Evaluating the Performance of Leadership in Energy and Environmental Design (LEED) Certified Facilities using Data-Driven Predictive Models for Energy and Occupant Satisfaction with Indoor Environmental Quality (IEQ)

by

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A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved November 2015 by the
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ARIZONA STATE UNIVERSITY

December 2015

ABSTRACT

Given the importance of buildings as major consumers of resources worldwide, several organizations are working avidly to ensure the negative impacts of buildings are minimized. The U.S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) rating system is one such effort to recognize buildings that are designed to achieve a superior performance in several areas including energy consumption and indoor environmental quality (IEQ). The primary objectives of this study are to investigate the performance of LEED certified facilities in terms of energy consumption and occupant satisfaction with IEQ, and introduce a framework to assess the performance of LEED certified buildings.

This thesis attempts to achieve the research objectives by examining the LEED certified buildings on the Arizona State University (ASU) campus in Tempe, AZ, from two complementary perspectives: the Macro-level and the Micro-level. Heating, cooling, and electricity data were collected from the LEED-certified buildings on campus, and their energy use intensity was calculated in order to investigate the buildings' actual energy performance. Additionally, IEQ occupant satisfaction surveys were used to investigate users' satisfaction with the space layout, space furniture, thermal comfort, indoor air quality, lighting level, acoustic quality, water efficiency, cleanliness and maintenance of the facilities they occupy.

From a Macro-level perspective, the results suggest ASU LEED buildings consume less energy than regional counterparts, and exhibit higher occupant satisfaction than national counterparts. The occupant satisfaction results are in line with the literature

on LEED buildings, whereas the energy results contribute to the inconclusive body of knowledge on energy performance improvements linked to LEED certification. From a Micro-level perspective, data analysis suggest an inconsistency between the LEED points earned for the Energy & Atmosphere and IEQ categories, on one hand, and the respective levels of energy consumption and occupant satisfaction on the other hand. Accordingly, this study showcases the variation in the performance results when approached from different perspectives. This contribution highlights the need to consider the Macro-level and Micro-level assessments in tandem, and assess LEED building performance from these two distinct but complementary perspectives in order to develop a more comprehensive understanding of the actual building performance.

ACKNOWLEDGMENTS

This research would not have been possible without the dedication and support of many people. First and foremost, I am extremely thankful to my advisor, Dr. *Mounir El Asmar*, who guided me tirelessly throughout my studies at Arizona State University. He has set an example of excellence as a researcher, mentor, instructor, and role model. I owe a debt of gratitude to his encouragement, inspiration, and motivation to push ideas one level further. I am also very grateful to my committee members Dr. *Oswald Chong* and Dr. *Kristen Parrish* for their enthusiasm, guidance, and support. Collectively, their passion for education and academic research challenged me to pursue my research interests.

The work on this thesis is the result of collaboration with many other researchers and colleagues. I was fortunate to work with Dr. *Issam Srour* from the American University of Beirut who was always ready to provide all the assistance when I have faced challenges. I thank my colleague at ASU *Claire Tilton* for helping me in the data collection. Dr. *Patricia Olson*, *Philip Plentzas*, *Donald Turner*, and *Robert Vandling* from the Facilities Development and Management (FDM) at ASU were always ready to provide any support. I would like to acknowledge Dr. *Gilbert Haddad*, *Nicholas Williard*, and Dr. *Meenakshi Mishra* for championing my enthusiasm for data mining and analytics. I am also extremely grateful to the guidance and support of Dr. *Kamil Kaloush* throughout my studies and research at ASU.

I was very fortunate to be a member of the π-DEAS research team at ASU. I am particularly grateful for the numerous times they have reviewed my work, provided valuable suggestions, and for having stood by me. I thank *Jera Sullivan* who provided fantastic advice and ideas on the research. *David Ramsey* and *Tober Francom* fostered my intellectual curiosity and made this achievement possible. I take this opportunity to express gratitude to all of the School of Sustainable Engineering and the Built Environment faculty and staff members for their help and support. In particular, I am grateful to Susan Garrison who made my journey at ASU an unforgettable experience.

Finally, I would like to acknowledge my heroes: my parents, my brothers and sister, my fiancée and her family, and my friends for being my foundation of compassion, understanding, and courage. You each vicariously lived this journey with me and without you it would not have been half as much fun. Thank you all for your loving support.

TABLE OF CONTENTS

CHAPTER Page

CHAPTER Page

LIST OF TABLES

LIST OF FIGURES

Figure Page

Figure Page

CHAPTER 1

INTRODUCTION

1.1. BACKGROUND

Buildings are responsible for about 40% of the energy (U.S. Energy Information Administration 2010) and 70% of the electricity (Koomey 2007) consumed in the United States. People spend on average 90% of their time inside buildings (Webster et al. 2008); however, the Environmental Protection Agency (EPA) reports indoor levels of pollutants may run two to five times – and occasionally more than 100 times – higher than outdoor levels (USGBC 2006). Accordingly, several organizations are avidly working to improve both their facilities' energy consumption and Indoor Environmental Quality (IEQ). One strategy used by organizations is requiring their buildings achieve the U.S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) certification.

1.1.1. LEED Certification

LEED is a third party certification program that serves as a design and construction tool for new and existing institutional, commercial and residential establishments (Cotera 2011). LEED's development was in response to the increasing awareness and concerns about the negative environmental impacts that can be generated by buildings, including energy consumption, depletion of natural resources, waste production, and the increasing reported incidences of the adverse health impacts caused by IEQ issues. Such issues include sick building syndrome and multiple chemical sensitivity (Lee and Guerin 2009). As the evidence challenging the long-term effectiveness of green design continues to compound, pressure is being placed on USGBC to make improvements to its rating system (Cotera 2011). After developing the pilot version, the USGBC added seven new versions of LEED before reaching the latest version: LEED v4. The latest version includes new market sector adaptations for data centers, warehouses and distribution centers, hospitality, existing schools, existing retail and mid-rise residential projects to ensure that LEED fits the unique aspects of projects (USGBC 2014). A building can earn credits under the *IEQ* category, the *Location and Transportation* category, the *Sustainable Sites* category, the *Water Efficiency* category, the *Energy and Atmosphere* category, the *Materials and Resources* category, and the *Innovation and Regional Priority* categories (extra points) to get certified. Depending on the total points earned out of 100 base points and 10 extra points, a facility can achieve one of the four levels: *Certified* (40-49 points), *Silver* (50-59 points), *Gold* (60-79 points), and *Platinum* (80 points and above).

1.1.2. Energy Consumption of LEED Buildings

There have been many studies related to energy consumption of LEED buildings. Turner (2006) assessed the performance of 11 buildings in the Cascadia region and found that although all sampled buildings had better savings than their designed energy use, only two of them performed better than the average commercial building stock. Diamond et al. (2006) investigated 21 LEED certified buildings and showed the LEED energy credits did not have any correlation with the actual energy use. Later, Fowler and Rauch (2008) found the energy consumption of 12 LEED government buildings is 25%-30% lower than the average of commercial building stock. Turner and Frankel (2008) investigated 552

LEED buildings and showed a 24% lower energy use intensity (EUI) than national counterparts. However, the final results of the study state “high energy use buildings [were] generally considered separately,” which eliminates data that contributes a larger EUI. Subsequently, Newsham et al. (2009) found the measured energy performance of LEED buildings had little correlation with the certification level of the building, or the number of energy credits achieved by the building. These results were contested later by Scofield (2009) who concluded, using the same dataset, there is no evidence that LEED certification has collectively lowered energy consumption for office buildings. Menassa et al. (2012) later tested the same hypothesis by investigating a more targeted dataset consisting of the U.S. Navy LEED certified buildings. Although these buildings were required to become LEED certified in an effort to improve energy efficiency and mitigate greenhouse gas emissions, the authors found only 3 out of 11 buildings showed energy efficiency gains compared to CBECS buildings, in addition to the absence of any correlation between the number of earned LEED points and energy savings.

1.1.3. Indoor Environmental Quality of LEED Buildings

Several studies investigated occupant satisfaction in both LEED and non-LEED buildings. For instance, Turner (2006) investigated 11 LEED certified buildings in the Cascadia region and established users are satisfied with lighting and air quality of their buildings, but unsatisfied with sound conditions, when compared to 1000-plus cases reviewed under the Buildings in Use (BIU) tool of Vischer and Preiser (2005). Similarly, Abbaszadeh et al. (2006) compared occupant satisfaction in 21 LEED certified buildings with that of 160 conventional buildings, and noticed that occupants in LEED buildings were more satisfied with thermal comfort, air quality, office furnishings, cleaning and maintenance, but less satisfied with lighting and acoustics than occupants of conventional buildings. Lee and Guerin (2009) later confirmed these same findings by surveying occupants in 15 LEED certified buildings. The authors found users were satisfied with cleanliness, maintenance, office furnishing quality and indoor air quality, but dissatisfied with thermal comfort and acoustic quality. Another study by Lee (2011) investigated whether indoor air quality (IAQ) and thermal comfort measured by occupants' satisfaction and their perceived job performance in personal workspaces of LEED certified buildings were associated with the rating level of the LEED certification. The author concluded the higher the certification level is, the higher the workers' satisfaction and perceived job performance would be. Cotera (2011) conducted a post-occupancy evaluation of two LEED certified education buildings at the University of Florida in Gainesville and found both buildings were 29% above the CBE standard. Researchers also studied the effect of LEED buildings on the occupant satisfaction through absenteeism and performance. For example, Issa et al. (2011) showed that student, teacher and staff absenteeism in LEED certified schools in Toronto improved by 2% to 7.5%, whereas student performance improved by 8% to 19% when compared with conventional schools. Besides the effect of a buildings sustainable design on the occupant satisfaction, scholars also investigated the correlation between building usage duration and occupant satisfaction. For example, Stefano and Sergio (2014) analyzed occupant satisfaction levels in 65 LEED-certified buildings – a subset of the CBE survey database – and called attention on the effect of time spent at the workspace (less or more than one year) on occupant satisfaction with the building. The obtained results suggest the positive value of LEED certification from the point of view of occupant satisfaction tends to decrease with time.

1.1.4. Costs Associated with LEED Certification

The impact of LEED certification on the facility cost was examined in several studies. Kats et al. (2003) compared the costs of 33 LEED buildings across the U.S. to their conventional counterparts. The study showed LEED *Platinum* buildings cost 6.50% more than conventional buildings, followed by LEED *Silver* buildings (2.11%), LEED *Gold* buildings (1.82%) and LEED *Certified* (0.66%). However, this order was different in Miller et al.'s (2008) study, which established an 8.6% cost premium for LEED *Platinum* buildings as compared to the LEED *Certified* buildings, followed by LEED *Gold* buildings (4.0%), and LEED *Silver* buildings (1.9%). The relationship between LEED certification levels and initial facility cost was also discussed in a study on New York City LEED certified buildings (Kaplan et al. 2009). The study reported the highest construction cost appertain to LEED *Platinum* buildings ($463/ft^2$), followed by LEED *Gold* buildings ($440/ft^2$), LEED *Silver* buildings ($439/ft^2$), and LEED *Certified* buildings ($315/ft^2$).

1.2. RESEARCH GAP AND OBJECTIVES

The results of the existing literature on LEED building performance are not unanimous. However, it is important to quantify and justify the long-term benefits of the certification because it often requires an additional first cost to the facility owner. Scholars have compared the actual performance of LEED buildings to that of non-LEED counterparts. However, such comparisons often do not control for the many variations between the different buildings' characteristics and features. Moreover, there is no conclusive evidence linking the increasing LEED certification levels to measured improvements in performance, in terms of energy savings and occupant satisfaction, in order to justify the additional first cost. The discrepancy in the existing literature between buildings' LEED ratings and their actual performance presents a series of interesting research questions:

1. Are the occupants of LEED buildings more satisfied than those of non-LEED building counterparts?
2. Do LEED buildings consume less energy?
3. How to best assess the performance of LEED certified buildings?

The contributions of this thesis include answering these questions for the focused scope of higher education facilities in climate zone 2B. The primary objectives of this thesis are to investigate the performance of LEED certified facilities and to introduce a more comprehensive framework to evaluate this performance.

1.3. RESEARCH APPROACH

The research approach consists of three phases as shown in Figure 1. Next, each phase is introduced and discussed individually.

<table>
<tr><th>Research Phases</th><th>Contributions to the Body of Knowledge</th></tr>
<tr><td>
Phase A: Indoor Environmental Quality

Investigating the IEQ for two sets of university buildings:

Selecting the buildings
Developing a survey for occupant satisfaction with IEQ
Collecting data
Analyzing and discussing the results

Comparing the differences between the results:

Underlining the factors that explain the difference in IEQ occupant satisfaction

</td><td>
“<u>Are Buildings Occupants Satisfied with Indoor Environmental Quality of Higher Education Facilities?” in Energy Procedia</u>

Factors that explain the differences across the two campuses:

Building age
Commitment to sustainable and environmentally aware design through the LEED certificate

Comparison between IEQ LEED points and occupant satisfaction rates:

No correlation between the buildings’ earned points on the LEED IEQ category and the level of users’ satisfaction

</td></tr>
<tr><td>
Phase B: Energy Consumption
Generating a model to predict the energy consumption of research facilities in climate zone 2B:

Selecting Non-LEED buildings
Collecting all relevant features
Developing eight different models
Adopting the best fit model

Investigating the energy consumption of LEED buildings:

Computing the deviation of LEED research buildings’ energy consumption from the non-LEED models
Correlating between LEED certification and the actual energy consumption of certified facilities

</td><td>
“<u>Applying Data-driven Predictive Models to Investigate the Energy Consumption of LEED-Certified Research Buildings in Climate Zone 2B” in Energy and Buildings</u>

Data-driven predictive model selection:

Gradient Boosting Regression

Comparison between Energy LEED points and actual energy consumption:

No correlation between the buildings’ earned points on the LEED Energy & Atmosphere category and the energy efficiency

Introducing a novel method to assess the energy efficiency of LEED buildings:

Using a robust model for non-LEED research buildings to investigate LEED research buildings’ energy consumption

</td></tr>
<tr><td>
Phase C: Introducing a Dual Assessment Framework to Assess LEED facilities’ Indoor Environmental Quality and Energy Consumption

Comparing LEED buildings performance to the actual performance of their conventional counterparts (Macro-level):

Indoor Environmental Quality
Energy Consumption

Comparing the number of LEED points allocated per category to the actual performance of LEED certified buildings (Micro-level):

Indoor Environmental Quality
Energy Consumption

Comparing Macro-level to Micro-level:

Introducing a more comprehensive assessment framework

</td><td>
<u>“Evaluating the Actual Energy Performance and Occupant Satisfaction of LEED Certified Higher Education Facilities” in the American Society of Civil Engineers’ Journal of Architectural Engineering</u>

On the Macro-level:

LEED buildings were performing better than their regional and national counterparts

On the Micro-level:

LEED buildings actual performance was not correlated with the original number of correspondent LEED points

Macro-level versus Micro-level:

Analyzing the same dataset from two different perspectives led to inconsistent results
Shifting to a certification model based on actual performance
Including measured savings as a prerequisite for certification, which should only occur after the building is in operation

</td></tr>
</table>

Figure 1. Research Phases and Contributions

1.3.1. Phase A: Indoor Environmental Quality

Phase A began with developing a survey to investigate the occupants satisfaction of higher education facilities. The objective of this phase is to measure the occupant satisfaction with key IEQ metrics during the operation phase of educational facilities. A comparison of the levels of satisfaction in IEQ for two sets of higher education facilities located in Arizona, US and Beirut, Lebanon respectively revealed two main factors that explain the differences across the two campuses: (1) the commitment to sustainable and environmentally-aware design through LEED, and (2) the building age. .A close examination of the occupant satisfaction rates in LEED certified facilities showed the absence of a clear correlation between the buildings' earned LEED points in the respective category, and the level of occupant satisfaction. The results of the conducted surveys highlighted the need to continuously monitor and improve indoor environmental conditions. The findings of this phase provided motivation for the second phase for a sizeable quantitative data collection effort to also investigate the performance of LEED certified facilities in terms of energy consumption.

1.3.2. Phase B: Energy Consumption

The objective of this phase is to investigate the energy consumption of LEED certified research buildings in climate zone 2B. After collecting the electricity, heating, and cooling energy consumption and other key features from research facilities in climate zone 2B, eight different predictive models were generated using a data-driven approach. The contributions of this phase include a comparison of those data-driven predictive models that led to the introduction of a novel method to assess LEED energy performance.

The results showed the superiority of the Gradient Boosting Regression over other regression methods in predicting energy consumption for this dataset. Moreover, the results showed an inconsistency between the buildings' earned LEED points and their energy performance. The method introduced in this phase for LEED performance assessment uses the robust regression model for non-LEED research buildings, which it applies to LEED certified facilities to investigate the deviation in energy consumption as well as the correlation between LEED certification and the actual energy consumption of certified facilities.

1.3.3. Phase C: Introducing a Dual Assessment Framework to Assess LEED Facilities' Indoor Environmental Quality and Energy Consumption

This phase introduced an assessment framework that considers two levels for a building performance evaluation while investigating both indoor environmental quality and energy consumption. On the Macro-level, the framework compares LEED buildings performance to the actual performance of their conventional counterparts. On the Micro-level, the framework compares the number of LEED points allocated per category to the actual performance of LEED certified buildings in this respective category. Analyzing the same dataset from two different perspectives led to inconsistent results. From a Macro-level perspective, the studied LEED buildings were performing better than their regional and national counterparts. However, when these same buildings were approached from a Micro-level perspective, their actual energy and IEQ performance was not correlated with the original number of LEED points allocated to the energy and IEQ categories in the design phase.

These results contribute to the body of knowledge on energy and IEQ performance improvements linked to LEED certification. Based on the results of this phase, the study showed the importance of assessing LEED buildings based on both levels for a more comprehensive assessment of LEED building performance.

1.4. THESIS FORMAT

The thesis is organized around three (3) journal papers. Each of the three subsequent chapters represents a stand-alone peer-reviewed technical article that has been accepted or is currently being reviewed (at the time of this writing) for an archival journal publication. Therefore, each chapter will have its own abstract, introduction, objectives, methodology, findings, conclusions, and referenced articles. The thesis concludes with Chapter 5, which summarizes the overall contribution of this study to theory and practice, and the recommended future research.

The investigation of the actual occupant satisfaction performance of higher-education facilities is presented in Chapter 2, which showcases Phase *A* of the study. The findings of this phase were published in Volume 50 of Elsevier's *Energy Procedia* journal: El Asmar, M., Chokor, A., and Srour, I. (2014). "Are Building Occupants Satisfied with Indoor Environmental Quality of Higher Education Facilities?" *Energy Procedia*, Volume 50, pp. 751-760.

Chapter 3 presents Phase *B* of the study. The chapter provides an in-depth investigation of the energy consumption of LEED-certified research facilities. The paper was submitted to Elsevier's *Energy and Buildings* journal, and was under review at the time of this writing: Chokor, A., and El Asmar, M.(2015). "Applying Data-Driven Predictive Models to Investigate the Energy Consumption of LEED-Certified Research Buildings in Climate Zone 2B." *Energy and Buildings* (under review).

Chapter 4 introduces a dual assessment framework to evaluate LEED-certified facilities' performance in terms of both occupant satisfaction and energy consumption. The chapter presents Phase *C* of the thesis. The findings from this phase were accepted in a special issue of American Society of Civil Engineers (ASCE)'s *Journal of Architectural Engineering*: Chokor, A., El Asmar, M., Tilton, C., and Srour, I. (2015). "Evaluating the Actual Energy Performance and Occupant Satisfaction of LEED Certified Higher Education Facilities." *ASCE Journal of Architectural Engineering*. (in press).

Chapter 5 summarizes the major findings, contributions, and limitations of the study and provides recommendations for future research. Following Chapter 5 is appendix A including the occupants' satisfaction survey for IEQ.

In addition to the three journal papers listed above, two conference papers also resulted from this research:

- El Asmar, M., Chokor, A., and Srour, I. (2014). "Occupant Satisfaction with Indoor Environmental Quality: A Study of the LEED-Certified Buildings on the Arizona State University Campus," *Proceedings of the International Conference on Sustainable Infrastructure*, Long Beach, California, November 6-8, 2014;

- Chokor, A. and El Asmar, M. (2016). "Predicting the Electricity Energy Consumption Research Buildings Using Big Data Tools," submitted to the *Construction Research Congress,* San Juan, Puerto Rico, May 31-June 2, 2016.

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Menassa, C., Mangasarian, S., El Asmar, M., and Kirar, C. (2012). “Energy Consumption Evaluation of U.S. Navy LEED-Certified Buildings”. *Journal of Performance of Constructed Facilities* , Volume 26, pp. 46-53.

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CHAPTER 2

ARE BUILDING OCCUPANTS SATISFIED WITH INDOOR ENVIRONMENTAL QUALITY OF HIGHER EDUCATION FACILITIES?

El Asmar, M., Chokor, A., and Srour, I. (2014). “Are Building Occupants Satisfied with Indoor Environmental Quality of Higher Education Facilities?” *Energy Procedia,* Volume 50, pp. 751-760.

2.1. ABSTRACT

Balancing energy performance and Indoor Environmental Quality (IEQ) performance has become a conventional tradeoff in sustainable building design. In recognition of the impact IEQ performance has on the occupants of educational facilities, universities are increasingly interested in tracking the performance of their buildings. This paper highlights and quantifies several key factors that affect the occupant satisfaction of higher education facilities by comparing building performance of two campuses located in two different countries and environments. A total of 320 occupants participated in IEQ occupant satisfaction surveys, split evenly between the two campuses, to investigate their satisfaction with the space layout, space furniture, thermal comfort, indoor air quality, lighting level, acoustic quality, water efficiency, cleanliness and maintenance of the facilities they occupy. The difference in IEQ performance across the two campuses was around 17%, which lays the foundation for a future study to explore the reasons behind this noticeable variation.

2.2. INTRODUCTION

Sustaining adequate Indoor Environmental Quality (IEQ) decreases the frequency and severity of illness and therefore the absenteeism and lost time of building users (Issa et al. 2011). In recognition of IEQ’s impact on the users of educational facilities, schools and universities are increasingly interested in measuring and understanding the performance of their buildings. The architecture, engineering and construction industries have developed several policies and practices to improve the health and maintain the comfort of faculty, staff, students and visitors of educational facilities. Concurrently, a recent surge in the green building movement led numerous universities to commit to employing sustainable building practices for their facilities. Accordingly, several building rating systems emerged to standardize some of these practices, such as Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM).

The aim of this study is to investigate the actual occupant satisfaction performance of educational facilities. First, the paper compares the level of satisfaction with IEQ of two higher educational campuses located in two different environments and countries: Arizona State University (ASU) in Tempe, Arizona, USA and the American University of Beirut (AUB) in Beirut, Lebanon. Second, the paper examines the factors that could affect the IEQ performance of educational structures including LEED design improvements and building age. The paper ends with a discussion of the recommendations to be implemented in designing, constructing and maintaining an educational facility.

