industry can learn from these findings. In fact, building professionals, researchers and certification bodies have long sought a better understanding of the associations between design strategies, rating criteria and workplace experience, although at times these might be outside the direct control of designers and even beyond the scope of green building certification systems based primarily on design intent.

Some reflections on the challenges occurring throughout the design, construction and operation of a building that may affect its performance from the point of view of the occupants are presented below. The next subsection interprets the findings of the analysis with regard to the relevance of IEQ credits towards user satisfaction. These are followed by a discussion of potential strategies to improve workplace experience. Further reflections are then presented on the areas of development of green building rating systems that offer the potential to enhance occupant satisfaction *beyond* the credits currently featured in the IEQ category.

Before discussing the results, however, some caveats are provided on the limitations of the conclusions. First, even though a large sample was used, our dataset cannot be considered representative of all certified office buildings and rating systems. As noted, all 93 LEED buildings were predominantly certified by versions 2.0, 2.1 and 2.2, and the dataset was skewed towards higher rating levels. Also, the buildings featured in the CBE database administer occupant surveys on a voluntary basis, hence they do not represent a randomized sample of the entire building stock. Second, even when a specific IEQ credit was not achieved by a building, there might still have been other strategies implemented to address the corresponding environmental factor, hence ‘diluting’ the difference between the buildings that did or did not obtain that IEQ credit. Third, although this discussion aims to be generalizable and transferable across rating tools, the analysis was only for LEED. Other certification systems (e.g. BREEAM, Green Mark, Green Star) might feature a different distribution of IEQ credits, and criteria for their achievement. Fourth, information related to the cost of construction and/or lease of buildings featured in the dataset was not consistently available, so it was not included in the analysis. As shown in the literature (Eichholtz, Kok, & Quigley, 2010, 2013), issues related to costs would be important to consider in future research as factors that could drive priorities in ‘green investment’ and, ultimately, influence occupant satisfaction and expectations. Last, the CBE survey uses *perceived* satisfaction as an assessment metric, although this might not necessarily be among the explicit targets of some IEQ credits. However, although green certification systems might have different aims and objectives depending on product and project type, their general goal towards building users is ultimately to ‘support occupant comfort and well-being’ (Owens, Macken, Rohloff, & Rosenberg, 2013, p. 13). In this direction, satisfaction is an important feature of comfort, as, for example, per the definition of thermal comfort given by the American Society of

Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE): ‘the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation’ (ASHRAE, 2013, p. 4). Similarly, satisfaction is an inherent part of subjective well-being as expressed by the ‘Satisfaction with Life Scale (SWLS)’ instrument, a short five-item tool designed to measure global cognitive judgments of satisfaction with people’s lives as a whole (Diener, Emmons, Larsen, & Griffin, 1985).

Satisfaction and IEQ credits

In our dataset, a negligible relationship was found to exist between occupant satisfaction and the achievement of the related IEQ credits. How can these results be interpreted and contextualized?

Design and certification versus occupancy and operation

For new constructions or renovations, the design intentions of a project – which are generally the basis for green certification – might be different than the operational characteristics of a building that are assessed using a survey in post-occupancy evaluation. Buildings are complex and dynamic and, in the time between design and occupancy, many intervening factors can alter the existence, or performance, of the strategies for which the green rating was awarded. This can begin during construction, particularly if contractors were not involved in the design phase and have to manage over-complex and inflexible building systems. The operation of buildings then often requires substantial fine-tuning and adjustments over time, which are frequently cited as being among the causes for recurrent performance gaps between modelled and measured energy use (de Wilde, 2014). Therefore, it would not be surprising that a similar gap might also manifest itself in occupant satisfaction with IEQ, regardless of the specific or total number of IEQ credits achieved at the design stage.

