Post Occupancy Evaluation of Indoor Environmental Quality in Commercial Buildings: Do green buildings have more satisfied occupants?

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Sahar Abbaszadeh Fard
Dedicated to my brother Sina, age 23. To me he represents the promise of a bright future – just like the green building movement.
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1 Introduction

Recent studies have shown that despite the developments in our understanding of the indoor environment and subsequent advancements in building performance standards, design methods, and building technologies, a high proportion of office workers work in un-‘acceptable’ indoor environments [1]. Physical Indoor Environmental Quality (IEQ) factors such as: air quality, thermal comfort, lighting, and acoustic conditions result mainly from design decisions and building operation procedures. IEQ affects occupant well-being and productivity, and that is why common definitions of green building emphasize employing design and building operation strategies aimed at improving IEQ. Improving IEQ is important in all buildings, because the goal of providing a space for healthy and productive occupants should prefigure design. It is especially important in green buildings, because a low-energy building with high occupant discomfort is no more sustainable than a high-energy one. Occupants might fall off the map of design, but this should rarely happen if at all, in green buildings. The current desirable green building trend presents an opportunity to reverse the heretofore undesirable conditions for occupants, by bringing these conditions into the center of attention.

The idea of building green is not new, but it has gained unprecedented momentum in recent years. The United States Green Building Council (USGBC) launched a major effort in 2000 by releasing the first formal framework for rating green buildings in the United States: Leadership in Energy and Environmental Design (LEED). USGBC defines green buildings, as ones that significantly reduce or eliminate the negative impact of buildings on the occupants and the environment [2]. LEED is a feature-oriented rating system where credits are earned for satisfying specified green building criteria. LEED for
New Construction (LEED-NC) is structured in five categories: sustainable sites, water efficiency, energy & atmosphere, materials & resources, and indoor environmental quality. The document sets forth prerequisites and credits in each category that will earn the building a certified, silver, gold, or platinum rating based on the number of credit points achieved.

In 2003, USGBC estimated that between 3-6% of all new construction was done using the LEED checklist as a guide ([3] and [4]). Based on official counts by year-end 2005, more than 2800 projects had registered to achieve various levels of LEED certification and 323 had been certified, for a total of 350 million square feet [5]. An unofficial count, recently sent to the Emerging Green Builders Email list, said that USGBC has just certified its 400th building for a total of over 390 million square feet, with 3000 more projects registered to achieve various levels of LEED certification.

“LEED has no where to go but up!” [6]

LEED-NC has gone through three iterations and serves as a basis for a range of other rating systems such as LEED for Existing Buildings (LEED-EB), and Commercial Interiors (LEED-CI). This green building rating system has been so appealing that the Governor of California, following New York and Pennsylvania, and 30 municipalities and counties all over the nation, has mandated all new and renovated state buildings to acquire a LEED rating of silver or higher [7].

Industry forecasts predict that LEED will soon represent a major part of the building industry activity; a dramatic change in what has traditionally been a conservative industry. This trend is transformative, where many more developers, designers and operators will adopt LEED or similar frameworks, as green building design guidelines,
leading us to believe that by affecting LEED and similar normative frameworks, we can potentially influence the building industry in a significant way. Poised at the threshold of this transformation, we have the critical task of examining its direction. Providing objective assessment along the way through systematic research can effectively guide these effort towards where it is truly green, for the occupants.

1.1 Statement of the problem

Although the LEED green building rating system has been received with open arms, disagreements about the extent to which LEED has actually reduced the negative impact of buildings on the occupants and the environment remain unresolved (see for example:[3], [8], and [9]). Some of the main questions being asked are: Do LEED-rated green buildings use less energy and improve occupants’ well-being and productivity? If they do, how much? And if they don’t, why not? As mentioned, I particularly value the great potential for improving occupant well-being and productivity in green buildings. This is where I will focus my inquiry.

Since the mid 60’s, Post-occupancy Evaluations (POE) have been used to evaluate the degree to which buildings enable users to fulfill their intended goals [10]. A comprehensive POE method, one that includes assessments of occupant well-being and productivity, completes the feedback loop that is essential for the future development of green buildings. But systematic POEs are not common in the building industry. And apart from commissioning (fine-tuning building systems after construction), there is no mandatory POE mechanism in LEED.

Given the fact that a universally accepted measure for occupant well-being and productivity is hard to find [11], it has been difficult to assess the impact of green
buildings on the occupants. It is for this reason that, so far, the few POEs that have been
done have focused on more easily quantifiable criteria, such as energy use. Or they have
relied mainly on physical measurements of IEQ factors that at best give a second-hand
assessment of how the building is affecting the occupants. Little is known about the
conditions of the occupants in LEED-rated green buildings.

1.2 Objective

The broad purpose of this study is to help provide healthier and more productive
environments for occupants. The LEED green building rating system presents an
effective and an industry-level outreaching channel to do so. My contribution on this path
is to present a clear and useful assessment of occupant well-being and productivity in
LEED-rated green buildings, one that lends results useful not just for one building, or a
group of green buildings, but for all buildings.

There are two challenges here. First, given the fact that IEQ is intermediary to
occupant well-being and productivity, physical measurements of IEQ by themselves have
proved insufficient in helping us get a clear or direct assessment of occupants’ conditions.
Second, since independent POEs of individual buildings tend to use different methods,
and be done sporadically, common measures of occupant well-being and productivity
have rarely been used to assess buildings in comparison to each other. My objective is to
overcome both these challenges, by presenting a measure for occupant well-being and
productivity, using this measure in an assessment method, and applying the method to
provide a clear and useful assessment of occupant well-being and productivity in LEED-
rated green buildings.
1.3 **Significance**

Green building guidelines, standards, and rating systems, with their potential for transforming the building industry, present a channel to encourage design of healthier and more comfortable buildings at large. Green building is still a developing field of knowledge and expertise, and there is great need for research that provides objective assessments of current efforts and proposes corrections for future ones. This thesis picks a piece of this research and asks how are green buildings affecting occupants? I will point to tried-and-true or shortcomings of design and operation practices currently in use for improving IEQ in LEED-rated green buildings. The results can inform best practices for a larger pool of buildings, and guide the future of green building standards, guidelines and rating systems.
2 Background

In this section I will introduce three major components of this research: Indoor Environmental Quality (IEQ), Post Occupancy Evaluation (POE), and LEED-rated green buildings. In addition to introducing these three components, I will lay the foundation for the methods and results chapters by introducing appropriate measures for occupant well-being and productivity, and how these measures can be used to assess occupant well-being and productivity in LEED-rated green buildings.

2.1 Indoor environmental quality

Indoor Environment Quality (IEQ) broadly refers to a multitude of physical and psychological factors that influence occupants in a space. The physical IEQ factors can be largely grouped into four major categories: thermal environment, air quality, lighting, and acoustics. Building design and operation strategies directly affect these IEQ factors, which in turn can influence occupant well-being and productivity. This section will review these relationships.

This review is organized in five parts: summarizing the effects of each of the four major IEQ factors, and then looking at their combined effect (which I will refer to as multi-sensory [13]). At the end of each section I will describe the practical implications of this knowledge for buildings in general, and for green buildings in particular.

In addition to describing main physical IEQ factors and their effects on occupant well-being and productivity, I would like to bring out two major points in this introduction. The first point is that occupant’s self-assessment is the closest measure for well-being and productivity. The reliability of self-assessments is often questioned in
light of confounding factors influencing people’s assessments. These confounding factors might include morale, job satisfaction, proximity of other occupants, size of working groups, etc. The question of reliability surfaces in real world research on IEQ, away from the laboratory, where it is difficult to control for confounding factors. And in many cases these factors may be the dominant determinants of people’s evaluation of IEQ. Measurement and assessment of the confounding effects of these factors would require exhaustive research outside the scope of this effort. I will focus on physical IEQ factors, acknowledging that it becomes less difficult to control for confounding factors when using a large sample in our study.

Second, I would like to emphasize the positive effect of occupants’ personal control over their indoor environment in improving their well-being and productivity. Recent building science research, especially in thermal comfort, marks a shift away from comfort engineering, towards providing adaptive opportunity for the occupants to seek comfort based on their personal preference. Until recently, mainstream building science research was embedded in a certain obsession with man-made and hard-controlled indoor environments. Some would say that this engineering imperative has fed itself by requiring indoor environmental conditions through codes and standards that could only be provided through the use of engineered systems [15]. This man-made and hard-controlled indoor environment approach has been challenged by those who view people not as passive recipients of the environment, but as active participants who interact with it. They underscore psychological/behavioral/physiological adaptation as natural strategies to cope with less-than-perfect environmental conditions [16]. Apart from physiological adaptation, behavioral and psychological adaptations go hand in hand with
the real or perceived ability to control one’s environment. As we will see in the forthcoming chapter, personal control makes for more satisfied occupants but also more sustainable buildings. Personal control is explored in detail throughout this section and is one of the main threads that run through my assessment of occupant well-being and productivity in green buildings.

I have been using “well-being and productivity” as an all-encompassing reference to occupants’ health, comfort, satisfaction and productivity. Before reviewing the IEQ literature regarding occupant well-being and productivity, I would like to bound my discussion of health and productivity as relevant to my research.

### 2.1.1 Health and productivity

My reference to health in this literature review is limited to Sick Building Syndrome (SBS). SBS refers to acute building-related health symptoms experienced by building occupants including irritation of eyes, nose, and skin, headache, fatigue, and difficulty breathing [17]. I will not be addressing Building Related Symptoms (BRS) or Illnesses (BRI), used to describe specific building-related health effects with known causes and objective clinical findings such as Legionnaires disease, hypersensitivity pneumonitis, lung cancer from radon exposure, etc. [18]. Nor will I be addressing other health effects associated with the indoor environment such as symptoms of allergies and asthma, respiratory illnesses, and toxic and systemic effects with known causes, e.g. carbon monoxide poisoning.

SBS is the most insidious source of dissatisfaction among office building occupants, since its causes are often hard to pin down. It is also elusive because other than in the extreme case, it does not lead to medical diagnosis or hospitalization. It might,
however, increase absenteeism - the measure often used to track the effects of SBS on productivity. Yet measuring absenteeism alone gives only an indirect measure of productivity. In contrast self-reported productivity has been identified as one of the valid methods in measuring productivity in the workplace [19].

While it seems natural that people would perform better in quality indoor environments, direct quantitative increases in health and productivity due to better IEQ has been a matter of great uncertainty ([19], [21], [22], and [23]). A groundbreaking study done by Fisk [24] quantified health and productivity gains from better IEQ in US dollars. Even in this study, due to a lack of adequate measures for productivity effects of SBS (apart from absenteeism), and for knowledge workers’ productivity, his numbers are presented as cautious estimates. Most studies quantify improved health and productivity impacts in relative terms, comparing before and after measurement results.

### 2.1.2 Thermal environment

Human perception of thermal sensation is a combination of environmental factors: dry bulb temperature, radiant temperature, humidity, air movement, and personal factors: the person’s metabolic rate and clothing [25]. Temperature complaints are the most common kind of service request from occupants in commercial buildings. Federspiel [26] found that thermal sensation complaints in buildings account for 75% of all environmental complaints from occupants.

Temperature has been associated closely with SBS symptoms, but this association is not equally evident in naturally ventilated as in air-conditioned buildings [27]. Zweers et al. [28] found that the prevalence of SBS symptoms is higher in air-conditioned buildings than naturally or mechanically ventilated buildings. Mendell [29] reviewed
findings of 32 studies of 37 variables potentially related to office worker health symptoms, and has found that relatively strong studies (in terms of method and rigor of analysis) associated high temperature and low relative humidity with increased SBS symptoms. People in air-conditioned spaces often find air too dry and considerably less acceptable as temperature climbs above 22 °C, which increase SBS [30]. Thermal conditions will also affect the occurrence and strength of SBS symptoms due to presence of Volatile Organic Compounds (VOC) in the air [31].

Seppanen et al. [27] have analyzed the literature relating productivity with temperature and found the results relatively consistent. The results of multiple studies show an average relationship of 2% decrement in work performance per °C when temperature is above 25 °C. They found less data on the relationship between performance and temperature in low temperatures.

### 2.1.3 Comfort and the adaptive opportunity

Thermal comfort is described as “that condition of mind, which expresses satisfaction with the thermal environment”[32]. ASHRAE Standard 55 -1992: Thermal Environmental Conditions for Human Occupancy specifies acceptable thermal environments primarily for air-conditioned buildings [33]. The American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) has reviewed and revised Standard 55 with the latest revision published in 2004 [32]. Standard 55-1992 is based on a model of thermal comfort derived from laboratory experiments, that posits the subjective thermal response as a function of the physics of the body’s thermal balance with its immediate environment, as mediated by the autonomic physiological responses. This model can then be used to determine the acceptable ranges of environmental
variables. An acceptable thermal environment in Standard 55 is defined as that in which 80% of the occupants express satisfaction with the thermal environment.

While originally intended to put forth guidelines for mechanically controlled buildings, in its broad application, Standard 55 has historically limited design of naturally ventilated and mixed mode buildings that may allow more variable temperature and humidity conditions that track the outdoor climate [16]. To remedy this, the latest revision of this standard, ASHRAE Standard 55-2004 [32], contains an additional thermal comfort model applicable to naturally ventilated buildings based on the theory of adaptive opportunity.

The history of the shift in Standard 55 deserves a more comprehensive description. The concept of adaptation to indoor environment was introduced as early as 1936, and formed the basis of a later comparison of field studies of thermal comfort responses in naturally ventilated and mechanically controlled buildings to account for discrepancies in thermal satisfaction ([34],[35]). Adaptation theory suggests that, when given the opportunity to change their environment, people have the ability to adapt over a wider range of thermal environments, accepting thresholds that can be quite different from what the earlier Standard 55-1992 delineated. Brager and de Dear [36] analyzed a database of 21,000 respondents from thermal comfort field studies and found that occupants in naturally ventilated buildings tolerated, in fact preferred, a wider range of indoor temperature that followed the seasonal cycles of the outdoors temperature. They found that the thermal heat balance model could accurately predict people’s patterns of thermal preferences in air-conditioned buildings but not in naturally ventilated ones.
Similarly, Nicol and Humphreys [37] maintain that the rate of change of comfort temperature is characterized by the running temperature of the indoor environment. If the indoor environment is directly affected by the outdoor temperature (i.e. in naturally ventilated buildings) this rate of change is greater than in steady conditions of an air-conditioned building. They believe that the more adaptive opportunities the occupants have (for example, the ability to put on or take off layers of clothing, open and close windows, adjust diffusers, etc.) the more relaxed their thermal environment can be. They are in agreement with Brager and de Dear in the possibility of improving thermal satisfaction by providing personal control over the environment.

The revision of ASHRAE thermal comfort standard in 2004 marked a paradigm shift away from reliance on man-made and hard-controlled indoor environments, to acknowledging other ways of providing comfortable conditions. This paradigm shift is important especially for green buildings where practical implications of reducing reliance on air-conditioning could lead to less energy use.

Today, thermal comfort research is moving towards “personalized air” [38] and embracing the dynamic and individual nature of comfort. Researchers are questioning the neutral state as the ideal condition to keep occupants in, and are looking at ways of providing delight in thermal conditions ([39], and [40]). Brager et al. [41] have crystallized the concept of adaptive opportunity in having personal control over one’s environment, and its effects on the occupants’ ability to accept broader ranges of temperatures. In practice, this philosophy can also lead to providing personal control through air-conditioning with Underfloor Air Distribution (UFAD) systems (with adjustable diffusers for individuals or small groups of users), in addition to giving
occupants control over operable windows, or employing both strategies in certain climates.

### 2.1.4 Air quality

Indoor Air Quality (IAQ) can be characterized by the concentrations of chemicals, particles, and biological agents in the air and on surfaces immediately surrounding the air in a space. It can also be characterized by the way it is perceived by occupants, although these perceptions of air quality may not relate directly to the potential health effects resulting from exposure to air. ASHRAE Standard 62.1: Ventilation for Acceptable Indoor Air Quality, defines acceptable indoor air quality as air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities, and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction [42]. The standard requirements include certain design features intended to avoid or mitigate potential sources of indoor air pollutants, including but not limited to: carbon dioxide (CO2), carbon monoxide (CO), nitrogen oxides (NOx), VOCs, radon, ozone, vapor, particles, and Environmental Tobacco Smoke (ETS). Indoor air pollutants have direct impact on human physiology, although there is disagreement about safe exposure levels.