2.3. LITERATURE AND BACKGROUND

The literature shows an increasing state of awareness concerning IEQ and its related effects on the satisfaction, health and performance of occupants. Indoor environment performance is considered a major factor of “sustainable” buildings and has been increasingly studied in the past decade. In fact, minimizing the effects of indoor pollutants is a priority in building design, especially since Americans spend on average 90% of their time indoors where the Environmental Protection Agency (EPA) reports those levels of pollutants may run two to five times – and occasionally more than 100 times – higher than outdoor levels (USGBC 2006). Consequently, the U.S. Green Building Council (USGBC) rated thermal comfort, lighting and acoustics as major aspects of indoor environmental quality (USGBC 2009). Although it is rarely achieved, the USGBC recommends also a minimum level of 80% of satisfaction regarding the thermal comfort of high performance facilities (USGBC 2006).

Several studies investigated the factors that affect educational facilities occupants' satisfaction and consequently their performance and grades. A preliminary study conducted by Heschong (1999) showcased the effect of daylighting in classes by improving the performance of students on math tests by 20% and reading tests by 26%. Moreover, Heschong (2003) established that good views could enhance student learning whereas glare, direct sun penetration, poor ventilation and poor indoor air quality could worsen it. Another study by Hathaway et al. (1992) found that studying in classrooms with natural daylight reduced the absenteeism 3.5 days per year compared to little daylighting classrooms. Issa et al. (2011) showed that student, teacher and staff absenteeism in green Canadian schools improved by 2–7.5%, whereas student performance improved by 8–19% when compared with conventional schools. Despite of the limited accomplished work on the indoor environments quality of educational buildings, researchers have not exposed the main parameters that might be affecting the users' satisfaction in education facilities.

The quality of the overall building is important to workers as their psychological well-being and morale at work are fulfilled (Webster et al. 2008). Lee (2011) concluded that an improvement in indoor air quality (IAQ) would increase worker satisfaction with the overall building quality. IAQ and thermal comfort are directly associated with worker productivity and health issues in the workplace. Since the cost of employees in doing business is substantially higher than the cost of energy, workplace designers need to provide workers an environment as comfortable and productive as possible through improved IAQ and thermal comfort. In addition, Miller et al. (2009) surveyed 2,000 workers and showed that improving the IEQ could increase the productivity by 4.8% and reduce the sick leave days by 3 days per year. Besides showing that user access to natural daylight and views, comfortable temperatures and appropriate acoustics can directly affect the sense of satisfaction, health and productivity, Fisk (2000) found that greener indoor environments could reduce allergies and asthmas by 8 to 25%, and reduce sick building syndrome symptoms by 9 to 20%, leading to savings in lost time and productivity of US $10 to 35 billion. Another study (Singh et al. 2011) noticed that improved IEQ contributed to reductions in perceived absenteeism and work hours affected by asthma, respiratory allergies, depression, and stress and to self-reported improvements in productivity. These improvements in perceived productivity were fairly substantial and could result in an additional 38.98 work hours per year for each occupant.

The IEQ parameters that mostly affect occupant satisfaction have been studied thoroughly. Frontczak and Wargocki (2011) found that thermal comfort is the most important factor among others IEQ parameter. Lee and Guerin (2009) showed that office-furnishing quality has a significant impact on occupants' satisfaction and performance while indoor air quality affected only the occupants' performance. Kim and De Dear (2012) identified the nonlinear relationship between IEQ factors and occupant overall satisfaction and categorized the factors into Basic Factors and Proportional Factors according to their influence on occupant satisfaction.

The U.S. Green Building Council (USGBC)'s LEED rating system organizes these different IEQ metrics as part of a structured category as shown in Figure 2. The primary goal of LEED is to promote green building practices to provide environmentally responsible, profitable and healthy environments for building occupants (USGBC 2008). The creation of LEED was a national response to the increasing social awareness and concerns about the negative environmental impacts that could be generated by buildings including increased energy consumption, depletion of natural resources and waste production, and the increasing reported incidences of the adverse health impacts caused by problems of indoor environmental quality (IEQ) such as sick building syndrome (SBS), multiple chemical sensitivity (MCS), and building related illness (BRI) (Lee and Guerin 2009). IEQ is one of the five main LEED categories whose design criteria are sought most often in LEED certification and whose points were most frequently earned in many early LEED-certified buildings (Building Design & Construction 2003). The LEED

IEQ category intends to provide indoor environmental design criteria to create healthy, comfortable and productive indoor environments for building occupants (CGOEM 2006).

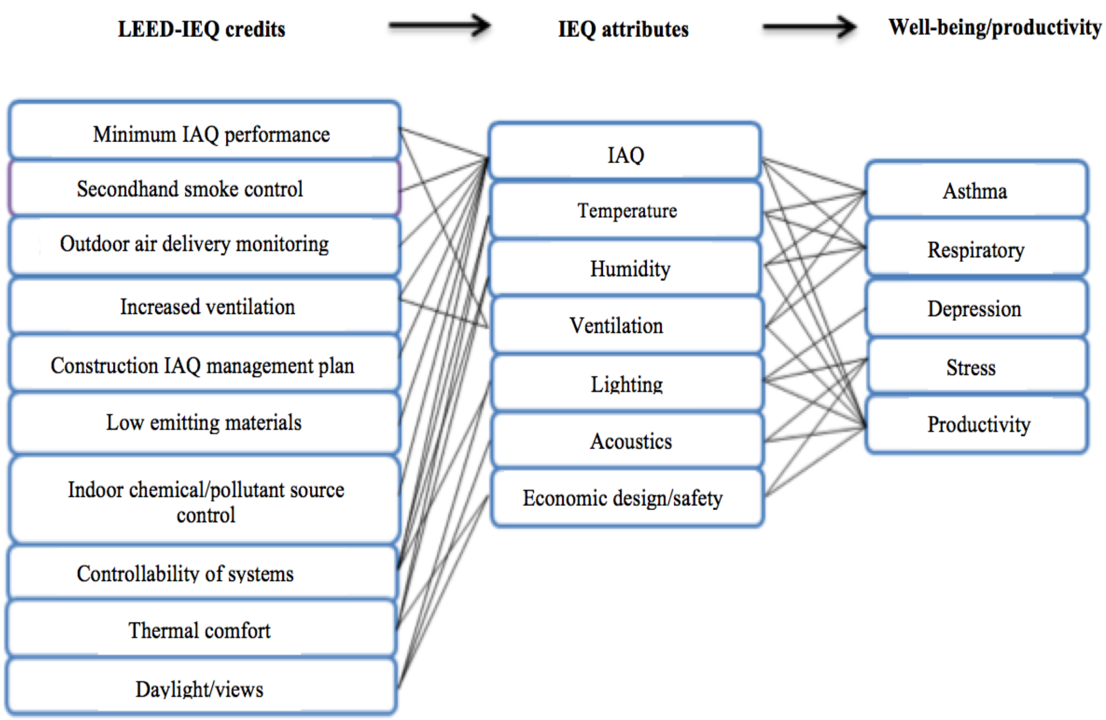

Figure 2. LEED-IEQ Occupant Well-being and Productivity Structure (Adapted from Singh et al. 2010)

2.4. OBJECTIVE AND RESEARCH METHOD

The main purpose of indoor environmental quality standards is to best serve the occupants' interest throughout the design, construction and operation phases of built facilities. The objective of this paper is to measure the occupant satisfaction with key IEQ metrics during the operation phase of educational facilities. The methodology used to collect data and compute levels of satisfaction is detailed next and entails four steps: (1) selecting buildings at the ASU Tempe campus and the AUB Beirut campus; (2) selecting a Post Occupancy Evaluation (POE) survey to evaluate the occupant levels of satisfaction; (3) collecting the satisfaction levels data from both campuses; (4) analyzing the levels of satisfaction in both campuses and discussing potential parameters that might be affecting the users' satisfaction with IEQ performance in higher education facilities.

2.4.1. Building selection

For a building to be selected, it had to be occupied for at least one year prior to the start of the data collection, i.e. June 2013. A total of seven ASU facilities were chosen for this study upon the suggestion of the ASU Facilities Development and Management (FDM) in Tempe, in Arizona, USA. Similarly, eight AUB facilities were selected according to their life of service on the Beirut campus in Lebanon. Table 1 summarizes the names, occupancy dates, gross area (m^2), net area (m^2), classroom area percentages, offices area percentages, research area percentages, library area percentages and classroom laboratories percentage of the buildings.

2.4.2. Survey Selection

In order to measure users' satisfaction with respect to the indoor environment performance of each building, a survey was developed based on the Occupant IEQ survey of the Center for the Built Environment (CBE) at the University of California at Berkeley. After analyzing the questions from the CBE' s original survey, an adaptation of Cotera' s Occupant Indoor Environment Quality Satisfaction Survey (Cotera 2011) was created to best fit the difference in environments and occupants characteristics in both campuses. The CBE's survey is recognized as a reliable post-occupancy evaluation tool for measuring occupants' opinions and satisfaction with the IEQ performance of buildings (Lee and Kim 2008). This tool offers a qualitative methodology to estimate how a building is performing through eight equally important sections. These are: workspace layout, workspace furniture, thermal comfort, indoor air quality, lighting levels, acoustic quality, water efficiency and cleanliness and maintenance in addition to the occupant background information and the overall satisfaction with space (Center for the Built Environment 2010). Building users across the two considered campuses were asked to rate their satisfaction levels in each section on a 5-point Likert scale (1 being very dissatisfied, 5 being very satisfied). All respondents were eighteen years old or more, and were classified according to their ultimate use and the duration of occupying the building. As such, users were categorized into three main types: (a) students who used the building continuously for more than three months; (b) faculty/staff who worked in the designated building for more than three months; and (c) visitors who spent less than three months using this building. Average satisfaction ratings for each of the eight survey sections were computed and compared to the CBE's database, which contains results from over 59,000 completed surveys.

2.4.3. Data Collection

Participants were invited at random in each campus to participate by completing a paper-based survey, which takes from 10 to 15 minutes. The responses were kept anonymous to guarantee a strict confidentiality and privacy of the provided information. In each of the 15 considered buildings, 20 persons were asked to complete the survey, which resulted in a total of 320 responses (The ASU Hassayampa Village was split into two buildings or sub-villages).

Table 1. Characteristics of ASU and AUB Selected Buildings

	Building name	Occupancy Date	Gross Area (m^2)	Net Area (m^2)	Classroom (%)	Office (%)	Research (%)	Library (%)	Classroom Laboratory (%)
ASU	Wrigley Hall	2004	4,807	2,790	30	70	0	0	0
	ISTB2	2005	6,596	3,437	0	30	60	0	10
	Fulton Center	2005	15,232	6,420	0	100	0	0	0
	ISTB1	2006	17,930	8,083	0	29	71	0	0
	Hassayampa Village	2006	55,294	N/A	N/A	N/A	N/A	N/A	N/A
	Barett Village	2009	54,404	N/A	N/A	N/A	N/A	N/A	N/A
	ISTB4	2012	30,379	14,864	0	24	16	57	3
AUB	Bliss Hall	1900	2,646	1,838	37	41	0	0	22
	Fisk Hall	1901	3,507	1,816	33	64	0	0	4
	Dal Al Handasah Architecture Building	1930	4,063	2,398	81	15	0	0	4
	Bechtel Engineering	1952	6,347	5,085	61	23	0	7	10
	Nicely Hall	1960	6,740	4,857	89	11	0	0	0
	Raymond Ghosn	2000	1,338	838	0	30	0	0	70
	CCC SRB	2006	5,416	2,626	0	13	0	0	87
	Olayan School of Business	2009	19,734	4,667	50	40	0	0	10

N/A: Not Available

2.4.4. Data Analysis and Discussion

For each campus, the collected data was entered and analyzed for all eight survey sections. First, the average satisfaction index was computed for each survey participant. Second, the average level of satisfaction for each building and consequently the average overall satisfaction level in each of the two campuses were calculated. An unpaired t-test was then used to check the statistical significance of the results across the two campuses.

2.5. RESULTS AND DISCUSSION

This section presents the results of the survey and ends with a discussion of the potential parameters that could explain the difference in performance across the two campuses. Of the respondents at AUB 16.9% were faculty/staff, 80.6% were students and only 2.5% were visitors. This percent split is comparable to the total number of users of the selected buildings. In contrast, of the respondents at ASU 41.9% were faculty/staff, 49.3% were students and only 8.8% were visitors (Figure 3). In order to check the statistical significance of the results, an unpaired t-test with unequal variances and a 0.05 significance level was used. For that purpose, the average points of 160 participants from AUB was compared to the average points of 160 participants from ASU. This contributes to the hypothesis that occupants' satisfaction of AUB users (x) is equal to that of ASU users (y). This assumption will be confirmed, at a 95% confidence level, for the null hypothesis (H0) or its rejection (H1):

- H0: $x = y$ if p-value is greater than 0.05; then, occupants' satisfaction with IEQ is similar for both campuses.
- H1: $x \neq y$ if p-value is less than 0.05; then, occupants' satisfaction with IEQ is different across the two campuses.

These results show that p-value is very small (less than 0.05) which correspond to the null hypothesis rejection; therefore, the collected data is statistically significant at a 95% confidence level.

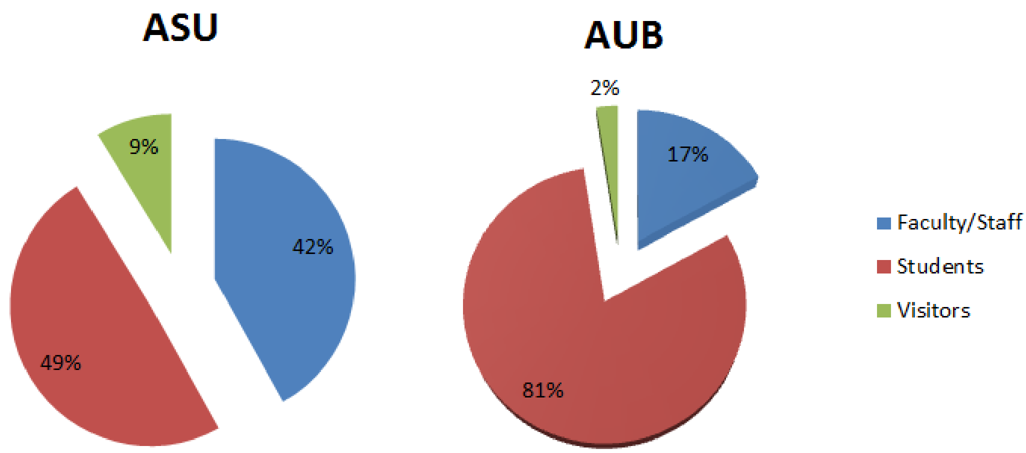

Figure 3. Participants' Characteristics

The average levels of satisfaction were calculated for both campuses by assuming equal weights for all eight sections and all the considered buildings. As shown in Table 2, the average satisfaction levels were 78% for ASU buildings and 61% for AUB buildings. Figure 4 provides a graphical illustration of the difference in performance throughout the eight survey questions across the two campuses. Figure 5 illustrates the CBE results (59,359 participants) compared to the selected buildings from ASU and AUB. Although both campuses failed to achieve the recommended levels of 80% for thermal comfort according to ASHRAE Standard 50 and USGBC, they performed better than the CBE benchmark. This is particularly true for ASU buildings. AUB building, on the other hand, had higher scores than the CBE benchmark in the areas of thermal comfort and acoustic quality, and similar performance in lighting level, indoor air quality, and overall satisfaction.

Several factors could play a role in determining occupant satisfaction with the IEQ of higher education facilities. This section suggests two main reasons that could explain the difference in IEQ performance across ASU and AUB buildings: LEED regulations and building age.

Table 2. ASU and AUB Survey Results

Survey Sections	ASU	AUB
Space Layout	80%	61%
Space Furniture	80%	61%
Thermal comfort	71%	58%
Indoor Air quality	79%	61%
Lighting level	77%	62%
Acoustic Quality	71%	60%
Water Efficiency	74%	58%
Cleanliness & Maintenance	83%	66%
Overall Satisfaction	83%	62%
Average	78%	61%

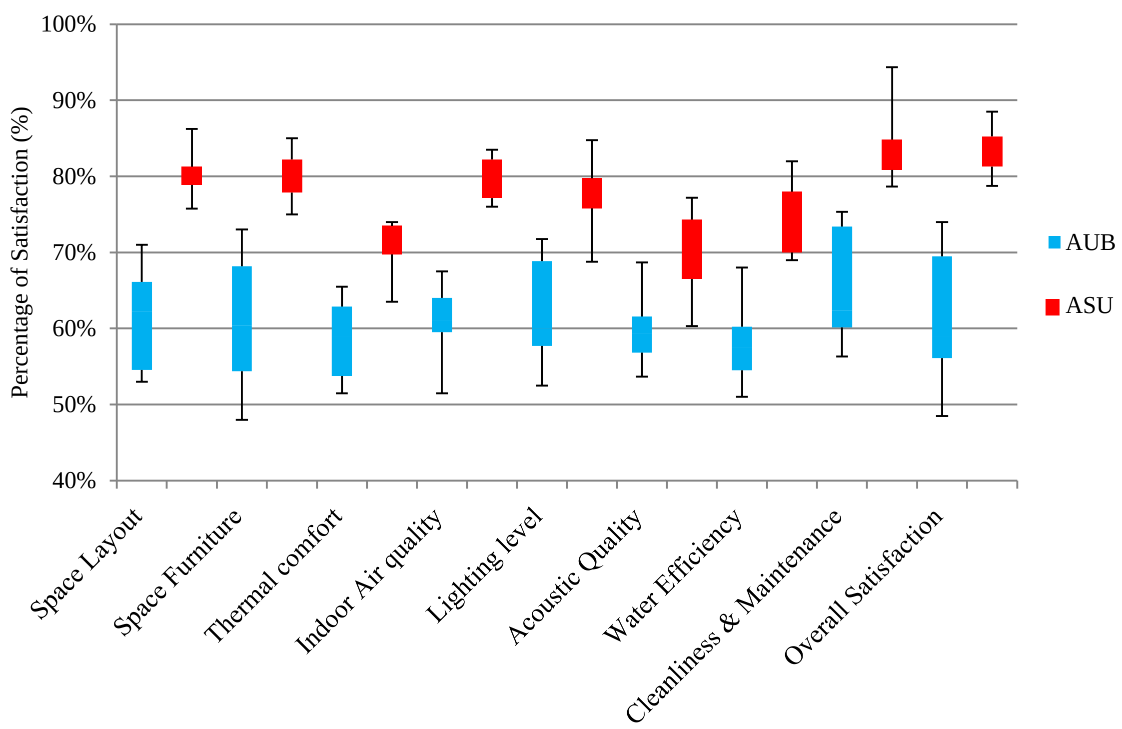

Figure 4. AUB vs. ASU Percentages of Satisfaction

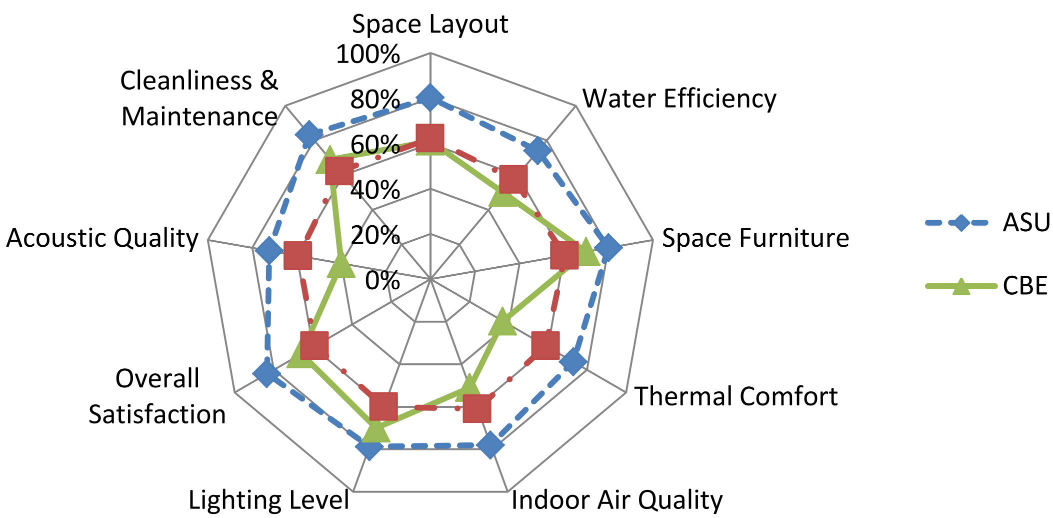

Figure 5. Overall Occupant Satisfaction Levels at ASU, AUB and CBE

ASU is committed to leadership in sustainability education, research, operations, and outreach. As such, the university has been implementing sustainable practices in the planning, design, construction, operation and maintenance of all university facilities (Arizona State University 2009). Therefore, all surveyed ASU buildings were LEED-certified (Table 3). In contrast, AUB buildings are all conventional and were not designed to meet eco-friendly requirements which could explain the difference in IEQ performance across the two campuses. These results are in-line with the literature and confirm the positive relation between improving IEQ design through LEED and occupants' satisfaction. Yet, the surveyed ASU buildings failed to achieve an adequate thermal environment. Only 71% of participants were satisfied with their workplace, which is lower than the USGBC's recommended value of 80%. A close examination reveals no clear correlation between the buildings' earned points on the LEED scale and the level of users' satisfaction. For example, Fulton Center had the highest percentage of satisfaction with IEQ performance (82%) although it achieved the least number of points on the LEED scale. USGBC's LEED system is often criticized for the absence of future assessment of certified buildings. With the exception of projects registered under LEED version 3.0, once a building is certified, it is certified for life.

Table 3. LEED Characteristics of ASU Buildings

Building name	Hassayampa Village	ISTB 1	ISTB 2	ISTB 4	Barrett Honors College	Wrigley Hall	Fulton Center
LEED Rating	Silver	Gold	Silver	Gold	Gold	Silver	Certified
Award Date	2009	2007	2006	2012	2010	2009	2007
Total points (out of 69)	33	39	33	48	39	37	26
Sustainable Sites (out of 14)	9	9	10	11	10	10	8
Water efficiency (out of 5)	3	3	3	3	3	3	3
Energy & Atmosphere (out of 17)	3	7	5	15	7	3	3
Materials & Resources (out of 13)	5	5	5	5	5	7	4
Indoor Environmental Quality (out of 15)	8	10	8	9	9	9	5
Innovation and Design (out of 5)	5	5	2	5	5	5	3
Occupant Satisfaction %	77	78	75	76	78	80	82

Though many steps are carefully taken to ensure that these buildings meet the required standards during the design and construction processes, none are taken to verify that the buildings are still maintaining their efficient performance levels after certification (Cotera 2011). That's why several recent studies, e.g. Menassa et al. (2012), raise many questions about the actual energy consumption of LEED versus Non-LEED buildings.

Building age is another important factor that could have an effect on IEQ performance and therefore could explain the difference in results across the two campuses. The selected buildings at ASU were recently constructed, i.e. over the past decade. In contrast, the selected AUB buildings had a wider age range, which allows for plotting building age versus IEQ performance (Figure 6). There seems to be a negative correlation between building age and level of satisfaction of building users, which suggests the need for continuous renovation and rehabilitation of indoor environments. More studies are needed to confirm this trend.