Noting that all our surveys were administered within two years from LEED certification, these considerations might help to explain why the total number of IEQ points earned did not influence workplace satisfaction. Conversely, the positive associations between total IEQ points and satisfaction for newer versions of LEED may be a reassuring indication of the improvements made in certification criteria. However, although building age was not included in our analysis due to lack of verifiable information, another possible interpretation of this trend may simply be that the buildings or spaces certified under newer versions of LEED had been more recently built or renovated. In

fact, as presented in Table 2, most of the buildings in the dataset were certified by LEED for New Constructions (NC; 62.4%) and Commercial Interiors (CI; 23.6%), while relatively few offices were rated by LEED for Existing Buildings (EB/EBOM; 14%). In this context, research has suggested the potential presence of a positive bias in IEQ satisfaction after the move into a new (or newly refurbished) office (Gou, 2016; Singh, Syal, Grady, & Korkmaz, 2010). In the short term, this might result in a favourable perception derived from the novelty and excitement about the new place of work. However, our previous work (Altomonte et al., 2017; Schiavon & Altomonte, 2014) found that the positive value of green certification from the point of view of occupant satisfaction might tend to decrease with time. In fact, in the medium and long term, IEQ satisfaction could reduce possibly also due to the higher expectations instigated by the attainment of green rating (Menadue et al., 2014). Nevertheless, it should be remembered that in our analysis the LEED product under which buildings were certified (NC, CI or EB/EBOM) was also not a good predictor of occupant satisfaction.

Finally, in terms of the lack of relationship between workplace satisfaction and rating level, it must be highlighted that certification systems have broad scopes, and are structured under several credit categories. Buildings could achieve a high rating in many ways, not only through compliance with IEQ criteria. This is why the comparison of occupant satisfaction with both individual and total points earned in the IEQ category was a more suitable method of analysis than considering the rating level alone.

Relevance of IEQ green certification metrics

One might question whether the current metrics used for attainment of an IEQ credit were designed to translate directly into improved user satisfaction (and into better comfort, health and wellbeing). IEQ certification metrics should focus on the occupants as much as on the building, but this is not always the case. This may represent a challenge for rating systems, particularly due to the substantial differences that characterize the modern workplace in terms of spatial needs (e.g. desk distribution and organization), task requirements (e.g. occupancy and working schedules), users’ personal characteristics (e.g. demographics, sex, age, socio-cultural habits), etc. Additionally, as it has long been embraced by the disciplines of ergonomics, product design and marketing (Abrams, Maloney-Krichmar, & Preece, 2004; Noyes, 2001), metrics and criteria that merely address the demands of an average *standard* user might not be

suitable to capture the intrinsic inter- and intra-variability of occupants' needs.

The criteria for daylighting and views offer a good example of the weak association between green certification metrics and related occupant satisfaction. Rating tools have traditionally focused primarily on how to get the highest *quantity* of light across the floor area – measured by horizontal illuminance, an indication of light distribution and energy efficiency – rather than on the *quality* of the luminous environment. To include consideration of visual comfort in the 'Daylight' credit, LEED v3 introduced the requirement for 'glare control devices to avoid high-contrast situations that could impede visual tasks' (USGBC, 2009a). However, despite the fact that LEED v3 also awards a 'Views' credit 'to provide building occupants a connection to the outdoors' (USGBC, 2009b), no guidance is given in terms of shading operating strategies nor the quality and contents of the views, factors that could strongly influence the magnitude of visual discomfort (Kent, Altomonte, Wilson, & Tregenza, 2017; Tuaycharoen & Tregenza, 2005, 2007). But there has been some improvement. Under the 'Daylight' credit in LEED v4, in fact, the climate-based metric Annual Sunlight Exposure (ASE) could now serve as an indicator for the potential occurrence of glare, although the conditions required for earning this point might still be too limited and strict for the design of comfortable and well daylit spaces (Reinhart, 2015). In addition, the 'Quality Views' credit now features a detailed description of the contents of external vistas (USGBC, 2017c).

