IMPACT OF GREEN DESIGN AND TECHNOLOGY ON BUILDING ENVIRONMENT

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Thesis Prepared for the Degree of

MASTER OF SCIENCE

UNIVERSITY OF NORTH TEXAS

December 2015

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Xiong, Liang. *Impact of Green Design and Technology on Building Environment.* Master of Science (Engineering Technology-Construction Management), December 2015, 79 pp., 19 tables, 21 figures, references, 82 titles.

Currently, the public has a strong sense of the need for environment protection and the use of sustainable, or "green," design in buildings and other civil structures. Since green design elements and technologies are different from traditional design, they probably have impacts on the building environment, such as vibration, lighting, noise, temperature, relative humidity, and overall comfort. Determining these impacts of green design on building environments is the primary objective of this study. The Zero Energy Research (ZOE) laboratory, located at the University of North Texas Discovery Park, is analyzed as a case study. Because the ZOE lab is a building that combines various green design elements and energy efficient technologies, such as solar panels, a geothermal heating system, and wind turbines, it provides an ideal case to study. Through field measurements and a questionnaire survey of regular occupants of the ZOE lab, this thesis analyzed and reported: 1) whether green design elements changed the building's ability to meet common building environmental standards, 2) whether green design elements assisted in Leadership in Energy and Environmental Design (LEED) scoring, and 3) whether green design elements decreased the subjective comfort level of the occupants.

ACKNOWLEDGEMENT

There are no proper words to express my gratitude to Dr. Zhenhua Huang, Dr. Michael Shenoda and Dr. Shuping Wang. Specially, I need to thank Dr. Zhenhua Huang, my mentor, for providing me all of the support, advice, and opportunities though these two years of research. Even Dr. Shenoda just became my thesis committee member, he gave me so much help for finishing my paper and I indeed appreciated for what he did for me. I'd also need to thank Dr. Desimone for providing me suggestion and help on this research.

Thanks to Dr. Tao and his Zero energy lab research team for assisting me to collect field test data. Specially, I appreciate for the help of Dr. Tao's research assistant Saif. Thanks all the respondents that participated in my questionnaire survey.

Thanks to my friends and colleagues for helping me when I am in trouble. In addition, I really appreciate what my family members and my parents had done for me.

Without all these people's support and encouragement, I don't have such courage to continue my study abroad.

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CHAPTER 1 INTRODUCTION

1.1 Impact of Green Design and Technology on Building Environment

Green buildings, as many know, have less negative impact on the environment than conventional buildings [1] and mean the houses that are efficient and healthy to live in [4]. Green building is also known as a sustainable or high performance building [5].

Nowadays, green buildings can be evaluated by Leadership in Energy and Environmental Design (LEED) developed by the U.S. Green Building Council, which is a set of rating systems for the design, construction, operation, and maintenance of green buildings [3]. According to the introduction to LEED, green building pursues solutions that represent a healthy and dynamic balance between environmental, social, and economic benefits [6].

With the idea of environment protection being enhanced, more and more energy efficient buildings are built up, and many green designs were applied to these green buildings to purchase the energy saving goal. In addition, the amount of buildings adopting the green housing materials, products, and structural and construction technologies is rapidly increasing [2]. Over 60,000 commercial projects worldwide are participating in LEED, and 1.7 million square feet are certifying every day [2]. LEED has also spawned an entire green building industry, expected to be worth up to $248 billion in the U.S. by 2016 [2].

In the future, the green buildings that is different from our traditional structures probably will occupy most of the proportion of total buildings, and this will lead to more research on them. As we know, green design, which is different from normal design, could have an impact on the environment of building. For example, more high-tech equipment installed for saving energy or environmental protection, the vibration created by those devices could have an effect on the people living in the building. Moreover, the operating facility in the building could produce some vibration on the wall or floor. Some energy efficient equipment could make noise so that people feel uncomfortable. So in our study, our research objectives are the green design elements and building environment. The definition of building environment is the combination of conditions which could influence, modify, or otherwise have an effect on an individual, piece of equipment, or system in a building such as lighting, noise, temperature, relative humidity, and/or odors [7].

1.2 Research Objectives

Nowadays, the public have strong environment protection sense and there are more and more green buildings and structures. Diverse green materials and products are used for building structures, and sustainable technologies are applied for saving energy and protect environment. As a result, a green building structure could be made of hundreds of nova materials and a variety of energy efficient equipment could be installed, which probably would have an impact on the building environment such as lighting, noise, temperature, relative humidity, and/or odors. In this study, the Zero Energy Research laboratory at the University of North Texas will be our study object. The Zero Energy (ZØE) lab is a distinctive research building in TX – designed specifically to study and test numerous alternative energy generation technologies so as to realize a goal of net-zero consumption of energy [8]. Combining various sustainable energy technologies in one building, like solar, geothermal and wind systems, could generate enough power to supply all kinds of the usage in this building, even in some cases produce extra energy to return back to the power grid and therefore lead to total zero energy consumption in the end.

Through field measurements and a questionnaire survey to regular occupants of the ZOE lab, this thesis analyzed and reported: 1) whether green design elements changed the building's ability to meet common building environmental standards, 2) whether green design elements assisted in LEED scoring, and 3) whether green design elements decreased the subjective comfort level of the occupants.

1.3 Organization

This thesis consists of six chapters. Chapter 1 introduced information on influence of green design and technology on building environment parameters, and followed by our study's objectives. A more detailed description of the contents of each chapter is as follows.

Chapter 2: Overview of green building design and assessment

The literature section will review the research about green building. The first section will include research on building environment and green design, then green building assessment tools will be discussed and LEED certification will be presented. Moreover, the methods of studying environment of green building will be reviewed. In the end, other studies on green designs' effect on other type of objects will be introduced.

Chapter 3 Building environment analysis

Chapter 3 will show the definition of the parameters in our study, which include temperature, humidity, noise, lighting, and vibration. After that the previous study methods on these parameters will be reviewed and summarized. In addition, the study methods for our research will be introduced: questionnaire survey, LEED certification and other design standards.

Chapter 4: Case study analysis

This chapter will firstly introduce development path of net zero energy building from low energy even zero energy building to net zero energy building. Then our case study of Zero Energy Lab in University of North Texas will be introduced, which includes its green designs and technologies shown in a table. In addition, the estimated impact of these green designs and technologies on certain kind(s) of building environment will be presented. Our analysis methodology will be explained and the analysis results of field test will be presented and discussed. Finally, comparisons between the field test results and LEED and other standards and questionnaire survey response will be presented, respectively.

Chapter 5: Implication for green building design and assessment

According to the results of field test, questionnaire survey and green standards of LEED and other assessment tools, the correlation between field test result with questionnaire and green standards will be discussed and presented. We will discuss the green design elements in our case study if they have an impact on our building environment parameters according to the field test result and questionnaire survey, and decide if they are acceptable or need to be changed.

Chapter 6: Conclusion and future work

The conclusion of the study will be presented in this chapter, and the future research work will be pointed out as well.

CHAPTER 2 LITERATURE REVIEW

2.1 Overview of research on green building environment

This chapter will review previous studies on building environment and green design, which includes the previous studies on building environment, green building designs and technologies. Moreover, several worldwide popular green building assessment tools will be introduced, in which the Leadership in Energy and Environmental Design (LEED) will be discussed in detail. Other relative studies and hot topics regarding green concepts will be shown in the end.

2.1.1 Research on indoor environment of conventional building

In developed countries, people spend over 90% of their time indoors [9], so in recent years the public pay more and more attention on indoor environment and have a growing awareness about the impacts of the indoor building environment on their health and performance [10]. However, it is still needed to educate the public how to maintain a good indoor environment and enhance their consciousness about the outcome of low quality indoor environment on their physical and psychological health [9]. Many scholars have studied various relative building environment topics such as thermal environment related to temperature and humidity, indoor air quality, ventilated level, acoustic and luminous environment and as well as vibration level of indoor or outdoor equipment. In New Zealand, Azizi et al. studied how occupants take an action when they are not comfortable with the indoor thermal environment [11]. Frontczak et al. conducted a questionnaire survey studying the factors affecting comfort with the indoor environment quality in Denmark [9].

For the thermal section, some studies are about the correlation of the satisfaction of occupants with acceptable thermal environment, some others discuss the correlation of subjective responses with variation of the indoor environmental conditions [12].

For vibration section, according to Svinkin's report, there are serious issues in vibration protection of high sensitive equipment in building from outdoor adjacent construction activities [13], which provides a good example for our case study, an energy high efficient laboratory with various facilities and experimental equipment.

For ventilation section, Sherman and Levin believed ventilation is the building service most related to controlling the indoor air quality to produce a healthy and comfortable atmosphere [14]. In addition, Hesaraki et al. was interested in the influence of different ventilation levels on indoor air quality [15].

For noise section, since there are many health issues including hypertension, myocardial infarction, stress, and sleep disturbance [15-17], annoyance [19,20], adverse learning and communication effects [21–24], and mental health issues [25] have relationship with noise exposure, this pushes the public and government to pay more attention to noise pollution study. A pilot study developed by Neitzel et al. was about using SLM and dosimeter to evaluate the in-home noise level and different traditional and smart devices for exposure assessment in the National Children's Study [26].

All the variables of building environment included in our study are vibration level, noise level, ventilation, lighting, and thermal condition, and each of them has been studied by many scholars. However, in our special case study, Zero Energy Laboratory in UNT, all of these variables will be linked with the relative green concepts and standards.

2.1.2 Green building designs and technologies

The green design is defined by ASHRAE Green Guide, which is careful and respectful to nature and natural order of things and reduces the side effect of human activity on the natural environments, materials, resources, and processes prevailing in nature [27]. With the rapidly developing advanced technology, nowadays people can use a wide variety of techniques to cost-effectively design a green building [28]. A long and narrow building shape, for example, maximizes natural lighting and ventilation for workers, and locating fixed elements like stairs, mechanical systems, and restrooms at the building's core creates a flexible and open perimeter, which also allows daylight to reach work areas [28]. Operable windows and skylights enable weather. Windows with low-E (low emission) glazing minimize interior solar heat gain and glare [28].