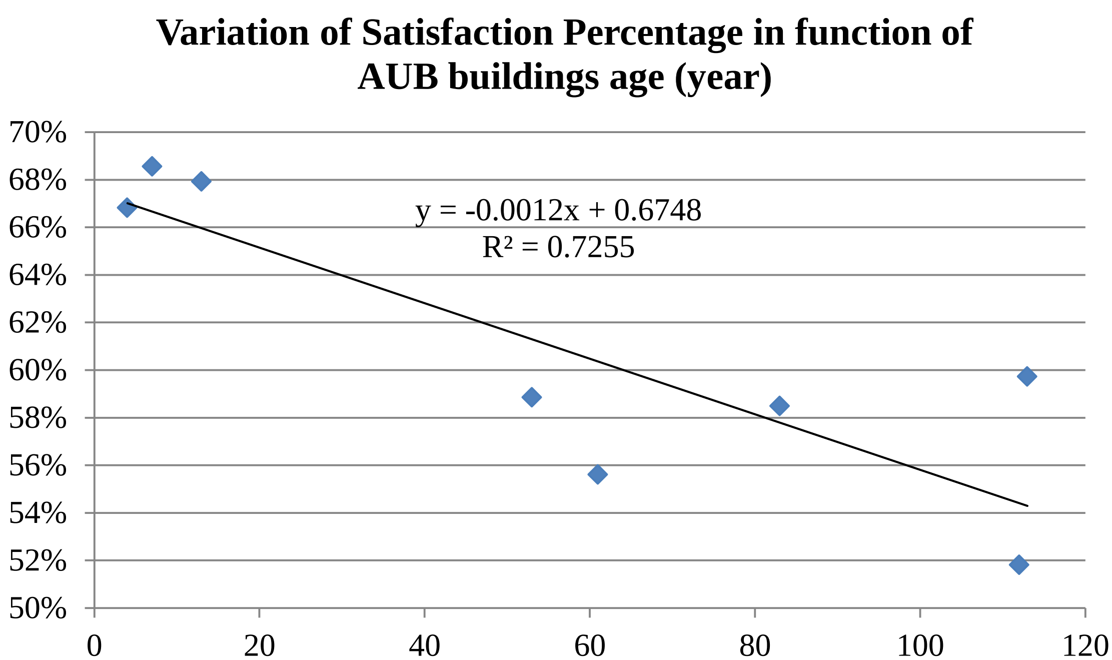

Figure 6. The variation of Satisfaction % in function of AUB buildings age

2.6. CONCLUSION

This paper compares the levels of satisfaction in IEQ for two sets of higher education facilities located in Arizona, US and Beirut, Lebanon respectively. Factors explaining the difference in performance across the two campuses might include commitment to sustainable and environmentally aware design, and building age. For the past 10 years, ASU has been designing and constructing buildings that are in-line with LEED requirements. AUB has recently made a similar commitment. Several ongoing projects are being designed and executed at AUB with the goal of obtaining LEED certification. Additionally, building age seems to have a correlation with level of satisfaction of users with IEQ. The results of the conducted surveys highlight the need to continuously monitor and improve indoor environmental conditions. This need is applicable not only to ASU and AUB buildings but also to any educational facility around the world. Improvements in IEQ performance could be costly; nonetheless, they can help reduce absenteeism and increase the productivity of students, staff, and faculty at higher educational facilities.

2.7. ACKNOWLEDGMENTS

The authors of this paper would like to acknowledge Mr. Jad Chalhoub and Mr. Jad Sabra for helping in the data collection and entering processes. Authors are also thankful to the Facilities Development and Management (FDM) at ASU and the Facilities Planning and Design Unit (FPDU) at AUB. Utilities managers and officers at ASU and AUB are not responsible for the results and conclusions presented by the authors in this paper.

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CHAPTER 3

APPLYING DATA-DRIVEN PREDICTIVE MODELS TO INVESTIGATE THE ENERGY CONSUMPTION OF LEED-CERTIFIED RESEARCH BUILDINGS IN CLIMATE ZONE 2B

Chokor, A., and El Asmar, M. (2015). "Applying Data-Driven Predictive Models to Investigate the Energy Consumption of LEED-Certified Research Buildings in Climate Zone 2B." *Energy and Buildings* (under review).

3.1. ABSTRACT

During the last decade, the Leadership in Energy and Environmental Design (LEED) rating system has embodied the efforts of the U.S. Green Building Council (USGBC) to recognize buildings designed to achieve superior performance in areas including energy consumption. Given the emergent interest in improving buildings' energy efficiency, researchers have generated predictive physical and data-driven models for energy consumption. Although the physical approaches aiming to calculate the thermal dynamics and the energy behavior at the building level are effective and accurate, the necessity of continuously inspecting and gathering data for all the input parameters often makes these approaches impractical in some applications. The objective of this study is to develop and investigate the performance of eight data-driven predictive models, and to introduce a novel assessment method that investigates the correlation between LEED certification and the actual energy consumption of certified facilities. This paper studies and compares the performance of 18 research buildings in climate zone 2B: five LEED certified buildings and 13 comparable non-LEED buildings. The research approach first consists of developing a performance model for non-LEED buildings, and then investigating the fit of this model to LEED certified buildings. Heating, cooling, and electricity data are collected from all buildings, in addition to multiple weather, time, and building

characteristics variables. The data are used to generate several regression models that predict the energy consumption of buildings in terms of their Energy Use Intensity (EUI). The results show the differences in energy use between LEED and non-LEED buildings are not as large as anticipated. This paper contributes to the body of knowledge by introducing a novel generic assessment method for non-LEED buildings and applying it on a sample of LEED buildings. In order to ensure a fair and representative assessment of LEED certification system, future studies are invited to adopt the presented methodology instead of comparing the actual performance of LEED buildings to that of non-LEED buildings.

3.2. INTRODUCTION

Buildings are responsible for about 40% of the energy (EIA 2010) and 70% of the electricity (Koomey 2007) consumed in the United States. Given the importance of buildings as major consumers of resources, several organizations are working avidly to ensure the negative environmental impacts of buildings are minimized. One such effort is the Leadership in Energy and Environmental Design (LEED) rating system that was developed by the U.S. Green Building Council's (USGBC). Despite the possible cost premium of LEED buildings (Miller et al. 2008; Kates et al. 2009), architects, engineers, and owners are adopting LEED, in part because they are hoping to achieve energy savings over the lifecycle of the buildings (Turner 2006; Newsham et al. 2009), as well as to benefit from the federal, state, and local incentive and tax rebates programs (DOE 2015). Nevertheless, the inconsistent findings of recent studies investigating the performance of LEED buildings undermine the reliability of the rating system (Turner

2006; Turner and Frankel 2008; Lee and Guerin 2009; Newsham et al. 2009; Scofield 2009; Menassa et al. 2012; Chokor et al. 2015).

The goal of achieving superior savings by improving energy efficiency, while also maintaining a satisfying built environment, has pushed researchers and practitioners to generate predictive physical models (e.g., White and Reichmuth 1996; Westphal and Lamberts 2004; Crawley et al. 2008; Al-Homoud 2011) and data-driven models (e.g., Bauer and Scartezzini 1998; Ansari et al. 2005). Although the physical thermodynamic approaches of calculating energy behaviors at the building level are effective and accurate (Zhao and Magoules 2012; Foucquier et al. 2013), the complexity of their systems and the necessity of continuously gathering most of the input parameters often makes these approaches impractical (White and Reichmuth 1996). This is mainly due to the fact that physical based models require a thorough understanding of the system. Thus, any changes in the design or the properties of the systems will require the development of a new model, which is a computation intensive task (An et al. 2015). Meanwhile, the evolution in remote sensing technology has provided a continuous data stream for building systems and therefore paved the way for data-driven prediction and monitoring of energy consumption (Pessenlehner and Mahdavi 2003; Wan et al. 2011; Parasonis et al. 2012). Unlike physical based approaches, data-driven models are moderate, fast to implement, and able to identify hidden relationships without prejudice (Line and Clements 2005).

A review of the literature highlights a conventional approach to assess the performance of LEED in saving energy. For instance, scholars have compared the actual consumption of LEED buildings to that of non-LEED building counterparts. However, such comparisons often do not control for the many variations between the different buildings' characteristics and features. This study builds on, and complements, the existing literature by considering these critical variables while also introducing a novel method to investigate the correlation between LEED certification and the actual energy consumption of certified facilities.

The research approach starts with the creation of a benchmark: an energy consumption predictive model of non-LEED research facilities located in the same climate zone. In order to create the model, the authors compare the accuracy(the closeness of a predicted value to its real value) and robustness (the effectiveness of the model while being tested on a new independent dataset) of the following predictive regression models for electricity, heating, cooling, and combined energy consumption in terms of Energy Use Intensity (EUI) of non-LEED research buildings: (1) Multiple Linear Regression (MLR), (2) Gradient Boosting Regression (GBR), (3) Random Forest Regression (RFR), (4) Classification and Regression Tree (CART), (5) k-Nearest Neighbors Regression (K-NN), (6) Kernel Ridge Regression (KRR), (7) Bayesian Ridge Regression (BRR), and (8) Support Vector Regression (SVR). Then, the most accurate and robust consumption models are selected based on five performance criteria. Finally, the models are applied on the LEED certified buildings to test whether these buildings behave differently as compared to the non-LEED benchmark.

Before presenting the details of this work, the literature is summarized and used as a point of departure for this paper. The following section recapitulates the extensive literature on LEED performance and energy predictive models.

3.3. CLOSELY-RELATED LITERATURE ON LEED PERFORMANCE AND PREDICTIVE ENERGY MODELS

LEED is a third party certification program serving as a design and construction tool for new and existing institutional, commercial and residential establishments (Cotera 2011). The development of LEED was in response to the increasing awareness and concerns about the negative environmental impacts that can be generated by buildings (El Asmar et al. 2014). After developing the pilot version v1.0, LEED has seen seven iterations (v2.0, v2.1, v2.2, v2007, v2008, v2008.2, and v2009) before reaching its latest version: LEED v4. The new version includes new market sector adaptations for data centers, warehouses and distribution centers, hospitality, existing schools, existing retail and mid-rise residential projects – to ensure that LEED fits the unique aspects of any project (USGBC 2014). A building can earn LEED credits from the following categories to become certified: *Location and Transportation*, *Indoor Environmental Quality*, *Sustainable Sites*, *Water Efficiency*, *Energy and Atmosphere*, *Materials and Resources*, and *Innovation and Regional priority*. Depending on the total points earned out of 100 base points and 10 extra points, a facility is granted to one of the four levels of certification: *Certified* (40-49 points), *Silver* (50-59 points), *Gold* (60-79 points), and *Platinum* (80 points and above).

Several studies examined the obstacles to greater mainstream acceptance of the LEED certification and found the cost premium of LEED buildings to be the main barrier facing the certification growth (Building Design & Construction 2003; Turner Construction Company 2005; McGraw-Hill Construction 2006; Galuppo and Tu 2010). For instance, Kats et al. (2003) compared the costs of 33 LEED buildings across the U.S. to their conventional counterparts. The study showed LEED Platinum buildings cost 6.50% more than conventional buildings, followed by LEED Silver buildings (2.11%), LEED Gold buildings (1.82%) and LEED Certified (0.66%). However, this order was different in Miller et al.'s (2008) study, which established an 8.6% cost premium for LEED Platinum buildings as compared to the LEED Certified buildings, followed by LEED Gold buildings (4.0%), and LEED Silver buildings (1.9%). The relationship between LEED certification levels and initial facility cost was also discussed in a study on New York City LEED certified buildings (Kaplan et al. 2009). The study reported the highest construction cost appertain to LEED Platinum buildings ($463/ft^2), followed by LEED Gold buildings ($440/ft^2), LEED Silver buildings ($439/ft^2), and LEED Certified buildings ($315/ft^2).

Therefore, and in order to justify the possible cost premium of LEED buildings, project stakeholders often tend to quantify the certification benefits over the lifecycle of the facility. Measuring energy consumption is one such approach to provide the users with information that support the ongoing accountability and optimization of building energy performance and identify opportunities for additional energy-saving investments (USGBC 2014). In general, energy efficiency of building depends on several phenomena such as geometrical and physical structure of building, occupant's behavior in maintaining thermal comfort and air quality, climatic conditions and energy sources integrated to buildings (Paudel et al. 2015). One of the approaches to overcome barriers in energy efficiency of building is convenient demand and supply management; therefore, by predicting the energy consumption ahead, peak energy demand can be diminished and managed. Researchers and practitioners have applied engineering and data-driven methods to investigate the energy consumption of building systems. Engineering approaches use physical factors to calculate the thermal dynamics for sub-level components on the entire building level (Zhao and Magoulès 2012). Data-driven machine learning approaches, mainly regression models, predict building energy consumption by correlating energy consumption of the building with some significant variables such as building characteristics and external weather conditions (Kusiak et al 2010). The next two subsections will provide a summary of literature on LEED performance and energy predictive models.

3.3.1. LEED Performance

Alongside the evolution of the LEED rating system, scholars have measured its efficacy and reached conflicting findings regarding the performance of LEED buildings. Some studies have shown the effectiveness of LEED in saving energy: Turner and Frankel (2008) investigated 552 LEED buildings and showed 24% lower EUI than their national counterparts. Baylon and Storm (2008) examined the characteristics of LEED commercial buildings in the US Pacific Northwest, and compared them to regional non-LEED buildings. The mean energy use per floor area for the 12 LEED buildings was 10% lower than the 39 similar non-LEED buildings in the same region. Similarly, Fowler and Rauch (2008) found the energy consumption of 12 LEED government buildings 25% to

30% lower than the average of commercial building stock. Newsham et al. (2009) also found the energy consumption of 18 LEED buildings to be 39% less than that of comparable conventional buildings.

However, other papers have shown the inefficacy of LEED system to result in energy savings. For instance, Turner (2006) assessed the performance of 11 buildings in the Cascadia region and found that although all sampled buildings had better savings than their designed energy use, only two of them performed better than the average commercial building stock. Diamond et al. (2006) investigated 21 LEED certified buildings and showed the LEED energy credits did not have any correlation with the actual energy use. Later, Menassa et al. (2012) later tested the same hypothesis by investigating a more targeted dataset consisting of the U.S. Navy LEED certified buildings. Although these buildings were required to become LEED certified in an effort to improve energy efficiency and mitigate greenhouse gas emissions, the authors found only 3 out of 11 buildings showed energy efficiency gains compared to the Commercial Buildings Energy Consumption Survey (CBECS) buildings, in addition to the absence of any correlation between the number of earned LEED points and energy savings.

3.3.2. Predictive Energy Models

Researchers have applied various models to predict building energy consumption. Bauer and Scartezzini (1998) proposed a regression method to predict both heating and cooling consumption. Ansari et al. (2005) predicted the cooling load of a building by comparing the inside and the outside temperatures. Ma et al. (2010) integrated multiple linear regression and self-regression methods to predict monthly power energy consumption for large-scale public buildings. Mohamed and Bodger (2005) predicted the electricity consumption in New Zealand buildings based on a multiple linear regression analysis. Tso and Yau (2007) compared regression analysis to decision tree and neural networks. The authors used the square root of average squared error (RASE) as a performance measure and found that decision trees are achieving slightly lower RASE values than other studied predictive methods. The efficiency of decision trees was also proven by other studies. Gilan and Dilkina (2015) proved the efficiency of Gaussian Process predictive models over the ensemble methods, such as random forest (Müller and Wiederhold 2002) and boosting models (Aman et al. 2011), while predicting building energy consumption. Support Vector Machines (SVM), a supervised learning model with associated learning algorithms, has been also commonly used to model and predict building energy consumption (Dong et al. 2005). SVM have proven to be highly effective and high performing models in solving non-linear problems even when there is only small and limited number of training data. SVM were first applied to predict the monthly energy consumption of four different buildings located in a tropical region. After building the model based on three years' data, testing based on one year data showed the adequate accuracy of SVM in predicting the total monthly energy consumption of buildings in that particular tropical area (Dong et al. 2005). Subsequently, SVM were applied to inspect the annual energy consumption for a specific building by considering different climate and environmental conditions (Lai et al. 2008). Though the proposed SVM models reached an accuracy of 97%, the small dataset used did not allow for conclusive results (Dong et al. 2005; Lai et al. 2008). Later, Li et al. (2010) built a model based not only on

SVM, but also on Radial Basis Function (RBF) Neural Networks and general Neural Networks. As part of the training data, 59 different buildings were used for the research and the subsequent generated model was tested on nine buildings. After applying all the three models on the test set, the authors found SVM performed better than the RBF Neural Network and general Neural Network in predicting energy consumption. Fu et al. (2015) compared the performance of the autoregressive integrated moving average with explanatory variable (ARIMAX), SVM with Gaussian kernel function, decision tree, and artificial neural network in predicting the energy consumption of public buildings in China. The results showed SVM achieving low values of normalized root mean square error compared to other methods. Overall, the reviewed literature reflects an increased awareness to monitor and forecast energy consumption by developing a plethora of predictive models.

Despite the inconsistency between the results, the literature review highlighted a uniform approach of comparing the performance of LEED buildings to their non-LEED counterparts. The next section discusses the gap in the existing literature.

3.4. RESEARCH GAP AND OBJECTIVES

A survey of existing research reveals a widespread application of regression models to predict the energy consumption of buildings. Although some of the models have reached a high forecasting accuracy, they are valid within specific constraints such as the climate zone and the type of buildings. Building performance was also the focus of scholars who compared the energy consumption of LEED buildings to that of conventional buildings. In addition to the inconsistent results of LEED buildings' energy savings, the differences in the characteristics of investigated buildings, including age, size, and weather conditions, raises several questions regarding the applicability of the findings beyond the respective dataset collected for each study. In addition to the absence of predictive energy consumption models for research buildings within the climate zone 2B in the reviewed literature, none of the reviewed papers had generated or applied data driven models on LEED certified buildings.

This paper bridges the identified gap by generating predictive models that account for building characteristics of research buildings within climate zone 2B. The paper also compares the performance of several regression methods. The need and contribution of this paper is further emphasized in Table 4, which highlights key building characteristics that are used in the literature to generate energy consumption models. As shown in this table, none of the previous studies have addressed all the features simultaneously to predict buildings' energy consumption. Moreover, this paper is accounting for the health index of a building, usually known as Facility Condition Index (FCI). FCI can be calculated by dividing the maintenance, repair, and replacement deficiencies by the current replacement value of a facility (Lance 2009). From the outcome of a facility condition assessment, a facility manager can estimate the cost of maintenance, repair and replacement deficiencies. Indeed, the current replacement value of the facility is what monetary value the organization is spending on the facility. The FCI is a relative indicator of condition, and should be tracked over time to maximize its benefit. It is advantageous to define condition ratings based on ranges of the FCI. *Managing the Facilities Portfolio* provided a set of ratings: good (under 0.05), fair (0.05

to 0.10), and poor (over 0.10) based on evaluating data from various clients at the time of the publication (Atkins 1999).

Table 4. Key Building Characteristics in the Literature and the Current Study

Building Characteristics	Belzer et al. (1996)	Datta et al. (1997)	Dong et al. (2005)	Baker and Rylatt (2007)	Rijal et al. (2007)	Neto and Fiorelli (2008)	Lee (2008)	Santin et al. (2009)	Yua et al. (2010)	Belussi and Danza (2012)	Korolija et al. (2013)	Yedra et al. (2014)	Sandels et al. (2015)	Li et al. (2015)	*Chokor et al. (current)*
Temperature	X	X	X		X	X	X	X	X	X	X	X	X	X	X
Humidity	X	X	X		X		X	X			X	X		X	X
Wind Speed	X				X	X				X	X	X	X	X	X
Precipitation	X				X	X	X					X			X
Square Footage			X	X		X	X	X	X	X	X			X	X
Building Age				X				X							X
Month of the year											X	X	X	X	X
Day of the week		X				X					X	X		X	X
Occupants				X	X	X	X	X	X				X	X	X
Activity Schedule		X				X		X							X
FCI Health Index															X

Therefore, generating a model based on all these features offers a more comprehensive and generic assessment method that can significantly contribute to the literature on the topic. The contributions of this paper also include introducing this applied methodology and its robust model for non-LEED research buildings to investigate the deviation of LEED research buildings' energy consumption.

3.5. STUDY APPROACH

The research approach used for this paper is addressed in this section and shown in Figure 7. The study implements a three-step approach:

A. Selecting research buildings in climate zone 2B; and collecting weather data, building characteristics, usage schedule data, and energy consumption data in terms of electricity, heating, and cooling between 2008 and 2014 in 15 minutes increments;

B. Developing and comparing eight regression methods that can predict the energy consumption of the non-LEED research buildings in order to select the best models based on five performance criteria that measure the goodness of fit and the deviation of the differences between predicted and observed values, such as: the coefficient of determination, the mean squared error, etc.; and

C. Assessing the performance levels of the LEED certified buildings by investigating their potential to fit the robust non-LEED predictive models.

3.5.1. Building Selection and Data Collection

Buildings were selected from a university campus in climate zone 2B. The campus tracks the energy consumption, including chilled water used for cooling, electricity, and hot water/steam used for heating, for all its facilities. The buildings are classified as research, academic, administration, athletics, residential, auxiliary, and parking facilities. In order to address the objectives of this study, the authors selected all the buildings classified as research facilities. A total of 18 buildings were found to fit this criterion: five LEED certified facilities and 13 non-LEED facilities.

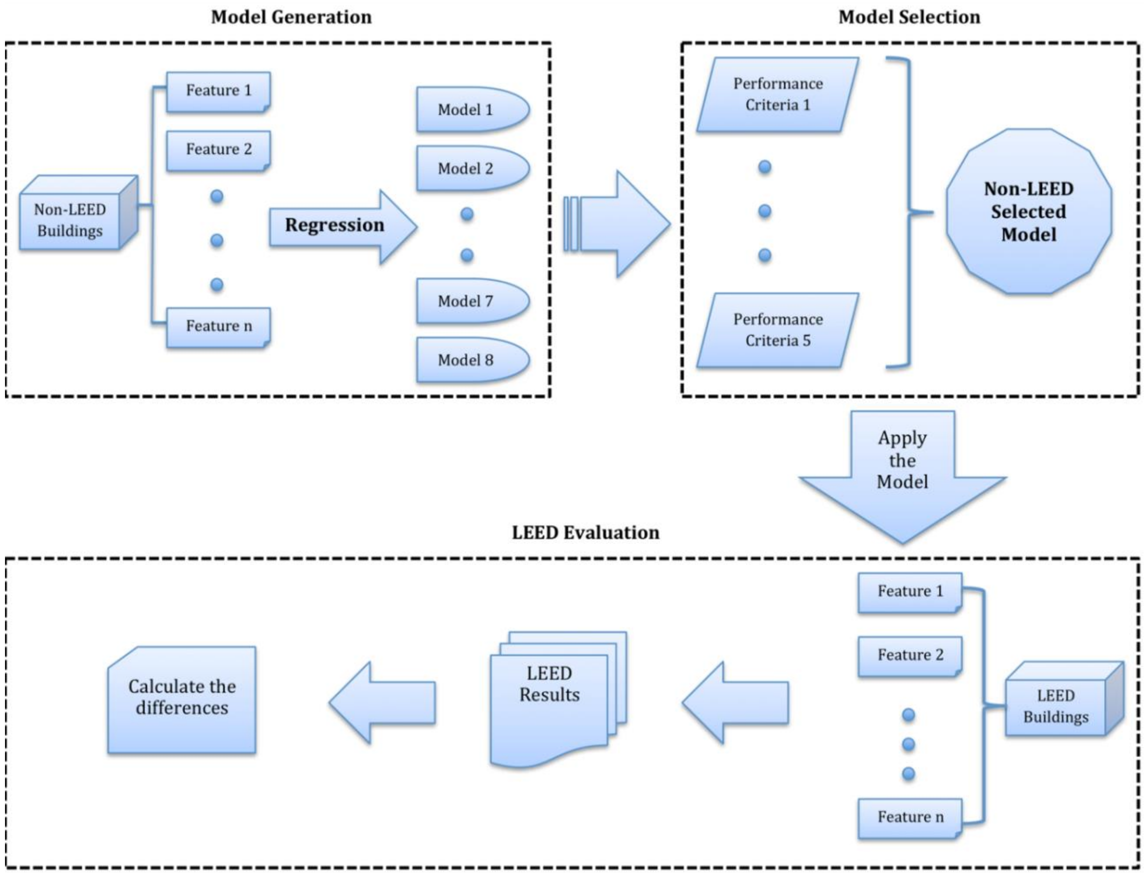

Figure 7. A Diagram Showing the Study Methodology

The data collection effort in preparation for the regression analysis consisted of gathering weather data, buildings characteristics and schedules, and electricity consumption data. The university facilities management provided seven years of data from January 1, 2008 to December 31, 2014 in 15-min increments. Energy metering data is collected in kWh of electricity (1 kW.h = 3.6 MJ), MBtu of heating (1 MBtu = 1,055.87 MJ), and ton-hour of chilled water (1 ton-h = 12.66 MJ). For each building, the total energy consumption is computed by adding the energy used for heating, cooling, and electricity, and then EUI values are obtained by dividing the total energy consumed by the size of the facility.