For many years, occupants were believed to be the only sources of pollution in the indoor environment. Recently however, the building and especially building materials have been acknowledged as major sources of pollution. These building materials can include, flooring, carpet, floor varnish, wall paint, sealants, and “fleecy” finishes for cubicle walls and furniture.
Exposure to VOCs at low levels in air results in SBS, their effect becomes severe at higher concentrations and in higher temperatures (0 mg/m³ and 10 mg/m³ of a mixture of 22 volatile organic compounds in 18, 22 and 26 °C) [43]. In a comparative study of two similar but independent office buildings in Denmark and Sweden, Wargocki et al. [44] have shown that introducing or removing the same pollution source, resulted in similar and repeatable effects on subjective assessments of perceived air quality, intensity of SBS, and productivity in both buildings. They showed that removing the pollution source improved perceived air quality, decreased perceived dryness of air and the severity of headaches, and increased typing performance (a measure of productivity). It is thought that complaints about dryness of air are more common in new air-conditioned buildings, while perceived air quality complaints (referring to odor and air being stuffy or stale) are more common in old buildings with poor outdoor air supply [45].

Aside from pollution concentration and outdoor air supply, perceived air quality is highly influenced by thermal sensations and indoor humidity. Fang et al. followed a trajectory of studies on concurrent assessments of air quality, air temperature, and humidity and posited that temperature and humidity have a strong and significant impact on the perception of air quality [46]. In earlier studies, Berglund and Cain [47] had found that for a subjective evaluation of indoor air quality, the concentration of pollutants in the air may, in some instances, prove secondary to the influence of temperature and humidity.

In a review by Seppanen et al. [48], 21 of 27 assessments meeting study quality criteria found low ventilation rates to be significantly associated with an increase in at least one SBS symptom. Wyon has shown the relationship between removing common
indoor sources of air pollution (such as floor-coverings, used supply air filters, and personal computers), or increasing the rate of outdoor clean air supply, with improved office work performance [49]. He states that it might be more cost effective to reduce source pollutants than increase ventilation rates in the building.

In general, air-conditioning, carpets, ventilation rates, the type of ventilation system, type or existence of humidifier, rate of outside air supply, the chemical and microbiological pollution in the indoor air and on indoor surfaces, indoor temperature, and indoor humidity influence perception of indoor air quality and SBS symptoms [29].

Potential health and productivity gains from improved IAQ in buildings has led to informed choices about low VOC materials, in addition to imposing limitations on indoor and outdoor air contaminants, such as ETS and other potentially hazardous chemical and particulate pollutants. Designers tend to use materials that off-gas less and introduce fewer pollutants to the indoor environment, which lead to reduced use of “fleecy” materials such as carpets and furnishings. They are also responding to an improved understanding about the link between increased outside air ventilation rates and reduced SBS complaints and improved productivity. Specifically in green buildings, designers and engineers tend to exceed normative standard limits (such as ASHRAE 62.1), which specify minimum levels.

2.1.5 Lighting

Lighting (including luminance, contrast between lit surfaces, and the spectrum of light) can affect occupants’ health and productivity both directly, because work performance depends on vision, and indirectly, because lighting may direct attention, or influence arousal or motivation [50]. But the potential to improve health and performance
by changing the electric lighting normally experienced within buildings is a different one. Fisk and Rosenfeld [51], in their literature review of the linkages between lighting and productivity, conclude that the potential to significantly improve the performance of office workers by improving the electric lighting quality, except in the case of visually demanding work, is not substantially supported by evidence. However, they agree that personal control over lighting improves occupant satisfaction with lighting and their satisfaction with the suitability of lighting to their work. In this context, lighting might be a factor (among others) that Oseland [19] refers to, when he says that “[the difficulty] in determining the impact of the indoor environment upon productivity, indicates that people are not aware of environmental effects as long as conditions are not too uncomfortable (painful).”

On the other hand, in recent years there have been many efforts to understand the effects of natural lighting on health and productivity, mainly due to the effects of Biophilia. Heschong et al. [52] found that horizontal daylight illumination levels have an inconsistent relationship to productivity, significant in only two out of eight productivity metrics tested in a call center study. Higher levels of daylight illumination were found positive for attention span and short-term memory, and negative for daily average speed of handling calls. These inconsistencies in increase and decrease of productivity with natural light also bring Oseland’s remark to mind. The natural log of daylight illumination levels was found to have the best mathematical fit to the data, implying more sensitivity to changes at lower levels of illumination and progressively less sensitivity at higher levels.
Another important consequence of daylight availability is views associated with seeing through a window. Having a better view out of a window, gauged primarily by the size of the view and secondarily by greater vegetation content, was most consistently associated with better worker performance in six out of eight outcomes considered in the Heschong call center study [52]. Workers in the call center were found to process calls 6% to 12% faster when they had the best possible view versus those with no view. In addition to call center workers, office workers were found to perform 10% to 25% better on tests of mental function and memory when they had the best possible view versus those with no view. Furthermore, they found that office workers reports of better health conditions were strongly associated with better views. Office workers with the best views were the least likely to report negative health symptoms. Reports of increased fatigue were most strongly associated with a lack of view.

The practical implications of these findings in green buildings are increased use of daylight, personal control over lighting levels, and provision of views, especially since these strategies can be coupled with energy efficient technologies and design with daylighting at the same time.

### 2.1.6 Acoustics

Within normal levels in today’s workplace, acoustic quality might have small health impacts other than inducing fatigue, but it has great impact on office worker productivity [53]. Sundstrom [54] notes that “the effects of noise on performance have been studied extensively in the laboratory, with complicated results” and he relates this to the variety of psychological processes evoked by noise. For example, consistent loud noise may increase arousal (and briefly enhance productivity) before it leads to irritation,
whereas hearing people’s conversations could cause distraction and become disturbing from the beginning. But it seems like intelligible noise and lack of speech privacy has a particularly important effect in real life situations in today’s office environments [55]. Jensen et al. [56], in their analysis of 23,450 survey respondents from 142 buildings in the CBE Occupant IEQ Survey database, showed that acoustic quality consistently receives the lowest average satisfaction score among all nine IEQ categories measured in the survey. He found that people are significantly more dissatisfied with speech privacy than noise level.

In spite of these findings, in most cases acoustics does not receive the level of design attention as other IEQ factors [57]. Perhaps this is because improving acoustic conditions (within the limits of today’s office environments) have no demonstrable health impacts. But as we see, it has been shown to have great implications on occupant productivity. This is important in green buildings especially, where open plan designs are pervasive for their numerous benefits (space efficiency, increasing daylight and ventilation penetration, team work, and equality of office space allocation). In order not to impede productivity, it becomes important to pay specific attention to noise and privacy preferences of the occupants in design of various office types and activities.

2.1.7 Multi-sensory approach to IEQ

There is growing concern about the limited applicability of laboratory studies that look at individual IEQ factors, to real-life environments where occupants are being affected by and are responding to multiple IEQ factors at the same time. The recent rise of multi-sensory field studies is in part a response to inconsistencies between outcomes of field and laboratory studies [13].
In order to quantify effects of each single IEQ factor on people, the effects of other IEQ factors have to be controlled on subjects in a laboratory environment. This method has led to what today might be considered a fragmented approach to IEQ, trying to get air quality, thermal comfort, lighting and acoustic conditions right as individual factors, but having no clear understanding of how these interact in the field. Except for air quality and thermal comfort, which are often studied together, our common understanding of interactions between IEQ factors is limited.

Each IEQ factor exerts a certain amount of influence on the occupants’ overall satisfaction and productivity. There are also trade-offs or weights associated with each of the individual IEQ factors [58]. Annoyance with one might not only decrease satisfaction overall, but also increase sensitivity to other factors. Recent research has focused on approaching IEQ from a more integrative approach that is multi-sensory. The goal is to find the balance of different environmental factors in order to achieve overall acceptance of the indoor environment.

Even where a building meets standards for individual IEQ factors, potential interactions among these factors and their combined effect on building occupants, can result in the overall quality of the indoor environment being unacceptable. For example, an odor that may be acceptable when thermal conditions are cool and dry, may be annoying or even sickening when thermal conditions are warm and humid. Or in the case of indoor air quality, particles that may not be annoying when humidity is at normal levels may be irritating to the eyes or upper respiratory tract when humidity is very low [59].
On the other hand, solutions to control one IEQ factor may result in problems in another variable. An illustrative case is that of acoustic conditions, where “fleecy” materials are often chosen for interiors and for mechanical ventilation system linings. Surfaces that have no sound absorption capacity can result in very uncomfortable and even dysfunctional indoor acoustic environments. This conflicts with the ideal indoor air quality solution of hard, durable, non-porous surface materials that reduce emissions and “sink effects” leading to secondary emissions [60]. Solutions to the acoustic problem must consider the air quality implications, and the air quality solutions must consider the acoustic implications, if designs are to produce satisfied occupants. An effective design integrates all IEQ concerns into one program.

Acknowledging this fact, the ASHRAE (the leading building performance standard-making body in the US) is leading a major effort to devise guideline criteria for achieving acceptable indoor environmental quality considering the combination of IEQ factors [60]. Unfortunately, the issues involved in the design of indoor environments to simultaneously satisfy occupants in all these areas remain hard to simplify.

Individual satisfaction with different IEQ factors does not always have predictable results in shaping overall assessments of the indoor environment. Humphreys [11] has shown that satisfaction with one factor does not necessarily render occupants satisfied with overall conditions. Dissatisfaction with one environmental factor does not necessarily render one dissatisfied with overall conditions either. He has even found a small but statistically significant negative direction effect between maximum level of satisfaction with one aspect of the environment and the overall comfort. This reinforces the notion that other factors deemed important by the occupant (but not necessarily
measured by the researcher) have high implications for occupants’ overall assessment of the environment. Leaman and Bordass [20] identify one of those factors as the occupant’s perceived control over their environment. They have elsewhere introduced the term “forgiveness factor” that kicks into effect if occupants have controls over their environment and are satisfied with this control. Forgiveness would entail that if one has control over one’s environment, one might be more tolerant with other deficiencies and thus the overall assessment might be more satisfactory than the combination of satisfactions with individual factors. Currently the list of design qualities, strategies, and operation practices that kick the “forgiveness factor” into effect include: personal control, views, amount of space, proximity to other occupants, aesthetics, and responsiveness of the building operations staff. Many others can be added to this list as our understanding of the complex interaction of psycho-social and physical environmental quality factors advance.

Other advocates of personal control concede that centralized control of the indoor environment based on the assumption that occupant response will follow a normal bell-shaped curve inevitably leaves some people out, and therefore cannot satisfy all occupants. According to this model, the bulk of people have similar preferences and it is impossible to satisfy all with one single environmental condition. A historic use of this model is to define “acceptability” limits where 80% or more people would be satisfied with the indoor environment. Levin [59] has argued that this model allows for more discrimination than is acceptable. In order to satisfy a larger group of people it is essential to delegate some degree of people’s IEQ controls to themselves.
One of the implications of a multi-sensory approach to indoor environmental quality, especially in green buildings, is acknowledging the complex interaction of IEQ factors in real-life environments, and trying not to undermine the positive effects of some design strategies with negative outcome of others that might have been given less diligence in design. In many cases designers might have to balance the results of multiple strategies (i.e. daylighting, ventilation, low-maintenance hard surfaces, and acoustic quality). Another implication would be to pay specific attention to the “forgiveness factors” in design. This highlights the importance of personal control, views, amount of space, proximity to other occupants, aesthetics, and the responsiveness of the building operations staff.

### 2.2 Post-occupancy evaluation

For more than four decades, Post-occupancy Evaluations (POE) have been used to evaluate the degree to which buildings enable users to fulfill their intended goals [10]. According to Weiss [61], evaluation research common in social programs and policy research has four key features: 1) measurement of effects (which refers to the research methodology used), 2) the effects themselves (which emphasizes the outcome of the program rather than its efficiency, honesty, or adherence to rules and standards), 3) the comparison of effects with goals (which stresses the use of explicit criteria for judging how well the program is doing), and 4) the contribution to subsequent decision-making and the improvement of future programs.

In this definition of POE, what might have been regarded as a loosely defined ex-ante study becomes a well-defined research problem with wider effects than the project at hand. In other words, POEs are part of a complete “feed-back loop” [61]. Applying
evaluation research to architecture brings it down from the ivory tower of magazine covers to where it can be treated as a product designed to fit a certain purpose and program.

This does not reduce architecture to the tangible qualities we can measure, but emphasizes its use value. In fact, POEs are known to differ from other forms of evaluation in that they focus on the requirements of buildings occupants, including health, safety, security, functionality and efficiency, psychological comfort, and aesthetic quality. Ideally, the information gained from the evaluation study is captured in lessons-learned programs and used in programming and design processes for new facilities to build on successes and avoid repeating mistakes [63]. Most researchers agree that the more targeted such evaluations are (good research design, clear objectives, variables, target group, and the narrower the scope of study), the more useful the results are in the feedback loop.

Originally, early POEs focused on assessing human response to buildings and other designed spaces using methods such as questionnaires, interviews, participant observations, and physical assessment. But due to the exhaustive format of these evaluations and their cost, these human interactive evaluations gave way to instrumental measurements of quantifiable aspects of architecture such as cost, energy use, temperature, concentration of gas, etc. While these quantifiable aspects remain important, they do not give a clear assessment of occupant conditions in buildings. Recent advances in E-communication now make it easy and inexpensive conduct occupant surveys via the Internet through web-based surveys. Occupant surveys are gaining new momentum.
Meanwhile, wireless technologies and smart devices make it easier to perform physical measurements.

A comprehensive but targeted POE is essential for improvements in design and operation of buildings. Leaman and Bordass led PROBE, a successful and comprehensive POE program in England during the 90s. PROBE relied on three evaluation components: Energy Assessment and Reporting Methodology (EARM), that comprehensively covers building energy performance; Building Use Studies (BUS), occupant questionnaire that covers occupant comfort, health and productivity; and an air pressure test [64]. Their most significant contribution to POE studies might be summarized in their investigations of occupant satisfaction and productivity in relation to personal control, facility manager responsiveness, building depth, and size of working groups. These aspects are what they call the “killer variables” of productivity in workplace [19].

In contrast to physical measurements of IEQ variables, occupant surveys give a first-hand account of how the building is affecting the occupants [65]. But they present specific challenges: respondents’ subjective assessments of their environment might be affected by non-building-related factors. This becomes less problematic as the sample size of the study becomes larger.

### 2.3 LEED green building rating system

Although hard to point to an exact date when the contemporary green building coalition came together, we can start with the inception of the US Green Building Council (USGBC) in 1993. At the time, USGBC membership was no more than a couple of dozen, comprising of private corporations, professional institutions, and state and federal agencies [66]. USGBC launched Leadership in Energy and Environmental Design
(LEED) Version 1.0 as a pilot green building rating program in 1998. This was not the first of its kind, and as precedents we can name UK’s BREEAM system (launched in 1990), BEPAC the Canadian model (begun in 1994), and the Hong Kong BEAM model (still in pilot format). LEED is a feature-oriented rating system where credits are earned for satisfying specified green building criteria. LEED for New Construction (LEED-NC) 2.0 and 2.1 (released in 2002) are consecutive revisions of the pilot program.

LEED-NC version 2.1’s 69 credit points are structured in five categories: sustainable sites (14), water efficiency (5), energy & atmosphere (17), materials & resources (13), and indoor environmental quality (15). There are 5 extra credit points for Innovation & Design Process. The document sets forth prerequisites and credits in each category that in total will earn the building a certified (26-32 total points), silver (33-38 total points), gold (39-51 total points) or platinum (52-69 total points) rating based on the total number of credit points achieved. LEED-NC serves as a basis for a plethora of other ratings systems or what are referred to as “products”, such as LEED for Existing Buildings (LEED-EB), LEED for Commercial Interiors (LEED-CI), LEED for Neighborhood Development (LEED-ND), LEED for Homes, and LEED for Core and Shell (LEED-CS). The three most relevant products to improving IEQ in commercial buildings are LEED-NC 2.1 [67], LEED-EB 2.0 [68], and LEED-CI 2.0 [12].