Among other rating systems, BREEAM International New Construction 2016 awards one 'Visual Comfort' point for glare control – to be met via building-integrated shading systems or occupant-controlled devices – alongside up to four points for daylight illuminance criteria, one for views, and one for internal and external lighting (BRE, 2016). Green Mark for New Buildings 2015 awards up to four points for effective daylighting, with one point earned for mitigation measures addressing visual discomfort (BCA, 2015). Finally, points for glare reduction and the provision of external views are also included in the 'Visual Comfort' credit under the Green Star – Design & As Built v1.1 rating tool (GBCA, 2015a).

These new criteria represent important advances, but further progress (*e.g.* predictive modelling for point-in-time and annual daylight glare probability (DGP) or high dynamic range (HDR) luminance mapping) would be necessary to address effectively issues of lighting quality and visual comfort in green-certified buildings (Altomonte, Kent, Tregenza, & Wilson, 2016; Kent, Altomonte, Tregenza, & Wilson, 2016).

Surveys and IEQ satisfaction

Occupant surveys rely on subjective measures; yet, perception might sometimes be disjointed from actual physical conditions, or a survey question about satisfaction with an IEQ parameter might be misinterpreted by a subject (Allen et al., 2015). As an example of the potential dichotomy between human experience and performance metrics, perceived air quality, air speed and temperature are connected and often confounded (Fang, Clausen, & Fanger, 1998; Fang, Wyon, Clausen, & Fanger, 2004; Melikov & Kaczmarczyk, 2012; Schiavon, Yang, Donner, Chang, & Nazaroff, 2017). The effectiveness of ventilation strategies might be considered by users more as a thermal comfort issue than a measure to dilute or eliminate air pollutants. In addition, over time occupants might become 'desensitized' to certain stimuli (*e.g.* odours) or attribute the physical impacts (*e.g.* headaches, dry eyes) of an environmental exposure to causes different from their original sources (Fanger, 1988). Further, while meeting minimum air-quality standards is a prerequisite for most certification systems, there are many pollutants that may not be perceived (or be considered hazardous) by people. Ironically, these might often be due to the use of cleaning products and air fresheners that could conversely give to occupants the perception of a healthier environment (Nazaroff & Weschler, 2004; Singer, Destailats, Hodgson, & Nazaroff, 2006). So, even if a particular pollutant did present potential risks for the occupants, this may not be reflected in survey responses (Spengler, Samet, & McCarthy, 2001).

Reported satisfaction can also be biased by personal attitudes, and might vary depending on the time spent in the building and the role the occupant has in the office hierarchy (Bozovic-Stamenovic, Kishnani, Tan, Prasad, & Faizal, 2016). Research has also demonstrated that 'green-branding' can enhance pro-environmental perceptions (Khashe et al., 2015), and that IEQ satisfaction may be influenced by corporate concerns for energy efficiency (Tsushima, Tanabe, & Utsumi, 2015). Lastly, it must be considered that the 'Hawthorne effect' (Franke & Kaul, 1978; McCarney et al., 2007), although disputed by some (Adair, 1984), has been linked to an alteration of reported perceptions resulting from the awareness of being observed – as is often the case when users are asked to respond to a workplace survey.

Control, integration and feedback

What lessons can building professionals, researchers, and certification bodies learn from this study in order to enhance occupant satisfaction in green-certified buildings?

Control, adjustments and adaptation

Green-rated buildings are often designed to be more ‘climate responsive’ than conventional offices, relying on passive strategies such as natural ventilation and daylighting. As such, it is more likely that their users may be exposed to variable conditions (daily, seasonally and spatially) and be required, at reasonable frequency, to engage with personal, environmental and behavioural controls in order to attain, maintain or restore their comfort (de Dear & Brager, 1998; Nicol & Humphreys, 1973). It has been shown that the capacity for building users to control their physical environment can significantly increase their tolerance to transient conditions of discomfort, while offering opportunities for adjustments and adaptation that have been positively associated to higher satisfaction with IEQ and feelings of wellbeing (Arens et al., 1998; Brager, Paliaga, & de Dear, 2004; Zhang et al., 2010; Zhang, Arens, & Zhai, 2015).