3.5.2. Model Development

Multivariate regression analysis seeks to establish a relationship between a dependent variable (in this case the energy consumption variables: electricity, cooling, heating and EUI) and two or more independent variables (Braun et al. 2014). Regression analysis validation is done in two distinct steps: training and testing. Training on a subsample drawn from the large dataset can considerably enhance the robustness of the model (Hertz et al. 2006). Thus, the rigorous method used in this paper is to train the model on a five percent (5%) random subsample of the energy consumption data between 2008 and 2012 and later test it on the 2013 and 2014 data. Table 5 summarized the commonly used methods in the literature for the prediction of building energy consumption.

Those eight different types of regression are compared in this paper to generate a robust and accurate model that predicts electricity, heating, cooling, and EUI of the non-LEED buildings sample as a function of weather, use schedules, and building features. These eight regression models are described below:

1. Multiple Linear Regression (MLR): attempts to model the relationship between two or more features and a response variable by fitting a linear equation to observed data. Every value of the independent variable x is associated with a value of the dependent variable y (Geladi and Kowalski 1986).
2. Gradient Boosting Regression (GBR): is a form of ‘functional gradient descent’. Boosting is a numerical optimization technique for minimizing the loss function by adding, at each step, a new tree that best reduces (steps down the gradient of) the loss function, such as deviance (Elith et al. 2010).

Table 5. A Summary of Commonly Used Regression Methods

References	Regression Methods							
	Multiple Linear	Gradient Boosting	Random Forest	Classification and Regression Tree	k-Nearest Neighbors	Kernel Ridge	Bayesian Ridge	Support Vector
Müller and Wiederhold 2002			x					
Dong et al. (2005)								x
Mohamed and Bodger (2005)	x							
Karatasou et al. (2005)				x			x	x
Tso and Yau (2006)	x			x				
Lai et al. (2008)								x
Neto and Firoelli (2008)	x							
Ma et al. (2010)	x							
Kusiak et al. (2010)		x	x	x	x			x
Tang (2010)	x	x	x					x
Wang and Yu (2011)						x		
Aman et al. (2011)		x						
Zhao and Maghoules (2012)		x	x	x				x
Rodger (2014)					x			
Fu et al. (2015)				x		x		

3. Random Forest Regression (RFR): adds an additional layer of randomness to bagging, a model averaging approach where each sample is uniformly selected to produce a training dataset. In addition to constructing each tree using a different bootstrap sample of the data, random forests change how regression trees are

constructed. In a random forest, each node is split using the best among a sub-set of predictors randomly chosen at that node. This somewhat counterintuitive strategy turns out to perform very well compared to many other classifiers, including discriminant analysis, support vector machines and neural networks, and is robust against overfitting (Breiman, 2001).

4. Classification and Regression Tree (CART): is an empirical and statistical technique based on recursive partitioning analysis. Unlike multivariable logistic regression, it is well suited to the generation of clinical decision rules. The CART method involves the segregation of different values of classification variables through a decision tree composed of progressive binary splits. Every value of each predictor variable is considered as a potential split, and the optimal split is selected based on impurity criterion, such as the reduction in the residual sum of squares due to a binary split of the data at that tree node (Yohannes and Hoddinott 2004).
5. k-Nearest Neighbors Regression (K-NN): is a non-parametric method that does not explicitly form a separate model from the calibration dataset. The K-NN regression uses the average value of dependent variable over the selected nearest neighbors to generate predicted value for scoring data point. The advantages of K-NN include: simplicity, effectiveness, intuitiveness and competitive regression performance in many domains. It is Robust to noisy training data and is effective if the training data is large (Alsberg et al. 1997).
6. Kernel Ridge Regression (KRR): imposes a penalty on the size of coefficients by minimizing the residual sum of squares. It thus learns a linear function in the space

induced by the respective kernel and the data. KRR can be completed in closed-form and is typically faster for medium-sized datasets (Kernel Ridge Regression 2015).

7. Bayesian Ridge Regression (BRR): includes regularization parameters in the estimation procedure; the regularization parameter is not set in a hard sense but tuned to the data at hand. This can be accomplished by introducing uninformative priors over the hyper parameters of the model. The method adapts to the data at hand and is used to include regularization parameters in the estimation procedure (Generalized Linear Models 2015).
8. Support Vector Regression (SVR): attempts to minimize the generalization error bound so as to achieve generalized performance, instead of minimizing the observed training error. The idea of SVR is based on the computation of a linear regression function in a high dimensional feature space where the input data are mapped via a nonlinear function (Basak et al. 2007).

Mathematically speaking, the established relationship in a regression model between a dependent variable Y and independent variables $x_1,x_2,\dots,x_n$ has a random error $\mathcal{E}$ that corresponds to the absolute difference between the observed value $Y_{obs,\ i}$ and the predicted value $Y_{model,\ i}$. In order to select the most fitting model that would maximize the goodness of fit, this study will use several criteria parameters such as the coefficient of determination; mean squared error; root mean squared error; etc. These criteria will be used by the authors to select the optimal energy consumption models.

3.5.3. LEED Certified Buildings Assessment

Once a performance model for non-LEED buildings is selected, the paper will assess the performance of LEED buildings by investigating whether they fit the same non-LEED model. Computing the differences, in terms of LEED versus non-LEED residuals will specify whether a LEED building is overusing or underusing energy compared to its conventional benchmark model. By defining the residual to be the difference between the observed value of a LEED building and the predicted value based on the non-LEED model:

- a positive residual, i.e. $Y_{\text{observed of LEED}} > Y_{\text{predicted based on the non-LEED model}}$, is equivalent to overusing energy in a LEED building compared to its conventional benchmark; and
- a negative residual, i.e. $Y_{\text{observed of LEED}} < Y_{\text{predicted based on the non-LEED model}}$, is equivalent to underusing energy in a LEED building compared to its conventional benchmark.

3.6. MODEL DEVELOPMENT AND FINDINGS ON THE PERFORMANCE OF LEED BUILDINGS

This section presents and compares the different predictive models developed in this research, and then uses them to investigate the energy performance results for LEED buildings. Table 6 details the features of the collected and calculated data, which are used as independent variables in the different energy consumption models.

After presenting the developed energy consumption models, the paper evaluates the robustness and accuracy of the predictive models using the following five performance measures:

- Coefficient of determination: $R^2 = 1 - \frac{\sum_{i=1}^{n}(Y_{obs,i} - Y_{model,i})^2}{\sum_{i=1}^{n}(Y_{obs,i} - \overline{Y})^2}$
- Mean squared error: $MSE = \frac{\sum_{i=1}^{n}(Y_{obs,i} - Y_{model,i})^2}{n}$
- Root-mean-square error: $RMSE = \sqrt{MSE}$
- Coefficient of variance of the root-mean-square error: $CVRMSE = {RMSE}/{\overline{Y}}$
- Normalized root-mean-square error: $NRMSE = {RMSE}/{(Y_{max} - Y_{min})}$

Comparing the different regression methods using these five performance measures highlights the superiority of the Gradient Boosting Regression (GBR) in predicting energy consumption for this sample of non-LEED buildings. Although RFR performed slightly better than GBR in the prediction of electricity consumption, Table 7 shows that GBR overall achieved the highest value of R^2 and the lowest values for MSE, RMSE, CV-RMSE, and NRMSE. GBR strategically resamples the training data to provide the most useful information for each consecutive model. The adjusted distribution during each step of training is based on the error produced by the previous models. Unlike the bagging method where each sample is uniformly selected to produce a training dataset, the probabilities of selecting each individual sample are not equal for the boosting algorithm: samples that are misclassified or incorrectly estimated have more chances to be selected. Therefore, each newly created model emphasizes the samples that have been misclassified by previous models (Zhang and Haghani, 2015).

Table 6. The Collected and Calculated Features

	Features	Description	Units and metrics
Weather Data	Temperature	Outside air temperature	Degree Fahrenheit (^{o}F)
	Humidity	Humidity in %	Percentage (%)
	Wind Speed	Wind speed in MPH	Mile per hour (MPH)
	Precipitation	Rainfall measured in inches	Inches (in)
Building Characteristics and Schedules	GSF	Gross square footage	Square footage (ft^2)
	NSF	Net square footage of a structure	Square footage (ft^2)
	Age	The age of a structure	Years (yr)
	Month	Month of the year	Varies from 1 to 12: 1 corresponds to January and 12 corresponds to December
	Day	Day of the week	Varies from 1 to 7: 1 corresponds to Monday and 7 corresponds to Sunday
	FCI Health Index	The FCI shows the general "health" of a building for maintenance purposes and is calculated annually; lower values represent longer building life cycles	• $0 \leq$ Index < 0.05: Good • $0.05 \leq$ Index ≤ 0.1: Fair • Index > 0.10: Poor
	Occupants	The average number of occupants per year	Occupants
	University Schedule	University business Days	Binary: 0 corresponds to holidays and non-work days and 1 corresponds to business work days
	Students Schedule	Class days	Binary: 0 corresponds to shutdown class days and 1 corresponds to actual class days
Energy Consumption	Electricity	Electricity consumption for the 15 minute time period	Kilowatt-hour (kWh)
	Heating	Steam used to heat the structure during 15 minutes	British Thermal Unit (BTU)
	Cooling	Chilled water consumption during 15 minutes	Ton-hour (Ton.hr)
	Energy use Intensity (EUI)	The total energy consumption per square foot for the 15-minute time period; it is the sum of the electricity, heating, and cooling consumption after being converted to $mmBTU/ft^2$ in 15 minute time period	Million British Thermal Unit per square foot ($mmBTU/ft^2$)

Table 7. Models Evaluation Parameters

Methods	Types	MSE	RMSE	CV-RMSE	NRMSE	R^2
Multiple Linear Regression (MLR)	Electricity	260,725	511	38	0.0836	0.0968
	Heating	1,114,301	1,056	115	0.1122	0.1685
	Cooling	11,509	107	57	0.1382	0.3903
	Combined EUI	35,248,693	5,937	43	0.1528	0.2809
Gradient Boosting Regression (GBR)	**Electricity**	**21,079**	**145**	**11**	**0.0238**	**0.9270**
	Heating	**279,978**	**529**	**58**	**0.0563**	**0.7911**
	Cooling	**2,583**	**51**	**27**	**0.0655**	**0.8632**
	Combined EUI	**6,052,773**	**2,460**	**18**	**0.0633**	**0.8765**
Random Forest Regression (RFR)	Electricity	18,780	137	10	0.0224	0.9349
	Heating	293,071	541	59	0.0576	0.7813
	Cooling	2,780	53	28	0.0679	0.8527
	Combined EUI	6,610,204	2,571	18	0.0662	0.8652
Classificati on and Regression Tree (CART)	Electricity	25,678	160	12	0.0262	0.9110
	Heating	412,910	643	70	0.0683	0.6899
	Cooling	4,451	67	35	0.0859	0.7594
	Combined EUI	10,815,490	3,289	24	0.0846	0.7794
k-Nearest Neighbors Regression (K-NN)	Electricity	52,380	229	17	0.0375	0.8185
	Heating	399,057	632	69	0.0672	0.7022
	Cooling	4,500	67	36	0.0864	0.7616
	Combined EUI	10,943,818	3,308	24	0.0851	0.7767
Kernel Ridge Regression (KRR)	Electricity	51,105	226	17	0.0370	0.8230
	Heating	366,456	605	66	0.0644	0.7265
	Cooling	4,528	67	36	0.0867	0.7601
	Combined EUI	11,105,067	3,332	24	0.0858	0.7735
Bayesian Ridge Regression (BRR)	Electricity	260,676	511	38	0.0836	0.0969
	Heating	1,116,382	1,057	116	0.1123	0.1669
	Cooling	11,696	108	57	0.1393	0.3804
	Combined EUI	36,142,865	6,012	43	0.1547	0.2627
Support Vector Regression (SVR)	Electricity	51,105	226	17	0.0370	0.8230
	Heating	366,456	605	66	0.0644	0.7265
	Cooling	4,528	67	36	0.0867	0.7601
	Combined EUI	11,105,067	3,332	24	0.0858	0.7735

Figures 8, 9, and 10 show the results of applying GBR with least squares loss on the training and validation of non-LEED buildings energy consumption data for electricity, heating, and cooling respectively. The changes in the training set and test set deviances illustrate the improvements in the model accuracy and robustness correspondingly. For instance, Figure 8 visualizes the drop in the deviances only after 500 iterations and therefore the improvement in the accuracy and robustness of the developed model. The same applies for the other models development. The figures also show the importance of the involved features. Training and testing the different models revealed the importance of temperature, building age, humidity, month of the year, and the FCI health index in predicting the energy consumption research buildings in climate zone 2B.

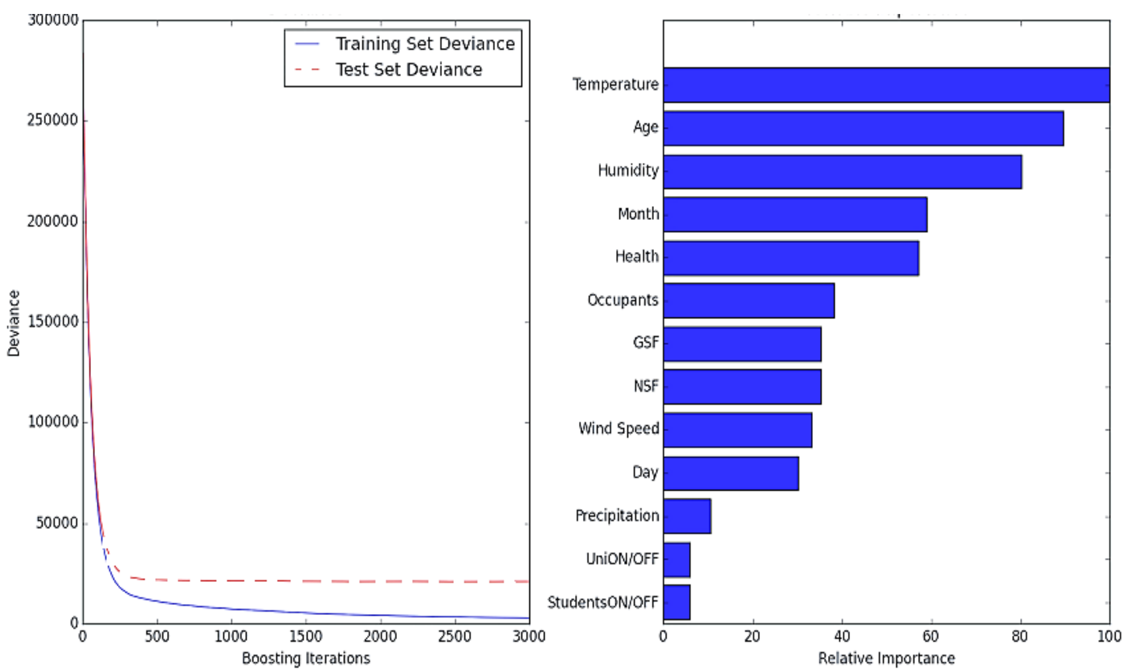

Figure 8. Gradient Boosting Regression Results for Electricity

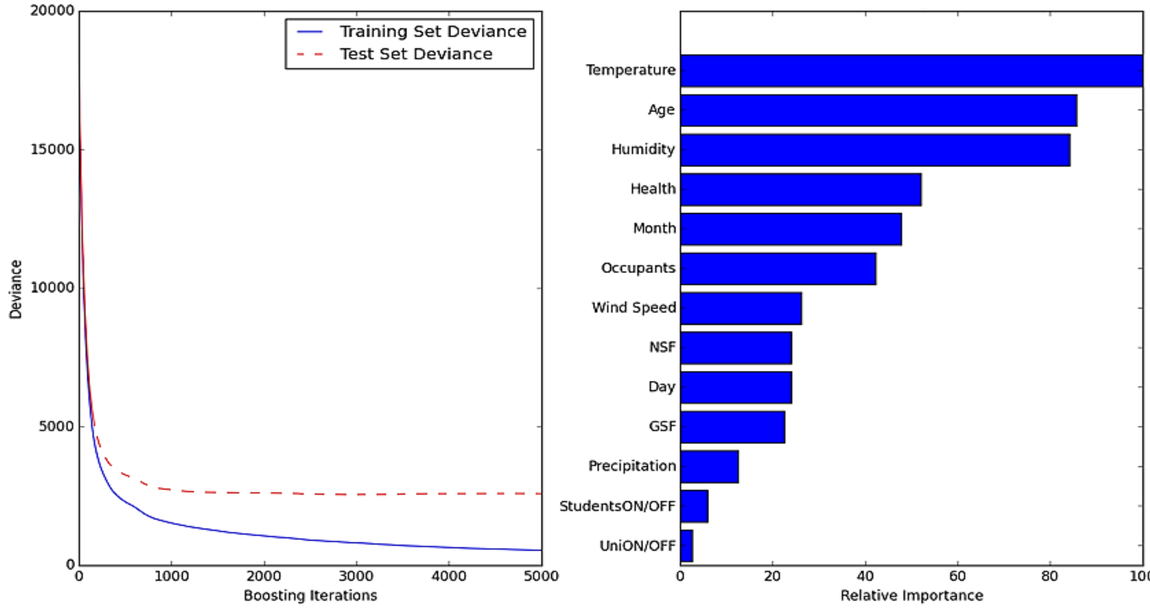

Figure 9. Gradient Boosting Regression Results for Heating

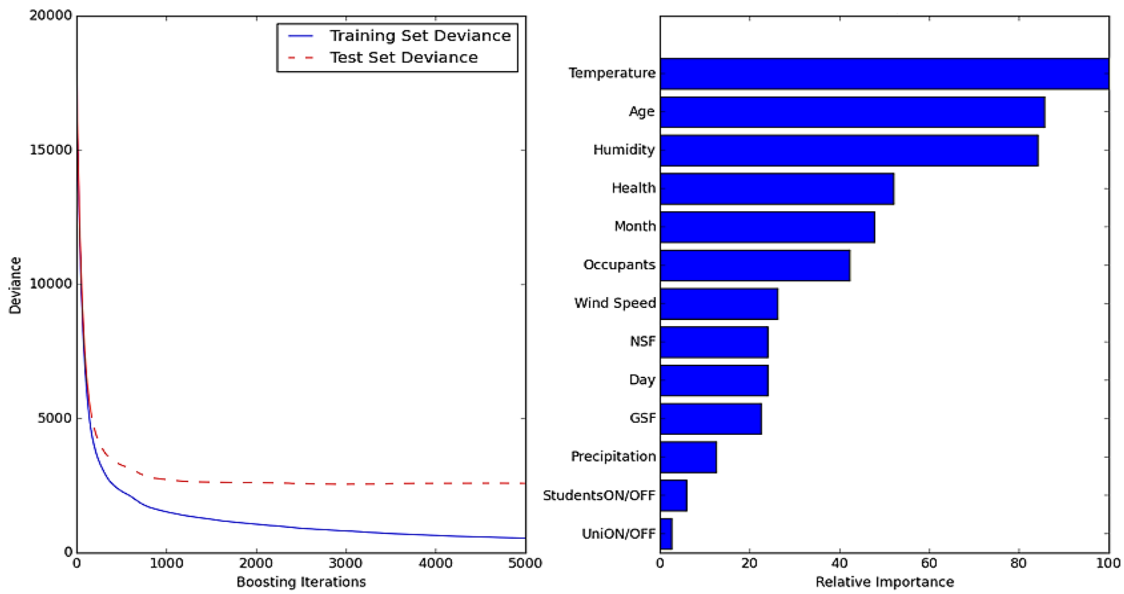

Figure 10. Gradient Boosting Regression Results for Cooling

While the models have allocated significant weights for several weather and building characteristics, the figures show a minor effect resulting from the university schedules. Applying the selected GBR predictive models on LEED building data can test whether the LEED certified facilities fit the same model of non-LEED certified facilities, or whether the LEED certified buildings exhibit a different energy consumption behavior. Figure 11 shows the overall results of the five LEED buildings' EUI performance. The cyclic results reveal a non-homogenous performance of the LEED buildings. Indeed, the selected LEED buildings are performing differently: buildings *C* and *E* are overusing energy, buildings *A* and *B* are underusing energy, and building *D* has to some extent a similar performance to that of the benchmark developed from non-LEED buildings. Figure 12 explains the differences in LEED buildings performance per type of consumed energy. Knowing that positive and negative residuals correspond to an overuse and underuse of energy compared to its conventional benchmark respectively, the results investigate the correlations between the actual energy consumption of certified facilities and the number of LEED points earned on the *Energy and Atmosphere* category. With the exception of building *D* that operated in 2012, the results present the variations in LEED performance for seven years in terms of electricity, cooling, and heating. Figure 12 underlines the absence of any correlation between the actual energy consumption and the original number of LEED points allocated to the facility in LEED's *Energy and Atmosphere* category. For example, although Building *A* earned only 5 points in LEED's *Energy and Atmosphere* category (significantly less than the 15 points earned by Building *E*), its electricity consumption performance was considerably superior to that of Building *E*. At the same time, Buildings *E* and *D* achieved the same number of LEED points in the energy category (15) but one shows superior electricity performance while the other one doesn't. Another visualization of the results displays the energy cyclic variations, as it is shown in Figure 13. The electricity loads are more consistent during the different times of the year. Out of the five buildings, two are underusing energy and three are overusing energy continuously.