As of year-end 2005, 323 projects had been rated under LEED-NC, and more than 2,800 projects were registered to achieve various levels of LEED certification. This makes for a total of 350 million square feet so far. Forecasting to 2007, about 1661 new LEED project registrations with an average area of 78,000 square feet will make up for another 130 million square feet [5]. That is about 20% of the commercial and institutional
building construction market, a major part of the building industry activity [3]. This trend
is transformative, where many more developers, designers and operators will adopt
LEED or similar frameworks, as green building design guidelines. In addition to LEED,
there are other emerging green building rating systems such as the Green Building
Initiative’s GreenGlobes [67] that aim to address smaller buildings with looser standards
for “green-ness”.

These efforts lead us to believe that by influencing LEED and similar normative
green building frameworks, we can potentially influence the building industry in a
significant way. My piece of this venture will be improving occupant well-being and
productivity and its physical antecedent, IEQ. For the purposes of this project, I will limit
my discussion to an evaluation of the LEED green building rating system with special
focus on IEQ.

2.3.1 IEQ in LEED

IEQ makes up 22% of total LEED-NC points (Figure 2.1), 26% in LEED-EB
(Figure 2.2), and 30% in LEED-CI (Figure 2.3). The main reason why this percentage
differs is that the number of interventions on other LEED categories such as sustainable
sites will inevitably be limited in an existing building or a commercial interior, and
consequently the number of credit points allocated to each category is different. The IEQ
prerequisites in the LEED-NC and LEED-CI address indoor air quality factors of the
indoor environment: “Environmental Tobacco Smoke control” and “minimum IAQ
performance” (compliance with ASHRAE standard 62.1). In addition to “Environmental
Tobacco Smoke (ETS) Control” the LEED-EB product specifies: “Outside Air
Introduction and Exhaust Systems”, “Polychlorinated Biphenyl (PCB) Removal”, and “Asbestos Removal or Encapsulation”.

The credit points in the IEQ category cover air quality, controllability, thermal comfort, daylight, and views. Comparing this list with the main IEQ factors I covered in section 2.1, it appears that acoustics is left out of the main components of IEQ in LEED rating system products. Considering that within the limits of today’s indoor environments, acoustics has a limited direct health impact, perhaps this is understandable. Yet, given the effects of acoustics on occupants’ productivity, and the aim to improve occupant well-being and productivity in green buildings, this will be a topic that I will explore further in forthcoming sections.

Controllability of light, ventilation and temperature has special importance in all three LEED products in question. LEED-NC 2.1 allocates two credit points for controllability over lighting, temperature, and airflow of the environment separately in perimeter and non-perimeter zones. LEED-EB 2.0 and CI 2.0 separate control over lighting, and control over temperature and air flow.
### Indoor Environmental Quality

<table>
<thead>
<tr>
<th>Prereq 1</th>
<th>Minimum IAQ Performance</th>
<th>Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prereq 2</td>
<td>Environmental Tobacco Smoke (ETS) Control</td>
<td>Required</td>
</tr>
<tr>
<td>Credit 1</td>
<td>Carbon Dioxide (CO₂) Monitoring</td>
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</tr>
<tr>
<td>Credit 2</td>
<td>Ventilation Effectiveness</td>
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<tr>
<td>Credit 3.1</td>
<td>Construction IAQ Management Plan, During Construction</td>
<td>1</td>
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<tr>
<td>Credit 3.2</td>
<td>Construction IAQ Management Plan, Before Occupancy</td>
<td>1</td>
</tr>
<tr>
<td>Credit 4.1</td>
<td>Low-Emitting Materials, Adhesives &amp; Sealants</td>
<td>1</td>
</tr>
<tr>
<td>Credit 4.2</td>
<td>Low-Emitting Materials, Paints</td>
<td>1</td>
</tr>
<tr>
<td>Credit 4.3</td>
<td>Low-Emitting Materials, Carpet</td>
<td>1</td>
</tr>
<tr>
<td>Credit 4.4</td>
<td>Low-Emitting Materials, Composite Wood &amp; Agrifiber</td>
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</tr>
<tr>
<td>Credit 5</td>
<td>Indoor Chemical &amp; Pollutant Source Control</td>
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<tr>
<td>Credit 6.1</td>
<td>Controllability of Systems, Perimeter</td>
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</tr>
<tr>
<td>Credit 6.2</td>
<td>Controllability of Systems, Non-Perimeter</td>
<td>1</td>
</tr>
<tr>
<td>Credit 7.1</td>
<td>Thermal Comfort, Comply with ASHRAE 55-1992</td>
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<tr>
<td>Credit 7.2</td>
<td>Thermal Comfort, Permanent Monitoring System</td>
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<tr>
<td>Credit 8.1</td>
<td>Daylight &amp; Views, Daylight 75% of Spaces</td>
<td>1</td>
</tr>
<tr>
<td>Credit 8.2</td>
<td>Daylight &amp; Views, Views for 90% of Spaces</td>
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Figure 2.1 - LEED-NC 2.1 checklist for indoor environmental quality

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<th>Minimum IAQ Performance</th>
<th>Required</th>
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<td>Environmental Tobacco Smoke (ETS) Control</td>
<td>Required</td>
</tr>
<tr>
<td>Credit 1</td>
<td>Outside Air Delivery Monitoring</td>
<td>1</td>
</tr>
<tr>
<td>Credit 2</td>
<td>Increased Ventilation</td>
<td>1</td>
</tr>
<tr>
<td>Credit 3.1</td>
<td>Construction IAQ Management Plan, During Construction</td>
<td>1</td>
</tr>
<tr>
<td>Credit 3.2</td>
<td>Construction IAQ Management Plan, Before Occupancy</td>
<td>1</td>
</tr>
<tr>
<td>Credit 4.1</td>
<td>Low-Emitting Materials, Adhesives and Sealants</td>
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<tr>
<td>Credit 4.2</td>
<td>Low-Emitting Materials, Paints and Coatings</td>
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<td>Credit 4.3</td>
<td>Low-Emitting Materials, Carpet Systems</td>
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</tr>
<tr>
<td>Credit 4.4</td>
<td>Low-Emitting Materials, Composite Wood and Laminate Adhesives</td>
<td>1</td>
</tr>
<tr>
<td>Credit 4.5</td>
<td>Low-Emitting Materials, Systems Furniture and Seating</td>
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</tr>
<tr>
<td>Credit 5</td>
<td>Indoor Chemical and Pollutant Source Control</td>
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</tr>
<tr>
<td>Credit 6.1</td>
<td>Controllability of Systems, Lighting</td>
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</tr>
<tr>
<td>Credit 6.2</td>
<td>Controllability of Systems, Temperature and Ventilation</td>
<td>1</td>
</tr>
<tr>
<td>Credit 7.1</td>
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</tr>
<tr>
<td>Credit 7.2</td>
<td>Thermal Comfort - Monitoring</td>
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</tr>
<tr>
<td>Credit 8.1</td>
<td>Daylight &amp; Views - Daylight 75% of Spaces</td>
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<tr>
<td>Credit 8.2</td>
<td>Daylight &amp; Views - Daylight 90% of Spaces</td>
<td>1</td>
</tr>
<tr>
<td>Credit 8.3</td>
<td>Daylight &amp; Views - Views for 90% of Seated Spaces</td>
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Figure 2.2 - LEED-CI 2.0 checklist for indoor environmental quality
Indoor Environmental Quality

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<th>Outside Air Introduction &amp; Exhaust Systems</th>
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<td>Prereq 2</td>
<td>Environmental Tobacco Smoke (ETS) Control</td>
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</tr>
<tr>
<td>Prereq 3</td>
<td>Asbestos Removal or Encapsulation</td>
<td>Required</td>
</tr>
<tr>
<td>Prereq 4</td>
<td>PCB Removal</td>
<td>Required</td>
</tr>
<tr>
<td>Credit 1</td>
<td>Outside Air Delivery Monitoring</td>
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<td>Credit 3</td>
<td>Construction IAQ Management Plan</td>
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<tr>
<td>Credit 4.1</td>
<td>Documenting Productivity Impacts - Absenteeism &amp; Healthcare Cost Impacts</td>
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<td>Documenting Productivity Impacts - Other Impacts</td>
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<td>Credit 5.2</td>
<td>Indoor Chemical &amp; Pollutant Source Control - High Volume Copy/Print/Fax Room</td>
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<tr>
<td>Credit 6.1</td>
<td>Controllability of Systems - Lighting</td>
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</tr>
<tr>
<td>Credit 6.2</td>
<td>Controllability of Systems - Temperature &amp; Ventilation</td>
<td>1</td>
</tr>
<tr>
<td>Credit 7.1</td>
<td>Thermal Comfort - Compliance</td>
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<td>Thermal Comfort - Permanent Monitoring System</td>
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<td>Daylight &amp; Views - Daylight for 50% of Spaces</td>
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<td>Daylight &amp; Views - Views for 40% of Spaces</td>
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<td>Credit 9</td>
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<td>Green Cleaning - Low Environmental Impact Cleaning Policy</td>
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<td>Green Cleaning - Low Environmental Impact Pest Management Policy</td>
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<tr>
<td>Credit 10.6</td>
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</tr>
</tbody>
</table>

Possible Points 22

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Figure 2.3 - LEED-EB 2.0 checklist for indoor environmental quality

### 2.3.2 Critique of LEED

While LEED has done well in terms of bringing green buildings into the spotlight by giving a formal definition to green buildings, and has also done fairly well in the market (due to its simple and playful structure, its appeal to the market, and its branded metric), all agree that as a work in progress it still has a few shortcomings. LEED in and of itself does not guarantee a green building [70], and is not a comprehensive tool for environmental impact assessment [71]. We should note that Life Cycle Assessment was not a priority goal in earlier versions of LEED. But the more LEED is going mainstream and is taken seriously in the building industry, the more developers, designers, and engineers would like to make sure that the outcome will live up to the high standards that green buildings are held to.

One can point to the fact that the weightings of different LEED categories (Sustainable sites, Water efficiency, Energy & atmosphere, Materials & resources, Indoor...
environmental quality, and Innovation & design), as signified by the proportion of the total points allocated to each category are not well thought out. And within each of those categories, the allocation of credit points sometimes seems arbitrary. For example, why are there five credit points allocated to low emitting materials, and only two allocated to controllability in LEED-NC 2.1?

Among the first 38 LEED-NC rated buildings, the top point-getter was ID 2 “LEED Accredited Professional” (38 out of 38 projects got it), followed by MR 5.1 “Local/Regional Materials, 20% Manufactured Locally” (38 out of 38 projects got it), and EQ 4.3 “Low-Emitting Materials, Carpet” (35 out of 38 projects got it). Other credit points in the top point-getters in the LEED IEQ category are EQ 4.1 “Low-Emitting Materials, Adhesives & Sealants” (33 of 38), EQ 4.2 “Low-Emitting Materials, Paints” (30 of 38), and EQ 8.2 “Daylight & Views: Views for 90% of Spaces” that requires achieving a direct line of sight to vision glazing for building occupants in 90% of all regularly occupied spaces (30 of 38).

The least sought after credit was EA 1.5 “Optimize energy performance by 60%” (1 of 38) and MR 3.2 “Resource reuse: Specify 10%” (1 of 38) And within this list of least sought after IEQ credits we find EQ 6.2 “Controllability of Systems, Non-Perimeter” that requires providing controls for each individual for airflow, temperature and lighting for at least 50% of the occupants in non-perimeter, regularly occupied areas (7 of 38) [66].

This pattern is of concern since the list of top point-getters does not include LEED points with the highest measurable sustainability effect. Whereas the least sought after credits are some of the most important LEED points in that respect.
This pattern of points might be due to the fact that the early crop of LEED buildings went for the low hanging fruit and the cheapest ones, such as using low-emitting materials. This pick-and-choose format means that, except for meeting the prerequisites, there is no minimum performance that we can hold buildings up to, and builders are free to give importance to certain credit points that they choose based on value, cost, practicality, or expertise. This can lead to what Schendler and Udall call “point mongering”: too much flexibility in the rating system with an emphasis on points rather than the intent behind each credit [8]. They admit: “Because you only need 26 points (of 67 possible), we’ve heard LEED consultants remark that you can ‘certify a building without getting any energy points.’” In their view, this aspect of LEED that leads to “mediocre green buildings where certification, not environmental responsibility, is the primary goal”, is broken and needs to be fixed in order to ensure that LEED buildings live up to their promise of sustainability.

The implications of the flexibility in LEED for my analysis, is that since buildings have different assortments of credit points on their score sheets, with a small sample size we cannot test the results of individual credits on IEQ. Instead, our results will be general assessments of a combination of strategies used in LEED-rated green buildings.
3 Methods and Data

This section describes and justifies the methods used in this project for data collection and analysis. In the previous chapter I touched on several key points as foundation for the methods used. First, I described the relevance of field studies as compared to laboratory studies to this research. Second, I described the importance of occupant self-assessment in measuring occupant well-being and productivity in relation to IEQ. Third, I emphasized the relevance of occupant surveys to this thesis. My objective is to assess occupant well-being and productivity in LEED-rated green buildings by asking the occupants directly about their perceptions. It is important to note that while coupling subjective surveys with physical measurements of IEQ is a powerful method, it is much more complex and time consuming. Within a given time frame (such as a student thesis), one might be able to do this kind of study in only one building, or use subjective surveys only in a large number of buildings. I chose the latter method.

Since there are no absolute singular criteria for occupant well-being and productivity, in order to assess buildings it is useful to compare them against a valid and reliable benchmark. A valid and reliable benchmark can come from a database of building POE results that is representative of the population in question.

The Center for the Built Environment (CBE) has developed a web-based occupant IEQ survey that is easy and cheap to administer widely. This method is used by designers, engineers, or building operators as part of more extensive POEs, or by large building owners such as the U.S. General Services Administration as systematic annual or bi-annual assessments of their building stock. Rather than relying on sporadic occupant complaints about the indoor environment to facilities staff, the CBE occupant
IEQ survey provides a standardized and systematic method for assessing occupant satisfaction with the indoor environment. The survey also provides a means for collecting diagnostic information to help identify problems with the indoor environment.

The CBE occupant IEQ survey is a well-fitting tool for my thesis. CBE has built a large database of standardized responses over the years, including occupants in green and not green buildings. Their large database provides a valid means for benchmarking in my analysis. The application of this method to assess IEQ in LEED-rated green buildings is one of the contributions of this thesis. In the following section I will describe the CBE occupant survey method and how it can be used to assess IEQ in green buildings.

### 3.1 CBE occupant IEQ survey

For the past several years, the Center for the Built Environment (CBE) at the University of California, Berkeley, has been administering a survey that assesses indoor environmental quality in office buildings. The survey measures occupant satisfaction and self-reported productivity in nine IEQ categories in an anonymous, invite-style web-based questionnaire [65]. Occupants in each building are invited to take the survey through an invitation Email including the URL that links to the survey. The survey takes about 10-15 minutes to complete and the link to the survey stays active usually for a period of two weeks. The survey has been conducted across seasons, but the majority of responses belong to the summer season.

The data collected by the CBE survey can be divided up into subjective and objective variables. The objective variables measured include gender, age group, type of work, office type, proximity to windows and exterior walls, and various types of control over workspace environment, such as window blinds. The subjective variables measured
include occupant satisfaction and self-reported productivity with the following nine IEQ categories: office layout, office furnishings, thermal comfort, air quality, lighting, acoustics, cleanliness and maintenance, general satisfaction with building, and general satisfaction with workspace. In satisfaction questions the CBE survey uses a 7-point semantic differential scale with endpoints “very dissatisfied” and “very satisfied.” (Figure 3.1) Similarly the survey uses a 7-point scale with endpoints “enhances” and “interferes” for self-reported productivity questions (Figure 3.2).