Green building technologies can help reduce and even generate energy. Many buildings, for example, install motion sensitive lighting sensors and individual climate controls in offices and at workstations. Again, some technologies like that cost more up front than standard building systems, but companies and developers can stay on a mainstream budget by taking advantage of the growing number of incentives and funding opportunities offered to companies installing building systems that save energy in the long run [28].

Here we take an example, the Sohrabji Godrej Green Business Centre in Hyderabad, India, was the greenest building in the world when it was completed in 2003, according to the U.S.

Green Building Council (USGBC), it was designed a circle shape that could receive sunlight to all part of the 20,000-square-foot building [28]. During the day time, this design can help to save artificial lighting energy up to 90% of whole Green Business Centre [28]. Moreover, this building incorporates several state of art energy and environmentally friendly features, including solar PV systems, indoor air quality monitoring system, a high efficiency HVAC system, a passive cooling system using wind towers, high performance glass, green roof gardens, rain water harvesting, root zone treatment system, et al. [28]. With the help of all the green design and energy efficient technologies, this building not only won the LEED-Platinum certification, but saved up to 55% energy comparing to a conventional building of a similar size [28].

2.1.3 Green building assessment tools

Worldwide, individuals and organizations have responded to the increased demand for green buildings. Many countries and international organizations have initiated rating systems for sustainable construction. Currently, a number of different rating systems are used to rate the environmental performance of buildings. These include but are not limited to: LEED (Leadership in Energy & Environmental Design), Green Star and NABERS (National Australian Built Environment Rating System) in Australia, BREEAM (Building Research Establishment Environmental Assessment Method) in the UK, China's Green Building Label, Japan's Comprehensive Assessment System for Built Environment Efficiency (CASBEE); the European Union's Energy Performance of Buildings Directive (EPBD), Canada's Building Environmental Performance Assessment Criteria (BEPAC), Korea's Green Building Certification Criteria (KGBCC), and in an international collaboration framework, the Green Building Tool (GB Tool) [29].

Moreover, others specific systems are only used for energy use rating such as HERS (Home Energy Rating System) and Energy Star (EPA) [30]. These green rating systems somehow differ in terminologies, process methods, environmental categories and requirements for certification, but most of these rating systems' primary criteria are similar in that they evaluate a building's energy consumption, water efficiency, material use and indoor environmental quality [30].

In the United States, the Leadership in Energy and Environmental Design (LEED) system is currently the most widely utilized method for rating a building's environmental performance, which also is our major reference source. LEED was developed by the U.S. Green Building Council (USGBC) in 1998 to provide building owners and operators a concise framework for identifying and implementing practical and measurable green building design, construction, operation and maintenance solutions [31] .The LEED credits are divided into six categories (LEED v4) as follows: sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, and innovation in design [32]. Under the rating system of LEED, a structure may earn up to 110 total credits, and under certain credit categories, multiple points may be earned for higher environmental performance levels [32]. In addition to credits, each section of the LEED rating system includes prerequisites which must be earned even though they do not count towards a building's point total [32]. There are four levels of LEED certification for latest version: LEED certified, silver, gold and platinum. The level of LEED certification a building earns is decided by the number of points awarded as follows (LEED v4): 40–49 points for LEED certified, 50–59 points for silver certification, 60–79 points for gold certification, and 80 to 110 points for platinum certification [32].

According to the introduction of LEED website, LEED can apply to all different types of project flexibly currently. There are five rating systems that focus on many various project types: Building Design and Construction; Interior Design and Construction; Building Operations and Maintenance; Neighborhood Development and Homes, which provide all the requirements that the specific type of project needed to achieve their LEED certification scores [32]. When a rating system is chosen by a project team, the requirement and guild lines of each credit will explain how to design and operate [32]. In our study, even though Zero Energy Lab is an existing building, the rating system of Building Design and Construction (LEED v4) will be our main reference, since Zero Energy Lab in UNT, a special renovation project with so many state-of-art green designs and technologies, "applies to buildings that are being newly constructed or going through a major renovation" [33].

2.1.4 Studies on green designs' effect on other type of objects

Rooshdi and Rahman et al. applied questionnaire survey method to study sustainable design for green highway [34]. Many studies have been developed over a decade to find out the potential building energy benefits of green roof designs, and the outcome was positive that green roof can reduce the energy consumption in winter heating and summer cooling [35]. Moreover, the study of Rajendran et al. was to investigate the impacts of green building design and construction on construction worker safety and health [36], and it was found that there was possibility of statistically significant difference in the recordable incident rates (RIRs) of the green and non-green building projects, but no statistically significant difference was found between the lost time case rates (LTCRs) for the green and non-green projects included in the study, which provided a useful reference to the construction industry about the safety and health precautions for construction workers. In paper of GhaffarianHoseini et al., they discussed the current trends and applications of green building design [37]. Moreover, in this article, they introduced a study by Ensen et al. that accordingly examines the energetic effectiveness of ground-coupled heat pump system for heating systems, which have an impact on the indoor temperature [38]. The use of green roofs, which is combined with solar shading equipment, as proposed by Kumar, could achieve a better thermal performance as well as a contribution to the reduction of energy consumption [39].

According to the literature we discussed above, many advanced green designs and technologies are applied on the building to pursue the maximum reduction of energy consumption and largest energy efficiency, and surely some of them could somehow have an influence on society, environment and economy.

CHAPTER 3 BUILDING ENVIRONMENT ANALYSIS

In previous chapter, it presented the general idea of building environment. In this chapter, the advanced knowledge of building environment parameters will be introduced, and their physical measurement methods will be explained as well. Based on the measurement method of building environment parameters introduced in current chapter, chapter 4 will present their field test results. In addition, in this chapter, previous study methods about building environment will be summarized. Refer to these study methods, our study method (LEED and other standards; questionnaire survey; physical measurement) will be described, respectively. The result and result analysis of survey and field test will be shown in chapter 4.

3.1 Building environment parameters

As we mentioned in first chapter, building environment includes lighting, noise, temperature, relative humidity, and/or odors etc. [40]. The definitions of them will be introduced below respectively. Certainly, there are more building environment parameters, but in our study, only the parameters introduced in this chapter will be our concerns.

3.1.1 Lighting or illumination

Lighting or illumination is "*the deliberate use of light to achieve a practical or aesthetic effect* "[41]. In addition, day-lighting is the oldest method of interior lighting in human history [41]. Day-lighting is simply designing a space to use as much natural light as possible and is also proven to have positive effects on patients in hospitals as well as working and learning performance [42-43].

Measurement of daylight

In our case, the visible light transmittance (VLT) of glass shown in table 17 refers to the product specification sheet. In addition, in order to measure the window and floor area of ZOE lab, we will use its blueprints and some measurement tool like tape measure to get the size of the windows, and the measurement will be shown in table 17.

3.1.2 Sound level

A noise is a sound that produces a disturbing or unwanted auditory sensation [44]. The human ear is sensitive to sound pressure ranging between the threshold of hearing P0 (2.10-5 Pa) and the threshold of pain (20 Pa). The latter value is a million times bigger [44]. Based on the research, our ear's perception is not linear, and for example, when sound pressure increases by 10 dB, the ear perceives a double increase in volume, and Figure1 shows some idea of acoustic perception levels [44].

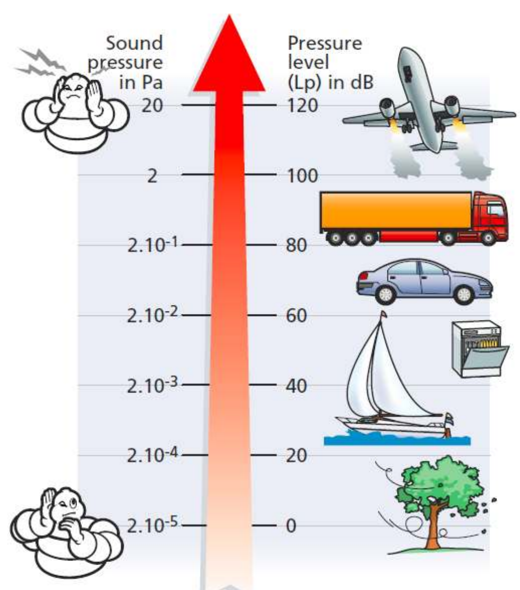

Figure 1 Sound pressure [44]

Sources of noise

"Primary sources of noise in the United States include road and rail traffic, air transportation, and occupational and industrial activities" [45]. Additional individual-level exposures include amplified music, recreational activities (including concerts and sporting events), and firearms etc. [45]. However, in our study, the sources of noise we explored are related to green designs and technologies in a building.

Field test device: decibel detector and decibel meter app software

The noise level field test experiment was based on Neitzel's study method [26]. The data collectors in our case are a sound level meter of Simpson model 884 and a smart phone with a decibel detector app. We explored a variety of smart devices and eventually selected Apple (CA, U.S.) iPhone 4s and iPhone 6s respectively. These devices use iOS operating system. More than 10 decibel monitoring apps were considered. Given our requirements (e.g., accurateness, convenience, data storage ability, and security requirements), we identified one suitable app: dB Decibel Meter PRO with SPL Graph software developed by Aexol. We utilized the internal microphone of the iPhone devices in order to evaluate the simplest possible measurement configuration.

Field test process

Three continuous days were set for collecting sound data from October 8 to October 10, 2015. The noise meters were set on the central desk in working room, mechanical room and outside the lab, respectively. Each testing time was set 60 seconds, the average decibel value were recorded in the testing devices. In addition, during this field test, the tests were conducted under 3 different conditions: when the water and heating pumps and all other mechanical equipment were under operation; when the water and heating pumps were on and all other mechanical equipment off; and when the water and heating pumps and all other mechanical equipment were off. The detail data will be shown in Table 12 to Table 17. The third day field test was arranged at night around 9:30 PM instead of daytime in order to avoid the daytime traffic or other interference.

3.1.3 Temperature

Temperature is "a degree of hotness or coldness the can be measured using a thermometer, and it is measured in degrees on the Fahrenheit, Celsius, and Kelvin scales" [46]. In our study, we accept air temperature, which is the average temperature of the air surrounding the occupant, with respect to location and time. According to ASHRAE 55 standard, the spatial average takes into account the ankle, waist and head levels, which vary for seated or standing occupants [47]. The temporal average is based on three minute intervals with at least 18 equally spaced points in time and the temperature is measured with a dry-bulb thermometer [46] [50].