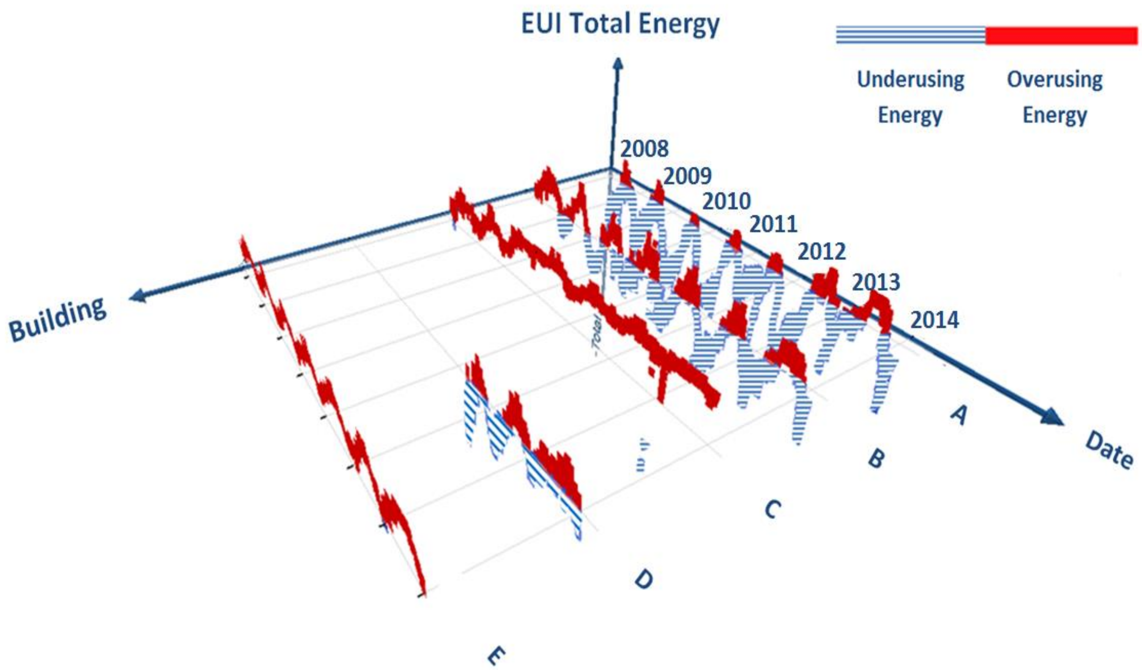

Figure 11. LEED Buildings' EUI Performance

However, an examination of the cooling results underlines a consistent energy overuse between June and October of each year. These observations call the results of model generation. Electricity loads are less dependent on the weather variations than cooling and heating loads are. Thus, the variation of EUI, for a specific facility, within time is more affected by the cooling and heating loads variation than electricity load variations. Therefore, any approach aiming to provide a convenient demand and supply management requires a deep focus on the prediction of cooling and heating loads.

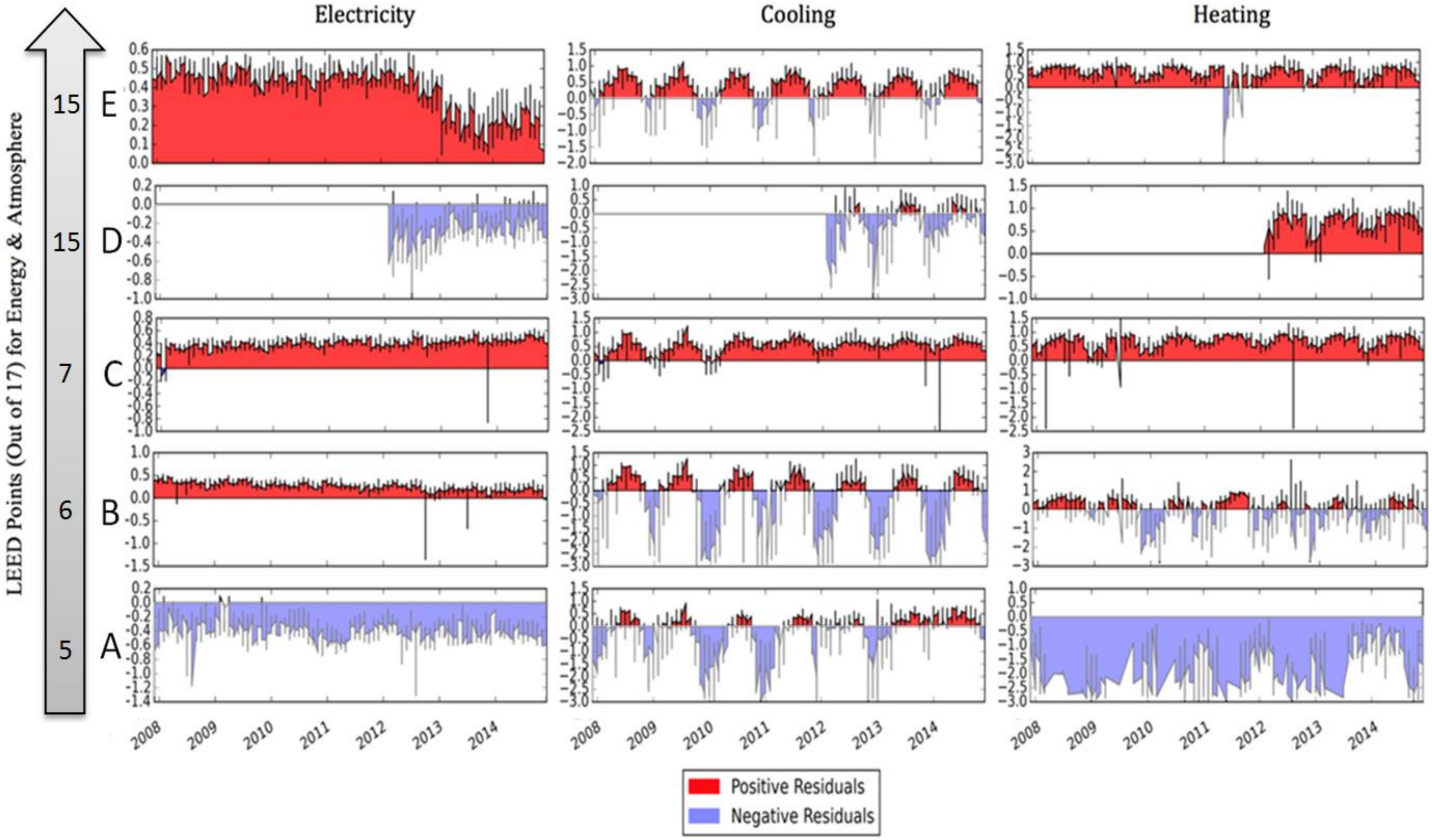

Figure 12. LEED Buildings Performance in Terms of Electricity, Cooling, and Heating Energy Consumption

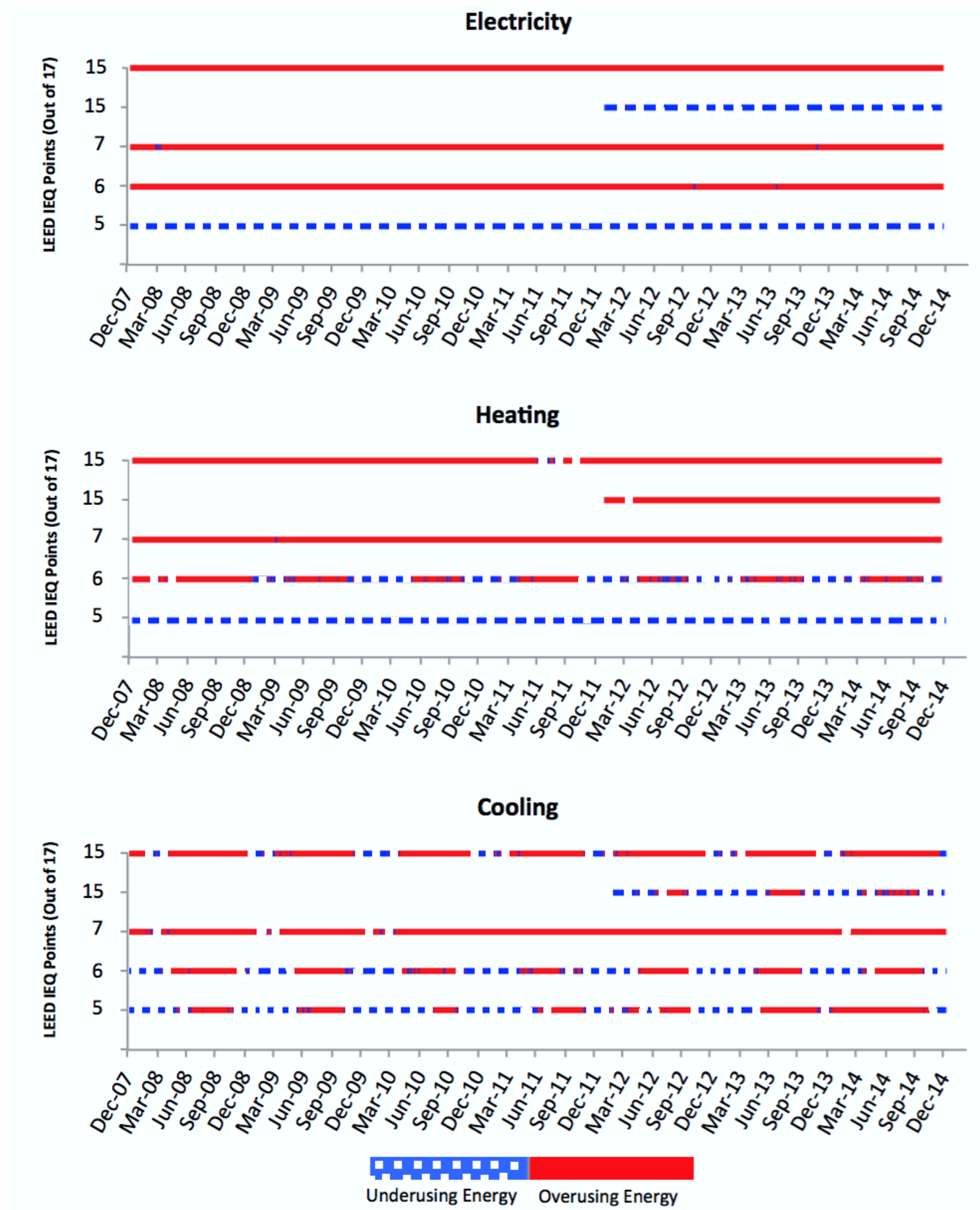

Figure 13. Cyclic Variation of the Results for LEED Buildings

3.7. COMPARING THE PROPOSED MODEL TO THE EXISTING LITERATURE

LEED certification was predominantly awarded based on the design and construction of the facility, which means a later change in occupancy-related variables, such as the type or number of occupants or equipment, may lead to changes in the intended performance. Yet, building energy performance became a mainstay and a prerequisite of the USGBC rating systems after launching LEED V4 in 2013 (USGBC 2014). In previous studies, scholars have compared the actual energy consumption of LEED buildings to a benchmark developed from the actual average of energy consumption of their non-LEED counterparts. However, such comparison does not take into account the variation and difference between the building characteristics and features. This paper introduced an assessment methodology that considers comparing LEED buildings to a benchmark developed from similar non-LEED building counterparts while also accounting for the main weather, building characteristics, and schedule variables. Table 8 differentiates the authors' method from the previous studies conventional approach using the same dataset. Following the approach used in the literature, an assessment of LEED buildings performance through comparing their actual energy consumption to that of the non-LEED benchmark shows the failure of LEED certification in saving energy. However, using this same dataset, the authors show an inconsistency in the performance of LEED buildings. This is mainly due to the impact of previously defined building characteristics on the energy performance and savings.

Table 8. Comparing the Proposed Method to the Existing Methods

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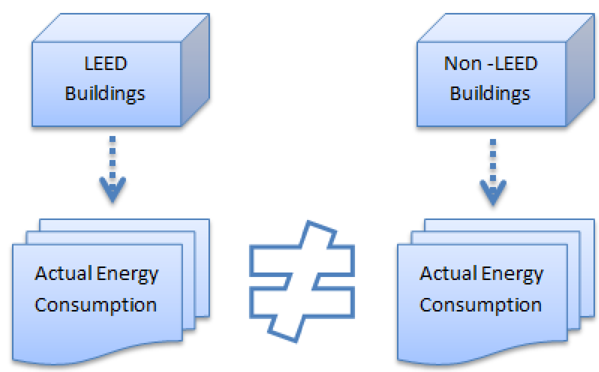
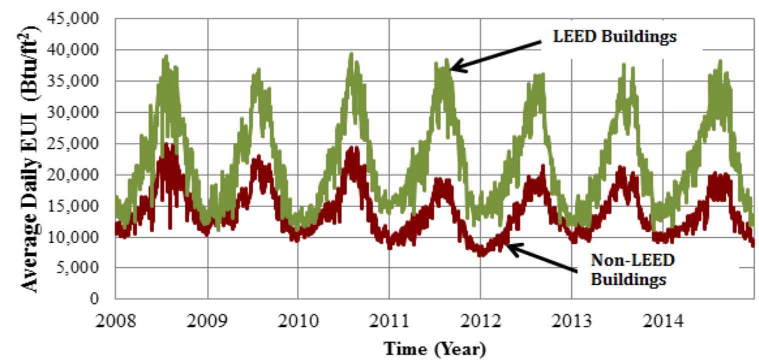
<tr><th></th><th>Methods</th><th>Results</th></tr>
<tr><td>Literature Conventional Appraoch</td><td>
</td><td>
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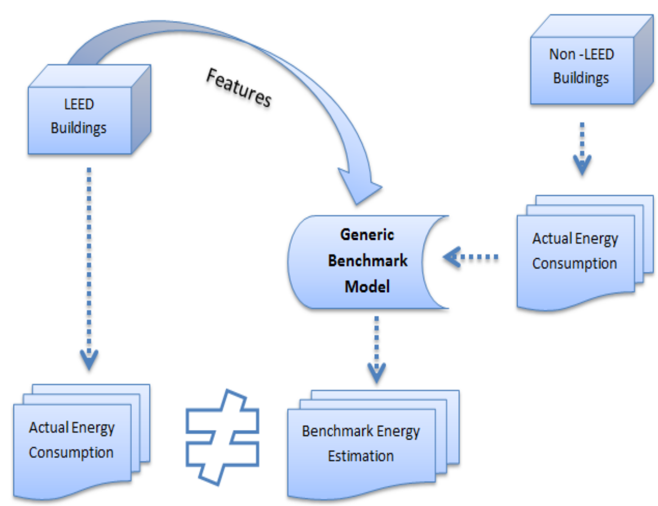
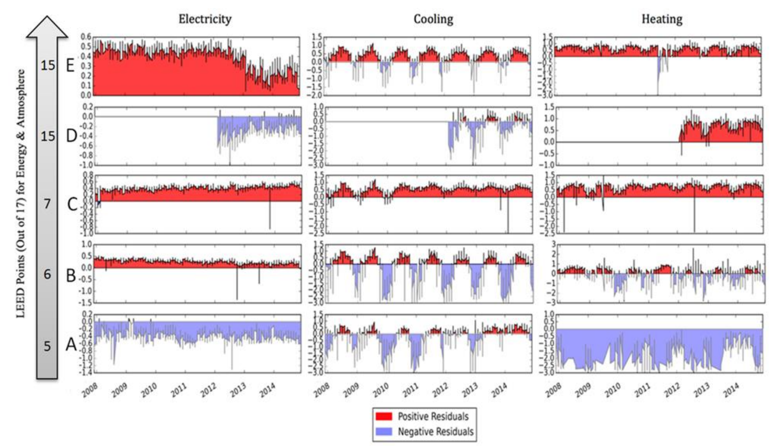
<tr><td>Proposed Approach</td><td>
</td><td>
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The results of the study contribute to the body of knowledge on LEED energy performance. However, the findings don't show the expected consistency in energy consumption of similarly rated facilities with similar types of use and occupancy in the same climate zone. Given this understanding, if the rating would be awarded after testing the building's actual performance, LEED's status symbol can be leveraged to provide a motivation and ensure consistency in the energy consumption profiles of similarly rated facilities.

3.8. CONCLUSIONS AND RECOMMENDATIONS

This paper investigates the impact of LEED certification on the energy consumption of research facilities in climate zone 2B. The contributions of this study include the comparison of eight data-driven predictive models and the introduction of a novel LEED assessment method. Electricity, heating, and cooling energy consumption were measured in 15 minutes increments over a seven-year period and focused on a specific type of facilities in one geographical location in order to limit the variation in the dataset. The results of this paper show the superiority of the Gradient Boosting Regression over other regression models in predicting energy consumption for this dataset of research buildings. The paper also introduces an applied method that uses a robust predictive model for non-LEED research buildings to investigate the deviation of LEED research buildings' energy consumption as well as the correlation between LEED certification and the actual energy consumption of certified facilities. The study highlights the differences between the benchmark addressed in the literature and the one proposed in this study in order to assess the performance of LEED buildings. While accounting for the main building characteristics, the proposed method is generic, comprehensive, and easy to implement.

The focused scope of this study on the energy consumption of research buildings in a specific climate zone adds value to the findings, but at the same time presents a limitation not being generalizable to the whole population of LEED certified facilities or to other types of facilities in different climate zones. However, the new method introduced in this paper can certainly be replicated for any type of facility in other climate zones.

In previous studies, the authors, along with many others in the architecture, engineering, and construction (AEC) industry, have recommended that sustainability rating systems be based on actual performance as opposed to design intent. The authors welcome the USGBC's recent move toward considering, in the newest version of the LEED rating system, the actual performance of buildings during the occupation phase as opposed to just the intended performance during the design and construction phases. Such improvements in the USGBC rating system incentivize building managers, owners, and occupants, to ensure buildings are performing adequately and meeting their design potential. This concluding thought applies not only to higher education facilities, but also to any facility in the built environment.

3.9. ACKNOWLEDGMENTS

The authors of this paper would like to thank the facilities management team officers who were extremely helpful with the data collection effort. Utilities managers and officers are

not responsible for the results and conclusions expressed in this paper; these are exclusively based on the analyses and interpretations of the authors.

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CHAPTER 4

EVALUATING THE ACTUAL ENERGY PERFORMANCE AND OCCUPANT SATISFACTION OF LEED CERTIFIED HIGHER EDUCATION FACILITIES

Chokor, A., El Asmar, M., Tilton, C., and Srour, I. (2015). "Evaluating the Actual Energy Performance and Occupant Satisfaction of LEED Certified Higher Education Facilities." *ASCE Journal of Architectural Engineering*. (in press).

4.1. ABSTRACT

Given the importance of buildings as major consumers of resources worldwide, several organizations are working avidly to ensure the negative impacts of buildings are minimized. The U.S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) rating system is one such effort to recognize buildings that are designed to achieve a superior performance in several areas including energy consumption and indoor environmental quality. This paper tests these hypotheses by examining LEED certified buildings on the Arizona State University (ASU) campus in Tempe, AZ, from two different perspectives: the Macro-level and the Micro-level. Heating, cooling, and electricity data were collected from the LEED-certified buildings on campus, and their energy use intensity (EUI) was calculated in order to investigate the buildings' actual energy performance. Additionally, Indoor Environmental Quality (IEQ) occupant satisfaction surveys were administered to investigate users' satisfaction with the space layout, space furniture, thermal comfort, indoor air quality, lighting level, acoustic quality, water efficiency, cleanliness and maintenance of the facilities they occupy. From a Macro-level perspective, the results suggest ASU LEED buildings consume less energy than regional counterparts, and exhibit higher occupant satisfaction than national counterparts. From a Micro-level perspective, data analysis suggest an inconsistency

between the LEED points earned for the *Energy & Atmosphere* and *IEQ* categories, on one hand, and the respective levels of energy consumption and occupant satisfaction on the other hand. Accordingly, this paper showcases the variation of LEED buildings' assessment results when approached from different perspectives. This contribution raises the necessity to consider the complementary Macro-level and Micro-level assessments in tandem. In order to ensure a fair and representative LEED certification system, the authors recommend basing the awarded LEED points on the actual performance of the building during the occupation phase, as opposed to the intended performance during the design and construction stages.

4.2. INTRODUCTION

Several organizations are currently working to improve their facilities' energy consumption and Indoor Environmental Quality (IEQ) by requiring the U.S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) system. Following an order by the Governor of Arizona in 2005 and in accordance with its president's leadership in the American College and University Presidents' Climate Commitment, Arizona State University (ASU) requires a minimum of LEED *Silver* certification for all new construction of university-owned and operated buildings. This requirement is part of ASU's sustainable design policy for new construction and major renovation projects on all ASU campuses (Facilities Development and Management 2009).

Recent studies have investigated the impact of the LEED rating system on energy consumption with mixed results (Turner and Frankel 2008; Scofield 2009; Menassa et al.

2012). Others studied the effects of space layout and furniture (Cotera 2011), thermal comfort (Kosonen 2004; Mohamed and Srinavin 2005; Mahbob et al. 2013), indoor air quality (Wyon 2004; Mahbob et al. 2013), lighting level (Abdou 1997; Nicol et al. 2006), acoustic quality (Kaarlela-Tuomaala et al. 2009), water efficiency, cleanliness, and maintenance, on the well-being, comfort, and production of building occupants (Haynes 2008; Rashid and Zimring 2008; Fisk et al. 2011; Issa et al. 2011; El Asmar et al. 2014a).

This study complements the existing literature by defining and introducing a Macro and Micro-level framework to investigate the impact of LEED certification on the actual energy consumption and occupant satisfaction of certified facilities. The Macro-level focuses on the overall performance of the buildings with respect to comparative actual performance benchmarks. The Micro-level focuses on the building's performance with respect to the LEED points it earned in the respective LEED categories. First, from a Macro-level approach, the paper compares the energy consumption of surveyed LEED facilities to regional benchmarks according to the Commercial Buildings Energy Consumption Survey (CBECS) and studies occupant satisfaction levels with IEQ relative to national benchmarks according to the Center for the Built Environment (CBE) and ASHRAE standards. Second, from a Micro-level approach, the study examined the correlation between LEED awarded points and the actual performance of the buildings. Third, the study compared the results between the two levels, and the results highlight the need for a comprehensive assessment approach to ensure a full understanding of LEED building performance, which lays the foundation for recommendations to improve rating systems.

4.3. LITERATURE REVIEW ON THE LEED PERFORMANCE

LEED is a third party certification program that serves as a design and construction tool for new and existing institutional, commercial and residential establishments (Cotera 2011). LEED was a national response to the increasing social awareness, and concerns, about the negative environmental impacts that could be generated by buildings including increased energy consumption, depletion of natural resources and waste production, and the increasing reported incidences of the adverse health impacts caused by IEQ problems. Such problems include sick building syndrome and multiple chemical sensitivity (Lee and Guerin 2009). As the evidence challenging the long-term effectiveness of green design continues to compound, pressure is being placed on USGBC to make improvements to its rating system (Cotera 2011). After developing the pilot version, USGBC added seven new versions of LEED before reaching the latest version: *LEED v4*. The latest version includes new market sector adaptations for data centers, warehouses and distribution centers, hospitality, existing schools, existing retail and mid-rise residential projects to ensure that LEED fits the unique aspects of projects (USGBC 2013). Accordingly, a building can earn credits from the IEQ category, the location and transportation category, the sustainable sites category, the water efficiency category, the energy and atmosphere category, the materials and resources category, and the innovation and regional priority categories (extra points) to get certified. Depending on the total points earned out of 100 base points and 10 extra points, a facility is attributed to one of the four measures: *Certified* (40-49 points), *Silver* (50-59 points), *Gold* (60-79 points), and *Platinum* (80 points and above).