**Figure 3.1 - Typical 7-point satisfaction scale in the CBE survey**

**Overall, does your thermal comfort in your workspace enhance or interfere with your ability to get your job done?**

**Figure 3.2 - Typical 7-point self-reported productivity scale in the CBE survey**

Each of the IEQ categories might include two or three satisfaction questions covering different aspects of that IEQ factor. For example in the lighting category of the survey, there are two satisfaction questions that ask about the amount of light and the visual comfort of lighting (e.g. glare, reflections, and contrast) separately.

The survey does not ask about health directly, and this has been a conscious decision. Due to liability issues involved in the workplace, CBE has found that asking about health limits the number of buildings willing to participate in the research. However, a direct relationship is implied in the satisfaction questions with health and comfort.
For the purposes of comparison, the CBE researchers assume that the scale is roughly linear, and assign ordinal values to each of the points along the scale, from -3 (very dissatisfied) to +3 (very satisfied) with 0 as the neutral midpoint. In the event that respondents indicate dissatisfaction with a survey topic, they are taken to a follow-up page containing drill-down questions about the source of the dissatisfaction, and a text box for open-ended comments. Occasionally I will refer to these possible sources of dissatisfaction in my analysis as “complaints”.

The questions asked in the survey have remained consistent over time to create a standardized database for benchmarking analysis. Using this database, we can compare a single building to the rest of the database and groups of buildings together. Benchmark is a standard or point of reference against which things may be compared or assessed, and benchmarking is to evaluate or check by comparison with a benchmark. While benchmarking has become the buzzword for the building industry [72], it is important to note that a valid and reliable benchmark must objectively represent the baseline of buildings out there; an average performance. The purpose of benchmarking is to understand what worked, what did not work, and why the numbers say what they say. A useful benchmarking analysis should describe how the results figure in the “feedback loop” informing the decision making process. While the CBE survey database is not a representative sample of all buildings, it is the largest and most reliable database available for occupant IEQ evaluations.

CBE survey average scores are the most reliable benchmark available to answer the question I am addressing in this thesis: how are green buildings affecting occupant well-being and productivity, compared to the conventional building stock? In order to
avoid making hasty conclusions, it is important to lay out the confounding variables and
their implications for the interpretations of the results. I will address this in the first part
of my data analysis in section 4.1. For now, I will describe the CBE survey database, its
analytic potential and limitations, and my quantitative method of analysis.

3.2 Data

3.2.1 CBE survey database

At the time the database was used for the analysis (September 27th 2005), the
CBE survey database contained 212 buildings and 34,369 respondents. The average
response rate within the buildings was 46%. 90% of these buildings are located in the
United States, the remainder in Canada and Finland. About 80% of the buildings are
owned or leased (and primarily occupied) by some government entity (federal, state or
local). As for building type, all are office buildings, with 22% providing some additional
functionality, such as courthouse, bank, educational, or laboratory.

3.2.2 Refined CBE survey database

The CBE survey is operating at two levels and in those two levels it can lend itself
to two different types of analyses. First, at the occupant level, it lends itself to analyses
that I will refer to as one-person/one-vote analyses. In this type of analysis each person
gets one vote regardless of which building they are located in. If we compute average
IEQ scores for the whole database, large buildings will have greater influence on the
outcome of this computation. Second, at the building level, it lends itself to analyses that
I will refer to as one-building/one-vote analyses. In this type of analysis each building
serves as the unit of measure represented by all its occupants. So we can compute average
IEQ category scores for the whole database by first computing the mean score for an IEQ
category in each building and then the building-based means are averaged across the entire database. This type of analysis gives equal weight to small and large buildings. One-person/one-vote analysis is especially relevant when talking about general patterns in the database, or to test a hypothesis (e.g. are people who have personal control over their lighting more satisfied with their workspace than those who do not have that control?) One-building/one-vote is especially relevant when we want to compare buildings, or groups of buildings with each other.

Size of a building is an important aspect in how people rate their satisfaction with building performance. In order to avoid comparing really small buildings with large buildings in the one building/one vote analysis, I have removed buildings with less than 15 respondents from the analysis.

In each building, since the survey is invite-style, it is potentially prone to response or non-response bias. Although it is difficult to know which direction the response bias might take (towards representing the building more or less satisfactory than it actually is), I have looked for trends in the data and have found no statistically significant relationship between response rate and occupant satisfaction levels. But in order to avoid extreme response bias among buildings I have removed buildings with less than 10% response rate from the analysis.

I have referred to this cleansed version of CBE database that does not include buildings with less than 15 respondents or less than 10% response rate, as the refined CBE survey database. The refined CBE survey database used in this analysis (based on data retrieved on September 27th 2005), contains 181 buildings and 33,285 respondents. The average response rate was 49%.
Starting in section 4.1, I will use the full CBE database for one-person/one-vote analysis. And starting in section 4.2, I will use the refined CBE database for one-building/one-vote analysis. The numbers in each dataset are summarized below:

<table>
<thead>
<tr>
<th></th>
<th>CBE survey database*</th>
<th>Refined CBE survey database*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of respondents</td>
<td>34,369</td>
<td>33,285</td>
</tr>
<tr>
<td>Total number of buildings</td>
<td>212</td>
<td>181</td>
</tr>
<tr>
<td>Number of LEED-rated / green buildings</td>
<td>25</td>
<td>21</td>
</tr>
<tr>
<td>Average response rate</td>
<td>46%</td>
<td>49%</td>
</tr>
</tbody>
</table>

* Numbers based on data last retrieved on September 27th 2005.

Table 3.1 - Characteristic numbers for datasets used in one-person/one-vote and one-building/one-vote analyses

### 3.3 Comparison groups

Out of the total CBE survey database population, 25 buildings are either LEED-rated or have been identified by their designer or owners as being green in both their design and operation. I call the latter self-nominated green buildings, while recognizing that many of them have also been given independent recognition as well. Out of nine self-nominated green buildings, 3 received national AIA Top 10 Green Building Awards, 2 received Environmental Design & Construction awards, 1 received Savings by Design award, 2 received local awards. But because they have not gone through the formal rating system, I do not have a systematic method to determine how green they are in comparison to each other or to LEED-rated buildings.

The refined CBE survey database includes 21 buildings that are either LEED-rated or self-nominated green buildings. I have identified self-nominated green buildings (n=6), as a distinct group in charts but grouped them with LEED-rated buildings (n=15).
in the quantitative analysis. Together this group comprises one of the main comparison
groups in this project, referred to as “LEED-rated/green buildings” (n=21) throughout
this thesis. The other main comparison group is made up of conventional (not green)
buildings referred to as “the rest of the CBE database” (n=160).

<table>
<thead>
<tr>
<th>Building identifier</th>
<th>Survey Date</th>
<th>LEED Product</th>
<th>Version</th>
<th>Level</th>
<th>Number of Invitees</th>
<th>Response Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sep-04</td>
<td>NC</td>
<td>2.1</td>
<td>gold</td>
<td>300</td>
<td>47%</td>
</tr>
<tr>
<td>2</td>
<td>Oct-03</td>
<td>NC</td>
<td>2.0</td>
<td>Silver</td>
<td>42</td>
<td>64%</td>
</tr>
<tr>
<td>3</td>
<td>Mar-04</td>
<td>NC</td>
<td>2.0</td>
<td>Gold</td>
<td>1353</td>
<td>53%</td>
</tr>
<tr>
<td>4</td>
<td>Apr-04</td>
<td>NC</td>
<td>2.0</td>
<td>Gold</td>
<td>95</td>
<td>47%</td>
</tr>
<tr>
<td>5</td>
<td>Jun-04</td>
<td>NC</td>
<td>2.0</td>
<td>pending</td>
<td>25</td>
<td>80%</td>
</tr>
<tr>
<td>6</td>
<td>Feb-05</td>
<td>NC</td>
<td>2.0</td>
<td>Certified</td>
<td>35</td>
<td>89%</td>
</tr>
<tr>
<td>7</td>
<td>Mar-05</td>
<td>NC</td>
<td>2.0</td>
<td>Silver</td>
<td>183</td>
<td>86%</td>
</tr>
<tr>
<td>8</td>
<td>Mar-05</td>
<td>NC</td>
<td>2.0</td>
<td>Platinum</td>
<td>150</td>
<td>62%</td>
</tr>
<tr>
<td>9</td>
<td>Nov-04</td>
<td>NC</td>
<td>1.0</td>
<td>Platinum</td>
<td>92</td>
<td>77%</td>
</tr>
<tr>
<td>10</td>
<td>Feb-05</td>
<td>NC</td>
<td>1.0</td>
<td>Platinum</td>
<td>27</td>
<td>63%</td>
</tr>
<tr>
<td>11</td>
<td>Mar-05</td>
<td>CI Pilot</td>
<td>pending</td>
<td></td>
<td>40</td>
<td>55%</td>
</tr>
<tr>
<td>12</td>
<td>May-05</td>
<td>CI Pilot</td>
<td>Gold</td>
<td></td>
<td>120</td>
<td>79%</td>
</tr>
<tr>
<td>13</td>
<td>Aug-05</td>
<td>CI Pilot</td>
<td>Certified</td>
<td></td>
<td>144</td>
<td>63%</td>
</tr>
<tr>
<td>14</td>
<td>Aug-04</td>
<td>EB Pilot</td>
<td>Gold</td>
<td></td>
<td>655</td>
<td>53%</td>
</tr>
<tr>
<td>15</td>
<td>Aug-05</td>
<td>NC</td>
<td>2.1</td>
<td>Silver</td>
<td>185</td>
<td>28%</td>
</tr>
<tr>
<td>16</td>
<td>Dec-04</td>
<td>green</td>
<td>-</td>
<td>-</td>
<td>100</td>
<td>27%</td>
</tr>
<tr>
<td>17</td>
<td>Dec-04</td>
<td>green</td>
<td>-</td>
<td>-</td>
<td>145</td>
<td>54%</td>
</tr>
<tr>
<td>18</td>
<td>Dec-04</td>
<td>green</td>
<td>-</td>
<td>-</td>
<td>250</td>
<td>69%</td>
</tr>
<tr>
<td>19</td>
<td>Jan-05</td>
<td>green</td>
<td>-</td>
<td>-</td>
<td>400</td>
<td>41%</td>
</tr>
<tr>
<td>20</td>
<td>Jan-05</td>
<td>green</td>
<td>-</td>
<td>-</td>
<td>35</td>
<td>69%</td>
</tr>
<tr>
<td>21</td>
<td>May-05</td>
<td>green</td>
<td>-</td>
<td>-</td>
<td>60</td>
<td>73%</td>
</tr>
</tbody>
</table>

Table 3.2 - LEED-rated and self-nominated green buildings in refined CBE survey database

3.4 Analysis method

In a given building, the satisfaction score for an IEQ category is derived from the
mean of all occupants’ votes on all satisfaction questions in that category. Similarly,
mean satisfaction scores in each group of buildings are computed through a one-
building/one-vote method to give buildings of various occupant population number equal
weights in the analysis.
The most commonly used methods for inference about the means of quantitative response variables assume that the variables in questions have normal distributions in the population or populations from which we draw our data. In practice, of course, it is unlikely that the distribution of field-based subjective responses would be exactly normal. And this is true in the distribution of occupant satisfaction votes on the 7-point scale. But our usual methods for inference about population means (the one-sample and two-sample t procedures and analysis of variance) are quite robust [73]. That is, the results of inference are not very sensitive to moderate lack of normality, especially when the samples are reasonably large. According to practical guidelines for inference on a single mean, the t procedure can be used even for clearly skewed distributions when the sample is large, roughly n\geq 40 [74].

The sample size in this study (around 34,000 respondents) is large enough that we can safely use parametric statistic inference tests. Where it is necessary to correlate IEQ factors together, or correlate number of LEED credit points achieved to IEQ satisfaction scores, I have used parametric Pearson’s correlation coefficient (signified as r). Where it is necessary to relate subjective and objective variables, I have used two sample t procedures to compare mean satisfaction scores for respondents with different objective responses such as office type, or gender. The p-values represent the probabilities that the Null Hypothesis is true; that there is no difference in the distribution of one satisfaction with another caused by the objective variable dividing the two groups. All relationships in the one-person/one-vote analysis have been examined to the statistical significance of p<0.01 and in the one-building/one-vote analysis to the statistical significance of p<0.05, unless noted otherwise.
The Occupant IEQ survey also includes what we call “drill-down” or branching questions. It asks those respondents who have indicated dissatisfaction with an IEQ category to identify problems contributing to their dissatisfaction on a follow-up page. The percentage of respondents indicating that a particular factor contributes to their dissatisfaction is calculated based on the number of respondents who saw the follow-up page. Where the frequency of a complaint in one group vs. another is in question, I have used two-sample t procedures to compare mean complaint percentages among the two main comparison groups.

### 3.5 Limitations

The limitations of the method and data used are:

1) A POE method that includes physical measurements of IEQ in addition to occupant surveys would give us a far more comprehensive picture of how each building is affecting occupants’ well-being and productivity. But the combination of these methods would make an exhaustive study far beyond the scope of this thesis, and more appropriate to single building in-depth POE case studies.

2) The CBE occupant IEQ survey relies on self-reported satisfaction responses. It does not ask about health directly. Due to liability issues involved in the workplace, asking about health would limit the number of buildings and people likely to participate in the study. A relationship between satisfaction and health is implied.

3) Using the survey method, we do not have a way to directly influence or control for psycho-social (non-physical) factors that affect occupants in the workplace. We rely on a large sample size to minimize the effects of these factors.
4) The survey follows up with drill-down branching questions in the event of a dissatisfaction vote. While this method allows us to understand the nature of problem areas, it limits our investigations into what contributed to positive satisfaction responses.

5) The CBE survey database is not necessarily representative of the entire U.S. population. CBE does not do systematic sampling of the commercial building stock. All of the buildings in the survey database have either been surveyed as part of a periodic assessment of facilities, or have voluntarily participated in the survey (to use it as part of a more extensive POE).

Future research addressing limitations of current methods and data could take advantage of wireless technology alongside occupant surveys to perform POE that are more in-depth but less costly. As benefits of occupant health and productivity in the workplace become more clarified, one can envision surveys where we can ask about health symptoms directly. More research is needed to understand how buildings as a whole influence occupant well-being and productivity. Developing a method to follow up on what contributes to occupant satisfaction will help us answer this and other questions about the nature of “forgiveness factors” and “killer variables”. CBE will continue to populate their database, and address the need to do a systematic comparison of how the database differs from a representative sample of the commercial building stock.
4 Results & Discussion

In this section, I will apply the methods described in the previous chapter to the problem at hand: assessing occupant well-being and productivity in LEED-rated/green buildings with respect to physical IEQ factors. I will start with an analytic overview of the CBE survey database, and then a comparative study of LEED-rated/green buildings with the rest of the CBE database. The first part will lay the foundation for the comparative analysis that follow: what can we learn from the CBE survey database that will guide the comparison of LEED-rated/green buildings with other buildings?

As highlighted in sections 2.1.3 and 2.1.7, personal control over the indoor environment has important implications on occupant well-being and productivity. The CBE occupant survey method collects data about respondents’ controls over the thermal, lighting, and acoustics conditions of their workspace environment. The survey allows us to examine occupant satisfaction and productivity in relation to personal control. This is one of the main threads that run through this analysis.

4.1 All database analysis

An overview analysis of the CBE survey database reveals that acoustics, temperature, and air quality are the lowest performing IEQ survey categories. Figure 4.1 presents one-person/one-vote mean overall satisfaction scores for each IEQ category in the CBE survey database. For survey categories that include multiple satisfaction questions about different aspects of one IEQ factor, such as lighting (amount of light and visual comfort of lighting) or acoustics (noise level and sound privacy), the mean score is equal to the average of the individual satisfaction questions in that category.
The mean acoustics score (-0.33) is the lowest of all categories followed by temperature (-0.14) and air quality (0.17). Other survey satisfaction categories perform around “slightly satisfied” or (+1 on the 7-point satisfaction scale) with standard deviations of approximately 1.4 to 1.8. Both temperature and acoustics have negative overall satisfaction scores, which means that on average occupants do not find them satisfactory.