Temperature monitoring system in ZOE lab

The temperature monitoring system records indoor and outdoor temperature each 15 minutes using over 90 sensors, and this system has been used since 3 years ago. In this study, we collected the data from January 1st to October 5th 2015 shown in Figure 17 and Figure 18, which almost covered a whole year's temperature information. The data analysis will be shown in chapter 4.

3.1.4 Humidity

Humidity is the amount of water vapor in the air, and there are three main measurements of humidity: absolute, relative and specific [48]. Relative humidity will be our study parameter, which is "*the ratio of the amount of water vapor in the air to the amount of water vapor that the air could hold at the specific temperature and pressure* [50].

Humidity monitoring system in ZOE lab

Similar with the temperature monitoring system, humidity system also records indoor and outdoor relative humidity each 15 minutes based on more than 90 sensors. In this study, we used the data from January 1st to October 5th, 2015 shown in Figure 19 to Figure 21. The humidity data analysis will be shown in chapter 4.

3.1.5 Vibration

A vibration is defined as *"the alternating movement of a physical system around an equilibrium position"* [44]. The simplest case of a vibratory or oscillatory movement is that of a pendulum, and when knocked, it swings in an alternating movement around its vertical position [44]. In an elastic medium such as water, air or a taut string, the vibration is revealed as a distortion [44].

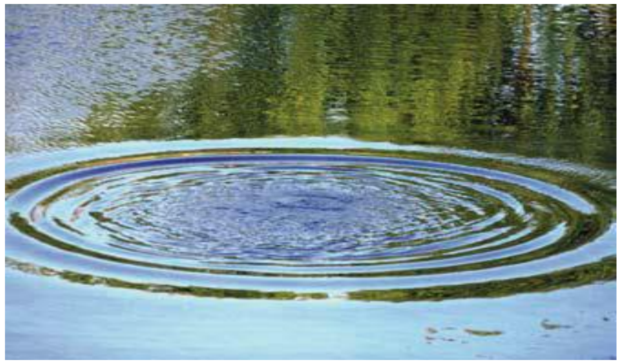

Figure 2 Water wave [44]

Take an example, the surface of water forms concentric ripples once a stone is thrown in, as shown in Figure2, when a tire is subjected to a shock, then it will be distorted because of the alternating motion of every point within the surrounding medium around its equilibrium position [44]. Once a point moves, it makes those around it move as well: the movement is propagated from point to point at a continuing speed, which itself depends on the physical medium and the temperature as well [44].

In addition, if the vibration is transmitted by a structure and picked up by another part of the body like in our case, the person's perception of its strength depends on which part of the body is affected (hands, for instance, react differently than feet) [44].

Mechanical vibrations

Fifty percent of the healthy population does not detect a mechanical vibration with an amplitude below 0.015 m/ s^2 [1], which is equal to about a thousandth of the acceleration of gravity (0.0015 g) [44].

According to the situation, a vibration may be considered unacceptable or pleasant [44]. Many factors (such as what the person is doing at the time) simultaneously affect the way in which discomfort may be felt or tolerated [44]. Nevertheless, the following Figure3 gives some idea of common perception.

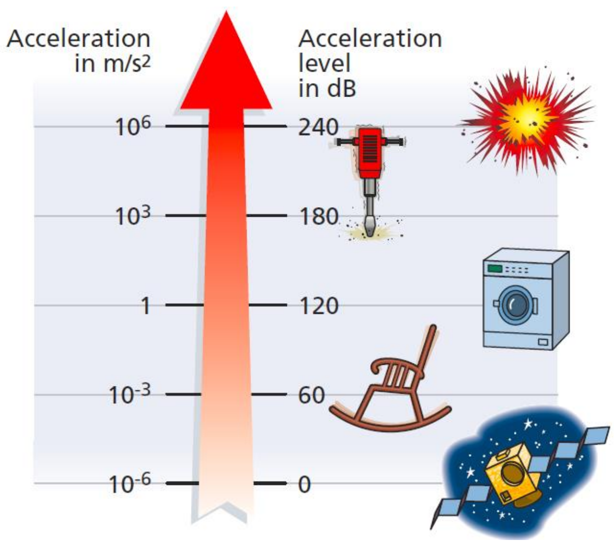

Figure 3 Acceleration level [44]

In our case study Zero Energy Lab in UNT, the geothermal heating system are installed in the central mechanical room that probably contributes most of the vibration and noise. In order

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[1] The perception threshold varies widely from one person to another. For a median perception threshold of approximately 0.015 m/ s^2, 25 % of the responses may range from about 0.01 to 0.015 m/ s^2, and another 25 % from 0.015 to 0.02 m/ s^2 [44].

to figure out the influence of this design and technology on the vibration, we will use monitoring devices to collect the useful information then analyze it.

Field test devices

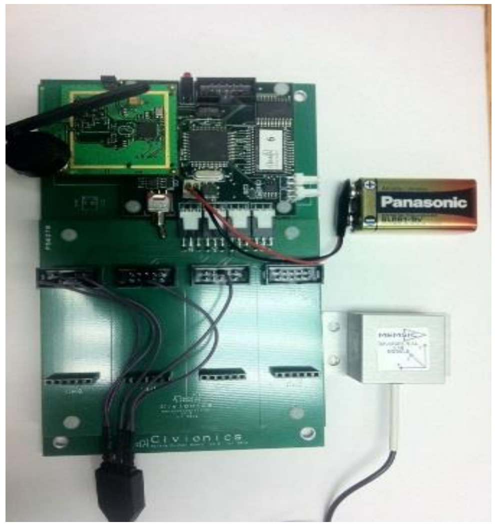

Figure 4 Narada wireless sensing device

For vibration parameter, we will use wireless sensing system named Narada wireless sensing network (WSN) shown in Figure 4 and as well the Memsic accelerometers shown in Figure 4 will be deployed to collect acceleration response data in our case.

Filed test design for vibration collection

Five field test spots were set in the ZOE lab. The layout figure and the field test pictures are shown below. Five wireless sensors were touched on the spots that have most relative obvious vibration, such as the wall of mechanical room, structural steel beam and ground near by mechanical room.

We assumed the most vibration could be from the mechanical room where not only includes geothermal heating and water pump system, also all other mechanical equipment. So the field test data about vibration, noise will be collected in or near this central mechanical room.

All the field tests for vibration were conducted in one day. During this field test, three group tests were conducted under 3 different conditions: when the water and heating pumps and all other mechanical equipment were under operation; when the water and heating pumps on and all other mechanical equipment were off; and when the water and heating pumps and all other mechanical equipment were off. The result will be presented in Table 10, Table 11 and Figure 7 to Figure 16.

3.2 Previous methods on building environment parameters of green building

There are a couple common methods to study building environment. Case study is one of the most common methods. Questionnaire survey and physical parameters measurement also play a critical role in this field. Below table 1 is the summary of methods of study on satisfaction with indoor environment of green building.

Table 1 Summary of studies on satisfaction with indoor environment of green building

Study	**Case study/ Place of experiment**	**Method**	**Population**	**Data analysis**	**Results**
[51]	A green university (CSU) building and two conventional university (LTU) buildings in inland southeast Australia	Comparative questionnaires were conducted to rate the aesthetics, serenity, lighting, acoustics, ventilation, temperature, humidity, and	Building occupants (n unknown RR 47% for CSU and RR of 41% for LTU)	Hotelling's T2 test; Ordinal regression analysis; W2-test of independence; w2-test of homogeneity	Only difference: perceived temperature (occupants of Then CSU building felt warmer), other factors: aesthetics, serenity, lighting, ventilation,

		overall satisfaction			acoustics, or humidity are same
[52]	Tow of 4 and 7 stores green building(TB and OGGB); two of 4 and 12 stores conventional building (FoE and OCH) in New Zealand	The aim of the questionnaires was to understand how occupants use the building to adjust their thermal comfort	Green building occupants (TB n=300, RR=40%; OGGB N=400, RR=45%); Conventional building occupants (FoE n=300, RR=47%; OCH n=100, RR=41%)	The Mann–Whitney U test shows that there are five actions showing great different between green (TB and OGGB) and conventional (FoE and OCH) buildings for occupants responses as they feel cold; Frequency analysis was used to identify the highest percentage of response for each factor.	The comparative study found that occupants in the green buildings engaged in less environmental adjustments, and adopted more personal and psychological coping mechanisms than those occupants in the conventional building
[53]	The green factory and the control factory both are two stores building in Sri Lanka	A questionnaire survey was administered among pairs of comparable workers using a Systematic Sampling Technique, and	n unknown RR unknown	The Mann-Whitney U-test for 11 parameters	Results showed that thermal comfort, ventilation, and ability to control indoor environment of the green factory were comparatively less satisfactory. Acoustics, indoor air

		plus the physical measurements to corroborate the survey results			quality and work layout did not indicate a significant difference between the factories. Views to outside, lighting, cleanliness, furniture, and privacy were better in the green factory compared to the control.
[54]	10 green office buildings and 42 conventional office buildings in China	A questionnaire was conducted to survey the users' habit and satisfaction of that building	More than 1000 valid questionnaires(n and RR unknown)	SPSS software is used for factor analysis, correlation analysis, regression analysis and analysis of variance to the data from questionnaires	The result of the questionnaire survey shows that the green buildings in China are significantly more satisfied than the conventional buildings in term of thermal, visual, acoustic environment, IAQ and the overall environment
[55]	Three being EEWH-certified green buildings and two of non-certified, conventional design	A questionnaire survey was developed to study the subjective perception and satisfaction of office occupants	Building occupants (Green buildings n=134 RR unknown; conventional buildings n=99 RR unknown)	The mean scores rated for the specific IEQ areas and for the overall IEQ between the two building groups were statistically	Overall IEQ satisfaction level of occupants in green buildings was higher than their counterparts in the

	buildings in mid Taiwan near the west coast	toward the quality of the acoustics, lighting, thermal comfort, indoor air, and overall IEQ in the building and the physical environment measurement were conducted		compared using the two-tailed t-test	conventional buildings
[56]	60 commercial or institutional buildings worldwide world-wide set of 31, selected on the basis of their sustainability credentials; and a set of 109 conventional selected from a larger database of commercial and institutional buildings	A questionnaire survey of the users including operational, thermal, lighting, noise, control and satisfaction parameters	Building occupants (n unknown; RR unknown)	A Z-scores formula for comfort overall, together with the main environmental factors of lighting overall, noise overall, temperature and air overall in both winter	The average of users' perceptions of sustainable buildings were significantly better than that of more conventional buildings in terms of operational and satisfaction factors, and most of the internal environmental factors

According to the previous study methods, most of them were focusing on the overall green building environment, even some of them have studied how the building environment parameters have an influence on occupants and compared with the physical field test data, their study and physical data do not focus on some specific green designs and technologies and how these specific elements have an impact on the building environment parameters.