When USGBC developed the LEED rating system in the 1990s, there was a limited amount of post-occupancy energy data from LEED certified buildings to conduct significant research. However, as a result of the rapid increase in social awareness and government commitment to high-performance and environmentally aware design, a large number of facilities have been required to obtain LEED certification. Therefore, more metering data has been available to test LEED's impact on building performance and its validity as a rating system. Consequently, previously completed studies that focus on energy consumption and IEQ satisfaction for LEED certified facilities are reviewed next.

Several studies investigated occupant satisfaction in both LEED and non-LEED buildings. For instance, Turner (2006) investigated 11 LEED certified buildings in the Cascadia region and established that users are satisfied with lighting and air quality of their buildings, but unsatisfied with sound conditions, when compared to 1000-plus cases reviewed under the *Buildings in Use* (BIU) tool of Vischer and Preiser (2005). Similarly, Abbaszadeh et al. (2006) compared occupant satisfaction in 21 LEED certified buildings with that of 160 conventional buildings, and noticed that occupants in LEED buildings were more satisfied with thermal comfort, air quality, office furnishings, cleaning and maintenance, but less satisfied with lighting and acoustics than occupants of conventional buildings. Lee and Guerin (2009) later confirmed these same findings by surveying the occupants in 15 LEED certified buildings. They found users satisfied with cleanliness, maintenance, office furnishing quality and indoor air quality, but dissatisfied with thermal comfort and acoustic quality. Another study by Lee (2011) investigated whether indoor air quality (IAQ) and thermal comfort that were measured by occupants' environmental satisfaction and their perceived job performance in personal workspaces of LEED certified buildings were associated with the rating level of the LEED certification. The author concluded that the higher the certification level is, the higher the workers' satisfaction and perceived job performance would be. Cotera (2011) conducted a post-occupancy evaluation of two LEED certified education buildings at the University of Florida in Gainesville and found that both buildings were 29% above the CBE standard. Other research studied the effect of LEED buildings on the occupant satisfaction through absenteeism and performance. For example, Issa et al. (2011) showed that student, teacher and staff absenteeism in LEED certified schools in Toronto improved by 2–7.5%, whereas student performance improved by 8–19% when compared with conventional schools. Other studies considered the influence of building usage duration on occupant satisfaction as an unrelated factor to environmental quality. For example, Stefano and Sergio (2014) analyzed occupant satisfaction levels in 65 LEED-rated buildings on a subset of the CBE survey database and called attention on the effect of time spent at the workspace (less or more than one year) on occupant satisfaction with the building. The obtained results suggest that the positive value of LEED certification from the point of view of the satisfaction of occupants tend to decrease with time.

To follow up on earlier findings related to energy consumption, Turner (2006) assessed the performance of 11 buildings in the Cascadia region and found that although all sampled buildings had better savings than their designed energy use, only two of them performed better than the average commercial stock. Diamond et al. (2006) investigated 21 LEED certified buildings and showed that the certified energy credits did not show any correlation with the actual energy use. Later, Fowler and Rauch (2008) found that the energy consumption of 12 LEED government buildings is 25%-30% lower than the average of commercial building stock. Turner and Frankel (2008) investigated 552 LEED buildings and showed a 24% lower energy use intensity (EUI) than their national counterparts. However, the final results of the study state "high energy use buildings [were] generally considered separately," which eliminates data that contributes a larger EUI. Subsequently, Newsham et al. (2009) found the measured energy performance of LEED buildings had little correlation with the certification level of the building, or the number of energy credits achieved by the building in the design phase. Further, Scofield (2009) concluded there is no evidence that LEED certification has collectively lowered energy consumption for office buildings. Menassa et al. (2012) later tested the same hypothesis by investigating a more targeted dataset consisting of the U.S. Navy LEED certified buildings. Although these buildings were required to become LEED certified in an effort to improve energy efficiency and mitigate greenhouse gas emissions, Menassa et al. found that only 3 out of 11 buildings showed energy efficiency gains compared to CBECS buildings in addition to the absence of any correlation between the number of earned LEED points and energy savings.

The results of the existing literature on LEED building performance are not unanimous. However, it is important to quantify the benefits of the certification because it often requires an additional first cost to the facility owner. In fact, the impact of LEED certification on the facility cost was investigated in several studies. Kats et al. (2003) showed LEED *Platinum* buildings cost 6.50% more than conventional buildings, followed by LEED *Silver* buildings (2.11%), LEED *Gold* buildings (1.82%) and LEED *Certified* (0.66%). However, this order was different in Miller et al.'s (2008) study, which established that LEED *Platinum* buildings cost an average of 8.6% more than LEED *Certified* buildings, followed by LEED *Gold* buildings (4.0%), and LEED *Silver* buildings (1.9%). The relationship between LEED certification levels and initial facility cost also was discussed in a study on New York City LEED buildings (Kaplan et al. 2009). The study reported the highest construction cost was for LEED *Platinum* buildings, followed by LEED *Gold* and *Silver* buildings, and finally LEED *Certified* buildings.

The literature highlights a positive relationship between the increase in the facility cost and the LEED certification level. However, there was no conclusive evidence linking the increasing LEED certification levels to measured improvements in performance, in terms of energy savings and occupant satisfaction, in order to justify the additional first cost. In fact, previous studies reveal a discrepancy between buildings' LEED ratings and their actual performance.

4.4. RESEARCH GAP AND OBJECTIVES

A survey of previous papers reveals inconsistent results in the performance of LEED buildings (Turner 2006; Abbaszadeh et al. 2006 ; Turner and Frankel 2008; Newsham et al. 2009; Scofield 2009; Menassa et al. 2012; Lee and Guerin 2009; El Asmar et al. 2014a). This performance has been approached from two different perspectives: several studies investigated the measured performance of LEED certified buildings as compared to their conventional counterparts, with regards to energy consumption and occupant satisfaction; while others investigated the correlation between the actual energy consumption and the number of awarded LEED points in the Energy and Atmosphere category.

None of the reviewed papers used the same dataset to assess the performance of LEED buildings from both perspectives presented above (versus non-LEED and versus awarded points,) while also using both energy consumption and occupant satisfaction simultaneously. This paper fills the identified gap by completing a balanced investigation of energy consumption and IEQ performance. To achieve this purpose, the authors introduce two levels of LEED performance assessment: a Macro-level that compares LEED certified buildings to their conventional counterparts; and a Micro-level that analyzes the actual performance of LEED buildings vis-à-vis the awarded points in the respective LEED categories. Table 9 illustrates the four quadrants of the assessment framework presented in this study, which summarizes relevant literature evaluating the overall performance of LEED buildings.

Table 9. The Four Quadrants of the Assessment Framework

Level	Comparison Parameters	
	Energy Consumption	IEQ
Macro-level	1st quadrant: Energy Consumption on Macro-level	2nd quadrant: IEQ on Macro-level
Micro-level	3rd quadrant: Energy Consumption on Micro-level	4th quadrant: IEQ on Micro-level

The need and contribution of this paper is further emphasized in Table 10, which compares key relevant studies in the literature. As shown in this table, none of the reviewed existing studies have tackled the fourth quadrant by comparing the granular level of IEQ versus the actual occupant satisfaction, or addressed all four quadrants simultaneously to comprehensively assess the performance of LEED buildings. Therefore, introducing the different assessment levels for both IEQ and Energy, which are complementary and inversely correlated factors that need to be evaluated concurrently on both levels, offers a more comprehensive assessment method that contributes to the (so far) inconsistent literature on the topic. For instance, a building may improve the IEQ by overusing energy or it may save energy by under-satisfying occupants. Moreover, a LEED building, analyzed from a Macro-level, could save energy and improve occupant's satisfaction when compared to its conventional counterpart; however, this same building may fail to reach its design intent when approached from a Micro-level, and vice versa.

Table 10. Applying the Assessment Framework to Differentiate between the Literature and the Contributions of this Paper

Previous Studies		**Macro-level** (LEED versus conventional)		**Micro-level** (LEED points per category versus actual performance)	
Index	**References**	**Energy** 1st Quadrant	**IEQ** 2nd Quadrant	**Energy** 3rd Quadrant	**IEQ** 4th Quadrant
1	Turner (2006)	X	X		
2	Diamond et al. (2006)			X	
3	Abbaszadeh et al. (2006)		X		
4	Fowler and Rauch (2008)	X			
5	Turner and Frankel (2008)	X			
6	Scofield (2009)	X			
7	Newsham et al. (2009)			X	
8	Cotera (2011)	X	X		
9	Issa et al. (2011)		X		
10	Menassa et al. (2012)	X		X	
11	*Chokor et al. (current)*	*X*	*X*	*X*	*X*

Therefore, the current study balances both metrics through a comprehensive approach that takes into consideration all four quadrants of the assessment framework and investigates the correlation between the actual occupant satisfaction and the number of awarded LEED points in the IEQ category. Throughout this paper, the authors evaluate the performance of LEED buildings, and highlight the need to adopt such assessments in future evaluations. This research study investigates the LEED buildings' actual performance in terms of indoor environmental quality and energy consumption over four-years and focuses on a specific type of facilities in one geographical location in order to limit the variation in the dataset.

4.5. RESEARCH METHOD

The methodology used to investigate the actual performance of LEED buildings is detailed next and involves three steps: (1) selecting LEED certified buildings on the ASU Tempe campus; (2) collecting four years of energy consumption data and conducting a Post Occupancy Evaluation (POE) survey to evaluate the occupant's level of satisfaction with the certified facilities; and (3) comparing the performance levels of the LEED certified buildings to the appropriate regional and national benchmarks.

4.5.1. Building Selection

The Facilities Development and Management's (FDM) record database stores the last four years of energy metering data for the ASU campus. In order to hold the location variable constant while addressing the objectives of this study, all the selected buildings are located on the ASU Tempe campus and have been occupied for at least four years prior to the start of data collection. The buildings are LEED certified and their energy consumption data is accessible. A total of eight ASU facilities fit the criteria set for this study. These buildings are described next and are classified according to their use: dormitories; research buildings; office and classroom buildings.

4.5.1.1. Dormitories

A. Barrett Honors College (BHC)

BHC is the nation's first four-year, residential college within a top-tier public university and supports students at all levels of their academic career. Solar panels, a grey water reuse system, an organic garden, an experimental green roof, and state-of-the-art energy use modeling are all extra features for the Honors campus. Besides diverting 89% of construction waste from landfills, this building was designed to save 53% of irrigation water and 44% of indoor water (ASU Online Tour).

B. Hassayampa Academic Village (HAV)

HAV incorporates several green building features into its design. Among these features are reflective roofs and paving materials (which reduce the urban heat island effect), low-flow faucets and toilets that reduce the building's water use by 40% compared to a conventional building of its size, and occupancy sensors and window shades that reduce HAV's energy needs by 25% compared to a conventional building. The landscaping around HAV uses native and drought resistant species that reduce water needed for irrigation by 50%. During its construction, over 50% of HAV's construction waste was recycled; and a significant amount of construction materials contained recycled content or were manufactured locally. For the purpose of this study, HAV was split into two sub-villages in order to match the energy metering divisions used by the Facilities Development and Management (ASU Online Tour).

4.5.1.2. Research Buildings

A. Interdisciplinary Science and Technology Building 1 (ISTB1)

ISTB1 provides laboratories and workspace as a research facility for bioengineering, neural engineering, and molecular, tissue, and cell engineering. Sustainable features of the building include drywells that reduce storm water runoff on the site by 25%; reflective pavements and roofing to reduce the urban heat island effect; natural and drought-resistant landscaping that reduces the site's irrigation needs by 50%; and waterless urinals and low-flow fixtures that reduce ISTB1's water consumption by 37% compared to a conventional building. To encourage public transportation, ISTB1 provides the infrastructure for 36% of its occupants to store their bikes on site. Additionally, over 60% of the waste generated during the construction of this building was recycled, and large portions of construction materials contain recycled content or were regionally manufactured (ASU Campus Metabolism).

B. Interdisciplinary Science and Technology Building 2 (ISTB2)

ISTB2 is a high-bay facility supporting research in advanced materials, transportation planning, geotechnical engineering, fluid dynamics and sustainable materials. It earned its LEED *Silver* rating by minimizing its urban heat island effect, reducing its water use by 30%, optimizing energy performance, diverting 75% of its construction waste from landfills, using recycled and regionally available building materials, and improving indoor environmental quality (ASU Campus Metabolism).

C. Interdisciplinary Science and Technology Building 4 (ISTB4)

ISTB4 is a research facility that provides flexible laboratories with adjoining workspace for the School of Earth and Space Exploration, the College of Liberal Arts and Sciences and the Ira A. Fulton Schools of Engineering. Some of the green design and construction features implemented in the building include: (a) optimal building orientation based on local climate conditions and a high performance façade with vertical sunshades to reduce heat gain and incorporate passive cooling strategies, (b) efficient building systems to reduce energy use by 40.7% below a typical laboratory building, and (c) on-site renewable energy produced by the photovoltaic array on the parking structure adjacent to ISTB 4, supplying an additional 11.6% of its energy use beyond the savings achieved by the building design (ASU Campus Metabolism).

4.5.1.3. Office and Classroom Buildings

A. Wrigley Hall (WGL)

WGL is home to ASU's Global Institute of Sustainability and School of Sustainability. This building was renovated utilizing sustainable products, including high-recycled content materials in the carpet and flooring. Indoor air quality is enhanced through the use of certified furniture and low-emitting paints, coatings and interior signage. Energy use is reduced with the use of natural light and solar tubes to take advantage of the abundant natural sunlight available, and an occupancy sensor-controlled lighting system. Water efficiency is incorporated throughout the building, including low water use fixtures and native drought-tolerant plantings (ASU Facilities Development and Management).

B. Fulton Center (FUL)

The Fulton Center earned its LEED certification by reducing its urban heat island effect through roof and landscape design, reducing its water use by more than 30%, using recycled and regionally available building materials, maximizing indoor environmental quality and reducing landscape water usage by 50% (ASU Online Tour). Table 11 presents each aforementioned building's age, location, size both in squared meters and gross square feet (GSF), and type of use for residential, classroom, office, research, library, and classroom laboratory, as well as the LEED rating and the earned points on each LEED category.

Table 11. Characteristics of the LEED Certified Buildings' Sample

	Types	Dormitories			Research Buildings			Office and Classroom Buildings	
General Facts	Buildings	BHC	HAV1	HAV2	ISTB 1	ISTB 2	ISTB 4	WGL	FUL
	Size (m^2)	54,404	23,954	29,891	17,958	6,619	30,403	4,664	15,232
	Size (GSF)	585,600	257,838	321,744	193,294	71,248	327,256	50,202	163,959
	Location	Tempe, AZ, 85287 USA							
	Buildings Ages during data Collection (Years)	4	7	7	7	8	4	9	8
Buildings Areas Percentages	Residential %	94%	100%	100%	0%	0%	0%	0%	0%
	Classroom %	0%	0%	0%	0%	0%	0%	30%	0%
	Office %	6%	0%	0%	29%	30%	24%	70%	100%
	Research %	0%	0%	0%	71%	60%	16%	0%	0%
	Library %	0%	0%	0%	0%	0%	57%	0%	0%
	Classroom Laboratory %	0%	0%	0%	0%	10%	3%	0%	0%
LEED Features	LEED Type	LEED for New Construction							
	LEED Ratings	Gold	Silver	Silver	Gold	Silver	Gold	Silver	Certified
	Total points	39	33	33	39	33	48	37	26
	Sustainable Sites	10	9	9	9	10	11	10	8
	Water efficiency	3	3	3	3	3	3	3	3
	Energy and Atmosphere	7	3	3	7	5	15	3	3
	Materials and Resources	5	5	5	5	5	5	7	4
	Indoor Environmental Quality	9	8	8	10	8	9	9	5
	Innovation and Design	5	5	5	5	2	5	5	3

4.5.2. Energy Consumption and Occupant Satisfaction Data Collection

The data collection effort consisted of gathering energy data and occupant satisfaction data. Four years of energy metering information was collected in kWh of electricity (1 kWh = 3.6 MJ), MBtu of heating (1 MBtu = 1,055.87 MJ), and ton-hour of chilled water (1 tonh = 12.66 MJ). For each building, the total energy consumption was computed by adding the energy used for heating, cooling, and electricity, and then average yearly EUI values were calculated by dividing the total energy consumed by the size of the facility.

For occupant satisfaction data, several IEQ surveys were reviewed in an effort to select the appropriate tool for measuring the satisfaction levels of ASU buildings occupants. Adapting widely-used surveys allows for a comparison of the results across similar studies completed previously. Therefore, a questionnaire was adapted based on one developed and used at the Center for the Built Environment (CBE) at the University of California at Berkeley, also known as Cotera's Occupant IEQ Satisfaction Survey (Cotera 2011). The survey examines the performance of buildings in eight major sections covering various facets of IEQ: workspace layout, workspace furniture, thermal comfort, indoor air quality, lighting levels, acoustic quality, water efficiency, and cleanliness and maintenance in addition to the occupant background information and the overall satisfaction with space (CBE 2010). Respondents were categorized into three main groups based on how familiar they are with the selected buildings in terms of usage purpose and duration: visitors who used the building for less than three months, students who spent more than three months using the building continuously, and faculty/staff who worked in the selected facility for more than three months. Twenty randomly selected participants from each building were asked to evaluate their satisfaction with the eight areas covered in the survey based on a 5-point Likert scale (from 1 meaning very dissatisfied, to 5 meaning very satisfied). Then the average satisfaction percentage was calculated for each performance area.

4.5.3. Data Analysis

The collected data for energy consumption and occupant satisfaction was combined and analysed from both Macro-level and Micro-level perspectives.

4.5.3.1. Macro-level

First, in order to gauge energy consumption performance, ASU LEED buildings were compared to their counterparts based on the Commercial Buildings Energy Consumption Survey (CBECS). The CBECS database is a national sample survey that collects information on the stock of U.S. commercial buildings, including their energy-related building characteristics and energy usage data per region and type (U.S. Energy Information Administration). Adequate counterparts were identified from the CBECS database by first selecting all facilities in the State of Arizona, then narrowing down the search to comparable areas, mostly in the Phoenix, AZ metropolitan area, by selecting climate zone 2B (Hot and Dry). Then comparable building types were selected to include educational facilities, office buildings, dormitories, and suitable public assembly facilities. Energy data collected from year 2001 to year 2013 was included. The resulting peer group consisted of 287 comparable facilities located in Arizona. After the energy consumption profile of the peer group was plotted, average EUI for ASU LEED certified dormitories, office, and classroom buildings were compared to the CBECS benchmark. Research buildings were excluded from the EUI comparison due to the unavailability of CBECS energy data from comparable counterparts in Arizona. In order to check the statistical significance of the differences, a two-tailed t-test test was used at a 0.05 significance level to compare the selected buildings' average EUI with the median of their CBECS counterparts.

Second, in order to gauge occupant satisfaction performance, average satisfaction ratings from each ASU LEED certified facility were compared to the CBE benchmark database, which is a global database based on a total of 59,359 occupant surveys. According to CBE, a good occupant satisfaction rating corresponds to a score that is greater than the 50th percentile. Moreover, an investigation of the results was conducted to indicate to what degree ASHRAE standards were met. ASHRAE Standard 55-2013 and 62.1-2013 define respectively acceptable thermal and air quality conditions in which more than 80% of people do not express dissatisfaction (ASHRAE 2013). Next, a single factor ANOVA test was conducted to evaluate the differences in occupant satisfaction among faculty and staff, visitors, and students. The variation of occupant satisfaction for different types of users is also illustrated in function of usage duration by considering Pearson correlation coefficients.

4.5.3.2. Micro-level

The Micro-level analysis entails a comparison between (1) the design intent as measured by the number of LEED points earned in the Energy and Atmosphere and IEQ categories, and (2) the actual performance of the certified facilities. Finally, a comparison of Macro-level and Micro-level results was completed for the same dataset to address the objectives of this study.

4.6. FINDINGS

This section presents and discusses the findings related to actual energy consumption and occupant satisfaction from both the Macro-level and Micro-level analyses, which correspond to a comprehensive study of the four quadrants previously described in the paper.

4.6.1. Macro-level

Macro-level analyses comprise the examination of the 1st quadrant (Energy Consumption on Macro-level) and 2nd quadrant (IEQ on Macro-level) already defined in the paper. With regards to the first quadrant, average levels of energy consumption were calculated for all selected buildings by combining heating, cooling and electricity consumption data. Then, ASU LEED certified dormitories, office and classroom buildings were compared to their peer group of 287 regional counterparts according to the CBECS database as shown in Figure 14. The null hypothesis (H0) tested states that energy consumption (in EUI) of ASU buildings (x1) is equal to the median EUI of Arizona comparable buildings (x2). The null hypothesis can be stated as:

- H0: x1 = x2

A two-tailed t-test is conducted to compare ASU buildings to their CBECS counterparts in terms of energy consumption. The t-test results in a p-value of 0.0158 and therefore rejects the null hypothesis that energy consumption of ASU buildings is equal to that of comparable AZ buildings. Even with a small sample size of the ASU building sample, the differences in energy consumption were found to be statistically significant, in favor of the ASU LEED certified buildings. Although one building's EUI was higher than the peer group median of 1,635 MJ/m^2/year (144 kBtu/ft^2/year), ASU LEED buildings were largely on the lower end of the energy consumption spectrum when compared to their regional counterparts.

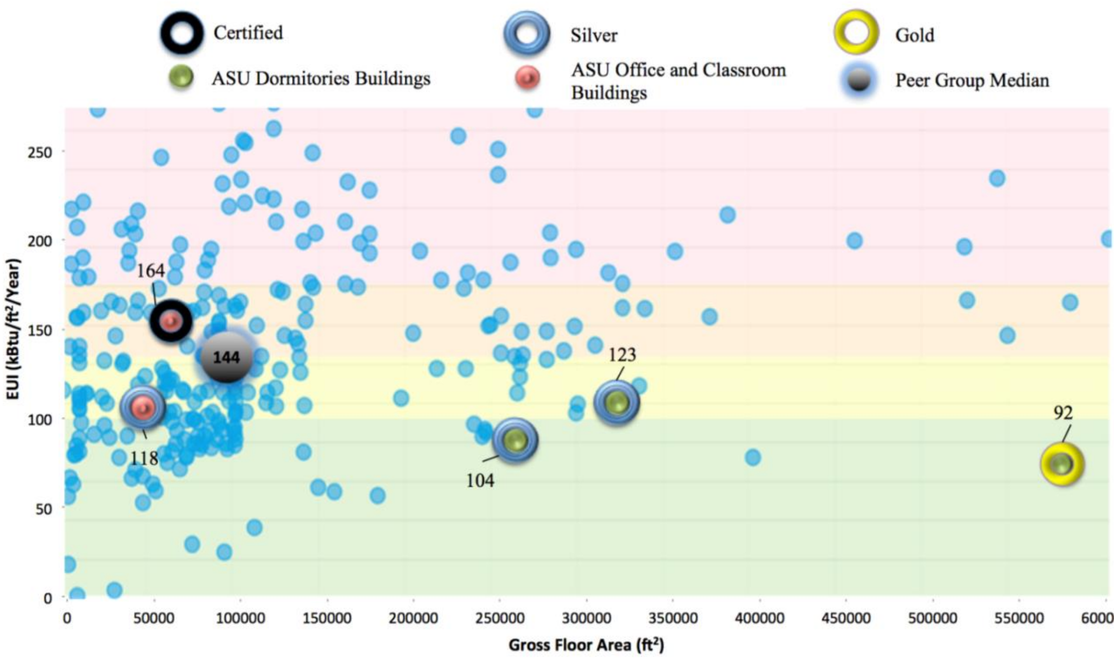

Figure 14. EUI Comparison of ASU LEED Certified Facilities and AZ CBECS Peer Group

In addition, the results from this small sample show a relationship between the level of LEED certification of a facility and its energy use: the buildings with higher certification levels have lower EUI values. In other words, the LEED gold buildings achieved the lowest EUI level by using about 20% less energy than the LEED *Silver* buildings, which in turn, consume 30% less energy than the LEED *Certified* building. One caveat here is that different building types are considered. However, this finding still holds when comparing the buildings of the same type; for example, the LEED Gold dormitory uses less energy that the two LEED *Silver* dormitories.