Occupants should, therefore, be provided with opportunities to engage with the operation of the building they inhabit, contributing to regulate their internal environmental conditions via openable windows, louvres, fans, shading devices, task lighting, thermostats, personal comfort systems, *etc.* Nevertheless, design strategies formulated to meet green certification criteria usually promote the design of shared open-plan spaces (*e.g.* for cross-ventilation and light distribution), hence reducing ‘ownership’ of the perimeter and constraining user actions on envelope control systems. An additional challenge of user engagement is the frequent inclination among building occupants to leave controls in one position, regardless of the continuing presence of causes of discomfort (*e.g.* closing shades for momentary glare, but then keeping them down all day). Therefore, it is also important that users are given effective knowledge of their possibilities of control, adjustment and adaptation, including understanding how such strategies impact their comfort, wellbeing and task performance.

Research has strongly emphasized that occupants who have received effective training on building systems and design features, and know how to operate controls, are more likely to be satisfied with their internal environment (Day & Gunderson, 2015). A high level of personal control has also been associated with lower odds of sick leave in offices (Bodin Danielsson, Singh Chungkham, Wulff, & Westerlund, 2014) and has been linked to substantial opportunities for enriched comfort and pleasure, and better energy performance (Brager, Zhang, & Arens, 2015).

For controls to be most effective, enhanced commissioning and handover criteria, including targeted guides and training for occupants and building/facility

managers, are gradually gaining relevance among green building certification systems. In this context, as an example, the Soft Landings framework in the UK aims to ensure that feedback and follow-through can become natural parts of the delivery of a project (Bordass & Leaman, 2005; Way & Bordass, 2005). However, in the conditions for attainment of green certification, such practices are often featured only as prerequisites for the highest rating levels (*e.g.* for BREEAM and Green Mark), or are uniquely offered as additional credits. Further development might be beneficial in this area.

Design innovation and integration

Just as for low energy performance, good IEQ can be facilitated by building design and operational strategies that work alongside each other. This necessitates collaboration between various building professionals in an integrated process starting from the early design stages. This is currently supported by points awarded by LEED, BREEAM, Green Star and Green Mark for innovations that go beyond standard performance, for the involvement of accredited professionals, and for the adoption of a collaborative design framework ‘to achieve synergies across disciplines and building systems’ (USGBC, 2013a).

Towards more effective integration, a further step could be represented by ‘multi-level’ credits, *e.g.* rewarding synergies that allow buildings to meet certification criteria across different rating categories (Ma & Cheng, 2016). Green certification systems, however, still tend to treat each IEQ credit independently. In this context, balancing air quality, thermal, lighting and visual performance with a satisfactory acoustic environment often represents a particular challenge. As emphasized by our previous research on the CBE database, in fact, satisfaction with noise and sound privacy is frequently characterized by low and negative scores, especially in green-certified offices (Altomonte & Schiavon, 2013; Frontczak et al., 2012; Schiavon & Altomonte, 2014). Yet, this is not entirely surprising considering that LEED has only recently introduced a credit on ‘Acoustic Performance’ in its v4 (USGBC, 2013b). This is a step in the right direction for LEED, particularly seeing that other rating systems have for long featured credits for acoustic quality. In BREEAM, the appointment of a qualified acoustician at early design stage is a prerequisite for certification, and up to four points are awarded for meeting criteria of indoor ambient noise, sound insulation and reverberation time (BRE, 2016). For Green Mark, the achievement of a credit on ‘Sound Level’ according to the building function is also a precondition for certification, while the ‘Acoustics’ category rewards sound transmission reduction, reverberation design and/or

aural comfort (BCA, 2015). Green Star awards up to three points for internal noise levels, reverberation time and acoustic separation (GBCA, 2015a).