![Mean Satisfaction Scores and Standard Deviation around the Mean](image)

**Figure 4.1 - Summary chart of one-person/one-vote mean satisfaction scores for categories in CBE survey database (n= 34,743)**

In addition to the satisfaction questions, each IEQ category of the survey (except general building and general workspace) includes a self-reported productivity question. Figure 4.2 shows the one-person/one-vote mean productivity scores for each IEQ category in the CBE survey database. Comparing Figure 4.1 and Figure 4.2 shows that
Productivity scores follow satisfaction scores closely. The same three IEQ categories with lowest mean satisfaction scores interfere most with occupants’ ability to get their job done (namely acoustics, temperature, and air quality in order from the worst).

Since temperature, air quality and acoustics have lowest survey category scores in the CBE database, I will do a detailed analysis of these three categories. But first, I would like to look further at the relationship between satisfaction and self-reported productivity votes among different survey IEQ factors.

### 4.1.1 Cross correlations

The self-reported productivity scores are highly correlated with satisfaction scores. For example, Figure 4.3 and Figure 4.4 show average temperature and air quality productivity responses binned by satisfaction response for the entire database. A linear regression yields the following relationship for temperature and air quality:

![Mean Productivity Scores and Standard Deviation around the Mean](chart.png)

**Figure 4.2 - Summary chart of one-person/one-vote mean self-reported productivity scores for categories in CBE survey database (n=34,743)**
temperature productivity = (0.84 x temperature satisfaction) + 0.008 (R² = 0.77)  

Equation 1

Correlation coefficient r= 0.88

air quality productivity = (0.79 x air quality satisfaction) + 0.04 (R² = 0.77)  

Equation 2

Correlation coefficient r= 0.88

Correlations between satisfaction and self-reported productivity scores for other IEQ categories of CBE survey range from 0.59 to 0.88. The strength of correlations between satisfaction and self-reported productivity scores has two important connotations. First, that occupants believe they are more productive when they are more satisfied with their IEQ. This corroborates with what other researchers have found about the relationship of IEQ with productivity, especially for air quality and thermal comfort (refer to section 2.1 for a review of this evidence). And second, that we can suffice to studying the relationship between occupants’ satisfactions with objective variables of
interest without repeating the same analysis with self-reported productivity scores. Building on the strong correlation between satisfaction and self-reported productivity in the CBE occupant survey database, from here on, I will limit this analysis to the study of satisfaction scores.

I have also investigated simple linear correlations between different IEQ satisfaction question scores. Table 4.1 shows correlations between individual satisfaction questions in the survey. Since satisfaction questions in each category of the survey (questions in the same survey page) are highly correlated with each other, I have removed these numbers in the matrix in order to draw attention to correlations between different survey categories. Cross-correlations between distinct survey IEQ categories range from 0.23 to 0.66. This table is presented here as reference and the condensed version, showing the most highly correlated responses, is presented in Table 4.2.
| Correlation coefficient r | amount of space | visual privacy | ease of interaction | comfort of furnishings | ability to adjust | colors and textures | temperature | air quality | amount of light | visual comfort | noise level | sound privacy | general cleanliness | cleaning service | general maintenance | general workspace | general building |
|--------------------------|----------------|----------------|---------------------|-----------------------|-------------------|-------------------|-------------|-------------|----------------|----------------|-------------|----------------|-----------------|-----------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| 1 amount of space        |                |                |                     |                       |                   |                   |             |             |                 |                 |             |                 |                 |                 |                       |                       |                       |                       | 0.46 0.58 0.36 0.35 |
| 2 visual privacy         | 0.58           | 0.34           | 0.29               | 0.27                  | 0.30             | 0.34             | 0.36         | 0.34         | 0.36           | 0.35           | 0.34         | 0.41           | 0.29             | 0.27             | 0.29                 | 0.66 0.59         |
| 3 ease of interaction    | 0.46           | 0.34           | 0.33               | 0.32                  | 0.26             | 0.31             | 0.35         | 0.34         | 0.38           | 0.34           | 0.38         | 0.41           | 0.29             | 0.27             | 0.30                 | 0.50 0.41         |
| 4 comfort of furnishings | 0.41           | 0.34           | 0.34               | 0.32                  | 0.31             | 0.36             | 0.38         | 0.41         | 0.31           | 0.29           | 0.31         | 0.41           | 0.29             | 0.29             | 0.32                 | 0.52 0.42         |
| 5 ability to adjust      | 0.41           | 0.32           | 0.33               | 0.31                  | 0.37             | 0.36             | 0.40         | 0.31         | 0.29           | 0.31           | 0.32         | 0.41           | 0.29             | 0.32             | 0.32                 | 0.51 0.41         |
| 6 colors and textures    | 0.36           | 0.29           | 0.32               | 0.30                  | 0.41             | 0.37             | 0.41         | 0.29         | 0.26           | 0.38           | 0.33         | 0.41           | 0.29             | 0.35             | 0.37                 | 0.48 0.47         |
| 7 temperature            | 0.29           | 0.27           | 0.26               | 0.31                  | 0.31             | 0.30             | 0.48         | 0.31         | 0.34           | 0.32           | 0.31         | 0.33           | 0.33             | 0.29             | 0.35                 | 0.42 0.42         |
| 8 air quality            | 0.34           | 0.30           | 0.31               | 0.36                  | 0.37             | 0.41             | 0.48         | 0.36         | 0.41           | 0.37           | 0.33         | 0.46           | 0.40             | 0.46             | 0.46                 | 0.47 0.53         |
| 9 amount of light        | 0.36           | 0.35           | 0.35               | 0.38                  | 0.36             | 0.37             | 0.31         | 0.36         | 0.35           | 0.31           | 0.32         | 0.46           | 0.40             | 0.30             | 0.33                 | 0.47 0.41         |
| 10 visual comfort        | 0.36           | 0.33           | 0.34               | 0.41                  | 0.40             | 0.41             | 0.34         | 0.41         | 0.36           | 0.32           | 0.34         | 0.34           | 0.32             | 0.34             | 0.32                 | 0.48 0.44         |
| 11 noise level           | 0.41           | 0.50           | 0.38               | 0.31                  | 0.31             | 0.29             | 0.32         | 0.37         | 0.35           | 0.36           | 0.30         | 0.28           | 0.30             | 0.56             | 0.56                 | 0.56 0.41         |
| 12 sound privacy         | 0.42           | 0.57           | 0.34               | 0.29                  | 0.29             | 0.26             | 0.31         | 0.33         | 0.31           | 0.32           | 0.30         | 0.24           | 0.24             | 0.24             | 0.24                 | 0.52 0.35         |
| 13 general cleanliness   | 0.29           | 0.24           | 0.30               | 0.32                  | 0.32             | 0.38             | 0.33         | 0.46         | 0.32           | 0.34           | 0.30         | 0.23           | 0.41             | 0.63             | 0.63                 | 0.63 0.41         |
| 14 cleaning service      | 0.27           | 0.23           | 0.27               | 0.29                  | 0.29             | 0.33             | 0.29         | 0.40         | 0.30           | 0.32           | 0.28         | 0.24           | 0.39             | 0.48             | 0.48                 | 0.48 0.66         |
| 15 general maintenance   | 0.29           | 0.23           | 0.30               | 0.32                  | 0.32             | 0.37             | 0.35         | 0.46         | 0.33           | 0.35           | 0.30         | 0.24           | 0.42             | 0.66             | 0.66                 | 0.66 0.64         |
| 16 general workspace     | 0.66           | 0.59           | 0.50               | 0.52                  | 0.51             | 0.48             | 0.42         | 0.47         | 0.47           | 0.48           | 0.56         | 0.52           | 0.41             | 0.39             | 0.42                 | 0.64 0.64         |
| 17 general building      | 0.41           | 0.36           | 0.41               | 0.42                  | 0.41             | 0.47             | 0.42         | 0.53         | 0.41           | 0.44           | 0.41         | 0.35           | 0.63             | 0.48             | 0.66                 | 0.66 0.64         |

Table 4.1 - Cross correlation between individual satisfaction questions (in order of appearance in the CBE survey)
Table 4.2 shows all satisfaction questions in their order of appearance in the survey, paired with the satisfaction question they were most highly correlated with. The table highlights the fact that occupants’ assessments of office layout, furnishing, lighting, and noise level have the highest correlation with general workspace satisfaction. And cleanliness and maintenance of the building, along with air quality have the highest correlation with general building satisfaction. Of special interest here, is the relative strength of the relationships between:

1. Temperature and air quality (two of the worst performing IEQ categories)
2. Air quality and general building
3. Sound privacy and visual privacy

<table>
<thead>
<tr>
<th>Page</th>
<th>Satisfaction with…</th>
<th>Most highly correlated with …</th>
<th>Correlation coefficient r</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>amount of space</td>
<td>general workspace</td>
<td>0.66</td>
</tr>
<tr>
<td>4</td>
<td>visual privacy</td>
<td>general workspace</td>
<td>0.59</td>
</tr>
<tr>
<td>4</td>
<td>ease of interaction</td>
<td>general workspace</td>
<td>0.50</td>
</tr>
<tr>
<td>8</td>
<td>comfort of office furnishings</td>
<td>general workspace</td>
<td>0.52</td>
</tr>
<tr>
<td>8</td>
<td>ability to adjust</td>
<td>general workspace</td>
<td>0.51</td>
</tr>
<tr>
<td>8</td>
<td>colors and textures</td>
<td>general workspace</td>
<td>0.47</td>
</tr>
<tr>
<td>9</td>
<td>temperature</td>
<td>air quality</td>
<td>0.48</td>
</tr>
<tr>
<td>11</td>
<td>air quality</td>
<td>general building</td>
<td>0.53</td>
</tr>
<tr>
<td>13</td>
<td>amount of light</td>
<td>general workspace</td>
<td>0.47</td>
</tr>
<tr>
<td>13</td>
<td>visual comfort</td>
<td>general workspace</td>
<td>0.48</td>
</tr>
<tr>
<td>15</td>
<td>noise level</td>
<td>general workspace</td>
<td>0.56</td>
</tr>
<tr>
<td>15</td>
<td>sound privacy</td>
<td>visual privacy</td>
<td>0.57</td>
</tr>
<tr>
<td>17</td>
<td>general cleanliness</td>
<td>general building</td>
<td>0.63</td>
</tr>
<tr>
<td>17</td>
<td>cleaning service</td>
<td>general building</td>
<td>0.48</td>
</tr>
<tr>
<td>17</td>
<td>general maintenance</td>
<td>general building</td>
<td>0.66</td>
</tr>
<tr>
<td>20</td>
<td>general workspace</td>
<td>amount of space</td>
<td>0.66</td>
</tr>
<tr>
<td>20</td>
<td>general building</td>
<td>general maintenance</td>
<td>0.66</td>
</tr>
</tbody>
</table>

All correlations are statistically significant (p<0.01).
Satisfaction scores in the same IEQ category of the survey (questions on the same page) are highly correlated with each other and these pairs have been excluded.

Table 4.2 - Highest correlation between individual satisfaction questions (in the order of appearance in the survey)
Since Table 4.2 does not confirm a causal relationship between any two IEQ factors, it is important to note the confounding effects of other variables involved. In statistical terminology, a confounding factor in the relationship between explanatory and response variables measured in a study may be either another explanatory variable (whose effect can not be distinguished from the explanatory variable measured in the study), or a lurking variable (causing a common response effect in both variables measured).

Table 4.2 indicates that when occupants are satisfied with the air quality of their workspace, it is highly likely that they would be satisfied with their building in general. As a confounding variable here, we can point to the age of the building causing a positive response to satisfaction with the building in general and with air quality. In comparison to new buildings, occupants in old buildings are more likely to be dissatisfied with the building in general. Occupants in old buildings also tend to be more dissatisfied with the air quality of their workspace (refer to section 2.1.4).

In the relationship between visual privacy and sound privacy, we can identify as a lurking variable the spatial relationship of the respondents to the people and objects around them (which could infringe on their privacy), causing a common satisfaction response to both sound and visual privacy. The spatial relationship depends strongly on whether the occupant is in an open plan, cubicle with high partitions, cubicle with low partitions, or enclosed private and shared office types. Occupants in open plan offices have less visual privacy and are also more likely to be dissatisfied with their sound privacy.
As for temperature and air quality, I noted in section 2.1.4 that perceived air quality is tied strongly to temperature satisfaction. But it is difficult to identify which of the two factors is driving the respondent’s satisfaction.

4.1.2 Thermal comfort

Figure 4.5 shows the distribution of thermal comfort satisfaction scores for all occupants in CBE survey database. Overall, slightly more occupants are dissatisfied (41%) than satisfied (39%), with 19% of occupants voting neutral on the 7-point scale. Of note is the relatively high percentage of responses in the –2 and –3 bins (28%). Other researchers have also shown that thermal comfort consistently figures in the highest number of complaints, and service requests ([1] and [26]).

![Figure 4.5 - Distribution of satisfaction with temperature votes in CBE survey database](image)

Figure 4.5 - Distribution of satisfaction with temperature votes in CBE survey database
The survey’s follow-up pages provide valuable information about why occupants tend to be dissatisfied with thermal conditions. Occupants who are dissatisfied (satisfaction with temperature vote <0) are presented with diagnostic questions about the sources of their dissatisfaction. Figure 4.6 shows a list of sources of dissatisfaction ranked by frequency of selection. After the first complaint that emphasizes the nature of temperature dissatisfaction (“My area is hotter/colder than other areas”) the next two most frequently indicated complaints are related to inadequate control over thermal environment. Since the influence of personal control over the environment is an important focus of this study, I will explore the relationship between personal control over the thermal environment with temperature satisfaction further.
Table 4.3 shows the mean temperature satisfaction scores for groups of occupants with and without access to a thermostat, operable window, portable heater, portable fan, floor air diffuser, or none of the above. Except for the floor air diffuser, all other differences are statistically significant (p<0.01). The most striking result is the improvement in satisfaction of 0.96 (close to one full satisfaction scale step) for those occupants that had access to a thermostat. Operable windows also significantly increase satisfaction with temperature. Occupants with portable heaters and fans have lower
satisfaction than those without. Presumably the presence of these devices indicates that there is a deficiency with the building HVAC system, which necessitated the occupants bringing them in.

<table>
<thead>
<tr>
<th></th>
<th>Mean temperature satisfaction score</th>
<th>N</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>all occupants</td>
<td>-0.14</td>
<td>32,329</td>
<td>100%</td>
</tr>
<tr>
<td>no control</td>
<td>-0.25</td>
<td>22,231</td>
<td>69%</td>
</tr>
<tr>
<td>some control</td>
<td>-0.10</td>
<td>10,098</td>
<td>31%</td>
</tr>
<tr>
<td>difference*</td>
<td>0.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>thermostat</td>
<td>0.72</td>
<td>3,427</td>
<td>11%</td>
</tr>
<tr>
<td>no thermostat</td>
<td>-0.25</td>
<td>28,902</td>
<td>89%</td>
</tr>
<tr>
<td>difference*</td>
<td>0.96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>operable window</td>
<td>0.31</td>
<td>2,727</td>
<td>8%</td>
</tr>
<tr>
<td>no operable window</td>
<td>-0.19</td>
<td>29,602</td>
<td>92%</td>
</tr>
<tr>
<td>difference*</td>
<td>0.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>portable heater</td>
<td>-0.74</td>
<td>3,306</td>
<td>10%</td>
</tr>
<tr>
<td>no portable heater</td>
<td>-0.08</td>
<td>29,023</td>
<td>90%</td>
</tr>
<tr>
<td>difference*</td>
<td>-0.66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>portable fan</td>
<td>-0.43</td>
<td>7,196</td>
<td>22%</td>
</tr>
<tr>
<td>no portable fan</td>
<td>-0.06</td>
<td>25,133</td>
<td>78%</td>
</tr>
<tr>
<td>difference*</td>
<td>-0.37</td>
<td></td>
<td></td>
</tr>
<tr>
<td>adjustable floor air vent (diffuser)</td>
<td>-0.28</td>
<td>911</td>
<td>3%</td>
</tr>
<tr>
<td>no adjustable floor air vent</td>
<td>-0.14</td>
<td>31,418</td>
<td>97%</td>
</tr>
</tbody>
</table>

* Difference is statistically significant (p<0.01).