With regards to the second quadrant dealing with IEQ, average levels of occupant satisfaction were calculated for each of the IEQ performance categories. A total of 160 respondents participated in the survey. Of the 160 respondents, 41.9% were faculty/staff, 49.3% were students and 8.8% were visitors, as shown in Figure 15. By assuming equal weights for all eight IEQ areas, the surveyed facilities earned an average of 77.7% satisfaction rating across all buildings.

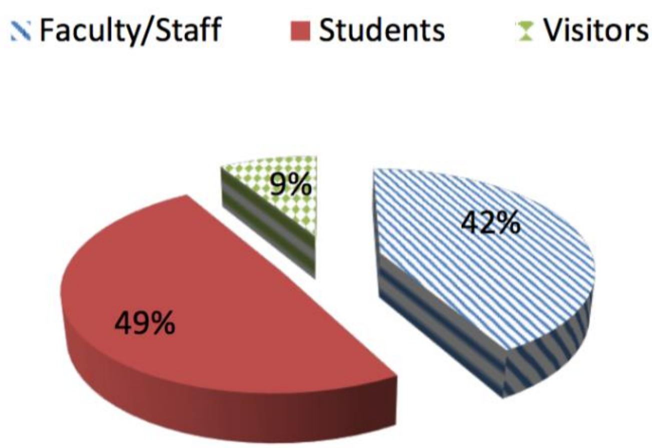

Figure 15. Respondent Characteristics

Figure 16 provides an illustration of the differences in performance for all eight survey questions across the selected buildings. Although ASU LEED buildings scored 71% in thermal comfort and 79%% in indoor air quality, flirting with but not consistently achieving the recommended 80% target according to ASHRAE Standard 55, a total of 82.8% of occupants were satisfied with the overall IEQ of the facilities. In fact, the selected buildings performed much better than the CBE national benchmark across all surveyed categories, as shown in Figure 17. The CBE benchmark is based on 59,359 participants. In addition, these results are in compliance with the literature and confirm the success of LEED in increasing occupant satisfaction with respect to IEQ.

Next, the data collected was grouped and analyzed by different user types: visitors, students, and faculty/staff. The analysis consists of analyzing occupant satisfaction scores from all buildings to test the statistical significance of the differences among different types of users, using a single factor analysis of variance (ANOVA) at the 95% confidence level.

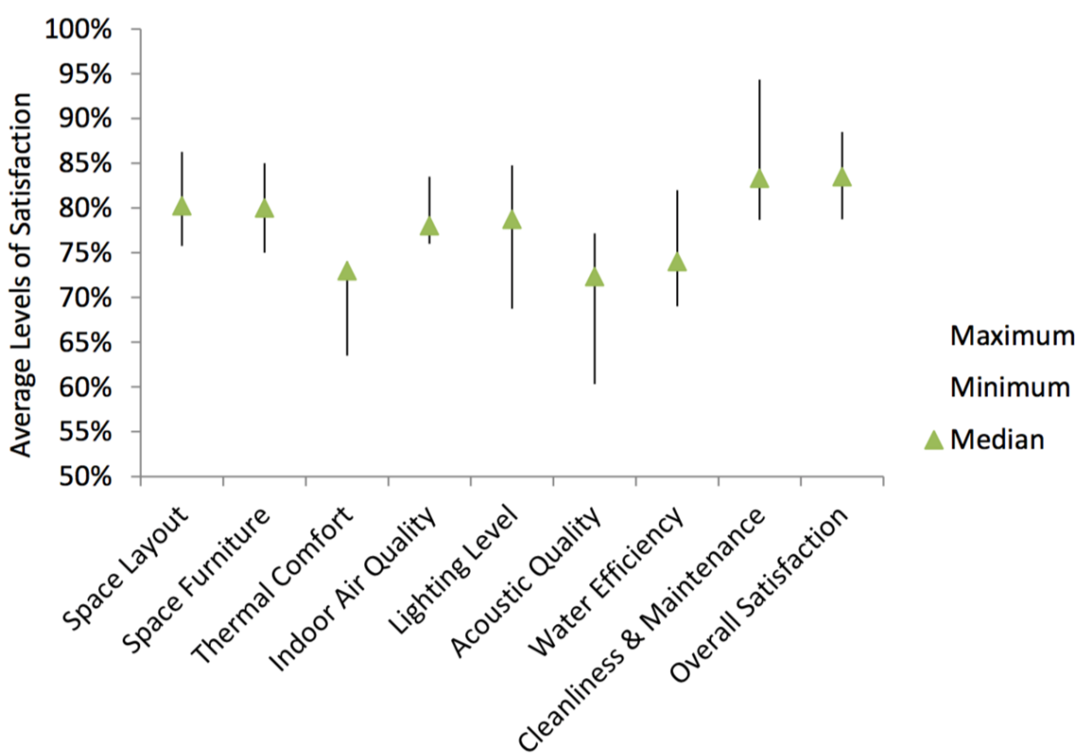

Figure 16. Occupant Satisfaction Levels for ASU LEED Certified Buildings

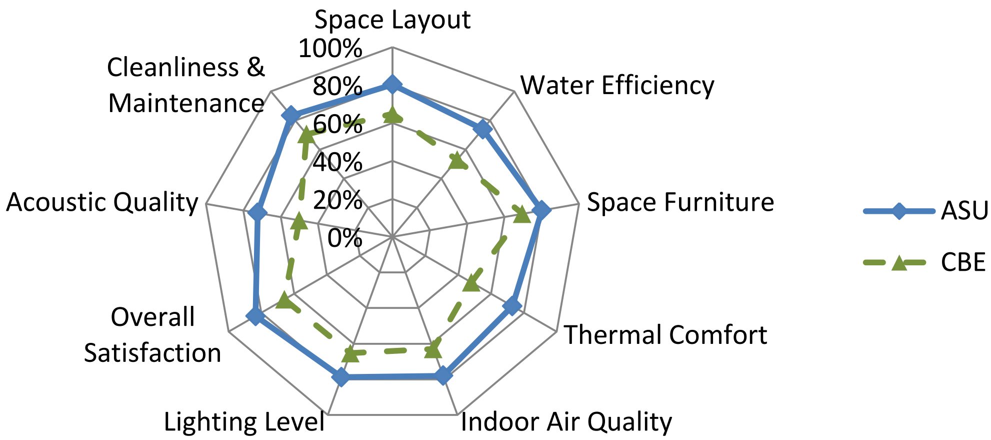

Figure 17. Comparison of ASU and CBE Occupant Satisfaction Scores

Table 12 and Figure 18 present the results of the ANOVA tests. The absence of significant differences among various types of users (p-value greater than 0.05) suggests that users, regardless of their use purpose of the selected buildings, have similar IEQ satisfaction. This similarity paves the way for additional analysis in terms of usage duration for each user type. Figure 19 shows the variation of occupants' satisfaction across all user types in function of their usage duration (in months). The results show that occupants become less satisfied when they spend more time in a building.

Table 12. ANOVA Results per User Type

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*
Between Groups	0.00207	2	0.00104	0.27426	0.76325	3.55456
Within Groups	0.06820	18	0.00379			
Total	0.07028	20				

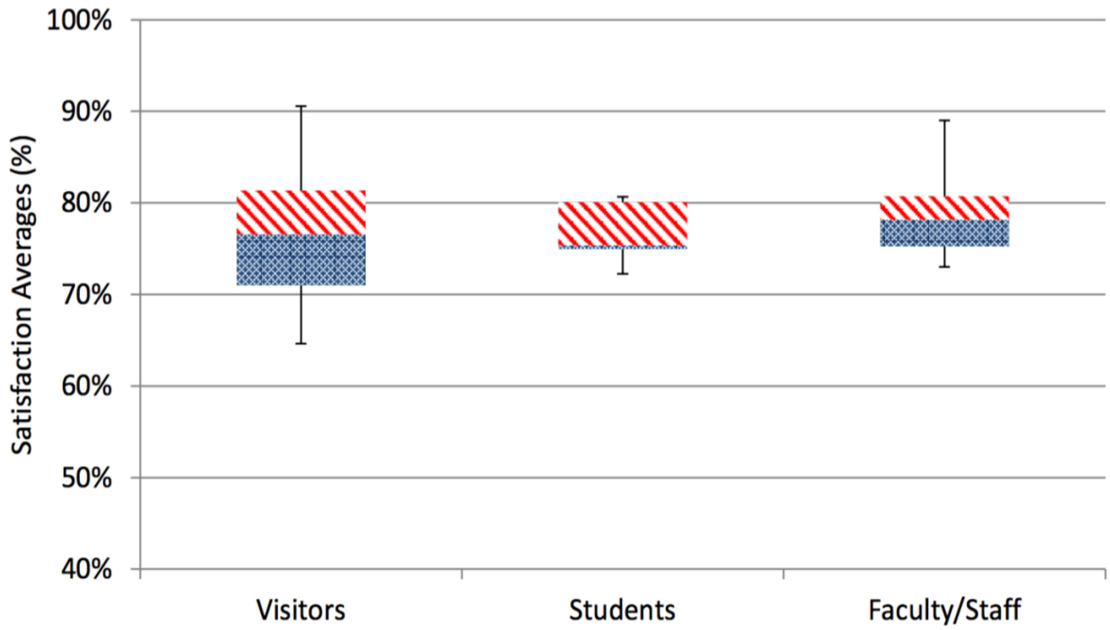

Figure 18. The Variation of Satisfaction Averages (%) per User Type

A Pearson correlation factor of -0.47 is significant and an additional breakdown analysis per user type was performed to highlight the reason behind this trend.

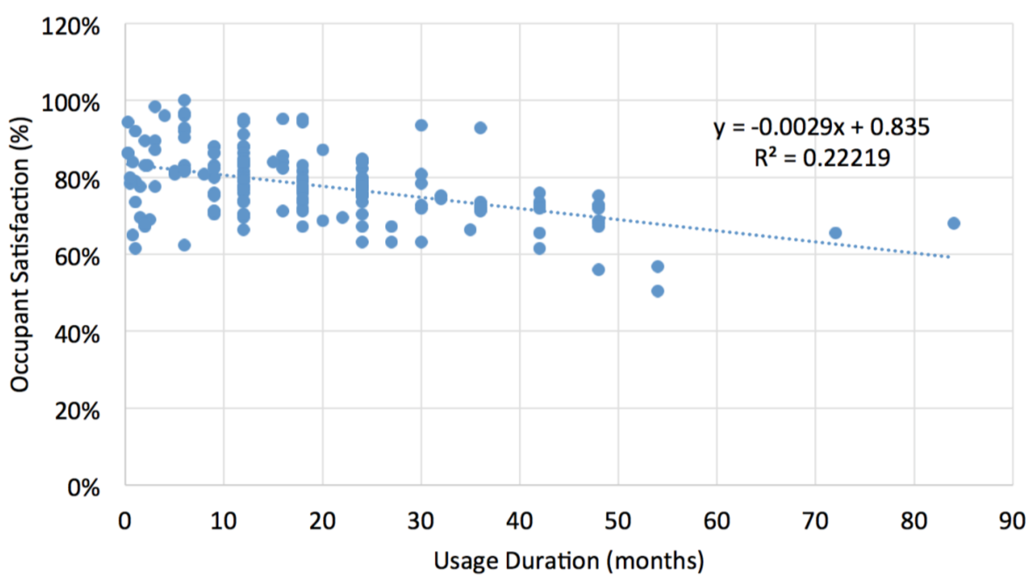

Figure 19. The Variation of Occupant Satisfaction as a Function of Usage Duration in Months

Figures 20, 21, and 22 highlight the variation of the user satisfaction level as a function of usage duration for visitors, faculty/staff, and students, respectively.

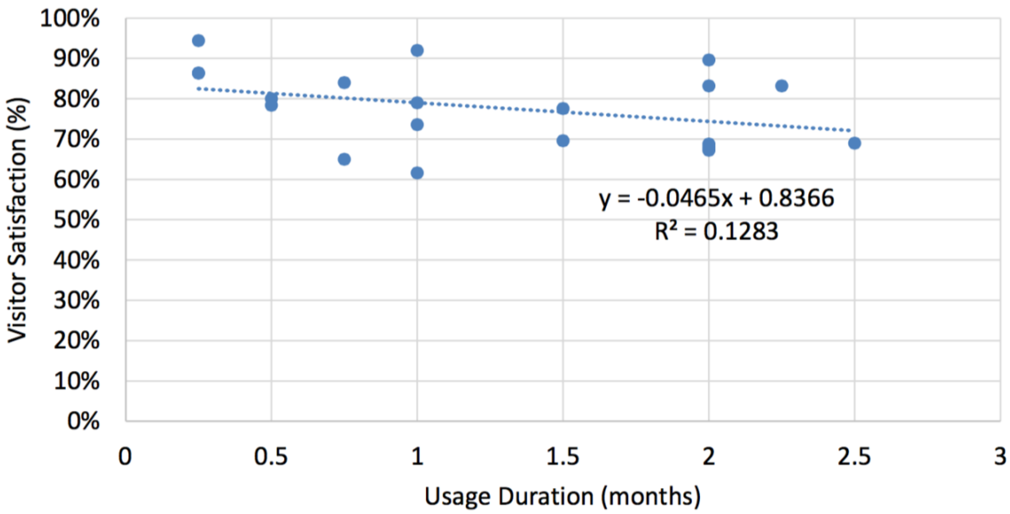

Figure 20. The Variation of Visitor Satisfaction as a Function of Usage Duration in Months

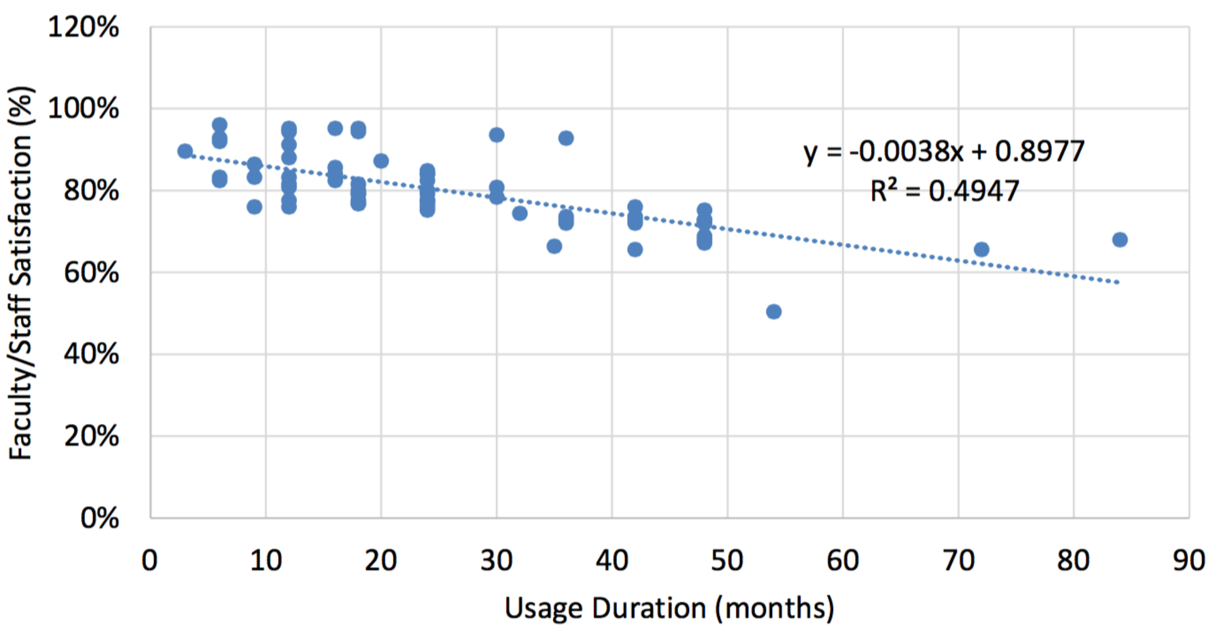

Figure 21. The Variation of Faculty/Staff Satisfaction as a Function of Usage Duration in Months

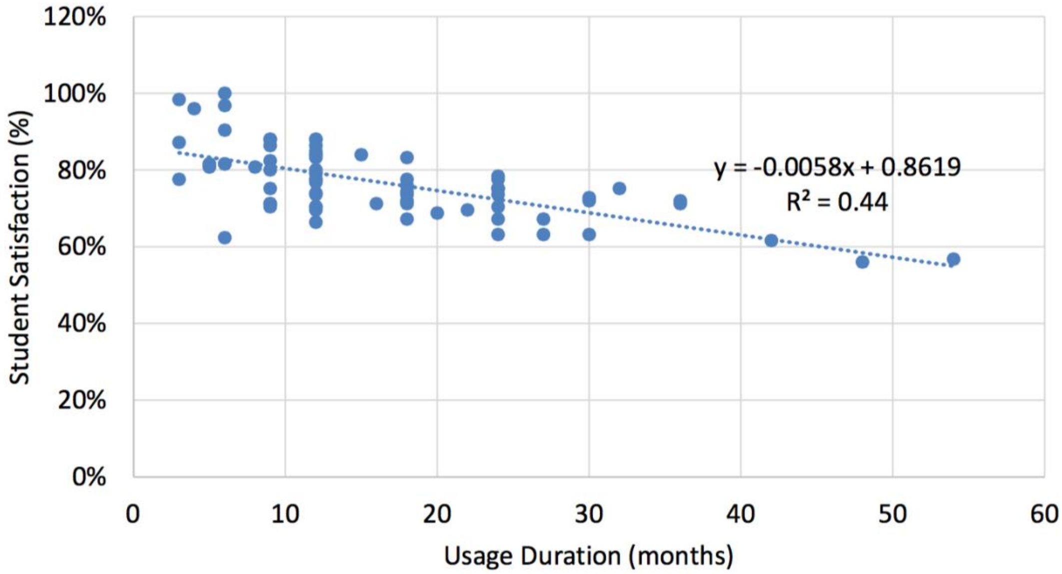

Figure 22. The Variation of Student Satisfaction (%) as a function of Usage Duration in Months

Table 13 summarizes the associated Pearson coefficient correlations. Although all relationships validate the fact that occupants will be less satisfied with their buildings with time, the negative correlation was more obvious in cases of students and faculty/staff as opposed to visitors.

Table 13. Pearson Correlation Coefficients between Occupant Satisfaction and Usage Duration for Different User Types

User Type	Pearson Coefficient Correlation
Visitors	-0.3582
Faculty/Staff	-0.7034
Students	-0.6633
All users	-0.4714

These results confirm the literature findings and are in line with Singh et al. (2010) who stated that there could be an improvement in satisfaction with perceived indoor environmental quality and self-assessed productivity after the move into a new LEED-rated workspace, possibly as a result of employees' excitement about their new place of work. Such results justify splitting the users into three types One potential reason for these results is the novelty factor known as "Hawthorne effect" (Franke and Kaul, 1978; McCarney et al. 2007) – although disagreed by other studies (Adair, 1984) - that has been linked to a temporary bias in occupants' perception of their performance and satisfaction resulting from a change in the work environment. When users move into a newly built facility, they tend to move from an older facility that may not offer all the advantages that a new building offers. With time, the novelty factor may fade. This effect more dramatic for students, but also can be seen with for faculty/staff that work in the buildings every day; their occupant satisfaction starts to decrease after two years.

4.6.2. Micro-level

Micro-level Analyses comprise the investigation of the 3rd quadrant (Energy Consumption on the Micro-level) and 4th quadrant (IEQ on the Micro-level) previously defined in the study. A close examination of the awarded LEED points under the *Energy and Atmosphere* and *IEQ* categories reveals no clear relationship between the actual performance levels and the points earned in the corresponding categories. Figure 23 presents the EUI and occupant satisfaction scores, on the y-axes, and the *Energy and Atmosphere* and *IEQ* points earned in LEED on the x-axis.

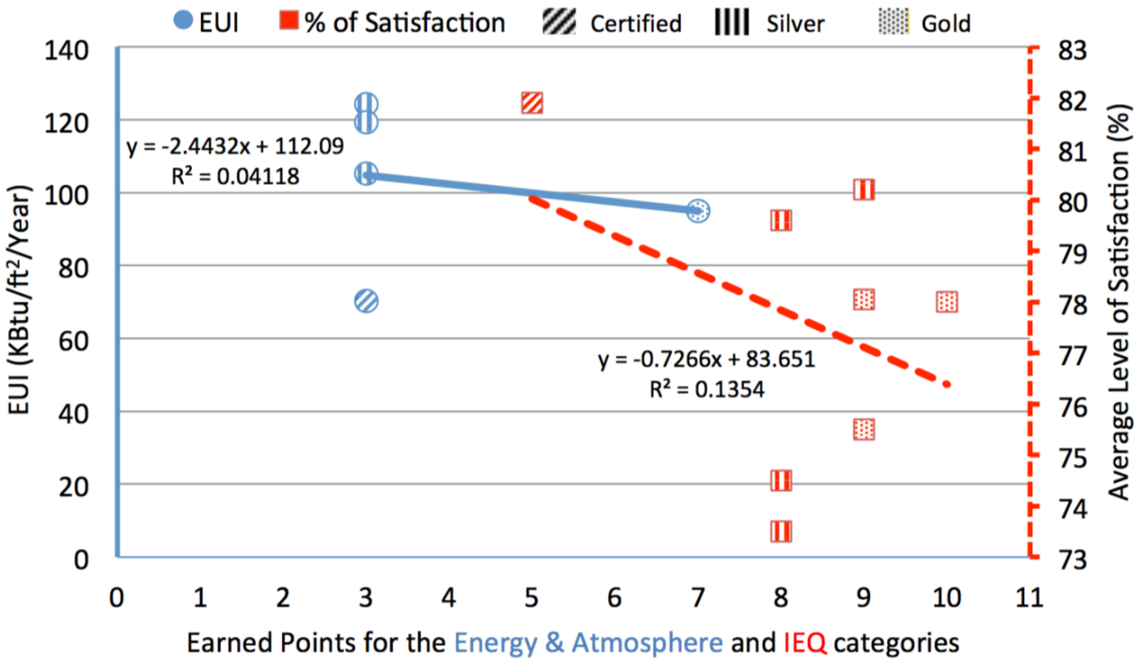

Figure 23. LEED Points Earned in Energy and Atmosphere and IEQ Categories versus Actual Energy and IEQ Performance

For example, the Fulton Center showed the lowest energy consumption with an EUI of 795 MJ/m^2/year (70.3 $KBtu/ft^2$/year), although it achieved the least number of points in the LEED *Energy and Atmosphere* category. Moreover, the occupants of Fulton Center (which earned only 5 out of 15 possible points for IEQ) were much more satisfied than the occupants of ISTB1, which achieved 10 LEED points for IEQ. Figure 24 shows the Principal Components Analysis (PCA) correlation circles for energy consumption and occupant satisfaction. The orthogonal lines highlight the absence of a clear relationship between the actual performance levels in terms of satisfaction and energy savings, on one hand, and the input variables on the other hand. For example, occupant satisfaction is not shown to be correlated with LEED earned points and IEQ earned points. Building age showed a similar behavior since they are all relatively new buildings and the age differences are minimal.