3.3 Methods in this study

The study methods in this research are regarding questionnaire survey, LEED requirements, and other standards.

3.3.1 Green standard of building environment parameters

Temperature and humidity

The guidelines such as ASHRAE Standard 55 and ISO standard 7730 provide references on thermal comfort and optimum temperature range for an indoor environment. New energy efficient building concepts and technologies require a revision of comfort standards to create a suitable thermal condition in avoiding occupant dissatisfaction, adverse effects on their productivity and overall building performance [57]. According to ASHRAE Standard 55, thermal comfort condition is achieved when 80% or more of the occupants are satisfied with the temperature [47].

Table 2 The LEED standard and other standard for temperature

Parameter	LEED v4 Standard	Other standard
Temperature	Option 1. ASHRAE Standard 55-2010; Option 2. ISO and CEN Standards	The temperature of 20◦C to 24◦C (68 °F to 75.2 °F) is an accepted comfort range for most occupants (ASHRAE 55 2010 standard and ISO 7730)

Wai (2011) suggested in office environment the air-conditioning temperature should be no lower than 24◦C to 25◦C and appropriate relative humidity of 50 % to 65% [57]. Then Sharharon and Jalaludin also recommended the optimum comfortable workplace for temperature is in range 20◦C to 26◦C and relative humidity is in range 40% to 60% should be maintained in office room [58]. This thermal condition was within the acceptable range of ISO 7730. As we know, there is a relationship between temperature and humidity in regard to thermal comfort. The summary standard table 3 shown below.

Table 3 The LEED standard and other standard for humidity

Parameter	Study	LEED v4 Standard	Other standard
Humidity	[57-58]	ASHRAE Standard 62-2001 recommends maintaining indoor relative humidity levels between 30 percent and 60 percent	The recommended level of indoor humidity is in the range of 30-60% in air conditioned buildings

Mechanical vibration

For medical or computerized equipment placed on the floors of buildings and historical significance, vibration limits should be between 2 mm/s (0.08 inch/s) and 3 mm/s (0.12 inch/s) [13]. However, since our field test device is limited and we only can obtain acceleration of unit g or mg (r.m.s), we will refer to some relative previous studies recorded as acceleration.

Obviously, human response to building vibration is a complex reaction with both psychological and physiological factors which include tactile, vestibular, proprioceptive, kinesthetic, visual and auditory cues, and visual-vestibular interaction [44]. Some factors such as experience, vibration expectation, habit, personality and even job satisfaction also play an important role, which makes predicting an individual's reaction to building vibration a complex task [59]. Moreover, not only there is no sufficient criteria and guideline of human comfort for local vibration produced by operating equipment and machines, but human perception and tolerance of local vibration are actually a subjective assessment. Therefore, it is no surprise that there are significant differences and uncertainties in the building vibration acceptability, occupant comfort criteria, and the assessment methodology currently. The significant variations amongst the commonly adopted criteria generally reflect country/ regional building code requirements, building design professionals' experience and habit, and market powers [59]. The study method of vibration parameter in this case study mostly is according to the design standard and studies for acceptable levels of wind-induced vibration in tall buildings because of the field test data having the similar comparable vibration unit, and there is lack of guidelines and standards for local vibration of building.

In 1977, National Building Code of Canada presented their first codified serviceability criteria which recommended limiting the peak building accelerations occurring once every 10 years to one percent of gravity for residential buildings and three percent of gravity for office buildings [60].

International Organization for Standardization (ISO) 6897, 1984 guidelines based on the natural frequency of the structure and specify limits for the standard deviation of acceleration determined from the worst consecutive 10 minutes of a wind storm with a recurrence interval of five years [59]. For a recurrence interval of one year, a factor of 0.72 be applied to the limiting accelerations is commended shown in Figure 8 [59]. In addition, the recommended reasonable acceleration magnitudes for a wind storm with a recurrence interval of one year are shown in Figure 8.

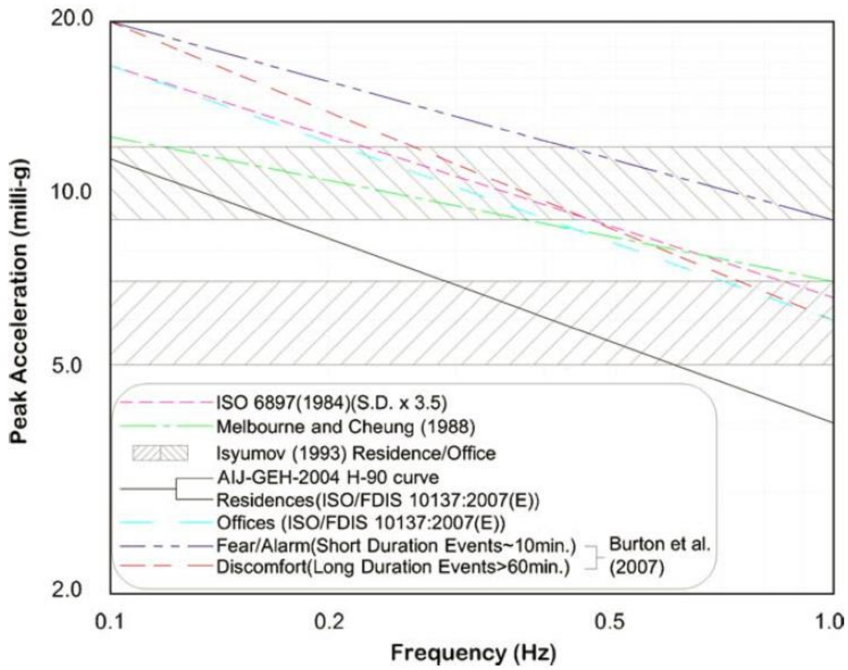

Figure 5 Comparison of occupant comfort serviceability criteria for a one year return period windstorm [61]

Two of shaded bands of Figure 5 represent two ranges of peak acceleration: 5–7 mg for residential buildings and 9–12 mg for office buildings with one year return period. Compared with other criteria, the most obvious difference is the lack of frequency dependence in these acceptance criteria [61].

According to the study of Michelin Tire Company about how amplitude affects the human perception of vibrations, we can summarize a table shown in Table 4 that shows the different perception levels on mechanical vibration.

Table 4 Different vibration levels and their perceptions [44]

Vibration level	
< 0.315 m/ s^2	not uncomfortable
0.315 to 0.63 m/ s^2	a little uncomfortable -> i.e. ~~ 0.05 g
0.5 to 1 m/ s^2	fairly uncomfortable
0.8 to 1.6 m/ s^2	uncomfortable -> i.e. ~~ 0.1g
1.25 to 2.5 m/ s^2	very uncomfortable
> 2 m/ s^2	extremely uncomfortable -> i.e. ~~ 0.2 g

In our result analysis, these standards and research outputs will be our criteria for determining if the mechanical vibration made by geothermal heating system or other mechanical system is acceptable or not.

Noise

Due to the many health effects caused by noise, and the relative importance of exposure timing for some health effects, a wide variety of exposure metrics and limits are in use nowadays [62]. Levels of 55 decibels outdoors and 45 decibels indoors are recommended by the U.S. EPA to prevent activity interference and annoyance [62]. These levels of noise are considered those which will allow spoken conversation and other activities such as sleeping, working and relaxing, which are part of the daily human condition [62].

The document identifies a 24-hr exposure level of 70 decibels as the level of environmental noise which will prevent any measurable hearing loss over a lifetime [45]. The U.S.

EPA recommends a second exposure limit of 70 dB to prevent hearing loss [45]. The limit is an equivalent continuous average exposure level over 24-hr Unlike the 55 dB limit designed to protect against all long-term health effects, the 70 dB limit considers daytime and nighttime exposures to be equally hazardous to hearing [45].

Noise levels for various areas are identified according to the use of the area [62]. Levels of 45 decibels are associated with indoor residential areas, hospitals and schools, whereas 55 decibels is identified for certain outdoor areas where human activity takes place [62].

Since the ZOE lab applies the central operating room design, and a small wind turbine is installed outside the lab, we assumed the noise sources could be mechanical room, wind turbine, high efficiency electrical equipment etc.

Table 5 The LEED standard and other standard for noise level

Parameter	**LEED v4 Standard**	**Other standard**
Noise level	EQ PREREQUISITE: achieve a maximum background noise level of 40 dBA from (HVAC) systems in classrooms and other core learning spaces. Meanwhile, to achieve a background noise level of 35 dBA or less to get LEED score; Meet the minimum composite sound transmission class (STCC) ratings 50 dBA for conference room	OSHA 1910.95: employers should notify an 8-hour time-weighted average of 85 decibels of the results of the monitoring to employees

Refer to table 5 and the discussion above, LEED standard seems more rigorous than OSHA and EPA, and this could make it harder for the designer and owner to obtain the LEED score for this category.

Day lighting and interior lighting

Lighting standard we based on LEED 2009 version. The certificated process shown below:

"*OPTION 2. Prescriptive*

Use a combination of side lighting and/or top lighting to achieve a total day lighting zone (the floor area meeting the following requirements) that is at least 75% of all the regularly occupied spaces.