Table 4.3 - Mean temperature satisfaction votes for groups of respondents with or without controls over their thermal environment

If we compare the mean temperature satisfaction scores for groups of occupants in different office types (Table 4.4), we see that occupants in private offices are significantly more satisfied with their temperature than occupants in other office types.
Private offices are generally more satisfactory than open offices. As an enclosed space, more indoor environment controls are available to an individual and IEQ can be adjusted to the occupant’s taste, as in turning the heat on or off, opening or closing windows/doors/vents, raising or lowering blinds, turning lights on or off, etc. Therefore office type is a confounding factor in many occupant indoor environment satisfaction votes. The superiority of occupant satisfaction with IEQ in private offices could be due to this effect, but also due to several other lurking variables. In the US especially, enclosed private offices are usually on the perimeter and thus would have access to windows and views. They are historically an entitlement of those higher in the hierarchy of the office.

<table>
<thead>
<tr>
<th>Workspace description</th>
<th>Mean temperature satisfaction score</th>
<th>N</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Enclosed office, private</td>
<td>0.19</td>
<td>9,341</td>
<td>29%</td>
</tr>
<tr>
<td>2 Enclosed office, shared with others</td>
<td>-0.01</td>
<td>2,190</td>
<td>7%</td>
</tr>
<tr>
<td>3 Workspace in open office with no partitions (just desks)</td>
<td>-0.18</td>
<td>1,606</td>
<td>5%</td>
</tr>
<tr>
<td>4 Cubicles with low partitions (lower than five feet high)</td>
<td>-0.25</td>
<td>6,003</td>
<td>19%</td>
</tr>
<tr>
<td>5 Cubicles with high partitions (about five or more feet high)</td>
<td>-0.38</td>
<td>11,293</td>
<td>35%</td>
</tr>
</tbody>
</table>

All differences, except between 2 and 3, are statistically significant (p<0.01).

Table 4.4 - Mean temperature satisfaction scores for respondents in different office types

It is interesting to note that occupants in open plan offices without any partitions are more satisfied than those in offices with high or low partitions. In fact, the difference between satisfaction scores for those in open plan office and those in cubicles with low partitions is very small. This implies that partition or no-partition has little impact on improving occupants’ satisfaction with temperature. Similarly we see that those in cubicles with high partitions are less satisfied with their temperature than those in
cubicles with low partitions, implying that increasing the height of the separating partition has little impact in improving occupant satisfaction. In other words, unlike the effect observed in private versus shared offices, more enclosure within an open landscape does not lead to improved satisfaction. One explanation for this counterintuitive effect could be that, in cases where the building ventilation system is not operating optimally, partitions create local thermal effects that could be undesirable. Another explanation for this could be that those in open plan offices and low partitions have lower expectations, and thus are more tolerant towards shortcomings in IEQ.

To control for the effects of office type as a confounding factor on satisfaction with temperature I have looked at mean temperature satisfaction for groups of occupants in five office types, with and without different types of control over their thermal environment. Even when controlling for office type the differences in Table 4.3 are still in effect. In enclosed private offices and enclosed shared offices, similar differences with statistical significance can be observed for those who have and do not have control over a thermostat, operable window, portable heater, portable fan, and floor air diffuser. Except for the floor air diffuser, all other differences are statistically significant (p<0.01). However, since the number of respondents who have and do not have controls become drastically different among occupants in cubicles with high partitions (300 respondents have controls, 10,000 do not have control), cubicles with low partitions, and those in open plan offices, the differences resulting from these comparisons are not statistically significant.
### 4.1.3 Air quality

Air quality satisfaction is somewhat higher than thermal satisfaction in the buildings surveyed. Figure 4.7 shows the distribution of air quality satisfaction votes across all occupants. In contrast to the thermal satisfaction votes, more occupants voted satisfied (45%) than dissatisfied (32%), and the average vote is positive (0.17).

![Distribution of satisfaction with air quality votes in CBE survey database](image)

Turning to the data collected by the air quality diagnostic page, presented to those dissatisfied with air quality, 74% identified “air is stuffy/stale” to be a major problem, 67% identified “air is not clean” to be a major problem, and 51% identified “air smelling bad (odors)” to be a major problem. The three most frequently identified sources of odor were food, carpet or furniture, and other people.
I have explored the relationship between air quality and controls over one’s thermal environment and have found that those with control over a thermostat, operable window, and adjustable air diffuser are also more satisfied with their air quality in their workspace (Table 4.5). The average air quality satisfaction vote for occupants with operable windows (N=2,663) was 0.47 compared to 0.15 for those without operable windows (N=29,222).

<table>
<thead>
<tr>
<th></th>
<th>Mean air quality satisfaction score</th>
<th>N</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>all occupants</td>
<td>0.17</td>
<td>31,885</td>
<td>100%</td>
</tr>
<tr>
<td>thermostat</td>
<td>0.62</td>
<td>3,395</td>
<td>11%</td>
</tr>
<tr>
<td>no thermostat</td>
<td>0.12</td>
<td>28,490</td>
<td>89%</td>
</tr>
<tr>
<td>difference</td>
<td>0.51</td>
<td></td>
<td></td>
</tr>
<tr>
<td>operable window</td>
<td>0.47</td>
<td>2,663</td>
<td>8%</td>
</tr>
<tr>
<td>no operable window</td>
<td>0.15</td>
<td>29,222</td>
<td>92%</td>
</tr>
<tr>
<td>difference</td>
<td>0.33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>portable heater</td>
<td>-0.01</td>
<td>3,268</td>
<td>10%</td>
</tr>
<tr>
<td>no portable heater</td>
<td>0.19</td>
<td>28,617</td>
<td>90%</td>
</tr>
<tr>
<td>difference</td>
<td>-0.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>portable fan</td>
<td>-0.23</td>
<td>7,132</td>
<td>22%</td>
</tr>
<tr>
<td>no portable fan</td>
<td>0.29</td>
<td>24,753</td>
<td>78%</td>
</tr>
<tr>
<td>difference</td>
<td>-0.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>adjustable floor air vent (diffuser)</td>
<td>0.38</td>
<td>896</td>
<td>3%</td>
</tr>
<tr>
<td>no adjustable floor air vent</td>
<td>0.17</td>
<td>30,989</td>
<td>97%</td>
</tr>
<tr>
<td>difference</td>
<td>0.21</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

All differences are statistically significant (p<0.01).

Table 4.5 - Mean air quality satisfaction scores for groups of respondents with or without controls over their thermal environment

It is interesting to see here that, similar to thermal comfort satisfaction, those with portable heaters and portable fans are less satisfied with their air quality. Presumably the fact that the respondent has these devices in their office indicates that they are dissatisfied
with what the building provides for them. Even though they are trying to compensate for this lack of building performance by providing for themselves, they still vote dissatisfied with their air quality and thermal comfort.

Since office type can be a confounding factor in influencing people’s assessment of their air quality I have checked satisfaction with air quality for people in different office types. Similar to what we observed in satisfaction with temperature scores, respondents in enclosed private offices are most satisfied with their air quality, followed by those with a workspace in an open plan office, enclosed shared office, cubicles with low partitions, and last cubicles with high partitions (Table 4.6).

The order of these results might seem counterintuitive at first. Why are those in open plan offices with no partitions more satisfied than those in cubicles? And why are those in cubicles with low partitions more satisfied with their air quality than those in cubicles with high partitions? One could explain these results physically by referring to ventilation effectiveness and air distribution. In the event where the building ventilation system is not operating optimally, partitions create local effects that could be undesirable. Another possible explanation for this comes from a common sense observation. As offices are enclosed, people’s expectations about their indoor environmental quality rises and therefore it becomes more difficult to satisfy their needs.
<table>
<thead>
<tr>
<th>Workspace description:</th>
<th>Mean air quality satisfaction score</th>
<th>N</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Enclosed office, private</td>
<td>0.42</td>
<td>9,276</td>
<td>29%</td>
</tr>
<tr>
<td>2 Workspace in open office with no partitions (just desks)</td>
<td>0.21</td>
<td>1,585</td>
<td>5%</td>
</tr>
<tr>
<td>3 Enclosed office, shared with others</td>
<td>0.19</td>
<td>2,165</td>
<td>7%</td>
</tr>
<tr>
<td>4 Cubicles with low partitions (lower than five feet high)</td>
<td>0.10</td>
<td>5,812</td>
<td>18%</td>
</tr>
<tr>
<td>5 Cubicles with high partitions (about five or more feet high)</td>
<td>0.00</td>
<td>11,166</td>
<td>35%</td>
</tr>
</tbody>
</table>

All differences, except between 2 and 3, are statistically significant (p<0.05).

Table 4.6 - Mean air quality satisfaction scores for respondents in different office types

4.1.4 Acoustics

Jensen et al. [56] have previously analyzed the CBE survey database with special emphasis on the acoustics satisfaction category. Overall acoustics satisfaction is the lowest performing of all IEQ categories in the CBE survey database. They found that occupants in private offices are significantly more satisfied with the acoustic quality than occupants in cubicles (p<0.01). Of those dissatisfied with their acoustics, the most prevalent complaints were: “people talking on the phone”, “people overhearing private conversations” and “people talking in surrounding offices”.

The acoustics category of the CBE survey includes two satisfaction questions regarding noise level and sound privacy, and therefore overall satisfaction with acoustics score is the mean of these two satisfaction scores. Jensen et al. found that respondents are significantly more dissatisfied with speech privacy than noise level (p<0.01). Office type plays an important role in respondents’ satisfaction with acoustics. Jensen et al. have divided the CBE survey respondents into five groups, based on their office type, and have
compared mean noise level and sound privacy satisfaction scores between these groups. Figure 4.8 shows that occupants in all office types are more dissatisfied with their sound privacy than with the noise level of their workspace. It also demonstrates that occupants in enclosed private offices are significantly more satisfied with their noise level and sound privacy than occupants in other office types.

![Figure 4.8 - Average occupant satisfaction score with acoustics (noise level, sound privacy) by office type (reproduced from Jensen et al. [56])]()

Seeing these results in light of the adaptive opportunity and personal control over one’s environment, we can observe that the prevalent acoustic complaints can all be related to the ability to control the source of distraction. In a private office one has the ability to close the door and shut out the source of distraction, and to provide oneself with the quiet environment to concentrate, and the privacy needed to have private conversations. The ability to control the source of distraction is strongly impeded in open plan or cubicle office environments. Earlier in this chapter, I presented another pattern in the data: the relationship between sound privacy and visual privacy (section 4.1.1, Table
4.2) I identified office type as the major confounding factor involved in influencing both sound and visual privacy. This is another indication of the relationship between office type and satisfaction with sound privacy.

### 4.1.5 Summary

Acoustics, thermal comfort, and air quality are the worst performing survey categories in the CBE database. If we improve these IEQ factors in buildings in general, and in green buildings in particular, we have taken a very important step. In the CBE survey database, consistent with the literature reviewed in section 2.1, personal control has a significant effect on improving occupant satisfaction with their indoor environment.

My objective is to assess IEQ in LEED-rated/green buildings. The CBE survey database, being a large and unique database, provides a valid benchmark that we can use to compare LEED-rated/green buildings with. I have so far laid the foundation for the benchmarking analysis to come: general patterns in occupant satisfaction and self-reported productivity votes with IEQ, the effects of personal control over the indoor environment in improving occupant satisfaction with IEQ, and the confounding factors that we need to be attentive to when interpreting the results. Now it is time to ask: how is occupant satisfaction with IEQ different in LEED-rated/green buildings as compared with other buildings?

### 4.2 IEQ in LEED-rated / green buildings

The basic hypothesis that I start with is that the strategies employed in LEED-rated/green buildings generally improve IEQ, and occupants are more satisfied in LEED-rated/green buildings. If these buildings perform better than the rest of CBE database in an IEQ category, this is consistent with my hypothesis and I associate this effect to the
green building strategies that are employed in LEED-rated/green buildings. Since a high proportion of buildings in this analysis are LEED-rated, I will use the LEED green building rating system checklist described in section 2.3.1 as the main list of the strategies used to improve IEQ in green buildings.

When the LEED-rated/green buildings do not perform better than the rest of the CBE database, I will ask why is this the case? This approach is partly due to the structure of the survey; only those who vote “dissatisfied” see the drill-down branching questions asking about the sources of their dissatisfaction. Therefore, I will not be able to investigate directly what the source of respondents’ satisfaction is, only what the source of their dissatisfaction is. I will use my specific lens of occupant personal control to answer why LEED-rated green buildings are performing worse.

Figure 4.9 shows the comparison of survey results in LEED-rated/green buildings with the rest of the buildings in our database. This figure shows that on average occupants in LEED-rated/green buildings are more satisfied in the following areas: office furnishings, thermal comfort, air quality, cleanliness and maintenance, and general workspace satisfaction and general building satisfaction. In subsequent sections I will perform detailed benchmarking comparisons for general building, general workspace, air quality, thermal comfort, lighting, and acoustics. As discussed in section 4.1.1, occupants’ assessments of office layout and furnishing are highly correlated with general workspace satisfaction. Similarly, cleanliness and maintenance of the building is highly correlated with general building satisfaction. As such, I will use general satisfaction with buildings and workspace as proxy measures of satisfaction with office furnishing, office
layout, and cleanliness and maintenance, and will not discuss these latter survey categories in detail.

Figure 4.9 - Survey results of one-building/one-vote mean satisfaction scores in LEED-rated/green buildings compared to the rest of the CBE survey database

4.2.1 General building and workspace

Figure 4.10 shows a percentile rank chart of buildings in the CBE database based on their mean score for general satisfaction with building. Percentile ranks are calculated by ranking all of the buildings in order of their mean satisfaction score with a particular satisfaction question. The 50th percentile on the x-axis is the median of all buildings in the CBE database: half of all buildings in the database have lower and half have higher mean satisfaction scores than the median. Medians can also be calculated separately for
subgroups within the larger database: the LEED-rated/green buildings and the rest of the CBE database.

![Graph showing satisfaction scores](image)

**Figure 4.10 - Median and mean general building satisfaction scores in LEED-rated/green buildings and the rest of the CBE database**

The mean occupant votes for the two main comparison groups are shown on the y-axis. The medians of the two main comparison groups are marked by the vertical lines. As shown in Figure 4.10, the mean satisfaction score in LEED-rated/green buildings (1.47) is significantly higher than the mean satisfaction score for the rest of the CBE database (0.93). So, on average, occupants in LEED-rated/green buildings are more satisfied with their building in general than occupants in the rest of CBE survey database. The shift of the median lines for two groups also marks this difference.
Figure 4.11 - Median and mean general workspace satisfaction scores in LEED-rated/green buildings and the rest of the CBE database

Figure 4.11 shows the comparison between LEED-rated/green buildings and the rest of CBE database for general satisfaction with workspace. While on average green buildings are performing better in occupant satisfaction with workspace, we see less of an overwhelming and consistent improved performance in this survey category compared to satisfaction with the building. One explanation for this is that people are more forgiving when assessing the building as a whole than they are when they are assessing their individual workspace. As previously shown in Table 4.2, general satisfaction with the building has the highest correlation with the cleanliness and maintenance category of the survey. LEED-rated/green buildings are relatively new buildings, most likely better maintained, and therefore promote higher general building satisfaction for the occupants.

When responding to the general satisfaction with workspace question, respondents tend to think about the physical aspects of their workspace, specifically as
previously detailed in Table 4.2: office layout, office furnishing, lighting, and acoustic. Except for office furnishings, we do not see an improved performance in office layout, lighting, and acoustic categories of the survey between LEED-rated/green buildings and the rest of the CBE survey database (Figure 4.9). This might explain why we do not see a consistent and overwhelming improvement in occupant satisfaction with general workspace as compared to occupant satisfaction with general building.