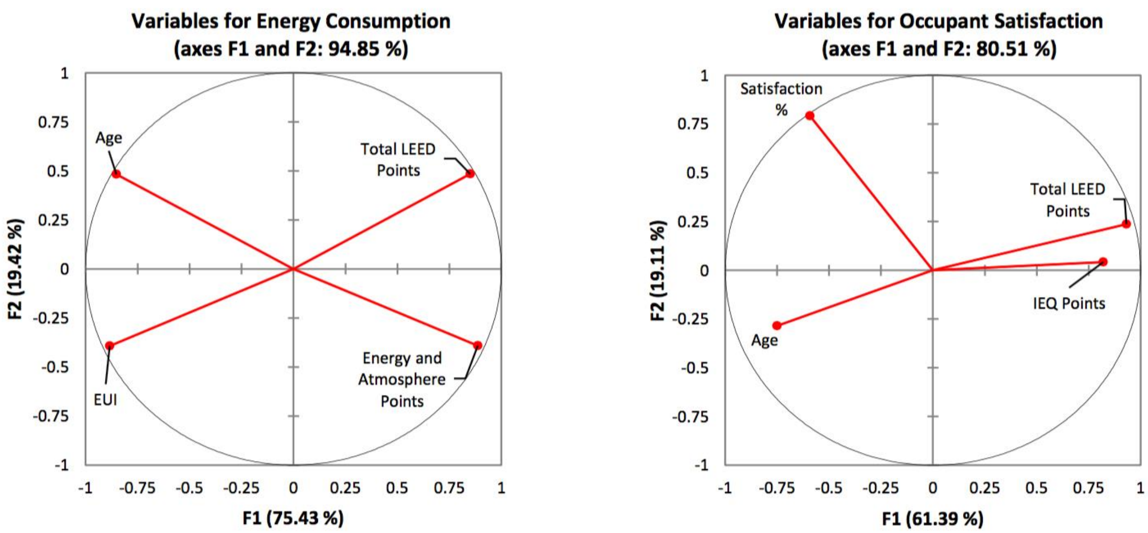

Figure 24. The PCA Test Correlation Circles for Energy Consumption and Occupant Satisfaction

The USGBC's LEED rating system for new construction is often criticized for not requiring continuous performance assessments of certified buildings throughout their occupation phase. With the exception of projects registered under LEED version 3.0, once a building is certified, it is certified for life. Though many steps are carefully taken to ensure these buildings meet the required standards during the design and construction phases, there are no mandatory requirements to verify the buildings are still maintaining their efficient performance levels after the initial certification (Cotera 2011) and throughout their lifecycle.

4.6.3. Macro-level versus Micro-level

Analyzing the same dataset from two different perspectives led to inconsistent results. From a Macro-level perspective, the studied LEED buildings were performing better than their regional and national counterparts. However, when these same buildings were approached from a Micro-level perspective, their actual energy and IEQ performance was not correlated with the original number of LEED points allocated to the energy and IEQ categories, respectively. Table 14 compares, summarizes, and synthesizes the existing literature as well as this study using the proposed framework.

The LEED certification is mostly awarded based on the design of the facility, which means any change in occupation variables, such as the type or number of occupants, may lead to changes in the intended performance. However, the LEED's status symbol and point system may allow to game the system without always prioritizing sustainable performance over the life cycle of the facility (Quirk 2012). As a result, some practitioners have started following some guidelines to "cheat" the LEED certification and certify buildings without necessarily ensuring an improvement in actual performance (Seville 2011). In order to evaluate the actual performance of LEED buildings, practitioners should consider both the macro and micro levels.

In addition to the investigated variables for which data was available, additional factors can affect the performance of buildings.

Table 14. Synthesis of the Literature and this Study Using the Proposed Framework (* denotes the paper index)

	Comparison Parameters			
	Energy Consumption		Indoor Environmental Quality	
	*	Findings	*	Findings
Macro -Level	1	Only 2 out of 11 LEED buildings performed better than the average commercial stock	1	Users of all 11 buildings are satisfied with the lighting and air quality of LEED buildings, but unsatisfied with sound conditions, when compared to their counterparts
	4	All 12 LEED government buildings consumed 25%-30% less than the average of commercial building stock		
	5	552 LEED buildings showed 24% lower EUI levels than their national counterparts	3	Occupants of 21 LEED buildings were more satisfied with thermal comfort, air quality, office furnishings, cleaning and maintenance, but less satisfied with lighting and acoustics than occupants of 160 conventional buildings
	6	There is no evidence that LEED certification has collectively lowered energy consumption for office buildings		
	8	The 2 sampled buildings performed better than their baseline cases	8	Occupants of both LEED buildings were 29% more satisfied than the CBE standard level.
	10	Only 3 out of 11 LEED certified buildings performed better than their comparable CBECS buildings	9	Students, teachers and staff of Toronto LEED schools were 8–19% more satisfied than their comparable conventional schools
	11	*Sampled LEED certified buildings performed better than their regional counterparts*	*11*	*LEED buildings performed much better than the CBE national benchmark across all surveyed categories*
Micro- Level	2	No correlation between the certified energy credits and the actual energy use	*11*	*No clear relationship between the actual performance level and the points earned in the IEQ category of LEED*
	7	Minor correlation between the energy performance and the number of energy credits achieved		
	10	No correlation between the total number of earned LEED points and energy savings		
	11	*No clear relationship between the actual performance level and the points earned in the Energy and Atmosphere category of LEED*		

The results showed even for similar buildings in the same climate zone, operating on the same schedules and with similar types of use, the energy performance and occupant satisfaction are varying. One of the main factors in determining the building actual performance is occupants. Setting thermostats at different temperatures, leaving lights on when buildings are not occupied, leaving windows open while operating heating or air conditioning systems are examples of occupants impacting intended building performance. One more reason that can explain differences in the results is the nature of activities and type of equipment used in the facility. These and other factors affecting the performance of buildings will be considered in future studies on the topic.

4.7. CONCLUSIONS AND RECOMMENDATIONS

Similar to other top ranked higher education institutions around the world, Arizona State University is committed to leadership in sustainability education, research, operations, and outreach. In fact, ASU houses the first-ever *School of Sustainability*, and its President is the Co-Chair of the *American College & University Presidents' Climate Commitment*'s Steering Committee. As such, the university has been implementing sustainable practices in the planning, design, construction, operation and maintenance of its facilities. This paper introduces an assessment framework that considers two levels for a building performance evaluation. On the Macro-level, the analysis shows LEED buildings are saving energy when compared to their regional counterparts according to CBECS. These results contribute to the body of knowledge on energy performance improvements linked to LEED certification. Energy consumption was measured on a granular level over a four-year period and focused on a specific type of facilities in one geographical location in order to limit the variation in the dataset. In addition, the surveyed LEED buildings earned, on average, a 77.7% overall satisfaction rating with respect to IEQ, and exhibited a performance superior to the CBE national benchmark; these results are in line with the literature on occupant satisfaction linked to LEED certification. However, from a Micro-level, the results of this study show the number of LEED points earned in the *Energy & Atmosphere* and the *IEQ* categories are not correlated with the superior performance in these respective categories. The dataset used includes a sample of LEED certified facilities from one university campus, and therefore the results may not be applicable to the whole population of LEED certified facilities.

At the same time, the results of the study highlight the need to assess LEED building performance from two distinct perspectives to get a comprehensive understanding of the actual performance in the context of the intended outcome. The authors welcome the USGBC's recent move toward considering, in the newest version of the LEED rating system, the actual performance of buildings during the occupation phases as opposed to just the intended performance during the design and construction phases. Such improvements in the USGBC rating system incentivize building managers, owners, and occupants, to ensure buildings are performing adequately and meeting their design potential. This concluding thought applies not only to higher education facilities, but also to any constructed facility aiming to advance its lifecycle performance.

4.8. ACKNOWLEDGMENTS

The authors of this paper would like to thank the Facilities Development and Management (FDM) officers at ASU. FDM officers are not responsible for the results and conclusions expressed in this paper; these are exclusively based on the analyses and interpretations of the authors. The authors also would like to thank all 160 survey respondents who took the time to provide data for this study.

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CHAPTER 5

CONCLUSIONS AND CONTRIBUTIONS

5.1. SUMMARY OF THE RESEARCH OBJECTIVES

In this thesis, the performance of LEED-certified buildings was studied in terms of energy consumption and occupant satisfaction with IEQ. An IEQ survey was used to gauge the satisfaction of occupants with LEED buildings. Electricity, heating, and cooling consumption data were collected to investigate the effectiveness LEED facilities to affect energy consumption. An analysis of energy consumption and occupant satisfaction was conducted before introducing a dual assessment framework to evaluate LEED certified facilities. The results of this thesis led to distinct contributions to the body of knowledge; the next section will provide a summary of these contributions along with the key results of this research.

5.2. SUMMARY OF THE RESULTS AND CONTRIBUTIONS

This section summarizes the research results and contributions. The results follow the three objectives previously defined in Chapter 1 of this thesis.

5.2.1. Indoor Environmental Quality

This study compares the levels of IEQ occupant satisfaction for two sets of higher education facilities located in the regions of Arizona, USA, and Beirut, Lebanon. Factors explaining the difference in performance across the two campuses include building age and commitment to sustainable and environmentally aware design through achieving LEED certification. Building age seems to have a correlation with level of occupant satisfaction with IEQ. Additionally, for the past decade, ASU has been committed to developing buildings that meet the LEED requirements. AUB has recently made a similar commitment; several ongoing projects are being designed and constructed at AUB with the goal of obtaining LEED certification.

A close examination of the occupant satisfaction results on the ASU campus shows the surveyed LEED buildings earned 28% overall satisfaction rating above the CBE national benchmark, which is based on 59,359 completed surveys. The study also shows that earning more IEQ points in LEED is not necessarily securing a superior indoor environmental quality. These findings call into question the effectiveness of the IEQ points awarded as part of the LEED rating system to help reduce absenteeism and increase the productivity of students, staff, and faculty at higher educational facilities.

5.2.2. Energy Consumption

This research investigates the impact of LEED certification on the energy consumption of higher-education research facilities. The contributions of this study include the comparison of eight data-driven predictive models that led to the introduction of a novel LEED assessment method. Electricity, heating, and cooling energy consumption were measured in 15 minutes increments over a seven-year period and focused on specific types of facilities in one geographical location in order to limit the variation in the dataset. The results of this study show the superiority of the Gradient Boosting Regression over other regression models in predicting energy consumption of research buildings. The study also introduces an applied methodology that uses the robust predictive model for non-LEED research buildings to investigate the deviation of LEED certified research buildings' energy consumption, as well as the correlation between LEED scores and the actual energy consumption of certified facilities. The study highlights the differences between the benchmark addressed in the literature and the one proposed in this study in order to assess the performance of LEED buildings. While accounting for the main building characteristics, the proposed method is generic, comprehensive, and easy to implement.

The focused scope of this study on the energy consumption of research buildings in a specific climate zone adds value to the findings, but at the same time presents a limitation not being generalizable to the whole population of LEED certified facilities or to other types of facilities in different climate zones. However, the new method introduced in this paper can certainly be replicated for any type of facility in other climate zones.

In previous studies, the authors, along with many others in the architecture, engineering, and construction (AEC) industry, have recommended that sustainability rating systems be based on actual performance as opposed to design intent. The authors welcome the USGBC's recent move toward considering, in the newest version of the LEED rating system, the actual performance of buildings during the occupation phase as opposed to just the intended performance during the design and construction phases. Such improvements in the USGBC rating system incentivize building managers, owners, and occupants, to ensure buildings are performing adequately and meeting their design potential.

This concluding thought applies not only to higher education facilities, but also to any facility in the built environment.

5.2.3. A Dual Assessment Framework to Assess LEED facilities' Indoor Environmental Quality and Energy Consumption

This study introduces an assessment framework that considers two levels for a building performance evaluation. On the Macro-level, the analysis shows LEED buildings are saving energy when compared to their regional counterparts according to CBECS. These results contribute to the body of knowledge on energy performance improvements linked to LEED certification. Energy consumption was measured on a granular level over a four-year period and focused on a specific type of facilities in one geographical location in order to limit the variation in the dataset. In addition, the surveyed LEED buildings earned, on average, a 77.7% overall satisfaction rating with respect to IEQ, and exhibited a performance superior to the CBE national benchmark; these results are in line with the literature on occupant satisfaction linked to LEED. However, and while the Macro level shows performance improvements for LEED facilities, from a Micro-level the results of this study show the number of LEED points earned in the Energy & Atmosphere and the IEQ categories are not correlated with the superior energy savings and IEQ occupant satisfaction. The results of the study highlight the need to assess LEED building performance from two distinct perspectives to get a comprehensive understanding of the actual performance in the context of the intended outcome. The authors welcome the USGBC's recent move toward considering, in the newest version of the LEED rating system, the actual performance of buildings during the occupation phase as opposed to just the intended performance during the design and construction phases. Such improvements in the USGBC rating system incentivize building managers, owners, and occupants, to ensure buildings are performing adequately and meeting their design potential. This concluding thought applies not only to higher education facilities, but also to any facility in the built environment.

5.3. RESEARCH LIMITATIONS AND FUTURE WORK

By investigating the occupant satisfaction and energy consumption of LEED buildings, this study contributes to the body of knowledge on the performance of LEED certified buildings. The focused scope of this study on specific types of buildings in a specific climate zone reduces variation and adds value to the findings, but at the same time it presents a limitation of not being generalizable to the whole population of LEED certified facilities or to other types of facilities in different climate zones. However, the new assessment methods and predictive models introduced in this study can certainly be replicated for other types of facilities in other climate zones.

The results of the study highlight the need to assess LEED building performance from two distinct perspectives to build a comprehensive understanding of the actual performance. This study recommends further enhancing the LEED rating system by making "*continuous performance monitoring throughout the facility's lifecycle*" a prerequisite for certification, and awarding the certification based on actual performance during the occupation phase, as opposed to the intended performance during the design and construction phases. Such improvements in the USGBC rating system also would incentivize building managers, owners, and occupants, to ensure buildings are performing adequately and meeting their design potential. This general recommendation applies not only to higher education facilities, but also to any constructed facility aiming to advance its lifecycle performance.

In addition to the investigated variables for which data was available, additional factors can affect the performance of buildings. The results showed even for similar buildings in the same climate zone, operating on the same schedules and with similar types of use, the energy performance and occupant satisfaction are varying. One of the main factors in determining the building actual performance is occupants. Setting thermostats at different temperatures, leaving lights on when buildings are not occupied, leaving windows open while operating heating or air conditioning systems are examples of occupants impacting intended building performance. One more reason that can explain differences in the results is the nature of activities and type of equipment used in the facility. These and other factors affecting the performance of buildings will be considered in future studies on the topic. Future work also will consist of continuing to collect data from an increasing number of buildings and expanding the analysis to include several campuses, different climate zones, and different building types. Follow-up research studies also may include applying the developed framework to investigate the performance of new datasets to further leverage the contributions of this thesis.

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APPENDIX A

OCCUPANTS SATISFACTION WITH THE INDOOR ENVIRONMENTAL QUALITY SURVEY

ASU Arizona State University

DEWSC Del E. Webb School of Construction

A Study of Occupant Satisfaction in LEED-certified Buildings

Leadership in Energy & Environmental Design (LEED) is a rating system that scores buildings based on their "sustainability" level. Arizona State University (ASU) is conducting a survey to investigate the occupant satisfaction level in LEED-certified facilities. You are invited to participate by completing this survey, which takes around 5 minutes to complete. The information you provide will be kept in strict confidentiality. In the event of a publication or presentation based on the results of this study, no personal identifiable information will be shared. Please feel free to may request a copy of the final report. If you have any questions, complaints or concerns regarding this research, you may contact Dr. Mounir El Asmar at (480) 727-9023.

SECTION 1: OCCUPANT BACKGROUND INFORMATION

a. Building name: ____________________
b. Your name: ____________________
c. Your Email: ____________________
d. You are using this building as a:
   O Student   O Faculty/Staff   O Visitor
   O Other (Please specify):____________
e. Please specify how many days, months, or years you have used this building:____________

SECTION 2: SPACE LAYOUT

a. How satisfied are you with the amount of personal space available for your work tasks and/or storage needs? *(1=Low, 5=High)*:
   Low Satisfaction O 1 O 2 O 3 O 4 O 5 *High Satisfaction*
   If dissatisfied, please indicate why: ____________

b. How satisfied are you with your ability to communicate/interact with others within your workspace? *(1=Low, 5=High)*:
   Low Satisfaction O 1 O 2 O 3 O 4 O 5 *High Satisfaction*
   If dissatisfied, please indicate why: ____________

c. How satisfied are you with the level of visual privacy provided within your workspace? *(1=Low, 5=High)*:
   Low Satisfaction O 1 O 2 O 3 O 4 O 5 *High Satisfaction*
   If dissatisfied, please indicate why: ____________

d. Does the layout of your workspace enhance or hinder your ability to do your job efficiently?
   Greatly Hindered O 1 O 2 O 3 O 4 O 5 *Greatly Enhanced*
   If hindered, please indicate why: ____________

SECTION 3: SPACE FURNITURE

a. How satisfied are you with your workspace furniture (seating, desk, computer, etc.)?
   Very Dissatisfied O 1 O 2 O 3 O 4 O 5 *Very Satisfied*
   If dissatisfied, please indicate why: ____________

b. How satisfied are you with the ability to adjust your furniture to meet your individual needs.)?
   Very Dissatisfied O 1 O 2 O 3 O 4 O 5 *Very Satisfied*
   If dissatisfied, please indicate why: ____________

c. Does your workspace furniture enhance or hinder your ability to do your job efficiently?
   Greatly Hindered O 1 O 2 O 3 O 4 O 5 *Greatly Enhanced*

d. How satisfied are you with the aesthetics of your furniture (color, texture, finish material.)?
   Very Dissatisfied O 1 O 2 O 3 O 4 O 5 *Very Satisfied*
   If dissatisfied, please indicate why: ____________

SECTION 4: THERMAL COMFORT

a. How satisfied are you with the thermal comfort of your workspace? *(1=Low, 5=High)*:
   Low Satisfaction O 1 O 2 O 3 O 4 O 5 *High Satisfaction*
   If dissatisfied, please indicate why: ____________

b. Does your office thermal comfort enhance or hinder your ability to do your job efficiently?
   Greatly Hindered O 1 O 2 O 3 O 4 O 5 *Greatly Enhanced*
   If hindered, please indicate why: ____________

SECTION 5: INDOOR AIR QUALITY

a. How satisfied are you with the indoor air quality of your workplace (i.e. dusty, stuffy/stale, cleanliness, odors)? *(1=Low, 5=High)*:
   Low Satisfaction O 1 O 2 O 3 O 4 O 5 *High Satisfaction*
   If dissatisfied, please indicate why: ____________

b. Does your indoor air quality enhance or hinder your ability to do your job efficiently?
   Greatly Hindered O 1 O 2 O 3 O 4 O 5 *Greatly Enhanced*
   If hindered, please indicate why: ____________

SECTION 6: LIGHTING LEVEL

a. How satisfied are you with amount of artificial light available in your workspace? *(1=Low, 5=High)*:
Low Satisfaction O 1 O 2 O 3 O 4 O 5 *High Satisfaction*
If dissatisfied, please indicate why: ________________

b. How satisfied are you with amount of natural light available in your workspace? *(1=Low, 5=High)*:
Low Satisfaction O 1 O 2 O 3 O 4 O 5 *High Satisfaction*
If dissatisfied, please indicate why: ________________

c. How satisfied with the visual quality of the lighting in your workspace (i.e. glare, reflection, contrast)? *(1=Low, 5=High)*:
a.
Low Satisfaction O 1 O 2 O 3 O 4 O 5 *High Satisfaction*
If dissatisfied, please indicate why: ________________

d. Does your workspace lighting enhance or hinder your ability to do your job efficiently?
Greatly Hindered O 1 O 2 O 3 O 4 O 5 *Greatly Enhanced*
If hindered, please indicate why: ______________

SECTION 7: ACOUSTIC QUALITY

a. How satisfied are you with the acoustic qualities of your workspace?*(1=Low, 5=High)*:
Low Satisfaction O 1 O 2 O 3 O 4 O 5 *High Satisfaction*
If dissatisfied, please indicate why: ________________

b. How satisfied are you with the acoustic privacy of your workspace?*(1=Low, 5=High)*:
Low Satisfaction O 1 O 2 O 3 O 4 O 5 *High Satisfaction*
If dissatisfied, please indicate why: ________________

c. Does the acoustics of your workspace enhance or hinder your ability to do your job efficiently?
Greatly Hindered O 1 O 2 O 3 O 4 O 5 *Greatly Enhanced*
If hindered, please indicate why: ______________

SECTION 8: WATER EFFICIENCY

How satisfied are you with the amount of water saving features available in your building? *(1=Low, 5=High)*:
Low Satisfaction O 1 O 2 O 3 O 4 O 5 *High Satisfaction*

If dissatisfied, please indicate why:____________

SECTION 9: CLEANLINESS AND MAINTENANCE

a. How satisfied are you with the general maintenance of your building? *(1=Low, 5=High)*:
Low Satisfaction O 1 O 2 O 3 O 4 O 5 *High Satisfaction*
If dissatisfied, please indicate why: ______________

b. How satisfied are you with the general cleanliness of your workspace? *(1=Low, 5=High)*:
Low Satisfaction O 1 O 2 O 3 O 4 O 5 *High Satisfaction*
If dissatisfied, please indicate why: ______________

c. Does the cleanliness and maintenance of your building enhance or hinder your ability to do your job efficiently?
Greatly Hindered O 1 O 2 O 3 O 4 O 5 *Greatly Enhanced*
If hindered, please indicate why: ______________

SECTION 10: OVERALL SATISFACTION SPACE

a. How satisfied are you with the overall function of your space? *(1=Low, 5=High)*:
Low Satisfaction O 1 O 2 O 3 O 4 O 5 *High Satisfaction*
If dissatisfied, please indicate why: ______________

b. How satisfied are you with the overall space and environmental conditions of your building? *(1=Low, 5=High)*:
Low Satisfaction O 1 O 2 O 3 O 4 O 5 *High Satisfaction*
If dissatisfied, please indicate why: ______________

c. Would you consider yourself satisfied with this building? O Yes O No

~ End of the questionnaire ~

~ Thank you for your participation ~