For side lighting zones:

- *Achieve a value, calculated as the product of the visible light transmittance (VLT) and window-to-floor area ratio (WFR) of daylight zone between 0.150 and 0.180.*

$$0.150 < VLT \times WFR < 0.180$$

- *The window area included in the calculation must be at least 30 inches (0.8 meters) above the floor.*
- *In section, the ceiling must not obstruct a line that extends from the window-head to a point on the floor that is located twice the height of the window-head from the exterior wall as measured perpendicular to the glass (see diagram on the next page).*

- *Provide glare control devices to avoid high-contrast situations that could impede visual tasks. However, designs that incorporate view-preserving automated shades for glare control may demonstrate compliance for only the minimum 0.150 value.*

For top lighting zones:

- *The top lighting zone under a skylight is the outline of the opening beneath the skylight, plus in each direction the lesser of (see diagram below):*
    - *70% of the ceiling height,*
    - *1/2 the distance to the edge of the nearest skylight,*
    - *The distance to any permanent partition that is closer than 70% of the distance between the top of the partition and the ceiling.*
- *Achieve skylight coverage for the applicable space (containing the toplighting zone) between 3% and 6% of the total floor area.*
- *The skylight must have a minimum 0.5 VLT.*
- *A skylight diffuser, if used, must have a measured haze value of greater than 90% when tested according to ASTM D1003*." [64]

In addition, table 6 shows the other standard for lighting parameter.

Table 6 The LEED standard and other standard for interior lighting and daylight

Parameter	LEED v4 Standard	Other standard
Interior lighting and daylight	Interior lighting: at least 90% of individual occupant spaces have control lighting at least three levels, and midlevel is 30% to 70% of the maximum illumination level; Daylight: spatial daylight autonomy and annual sunlight exposure 75%	The value of 95% of spaces that comply with criteria requirements is too stringent, even for the highest levels of certification, so 90% can be regarded as an adequate demand

3.3.2 Questionnaire survey for the study parameters

The purpose of questionnaires is to find out if there is a difference in the real feeling of occupants about the building environment between the results from field test data analysis.

As an evaluation tool for collecting information and opinion, questionnaires have many advantages and disadvantages. The major upsides of questionnaires are: firstly, it is possible to get a large number of responses with a very low cost and a high response rate. Secondly, it could be anonymous and allows respondents to think by themselves without interruption by the interviewer. Moreover, it is convenient to the researcher to address their questions in a good efficient way because the data could be coded and its standard format [65].

However, the downsides also are obvious that in some cases it is quite hard to obtain a high response rate without a strong motivation for the respondents, and it is easy to mislead the respondents without a good design [66].

Questionnaires are best used for factual data collection, and good questionnaire design is crucial to make sure that we can get valid responses to our questions. The questionnaire we used in this study is to measure indoor environmental quality consisted of two sections which are all close questions. Section A requested information from respondents on potential covariates (i.e., their age, sex, type of work, and frequency of attendance) that might contribute to the effect of green design and technology on comfort. Section B posed a number of multiple-choice questions (on a 5-point scale) that aimed to show an occupant's perception of their working space with regard to comfort. This part of the questionnaire was adopted from Levermore [67]. Section B also asked occupants to rate their satisfaction with their overall environment. A copy of the entire questionnaire is attached in this study as Appendix A.

In this study, our questionnaire is not applied to statistical analysis. Even though there are many assessment tools and specific standards to evaluate the building environment, without the perceptive response from the actual occupants, this circle of study is not completed. The questionnaire response can tell us if the field test data matches with the subjective feedback.

However, we need to know that all these building environment parameters like thermal comfort, noise level, vibrations and lighting condition may be perceived very differently from one person to another and one situation to another, as human perception depends on the characteristics of the person in question: age, sex, size, fitness, state of mind; experience, individual or cultural habits; expectations, motivations et al. Moreover, it is relative to contextual factors: body position; activity at the time of this environment etc. [44].

Take vibration as an example: the way people perceive vibrations depends on factors which can be divided into these main categories [44]. First of all, the perception of a vibration depends primarily on two types of objective [44]:

1. Factors related to the vibration itself:

- Magnitude
- Frequency
- Damping

Moreover, we shall see that the perception of a vibration depends on its frequency and magnitude, which determine whether it is considered acceptable or uncomfortable.

2. Factors related to the propagation mode and the receiving sense organ:

- airborne or structure-borne propagation
- Perception by the ear, muscles or other organs
- The direction of propagation

The perception of vibrations is thus partly subjective. Nevertheless, we will not address these factors in great detail. Our survey questions mainly focus on average occupants or local residents. The obvious deficiency of our questionnaire survey is shortage of enough potential respondents due to there being only 15 maximum researchers who spend most of their working time in this lab, so our respondent number is extremely low even though we can get a very high response rate. This is also why we do not use these questionnaire survey results to do some advanced statistical analysis. Still this subjective feedback is critical for our study reference and completion.

CHAPTER 4 CASE STUDY ANALYSIS

In chapter 2, we presented the general idea of green building and how previous scholars study on building environment. Moreover, the basic knowledge of building environment parameters were explained in chapter 3, and the previous methodology and the methodology in our study were introduced respectively as well. In chapter 4, the research of all previous chapters will be used to study our case study Zero Energy (ZOE) Lab in UNT. By obtaining the data of each building environment parameter from field test in ZOE lab, the analysis result will be compared with the standards introduced in chapter 3, and the subjective perception of occupants from questionnaire survey, which discuss whether green design elements changed the building's ability to meet common building environmental standards and whether green design elements decreased the subjective comfort level of the occupants. More detail description will be shown in this chapter.

4.1 Zero Energy (ZOE) Laboratory in University of North Texas (UNT)

4.1.1 Low and zero energy buildings

The concept of Zero Energy Building (ZEB) is an innovative idea, is discussed all over the world recently, and could become the ultimate future target for the design of [80]. Before the zero energy concept comes up, researchers have already explored how to reduce the energy consumption of buildings under different climates. Most of them were trying to maintain the energy consumption of the buildings as low as they could through the Super-insulated design and the photovoltaic system technology, which mixed the phase of saving and producing energy. Iqbal's paper presented a feasibility study of a wind energy conversion system based zero energy home in Newfoundland [68]. In this building, water heating, cooking, lighting and electrical appliances can be provided by a 10 kW wind turbine, which can meet all energy requirements of an R-2000 complaint single-family home in Newfoundland, Canada [68]. In this section, some impressive studies and experiments are listed in the table 7.

Table 7 Previous studies and experiments on low and zero energy buildings

Case Study	Time	Place of experiment	Green designs and technologies	Outcome
[69]	1958-1961	M.I.T. Solar House IV at the Massachusetts Institute of Technology; Solar air collector systems by Lof in Denver	60 m^2 of active solar collectors; solar air collector systems	Covered 57% of measured space and domestic water heating
[70]	1976	Lo-Cal house designed by the Small Homes Council at University of Illinois Urbana	Super-insulated design facet: ceiling, walls and floor; very tight air construction and sun-tempering; air to air heat exchanger ventilation	Unknown
[71-73]	1977-1984	a).A cube-shaped Saskatchewan House was built in Regina, Saskatchewan; b). The Leger Super-insulated House was built in East Pepperell, Massachusetts; c). Three 223 m^2 super-insulated homes built in Great Falls, Montana	Superinsulation; air to air heat exchanger for ventilation and no furnace installed	a). Unknown; b). an annual natural gas heating cost of only $50 c). 20 kWh/$m^2$

[74]	1998	Two highly instrumented homes (one of them served as the project control) were built in Lakeland, Florida	Interior duct system with a high efficiency heat pump, better wall insulation, a white reflective roof system, solar water heating and efficient interior appliances and lighting and a 4 kW DC PV system	A reduction in energy use of 92% relative to the control. Moreover, the project showed the possibility of zero net utility consumption
[75]	2001	A 268 m^2 modular Zero Energy Home (ZEH) called the ‘‘Solar Patriot’’ or Hathaway home [13] was created to demonstrate potentials in a mixed climate in Washington, DC	The better insulated walls and foundation with low-e windows and high efficiency appliances and lighting throughout; and an advanced geothermal heat pump; an evacuated tube solar water heating system; A 6 kW PV system	Total measured electricity consumption in 2002 was 10585 kWh against the 7510 kWh produced by the PV system
[76]	2002	A 286 m^2 ZEH was designed by Davis Energy Group and built by Centex Corp in Livermore, California	High levels of insulation; an innovative (night) cooling system (NightBreeze); high performance windows; highly efficient appliances and lighting; a tankless gas water heater; a 3.6 kW PV system	The 3.6 kW PV system produced more electricity (4890 kWh) than the house used (4380 kWh), which led to negative consumption
[77]	2002 to 2005	Five successively more advanced small near zero energy homes constructed by Oak Ridge National Laboratories in Lenoir City, Tennessee [15] J.E. Christian, D. Beal, P. Kerrigan, Toward simple affordable zero energy houses, in: Proceedings of the Thermal Performance of	The Heat Pump Water heater; the thermostat; Ground Source Heat Pumps using foundation heat recovery; Structural insulated panels (SIP); Interior duct system; High performance windows; efficient appliances; Grey water waste heat recovery system; a PV system	Compared with the first home built in 2002 costed $54,000 energy consumption with solar production-84 kWh/ m^2, fifth home constructed in 2005 had dropped net consumption to 33.9 kWh/ m^2 while reducing added costs to $48,000

[78]	2007 to now	A 119 m^2 Habitat for Humanity home designed by National Renewable Energy Laboratory (NREL) in Wheat Ridge, Colorado	the RSI-10.8 ceiling insulation, RSI-7.2 double stud walls and RSI-5.4 floor insulation; a small heat recovery ventilator; the very high performance low-e solar glass window (U-factor 1.14/1.70); a 9 m^2solar collector with 757 L of storage; a 4 kW roof-top PV system	The PV system produced 1542 kWh that was over the electricity used in the building

4.1.2 Net Zero Energy Building (ZEB)

As we discussed above, it is possible to reach the goal of close zero energy consumption with the advanced sustainable designs and energy producing equipment, but the price for this goal still does not satisfy the expectation of the public market. The term of Net Zero Energy Building means the building is connected with the power grids [79]. The on-grid ZEB, also known as 'net zero energy', 'grid connected' or 'grid integrated' has the connection to one or more energy infrastructures: electricity grid, district heating and cooling system, gas pipe network, and biomass and biofuels distribution networks. So the on-grid buildings can both purchase energy from the grid and return the extra energy to the grid, thus avoiding on-site electricity storage [80]. Connecting with the power grids allows the buildings to produce over-needy energy in some period of time in a year like in summer, and use the energy from utility in the other time that PV system could not collect enough sun energy like in winter, which means the buildings do not need to install only super high efficient equipment or energy storage system, and therefore they can use some reasonably efficient facilities.