Heerwagen and Zagreus [75] have also identified the difference between occupants’ general satisfaction with building and with the workspace. For them, this is a sign that “the whole is greater than its component part”, and that the environmental factors measured separately in the CBE occupant IEQ survey do not fully capture the building experience for the occupants. They found that many of the perceived benefits of the green buildings for occupants had more to do with general qualities such as social and emotional values of their work environment overall, rather than specific elements of design. The social and emotional values in the new sustainable building they studied as identified by the occupants include: improved communication, sense of community, more egalitarian, connection to mission and values, connection to nature, reduced stress, positive experience, inspirational, and great place to work.
4.2.2 Air quality

Figure 4.12 shows that occupants in LEED-rated/green buildings are on average more satisfied with the air quality in their workspace than occupants in the rest of the CBE database (compare mean 1.14 with 0.21, respectively). The mean satisfaction scores in both groups have positive signs, showing that on average air quality in both groups is satisfactory.

This seems intuitive because indoor air quality is the major emphasis of the IEQ category in LEED green building rating system. Aside from the air quality prerequisites (2 in LEED-NC and 4 in LEED-EB), out of 15 points dedicated to IEQ in LEED-NC 2.0 and 2.1, nine points are related to indoor air quality. This represents 60% of points in the LEED IEQ category. This pattern also exists in LEED-EB 2.0, where 12 points out of 22
(54% of points in IEQ category) are related to air quality (refer to Figure 2.1, Figure 2.2, and Figure 2.3).

Given the fact that LEED-rated/green buildings in CBE database are all relatively new buildings, it is important to check for age as a confounding factor in our analysis. Figure 4.13 shows that even when considering only buildings newer than 15 years, the mean satisfaction score with air quality is still significantly higher for LEED-rated/green buildings (1.14) than the rest of the CBE database (0.52). Interestingly, we do see the effect of age on air quality satisfaction by comparing scores in new database buildings (0.52) to the all-age-inclusive CBE database (0.21).

![Figure 4.13](image-url)

**Figure 4.13 - Median and mean air quality satisfaction scores in LEED-rated/green buildings and the rest of the CBE database, all buildings younger than 15 years**

Table 4.7 shows the database, “new building” database (age<15), and LEED-rated/green building comparison for all survey categories. When including only buildings newer than 15 years old in our analysis, the direction of the differences among LEED-
rated/green buildings and the new conventional buildings in the CBE database remain consistent. However, aside from air quality satisfaction, the relationships between LEED-rated/green buildings and new database buildings in other IEQ categories of the survey are not statistically significant.

This effect highlights the confounding effect of age of the building on occupants’ assessment of building performance. It also shows that we must proceed cautiously when associating better occupant satisfaction to green building strategies employed in LEED-rated/green buildings. Age of the building has an important role to play here, but it is difficult to tell how important.

<table>
<thead>
<tr>
<th>Mean satisfaction score</th>
<th>Database buildings: all (non-green)</th>
<th>Database buildings: age&lt;15 (non-green)</th>
<th>LEED-rated / green buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Office Layout</td>
<td>0.95</td>
<td>1.03</td>
<td>0.94</td>
</tr>
<tr>
<td>Office Furnishings *</td>
<td>0.84</td>
<td>1.03</td>
<td>1.26</td>
</tr>
<tr>
<td>Thermal Comfort *</td>
<td>-0.16</td>
<td>0.17</td>
<td>0.36</td>
</tr>
<tr>
<td>Air Quality * ^</td>
<td>0.21</td>
<td>0.52</td>
<td>1.14</td>
</tr>
<tr>
<td>Lighting</td>
<td>1.12</td>
<td>1.16</td>
<td>1.08</td>
</tr>
<tr>
<td>Acoustics</td>
<td>-0.20</td>
<td>-0.01</td>
<td>-0.27</td>
</tr>
<tr>
<td>Cleaning and Maint…*</td>
<td>0.91</td>
<td>1.15</td>
<td>1.48</td>
</tr>
<tr>
<td>General Workspace *</td>
<td>0.84</td>
<td>1.03</td>
<td>1.13</td>
</tr>
<tr>
<td>General Building *</td>
<td>0.93</td>
<td>1.14</td>
<td>1.47</td>
</tr>
<tr>
<td>Number of buildings</td>
<td>160</td>
<td>35</td>
<td>21</td>
</tr>
</tbody>
</table>

* Difference b/w LEED-rated/green and the rest of CBE database is statistically significant.

^ Difference b/w LEED-rated/green and new buildings in the rest of CBE database (age<15) is statistically significant.

Table 4.7 - Mean satisfaction score comparison across all CBE survey categories among three groups: database buildings, new database buildings, and LEED-rated/green buildings

One question we can explore with the database is the relationship between green building strategies employed in LEED-rated/green buildings and occupant satisfaction with IEQ categories of the survey. I have used the LEED score sheet for each building to
determine which credits points each building has achieved. I have examined the correlation between total percentage of points achieved in the IEQ category of LEED and the mean air quality satisfaction score in the survey. We would expect to see a positive correlation between percentage of LEED IEQ points and the building’s air quality score (i.e. presumably the more air quality point the building has achieved in the LEED rating system, the better it is performing in the air quality category of the survey). But I have found no significant relationship between the two. I will present the air quality score analysis here, to highlight this point.

![Scatterplot and trend line of association between building air quality satisfaction score and the percentage of LEED IEQ points achieved](image)

**Figure 4.14 - Scatterplot and trend line of association between building air quality satisfaction score and the percentage of LEED IEQ points achieved**

For the 15 LEED-rated buildings, Figure 4.14 shows the scatterplot of each building’s mean air quality score vs. the percentage of IEQ points achieved on the LEED rating system score sheet. Due to the small number of LEED buildings in this study it is hard to draw a statistically significant relationship between percentage of LEED points
achieved by the building and its air quality satisfaction score. But it is interesting to note
the slight negative correlation between mean air quality satisfaction scores and the
percentage of IEQ points the LEED-rated buildings have achieved (correlation coefficient
r=-0.3). This association is demonstrated in Figure 4.14 by the solid trend line (R²=0.09).

Consistent with the hypothesis stated at the beginning of this analysis (refer to
section 4.2) I might have expected to find buildings with higher number of LEED IEQ
points to have higher air quality satisfaction scores in the survey. While I have
demonstrated that LEED-rated/green buildings on average perform better than the
conventional buildings in the CBE survey database, Figure 4.14 shows that there is not
strong evidence supporting the association of the buildings’ occupant satisfaction with
the number of LEED IEQ points.

It is possible that buildings with high number of LEED IEQ category points and
low air quality satisfaction score (high-point/low-score), and those with low number of
LEED IEQ category points and high air quality satisfaction score (low-point/high-score)
would be outliers. Figure 4.15 shows the trend line resulting from excluding high-
point/low-score and low-point/high-score buildings from the analysis. It shows that if we
removed these suggested outliers, then a positive correlation could be established
between the number of points and building air quality satisfaction score (correlation
coefficient r=0.46). But even this relationship is very weak (R²=0.2). And the limited
sample of buildings available in this study does not justify grouping high-point/low-score
and low-point/high-score buildings as outliers. A larger sample could help us identify the
dominant trend of LEED-rated building performance in association with IEQ points. In
addition more in-depth POE investigation into high-point/low-score and low-point/high-
score buildings is needed to help us understand why these buildings are performing outside of the normal trend.

![Air Quality Satisfaction Score by % of LEED IEQ Points Achieved](image)

**Figure 4.15** - Scatterplot and trend line of association between building air quality satisfaction score and the percentage of LEED IEQ points achieved, high-point/low-score and low-point/high-score buildings removed from trendline calculation

### 4.2.3 Thermal comfort

Figure 4.16 shows that occupants in LEED-rated/green buildings are on average more satisfied with their thermal comfort than occupants in the rest of the CBE database (compare mean scores of 0.36 and –0.16 respectively). Unlike the other buildings in the database, LEED-rated/green building scores on average tend to be on the positive side (i.e. the “satisfied” side) of our 7-point scale for thermal comfort.
Figure 4.16 - Median and mean thermal comfort satisfaction scores in LEED-rated/green buildings and the rest of the CBE database

The LEED-rated/green building group here shows a less consistent performance in thermal comfort category in comparison to the air quality category of the survey. There are three LEED-rated buildings and one self-nominated green building that rank in the lower two quartiles.

The credit points directly associated with thermal comfort in LEED (similar in all versions and products) are:


2. Credit 7.2 Thermal Comfort, Permanent Monitoring (This credit has changed to Verification in LEED-NC 2.2)
The credits indirectly associated with thermal comfort in LEED-NC 2.0 and 2.1 (majority of the buildings in my sample are rated using these products) are:

1. Credit 6.1 Controllability of systems, perimeter (provide at least an average of one operable window and one lighting control zone per 200 square feet for all regularly occupied areas within 15 feet of the perimeter wall – strategies to consider include lighting controls, task lighting, and operable windows)

2. Credit 6.2 Controllability of systems, non-perimeter (provide controls for each individual for airflow, temperature, and lighting for at least 50% of the occupants in non-perimeter permanently occupied areas – strategies to consider include task lighting and underfloor HVAC systems)

These credits have been changed in LEED-EB (only one building in my sample is rated using this product), CI, and NC-2.2 to:

3. Credit 6.1 Controllability of systems, Lighting

4. Credit 6.2 Controllability of systems, Thermal comfort

So, the strategies used to improve thermal comfort in LEED-rated/green buildings emphasize complying with the thermal comfort standards and increased controllability over the temperature and airflow. The average improved occupant satisfaction in green buildings as compared to the rest of the database shows the positive impact of these strategies in improving occupant satisfaction.

To take this a step further I have investigated the relationship between occupant thermal satisfaction and the number of LEED IEQ points that are directly and indirectly related to thermal comfort (EQ credits 6.1, 6.2, 7.1, and 7.2). I expected to find buildings
with high number of LEED IEQ points to all have high thermal satisfaction scores in the survey and rank high in the CBE database. Oddly, this was not the case.

<table>
<thead>
<tr>
<th>LEED product version rating</th>
<th>Thermal Comfort Percentile Rank</th>
<th>Controllability Perimeter</th>
<th>Controllability non-Perimeter</th>
<th>Thermal Comfort monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC 2 Certified</td>
<td>96%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>EB Pilot Gold</td>
<td>83%</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>NC 1 Platinum</td>
<td>82%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CI Pilot Gold</td>
<td>82%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NC 2 Gold</td>
<td>80%</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CI Pilot Certified</td>
<td>80%</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>NC 2 Silver</td>
<td>79%</td>
<td>-</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CI Pilot pending</td>
<td>77%</td>
<td>Unavail</td>
<td>Unavail</td>
<td>Unavail</td>
</tr>
<tr>
<td>NC 2 Silver</td>
<td>77%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NC 2 pend</td>
<td>75%</td>
<td>-</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>NC 1 Platinum</td>
<td>68%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NC 2 Gold</td>
<td>58%</td>
<td>-</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>NC 2 Platinum</td>
<td>38%</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>NC 2 Silver</td>
<td>22%</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>NC 2 Gold</td>
<td>12%</td>
<td>-</td>
<td>1</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4.8 - LEED-rated building thermal comfort percentile rank score in CBE survey database with the LEED credit points directly or indirectly related to improving thermal comfort

As shown in Table 4.8 there is no relationship between the number of LEED thermal comfort related credit points achieved and the building’s rank in thermal comfort performance in the CBE survey database. To put this in statistical terms: there is an insignificant negative correlation between the two (correlation coefficient $r = -0.14$). Contrary to what we might expect, the top performer has achieved none of the thermal comfort related credit points in LEED-NC 2.0, and the worst performing building has achieved three of the thermal comfort related credit points in LEED-NC 2.0. Similarly, I have found no significant relationship between the total percentage of LEED IEQ points achieved and the building’s thermal comfort satisfaction score in the CBE database.
This means that while on average LEED-rated/green buildings show improved occupant satisfaction with thermal comfort, I could not establish a strong association between occupant satisfaction and the total number of LEED points achieved, or individual LEED IEQ credit points related to thermal comfort. Future studies with a larger sample will help shed light on these associations.

4.2.4 Lighting

As shown in Table 4.7 and Figure 4.9, the difference between mean occupant satisfaction votes in LEED-rated/green buildings and the rest of CBE database is small and not statistically significant for lighting. Figure 4.17 shows the percentile rank chart of buildings in the CBE database based on their mean overall satisfaction score with lighting. The median for LEED-rated/green buildings is slightly higher, but the average scores of the two groups are very close together. Figure 4.17 shows that the best performers and the worst performers in the CBE database are both LEED buildings. There are three distinct clusters; the LEED-rated/green buildings have grouped together in the top, middle and bottom of the database.
By analyzing responses from the branching pages, and comparing the distribution of controls and complaints in the two groups, we get a detailed view of what is contributing to occupants’ dissatisfaction with lighting and acoustics. It is important to note that when comparing the LEED-rated/green group with other CBE database buildings, only those who were dissatisfied with the category saw the page. If the percentage of complaints are consistently higher in one group, it does not mean that on average that group would have scored lower in the IEQ category in question. It means that among those dissatisfied, a higher percentage in one group had complaints about any given source of dissatisfaction than the other group.

Figure 4.18 shows the average distribution of lighting complaints in the two main comparison groups. The chart shows that major lighting complaint areas in LEED-rated/green buildings and the rest of the CBE database are, in descending order, “not
enough daylight”, “reflections in the computer screen”, and “too dark”. It is interesting to note that the frequency of complaints follow the same order in both groups. This suggests that in both comparison groups, respondents prefer more daylight, less glare, and higher ambient lighting levels. It also suggests that the LEED-rated/green buildings have not significantly altered the frequency and distribution of lighting complaints.

**Figure 4.18 - Mean percentage of lighting complaints in LEED-rated/green buildings and the rest of the CBE database**
The credit points directly associated with lighting in LEED (similar in all versions
and products) are:

1. Credit 8.1  Daylight and Views, Daylight 75% of spaces
2. Credit 8.2  Daylight and Views, Views for 90% of spaces

The credits indirectly related to with lighting are the same as those indirectly related to thermal comfort:

3. Credit 6.1 (Controllability of systems, perimeter)
4. Credit 6.2 (Controllability of systems, Non-perimeter)

(Refer to the detailed description of these credits in section 4.2.3)

The strategies employed in LEED-rated buildings to improve lighting quality emphasize availability of daylight, views, and controls: blinds or shades for daylight control in the perimeter, and light switches for task lighting in non-perimeter areas.

<table>
<thead>
<tr>
<th>LEED</th>
<th>Lighting Percentile Rank</th>
<th>Daylight 75% of spaces</th>
<th>Views for 90% of spaces</th>
<th>Controllability Perimeter</th>
<th>Controllability non-Perimeter</th>
</tr>
</thead>
<tbody>
<tr>
<td>product version rating</td>
<td>EQ 8.1</td>
<td>EQ 8.2</td>
<td>EQ 6.1</td>
<td>EQ 6.2</td>
<td></td>
</tr>
<tr>
<td>NC 1.0 Platinum</td>
<td>99%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CI Pilot Gold</td>
<td>98%</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CI Pilot pending</td>
<td>97%</td>
<td>Unavail</td>
<td>Unavail</td>
<td>Unavail</td>
<td>Unavail</td>
</tr>
<tr>
<td>NC 1.0 Platinum</td>
<td>94%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CI Pilot Certified</td>
<td>92%</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NC 2.0 Certified</td>
<td>54%</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NC 2.0 Silver</td>
<td>43%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NC 2.0 Platinum</td>
<td>42%</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>EB Pilot Gold</td>
<td>39%</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>NC 2.1 Gold</td>
<td>4%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>NC 2.0 pending</td>
<td>3%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>NC 2.0 Gold</td>
<td>2%</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>NC 2.0 Silver</td>
<td>2%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NC 2.0 Gold</td>
<td>1%</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4.9 - LEED-rated buildings lighting percentile rank score in CBE survey database with the LEED credit points directly and indirectly related to improving lighting quality
As shown in Table 4.9 there is no relationship between the total number of lighting related LEED credit points achieved and the building’s rank in lighting satisfaction in the CBE survey database. We can also look not just at total points, but specific credits. It is interesting that out of the five lowest-ranked buildings four received the EQ Credit 6.2 (Controllability for non-perimeter spaces). This credit generally translates to relying on task lighting in non-perimeter areas. It is also interesting that only one out of the five has received the EQ credit 6.1 (Controllability for perimeter space). This credit generally translates to giving occupants control over blinds or shades in perimeter areas. This suggests that control of non-perimeter spaces does not necessarily guarantee improved occupant satisfaction with lighting. I will explain why this is the case.