Research has also revealed a strong association between workplace satisfaction, noise, sound privacy and spatial layout, highlighting the challenge to find suitable compromises between dynamic changes in work organization, fit-out of spaces, ergonomics, proxemics and current trends in office design (Frontczak & Wargocki, 2011; Kim, Candido, Thomas, & De Dear, 2016; Leder et al., 2016; Sakellaris et al., 2016). Open-plan layouts have been commonly assumed to enhance communication and promote teamwork effectiveness (Heerwagen, Kampschroer, Powell, & Loftness, 2004). However, open spaces have also been recognized to be potentially more disruptive, such that the benefits of greater interaction might fail to offset the penalties of increased noise and decreased feelings of privacy (Kim & De Dear, 2013; Schiavon & Altomonte, 2014).

Monitoring and feedback

The effectiveness of any design strategy towards enhanced satisfaction requires continuous monitoring of building performance and collection of comprehensive occupant feedback. By fine-tuning operating strategies, this can help bridge the gap between design intent and user satisfaction throughout the lifetime of a building. Appraisal of occupants' views might also enable them to feel actively involved in the management of their place of work, with a likely increase in satisfaction simply due to the awareness that their concerns are being listened to. This implies a need to adopt systematic methods for handling and following up complaints, closing the feedback loop by reporting solutions back to the users (Brown & Arens, 2012). In addition, including designers in performance monitoring might facilitate the transfer of the collected experience to improved industry standards.

Various diagnostic tools can be used to evaluate buildings from the perspective of their occupants, including consideration of physical, psychological, social and experiential categories (*e.g.* spatial territories, aesthetics) (Mansour & Radford, 2016), as well as methods for benchmarking workplace effectiveness (Leesman, 2017). However, even if surveys are key techniques to obtain this information in a rapid, responsive and inexpensive fashion, they might not provide full contextual information about the building or the workspace nor offer the opportunity for continuous data collection. Ideally, they should be part of broader and interdisciplinary measurement protocols that exhaustively capture the functioning of a building (ASHRAE, 2012). Among available tools, the Building Use Studies (BUS) method

has been developed over the last 30 years for benchmarking occupant satisfaction in buildings (Arup, 2017). The CBE Occupant IEQ survey used in this study is part of the CBE's 'Livable Analytics' methodology, with several additional questions aimed at gathering building-level information for actionable improvements (CBE, 2017). A holistic approach to building performance evaluation, collecting objective and subjective data, was also recently launched in Australia (Candido, Kim, de Dear, & Thomas, 2016): the Building Occupants Survey System Australia (BOSSA).

Rating systems should reward ongoing performance monitoring and occupant feedback to guarantee that, following certification, the building continues to operate based on design intentions. This is beginning to occur. LEED NC v2009 included an IEQ credit – 'Thermal Comfort – Verification' – requiring a survey to be conducted within 6–18 months after occupancy, while LEED BD + C v4 now features this criterion as an Innovation credit. LEED O + M v4 also awards one point for 'Occupant Comfort Survey', requiring at least one survey to be administered every two years (USGBC, 2017c). Among other rating tools, BREEAM awards one point for the commitment to conduct a post-occupancy evaluation one year after occupation and disseminate its findings (BRE, 2016). Green Mark awards 0.5 points for administering a survey within 12 months of operation; meeting this credit is a prerequisite for achieving the highest rating levels (BCA, 2015). Green Star also rewards pre- and post-occupancy evaluation through an 'Innovation Challenge' credit based on the use of BOSSA (GBCA, 2015a). In addition, the USGBC administers the LEED Dynamic Plaque scheme, a building performance monitoring and scoring platform based on continuous benchmarking that provides annual LEED recertification over time (USGBC, 2016).