Moreover, many scholars have found how to define a net zero energy building and the methodologies of calculating for "zero". Even though some environmental assessment methods like LEED or BREEAM provide the framework for the ZEBs, their scopes are too wide [80]. Therefore, in the review of Marszal et al., they believed a physically persuasive and communicable calculation methodology that presents the idea and promote the work of both aesthetics and engineers in designing Zero Energy Buildings is needed [80]. Accordingly, Wang et al elaborated the methodologies of calculating for "zero", and used Energy Plus and TRNSYS 16.0 software to demonstrate that it is possible to build efficient affordable zero energy homes in cold regions [81].

4.1.3 Zero Energy (ZOE) Laboratory at UNT

According to the introduction of Department of Mechanical and Energy Engineering of University of North Texas about the Zero Energy (ZOE) research lab, this structure contains a variety of advanced energy technologies in its 1,200 square-foot footprint, as well as an energy heat pump, a radiant heated floor slab, solar panels, a building energy monitoring and control system and a rain collection system etc., which are the research elements in our study. Most of these green designs will be tested and discussed following the standard of their own field. Besides, outside of the facility, there is a residential-scale wind turbine and an electric vehicle charging station [8].

4.1.4 Green Design and Technology of ZOE lab

Marszal et al. [80] show the examples of possible sustainable energy supply options for the buildings shown in Table 8. Many sustainable designs and technologies in Table 9 are virtually applied on ZOE lab in UNT shown in Figure 6 and Table 9.

Table 8 Possible sustainable energy supply options for the buildings [82]:

On-site supply options	**Day lighting, high-efficiency HVAC equipment, natural ventilation, evaporative cooling, etc.**
	PV, solar hot water, and wind located on the building
	PV, solar hot water, low-impact hydro, and wind located on-site, but not on the building
Off-site supply options	Biomass, wood pellets, ethanol, or biodiesel that can be imported from off site, or waste streams from on-site processes that can be used on-site to generate electricity and heat
	Utility-based wind, PV, emissions credits, or other “green” purchasing options. Hydroelectric is sometimes considered

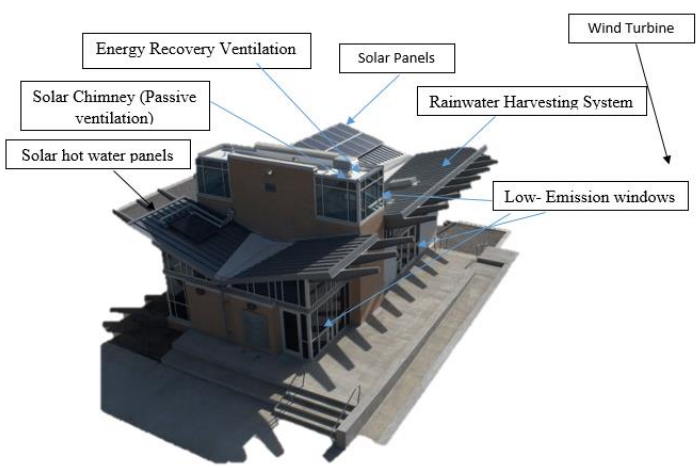

Figure 6 Sustainable designs and technologies of ZOE lab

Table 9 Green designs of ZOE lab and the building environment parameters

Green Design of Zero Energy lab in UNT		**The building environment parameters**
a)	**Wind Turbine**	Noise/Vibration
b)	**Solar PV (Photovoltaic) Panels**	N
c)	**Solar hot water panels**	N
d)	**Rainwater Harvesting System (Inverted roof shape for rainwater collection maximum)**	Vibration
e)	**Post storage tank filtration (Sanitron UV filter)**	Noise/Vibration
f)	**Low- Emission windows (Allows light in but keeps the heat out)**	Lighting/Temp./Humidity
g)	**Vertical Closed Loop Heat Exchanger (Radiant floor system, water to water et al. heat pump)**	Noise/Vibration
h)	**Geothermal Heat Pumps**	Noise/Vibration
i)	**Solar Chimney (Passive ventilation)**	Air quality/ Temp./Humidity
j)	**Energy Efficient Lighting (Natural light, LED lighting for outdoors, halogen light system and daylight detecting sensors); Skylight and Side Window**	Lighting
k)	**Energy Recovery Ventilation (ERV)**	Air quality /Temp./Humidity Fresher air
l)	**Control System (90 sensors): Chiller, boiler, outside air room air and system fluid information**	Temperature/Humidity
m)	**Bamboo Millwork/Bamboo flooring/ Recycled Glass Countertops**	Air quality
n)	**Structural Insulated Panels (walls and roof)**	N

4.1.5 ZOE and LEED

Even though ZOE lab in UNT is a totally sustainable and green building and it has never applied for LEED certification, LEED v4 will be our green design and technology criterion. Zero Energy Lab is a state-of-the-art building with so many advanced sustainable technologies and structural designs, according to the score list of LEED v4, this building could meet most of the categories LEED requires. We will show which category ZOE lab could satisfy and which of them are relative with our study objects.

4.2 Analysis methodology

Through the field test, we will gather the data about the physical performance of each building environment parameter, which will be summarized and tabulated or charted so as to be comparable intuitively. The aim of the field test is to examine if the green designs and technologies in ZOE lab have an impact on our building environment parameters; therefore, all the testing spots are closed or aimed to these green designs and technologies. The field test result of each building environment parameters in our case study will be compared with the requirement of LEED and other building and environment criteria or standards to check if our physical measurement results satisfy their requirement and limitation.

In addition, the survey response of each of these study parameters will be analyzed by some simple statistical methods like mean and standard deviation. Through the questionnaire, we could know the occupants' perception and evaluation about the building environment parameters, which can tell us if this subjective feedback from the questionnaire survey match the field test results. The comparison between field test result and LEED standard or other standard is to find out there is a direct relationship between the green design or technology elements of ZOE lab with the change of each building environment parameter. The future work will depend on the findings of this case study analysis.

4.3 Result of field test

We decided five field test spots in ZOE lab, which of them were the wall of kitchen room, steel beam in working room, wall of mechanical room, wall of working room and ground in working room, respectively.

4.3.1 Vibration

Wall of kitchen Room

Figure 7 Transducer unit 8 on the wall of kitchen room

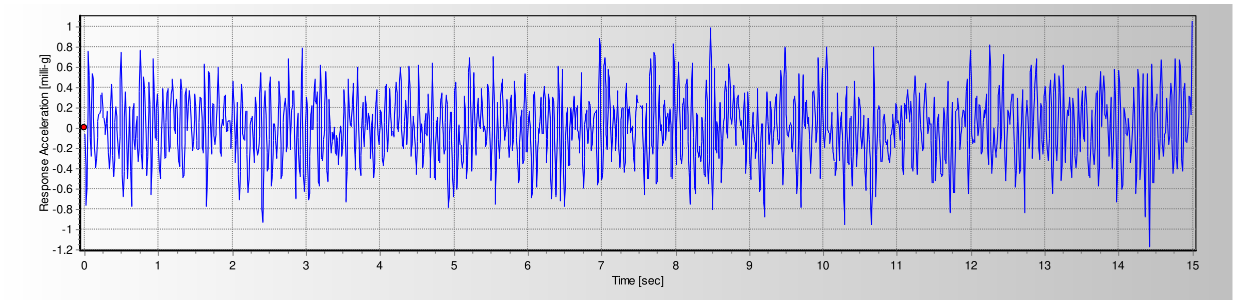

Figure 8 Response acceleration output of unit 8 (Z direction)

Steel Beam of working room

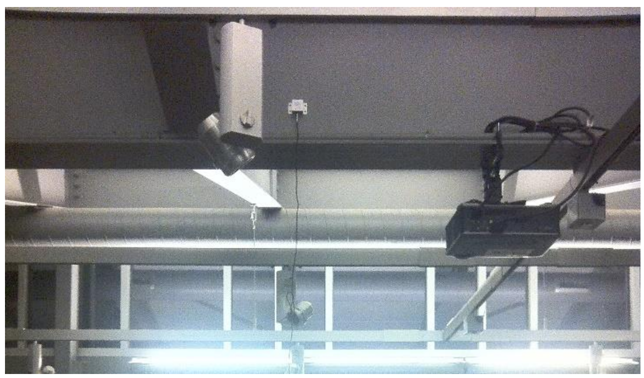

Figure 9 Transducer unit 3 on the steel beam in working room

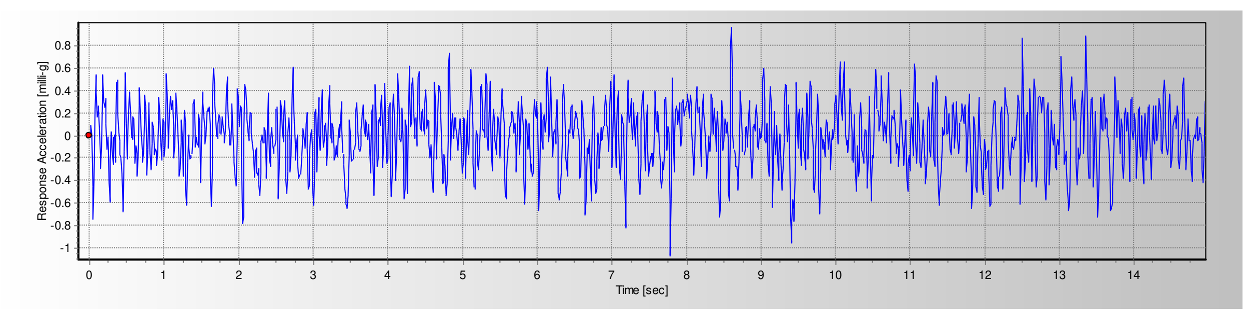

Figure 10 Response acceleration output of unit 3 (Y direction)