It is common in green buildings to rely on lower levels of ambient electric lighting to save energy, and higher availability of daylight to save energy and enhance the quality of the indoor environment. These design strategies rely mainly on occupant control over their lighting to be effective. Whereas daylighting can save energy and enhance the quality of light indoors, it can also be a potential source of glare and thermal gain if not designed properly. Occupants must have controls over blinds or shades to control for these effects of daylighting, to avoid “too bright” and “reflections” or “glare” complaints. Similarly, while lower levels of ambient lighting save energy, the ambient lighting levels must be high enough to prevent “too dark” complaints. And enough task lighting should be provided to give occupants control over their lighting levels.

Figure 4.19 shows the lighting control profiles comparing LEED-rated/green buildings with the rest of the CBE database. Control items where the difference between
the two main comparison groups is statistically significant (p < 0.05) are circled. Contrary to what we would expect to see in terms of a higher degree of controllability in LEED-rated/green buildings, these buildings on average have a significantly lower percentage of people who have control over “light switch”, and “window blinds or shades”. LEED-rated/green buildings also have a higher percentage of people who have voted they have control over “none of the above”, i.e. no control over the lighting in their workspace. But in accord with what I described as reliance on lower levels of ambient lighting in green buildings, a higher (but not statistically significant) proportion of respondents in LEED-rated/green buildings in CBE survey database have voted that they have control over task lighting.

![Graph showing average lighting controls in LEED-rated/green buildings and the rest of CBE database](image-url)

*Figure 4.19 - Mean percentage of lighting controls in LEED-rated/green buildings and the rest of the CBE database*
This explains why a few LEED-rated green buildings have formed a cluster in the lowest quartile of the CBE survey database as evident in Figure 4.17, and Table 4.9. These are buildings that either have:

- Too low ambient lighting levels, or have low ambient lighting levels and not enough task lighting to make up for it
- Relyed on daylighting strategies but have not provided enough or effective controls in the form of blinds or shades, or have ineffective controls.
- All of the above shortcomings in one place

Here are a few representative comments that the respondents have put in the comments section of the lighting drill-down branching page from each building:

“*There is no overhead lighting. I have purchased a floor lamp and table lamp to compensate. The only lighting controlled by the light switch is indirect above a grey shelf. This is inadequate. When the sun goes down or it is cloudy the office is too dark. This is most of the winter in [our city].”*

“The window shades are ineffective in blocking sunlight. It becomes very uncomfortable (nearly impossible) to work at my computer on sunny afternoons due to the reflections on my computer screen. The shades allow too much afternoon light inside. The problem is worse during the fall-winter-spring season as the sun is lower in the sky. Additionally, a couple of the windows on the southwest corner were not equipped with any shades/coverings. This adds to the problem in the afternoon.”

The two following comments are from the same building (note that there are two opposite complaints in the same building):
“There is too much glare and the orientation of my cube and the location of nearby windows and the lousy overhead lighting all create an environment that has too much glare.”

“Since I do not have lighting directly above my cubicle it was necessary to get two task lights for my office. It took nearly a year to get the second task light so I could only comfortably use half of my office work surface until I got the second light.”

### 4.2.5 Acoustics

Figure 4.20 shows the percentile rank chart of buildings in the CBE database based on their mean overall satisfaction score with acoustics. The median is slightly higher for LEED-rated/green buildings but their mean score is slightly worse than the rest of CBE database (indicating that the ones that did poorly did really poorly). It is interesting that in contrast to the pattern visible in general building, thermal comfort, and air quality satisfaction, here we do not see a grouping of LEED-rated/green buildings in the top of the percentile rank chart. On the contrary, in acoustics, similar to lighting, we observe a grouping of LEED-rated/green buildings in the bottom of the database.
Overall Satisfaction - Acoustics
LEED-rated/green (n=21) Compared to CBE Database (n=160)

<table>
<thead>
<tr>
<th></th>
<th>Database building</th>
<th>LEED-rated building</th>
<th>Green building</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median</td>
<td>-0.20</td>
<td>-0.27</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.20 - Median and mean acoustics satisfaction scores in LEED-rated/green buildings and the rest of the CBE database

Figure 4.21 shows the acoustic complaints profile in the two main comparison groups. Comparing the two groups, on average a higher percentage of people in LEED-rated/green buildings complain about “people overhearing my private conversations”, “people talking on the phone”, and “telephones ringing”. Interestingly, the frequency of acoustic complaints follows the same order in both of our comparison groups.

The top three complaints in both groups are related to a lack of speech privacy, and distractions from hearing others’ intelligible speech, rather than excessive distractions with noise. These results are similar to what Jensen et al. found in their early analysis of the CBE survey database (refer to section 2.1.6). They found that occupants in CBE survey database are more dissatisfied with sound privacy than noise level.
Figure 4.21 - Mean percentage of acoustic complaints in LEED-rated/green buildings and the rest of the CBE database

As fully explored in section 4.1.4, office type is a confounding factor affecting occupant satisfaction with acoustic quality. I have presented this as an issues related to personal control over IEQ. One has less control over the source of distraction or intrusion in cubicles with high partitions, low partitions, or open plan offices as compared to enclosed private offices. Accordingly, I have checked for the distribution of office types in LEED-rated/green buildings and the rest of the CBE database.

Figure 4.22 shows the comparison between the two groups. The circled office types are those where the difference between percentage of people in the two main comparison groups is statistically significant with p-value <0.05. On average, LEED-rated/green buildings have a higher percentage of people in “cubicles with low partitions”, and “workspace in open plan office with no partition”. LEED-rated/green
buildings have a significantly lower percentage of people in private offices. This trend is neither surprising, nor necessarily negative.

Figure 4.22 - Mean percentage of office types in LEED-rated/green buildings and the rest of the CBE database

Open plan and cubicle office types have been around for a long time, and they are especially attractive in green buildings due to their sustainable benefits. These benefits include reduced material and resource use, enhanced views and daylight penetration, improved airflow and natural ventilation. In addition to these, cubicles and open plan offices enhance ease of interaction in workspace. Heerwagen and Zagreus [75] call the conflicting positive and negative effects of open plan office layouts “the open environment conundrum”. Open plan environments create difficulties for complex cognitive tasks that characterize high value knowledge work, very common in today’s office environment. They emphasize the need for a balance between ease of interaction and the ability to concentrate in open plan offices.
As mentioned in section 4.1, acoustics is the worst overall performing category in CBE survey database. I also mentioned that acoustics is not covered as one of the main components of IEQ in any LEED product (refer to section 2.3.1). Considering that within the limits of today’s indoor environments, acoustics has a limited direct health impact, it is understandable why this IEQ category was not covered in early renditions of LEED green building rating system. Improving thermal comfort, air quality, and lighting all of which have health impacts take priority when designing a green building. In section 2.1.6 I reviewed literature demonstrating the effects of acoustics on occupants’ productivity. Unfortunately, my analysis shows that in acoustics, LEED-rated/green buildings are performing poorly in comparison to other buildings in the CBE survey database. Given the positive objective of improving occupant well-being and productivity in green buildings, acoustics deserves special attention in future renditions of LEED.

4.2.6 Summary

In summary, the result of my benchmarking analysis shows that occupants in LEED-rated/green buildings are more satisfied with their building in general, workspace in general, air quality, and thermal comfort than occupants in the rest of CBE database. Given the fact that thermal comfort, and air quality are two of the worst performing categories in CBE survey database, green buildings mark a positive and so far effective step towards improving these conditions for the occupants.

Given the sample in this study, I could not deduce a significant relationship between individual, total number, or percentage of IEQ credit points achieved in LEED, with the building’s performance in the CBE survey database. In particular, the buildings that perform contrary to the expected trend lead to the following questions:
1. Why do some buildings perform well in a survey category (e.g. air quality, thermal comfort, lighting, etc.) from the occupants’ perspective, despite lack of LEED IEQ points in that category? (I have previously referred to these buildings as low-point/high-score).

2. Why do some buildings perform poorly in a survey category from the occupants’ perspective, despite achieving IEQ points in that category? (I have previously referred to these buildings as high-point/low-score).

The sample size, and the set of variables measured in my study, do not allow me to give definite answers to these questions. But I would like to go back to the topic discussed in section 2.1.7: multi-sensory approach to IEQ, to highlight a few potential answers.

Interactions between IEQ factors in the field have unexpected outcomes for researchers who study occupants’ satisfaction and productivity with their indoor environment. These effects are not easy to parse out. For example, satisfaction with any one IEQ factor can be the result of broad and relatively good (but not astounding) performance across all IEQ categories. It could also be due to getting a few key satisfaction factors right in the building, and thus invoking the “forgiveness factor”. These key satisfaction factors include personal control, views, amount of space, proximity to other occupants and the perimeter, aesthetics, and the responsiveness of the building operations staff. Respondents with good morale, sense of pride in the building, sense of connection to the mission of the organization, connection to nature, knowledge and receptiveness towards sustainability, also have the right psycho-social state of mind to rate their satisfaction with IEQ high across the board. While these psycho-social
qualities can be influenced through integrative green design, my research has focused on specific physical aspects of the indoor environment that enhance occupant satisfaction. Therefore, I stress the importance of a multi-sensory approach to the design and operation of the indoor environment (that would result in a good performance across all IEQ categories), with specific emphasis on key satisfaction factors that invoke the “forgiveness factor”. In the case of the low-point/high-score buildings, this approach might have been more influential in improving occupant satisfaction with IEQ than specific LEED points.

On the contrary, in the case of high-point/low-score buildings, poor performance despite achieving IEQ credit points might be due to some of the LEED credit points not living up to the intent behind them (i.e. the credit point might have been misleading, weak, or inadequate), or a sign of bad implementation of the green building strategy (inadequate information about a new technology, poor implementation of the technology, lack of commissioning). It could also be due to the reverse effects of the “forgiveness factor”. Bordass and Leaman [19] call this reverse effect the “revenge effect”: frustration resulting from the occupants’ disappointment with certain building services or design strategies that reflects on the occupants’ assessment of IEQ across the board. One CBE survey respondent crystallized this effect clearly through this comment: “take down the green crap, this building is not green!” LEED credit points and their implementation will improve in a process of trial and error, as green building design, construction, and operation expertise and experience becomes widely applied. But the “revenge effects” deserve the designers’ and operators’ specific attention.
5 Conclusion

The broad purpose of this study was to help provide healthier and more productive environments for occupants, through improving the effectiveness of the LEED green building rating system as an industry-level outreaching channel. My contribution on this path was to present a clear and useful assessment of occupant well-being and productivity in LEED-rated / green buildings, and present lessons learned that could be used for the future design of green buildings in particular, and all buildings in general.

In my assessment of occupant well-being and productivity in green buildings, I observed that occupants in green buildings are on average more satisfied with their air quality and thermal comfort. Although we still see some green buildings in the lower quartiles of the CBE database, the results of my study suggest that the strategies commonly employed in green buildings have been generally effective in improving occupant satisfaction with air quality and thermal comfort. Considering the fact that air quality and thermal comfort are two of the lowest performing categories in the overall CBE database, these improvements mark positive steps towards providing healthier and more productive environments for the occupants.

Conversely, I observed that lighting and acoustic quality in the green buildings I studied did not show a significant improvement in comparison to conventional buildings. Moreover, the complaint profiles of the two groups in lighting and acoustics category were surprisingly similar, indicating that the green buildings have not significantly altered the frequency and distribution of occupants’ lighting and acoustic complaints.

Complaint profiles of those dissatisfied with their lighting, similar in both green and conventional buildings, point to problems with daylighting and electric lighting
levels. In both groups, respondents preferred more daylight, less glare, and higher ambient lighting levels. It is common in green buildings to provide lower levels of ambient electric lighting to save energy, and more daylight to save energy and enhance the quality of the indoor environment. These design strategies rely mainly on occupant control over their lighting to be effective. Whereas daylighting can save energy and enhance the quality of light indoors, it can also be a potential source of glare and thermal gain, if not designed properly. Occupants must have controls over blinds or shades to control for the effects of daylighting, to avoid “too bright” and “reflections” or “glare” complaints. Similarly, while lower levels of ambient lighting save energy, the ambient lighting levels must be high enough to prevent “too dark” complaints. And enough task lighting should be provided to give occupants control over their lighting levels.

Complaint profiles of those dissatisfied with the acoustics quality of their workspace, again similar in both green and conventional buildings, point to problems due to lack of sound privacy or ability to concentrate in the workspace. Common strategies to maximize daylight, views, ambient lighting opportunity, personal control, flexibility, and equality of workspace allocation in green offices, better conform with a spatial layout of open or partitioned floor plans, as compared with enclosed private offices. I observed this trend in the green buildings in the CBE database: I found that a higher percentage of respondents in green buildings work in cubicles or open plan offices.

Unfortunately, a natural tension exists between the benefits provided by open spaces, and the need for speech privacy to concentrate or perform confidential tasks. While it is unrealistic to provide every occupant with a private office, and counter to strategies for effective daylighting and natural ventilation, my results suggest that there is
need for innovative strategies that provide occupants with opportunity to choose quiet and privacy when required. One mitigation strategy would be to provide optional places of retreat for occupants where they could concentrate on tasks, conduct private conversation, or shut down the noise if need be. Another strategy is sound masking or improving acoustical properties of room and workstation surfaces. Due to the demonstrable impacts of acoustics on productivity, it is essential that acoustics becomes an early design consideration and concern.

Throughout my thesis, I paid specific attention to the relationship between personal control over the indoor environment and occupant satisfaction with IEQ. I presented evidence why I believe that personal control will improve occupant satisfaction with IEQ. Personal control over the indoor environment includes the possibility to raise or lower temperature and airflow, to raise or lower blinds and shades, switch on or off lights as per their task requirements, and close or open a door when they need more privacy or more workspace interaction.

The occupant survey method used in this study is an effective tool that can be used in systematic assessments of buildings, benchmarking, and building diagnostics. The relative low cost of conducting web-based occupant surveys has made it possible for CBE to collect a unique and rich database of standardized occupant responses about their satisfaction and productivity in relation to IEQ. Using this unique database, I was able to present lessons learned from a large benchmarking analysis.

The web-based occupant survey can also be used in more comprehensive POEs that include physical measurements and face-to-face interviews with occupants, designers, and operators of the building. POE completes the feedback loop that is
essential for the future development of green buildings, revisions to green building normative frameworks such as LEED, and advancing our understanding about the complex interactions of physical and psycho-social environmental factors in real-world environments.
6 Future research directions

Due to the limitations of the type of data available in this study (occupant survey results only, no physical measurements), the scope of this study (a general assessment of multiple buildings rather than an in-depth case study), and the sample size available (only 21 LEED-rated/green buildings), I could not explore the direct relationships between each individual green building design and operation strategy with occupant satisfaction. As green buildings become a more substantial part of the building construction market, and the LEED-rated/green building sample in the CBE survey database grows, the direct relationship between each green building strategy and occupant satisfaction can be more strongly established. Such a study would need to be complemented with physical measurements, which could confirm the actual outcome of the green building strategy on the physical indoor environment. The study could be further complemented through in-depth case studies of the outlying green buildings, i.e. LEED-rated green buildings that have high-points/low-score and low-points/high-score.

Addressing the varied performance of LEED-rated green buildings, some of which may result from “point-mongering” in LEED, it will be essential in the future to investigate the green building design process. How do design teams, owners, and operators decide on which points to pursue and which points to leave off? What are the values hidden in such decisions? If some important IEQ points are consistently value-engineered out, or ignored due to lack of expertise and knowledge, the USGBC might consider reworking the distribution of points, their allocations in different categories, and putting heavier emphasis on performance evaluation rather than design criteria.
7 References


Also see:


Also see:


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