IEQ beyond IEQ credits

Other than recognizing design quality via certification, green building rating systems can further support best practice in the construction industry by driving design priorities, informing conversations between stakeholders, providing guidelines from which design can evolve, benchmarking performance and setting increasingly ambitious targets. To this aim, rating tools are also constantly introducing new certification criteria, from pilot credits (USGBC, 2013c) to innovation challenges (USGBC, 2013d; GBCA, 2015b). Yet, there is still a need to promote research and development on design strategies that can improve the quality of the indoor environment, and its impacts on building occupants, even *beyond* the credits featured in the IEQ category.

Occupant satisfaction, in fact, needs to be considered as a comprehensive design objective that is not only affected, directly and indirectly, by the conventional IEQ parameters of heat, light, sound and air quality, but also is driven by complex physio-psychological dimensions pertaining to personal health and wellbeing. In this context, new and emerging rating systems – such as the WELL building standard (Delos, 2015) – are focusing specifically on the multi-layered and interdependent interactions between the built environment and the various systems of the human body, translating interdisciplinary research into health-based building design strategies (IWBI, 2017).

There is no ‘silver bullet’ for creating a satisfactory and healthy work environment. Given the dynamic nature of buildings, the complexity of their users, the diverse and evolving demands of the workplace, and the need for these factors to be effectively monitored and analysed, there are still many challenges that the green building industry needs to tackle in order to promote indoor environmental qualities conducive to satisfaction, health and wellbeing. However, if sustained by advancements in research and design practice, rating tools can offer significant opportunities towards better, more comfortable, higher performing and healthier green-certified buildings.

Conclusions

Based on the analysis of a dataset featuring 11,243 responses from 93 LEED-rated buildings:

- the achievement of a specific IEQ credit did not substantively affect occupant satisfaction with related characteristics of the indoor working environment
- the total number of IEQ points earned did not influence workplace satisfaction, independent of the product under which certification was awarded
- occupant satisfaction with the building and workspace was not affected by the rating level achieved

From these conclusions, this study leads to the following recommendations.

For designers and building managers:

- there are many things that can change between the design of a project and the post-occupancy evaluation requiring the direct involvement of building professionals in performance monitoring to fine-tune operating strategies and transfer best practice to the building industry
- collaboration between building professionals from the early design stages can support innovation and the formulation of integrated strategies

- personal control can provide significant opportunities for enriched comfort, energy performance and enhanced satisfaction with the indoor environment

For building scientists and researchers:

- surveys rely on subjective measures and are best used if supported by physical data collection and in-person interviews to appraise building performance holistically
- reported satisfaction might be driven by factors other than IEQ parameters, such as the time spent in the workspace, attitudes, expectations, workplace culture, misinterpretations, *etc.*
- new interdisciplinary areas of research and development should address how we can enhance satisfaction, health and wellbeing beyond typical rating tools’ criteria

For green building certification systems:

- the metrics for attaining IEQ credits need to better represent reliable indicators of user satisfaction
- IEQ metrics and criteria need to consider the substantial differences – demographic, physiological, socio-cultural, *etc.* – that characterize building occupants, rather than solely responding to the needs and expectations of an average standard user
- credits should address user training on building operating strategies, which can increase satisfaction and foster adjustments and adaptive behaviours
- rating systems should encourage continuous building performance monitoring and offer opportunities for recertification over time

Acknowledgements

The authors thank Mark Mendell and Chris Pyke for their revision of the manuscript, and Kristine Walker for her contribution to this study as part of her Master of Science thesis at UC Berkeley, under the supervision of Stefano Schiavon and Gail Brager. The authors also gratefully acknowledge the support of Giusi Di Giorgio, University of Nottingham, for the review of the literature.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Engineering and Physical Sciences Research Council [grant number EP/N50970X/1]; the University of Nottingham [International Collaboration Fund] and the Industrial Partners of the Center for the Built Environment.

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