Wall of mechanical room

Figure 11 Transducer unit 4 on the wall of mechanical room

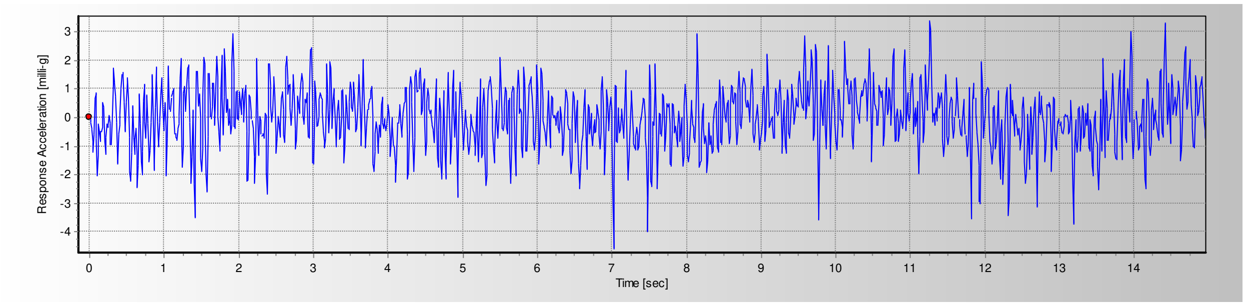

Figure 12 Response acceleration output of unit 4 (Z direction)

Wall of working room

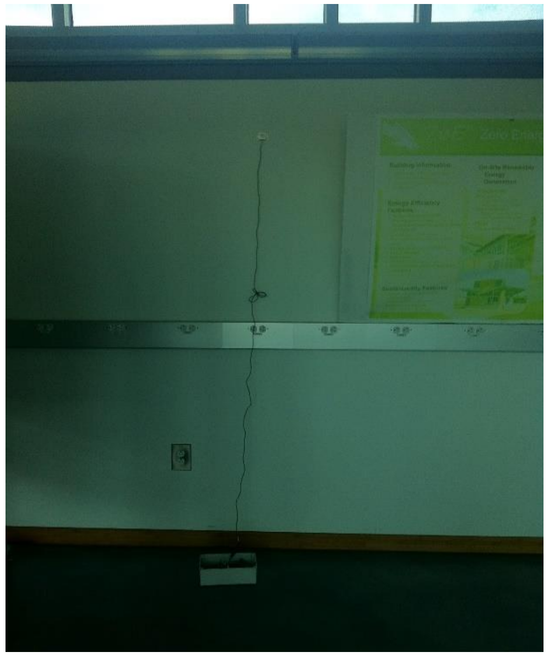

Figure 13 Transducer unit 5 on the wall of working room

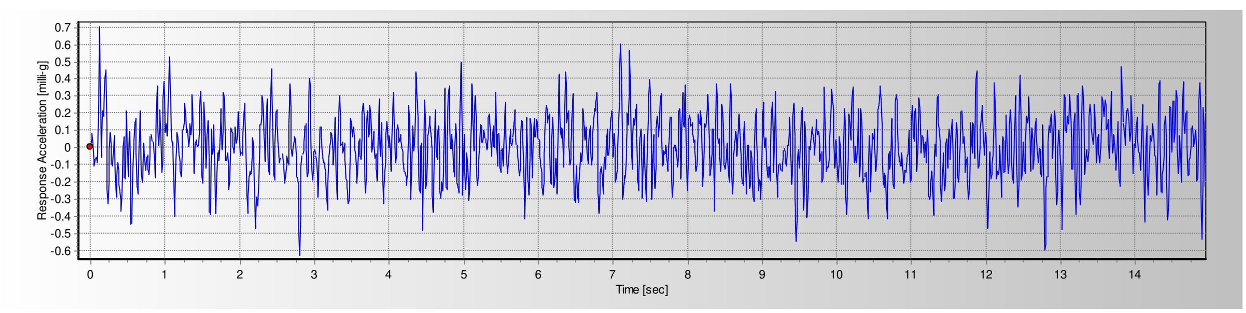

Figure 14 Response acceleration output of unit 5 (Z direction)

Ground of working room

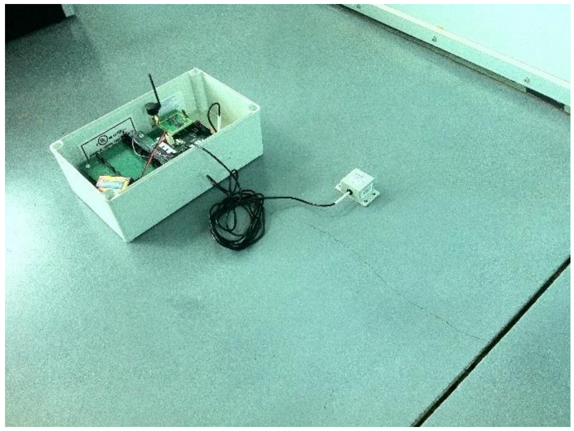

Figure 15 Transducer unit 7 on the ground of working room

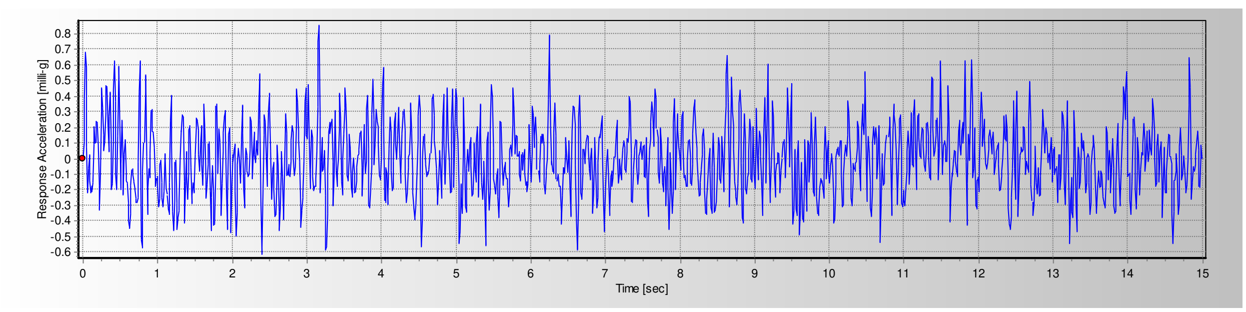

Figure 16 Response acceleration output of unit 7 (X direction)

Table 10 Vibration field test result summary when heating and water pumps all on

Heating and water pumps all on			
	X (max./mg)	Y (max./mg)	Z (max./mg)
Steel beam unit3	1.111	0.595	0.643
Mechanical room unit 4	3.216	1.752	4.583
Working room unit 5	0.637	0.624	0.654
Ground unit 7	0.684	0.637	0.637
Kitchen unit 8	0.835	0.751	1.169

Table 11 Vibration field test result summary when heating and water pumps and all equipment off

Heating & water pumps and all equipment off			
	X (max./mg)	Y (max./mg)	Z (max./mg)
Steel beam unit3	1.064	0.635	0.677
Mechanical room unit 4	1.226	0.622	0.553
Working room unit 5	0.643	0.577	0.628
Ground unit 7	0.855	0.638	0.637
Kitchen unit 8	0.599	0.619	0.613

By comparing all the maximum values in table 10 and table 11, it obviously shows that the biggest maximum acceleration magnitude among them is 4.583 mg recorded on the wall of mechanical room in Z direction. The acceleration magnitudes of unit 3 and unit 8 have each value over 1 mg, which are 1.111 mg and 1.169 mg, respectively when all the heating and water pumps are on. However, it is surprise that unit 3 recorded close acceleration magnitudes neither all equipment on or off, and both of them are relatively high (over 1 mg) compared with the rest of areas, which probably means they are not affected by the working states. As we assume that the most vibration is generated from the geothermal system in the mechanical room, the maximum acceleration magnitude even reaches 4.583 mg, and the vibration level when all the equipment in the mechanical room are off work is much lower than when they are all on.

4.3.2 Noise level

Table 12 Average decibel in working room during 3 days

	Heat and cool pump both on, working room	Heat and cool pump both off, working room
10/6/2015	51	43
10/7/2015	50	44
10/8/2015	46	43

According to the table 12, the average decibel of working room were from 46 dB to 51 dB when the geothermal system were on during the three days field test. In addition, the average decibel of working room were almost at same level around 43 dB during the three days test.

Table 13 Average decibel in working room on 10/8/2015 at night

	All mechanical and electrical equipment off, working room
10/8/2015	36

Table 13 shows average sound level of 36 dB was recorded at the nighttime of Oct. 8th when all the mechanical and electrical equipment was off.

Table 14 Average decibel in mechanical room during 3 days

	Heat and cool pump both on, mechanical room	Heat and cool pump both off, mechanical room
10/6/2015	72	42
10/7/2015	69	40
10/8/2015	69	35

Based on the table 14, the average recorded noise level was 69 dB and up to 72 dB in the mechanical room during the field test when the geothermal system was working. However, these values drop down to the level of between 35 dB and 42 dB when the geothermal system was stopped.

Table 15 Average decibel in mechanical room on 10/8/2015 at night

	All mechanical and electrical equipment off, mechanical room
10/8/2015	35

In table 15, it was a low sound level which was average 35 dB at night on October 8th when all the mechanical and electrical equipment were off in mechanical room.

Table 16 Average decibel outside of lab during 3 days

	Outside the lab
10/6/2015	52
10/7/2015	58
10/8/2015	54

In table 16, the average decibel outside of the lab during the three days' field test varied between 52 dB and 58 dB, meanwhile, the wind turbine was slow on 10/6/2015, and it was stopped both 10/7/2015 and 10/8/2015 during the field test.

Table 17 Average decibel outside of lab on 10/8/2015 at night

	All mechanical and electrical equipment was off, outside of the lab
10/8/2015	53

In table 17, the average decibel outside of lab during the three days' field test was 53 dB.

4.3.3 Temperature

In ZOE lab, the self-monitoring and controls system was monitoring the temperature and humidity inside and outside of the lab. The monitoring system collected one average indoor temperature and relative humidity for each 15 minutes of 24 hours. According to our study method, we preferred to only consider the daytime or normal working time frame, in our case it was from 8:00 to 18:00. So we filtered the rest of the data except for 8:00 to 18:00, which is shown in Figure 17.

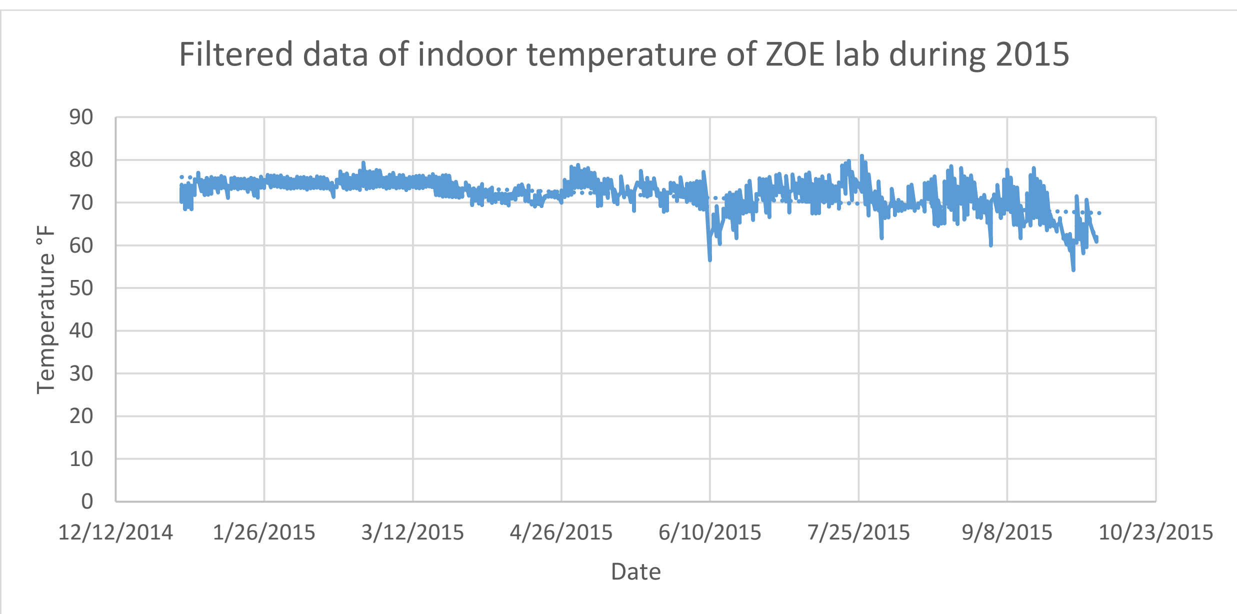

Figure 17 The filtered data of indoor temperature of ZOE lab during 2015

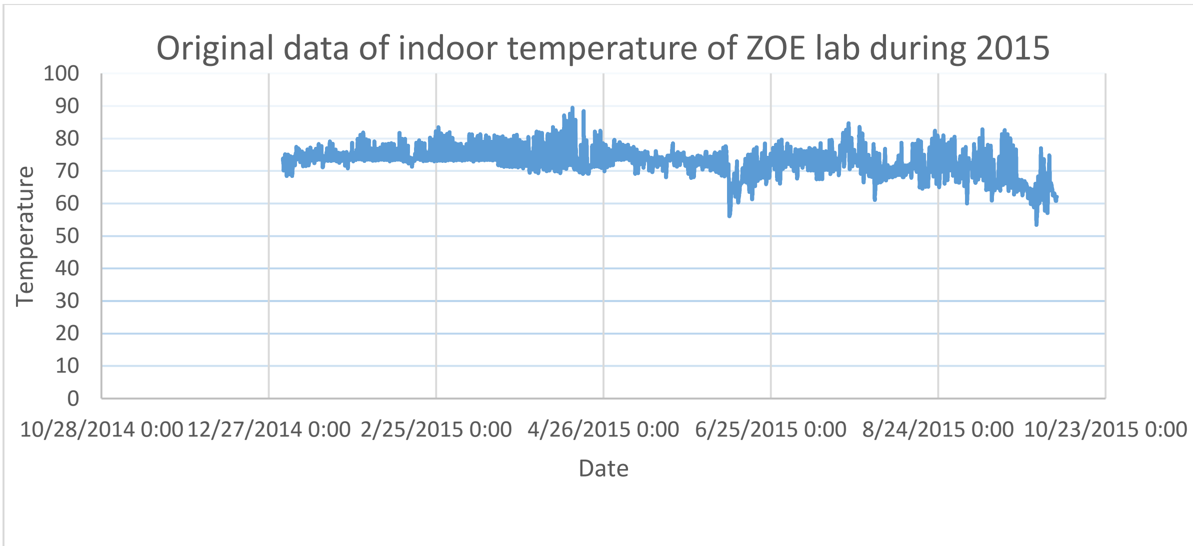

Figure 18 The original data of indoor temperature of ZOE lab during 2015

According to the data of indoor temperature of ZOE lab during 2015 shown in Figure 17, we can see that the indoor temperature during working time is roughly between 72 °F to 75 °F. However, by comparing the original data of indoor temperature of ZOE lab during 2015 shown in Figure 18, it varied greatly and the trend of the temperature of ZOE lab is not clear, as we can see on some dates the temperature was even up to 90 °F.

4.3.4 Humidity

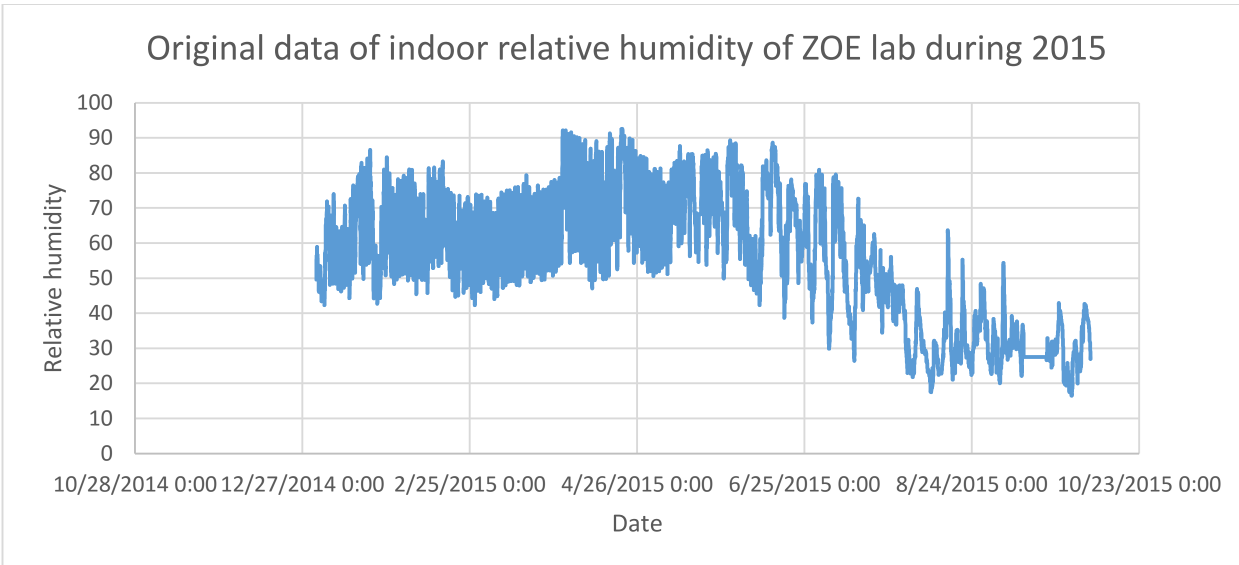

Figure 19 The original data of indoor humidity of ZOE lab during 2015

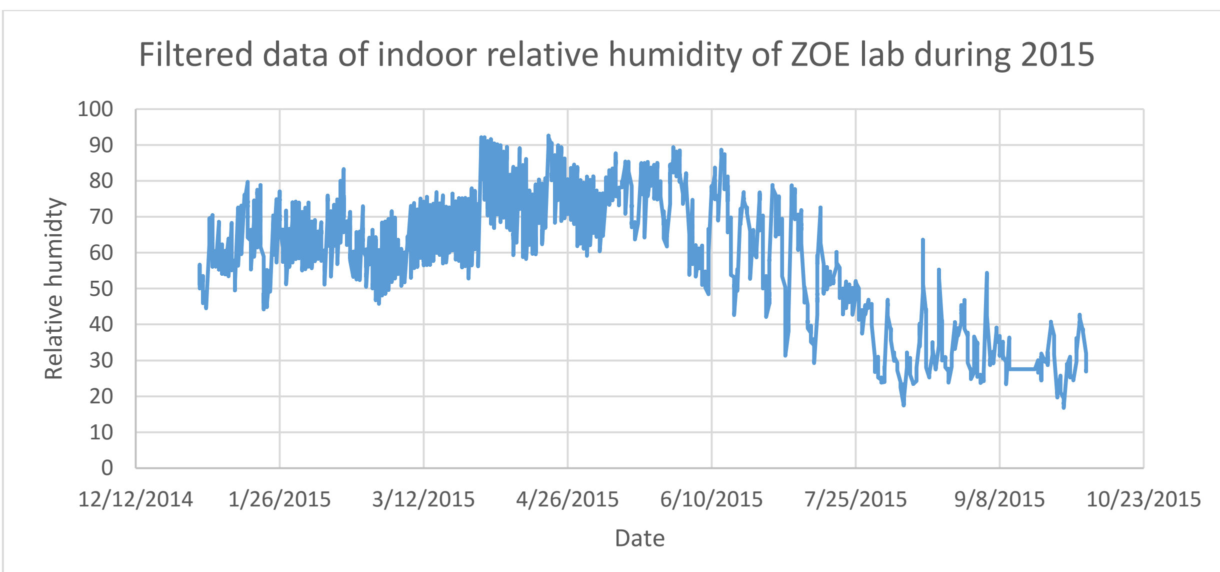

Figure 20 The filtered data of indoor relative humidity of ZOE lab during 2015

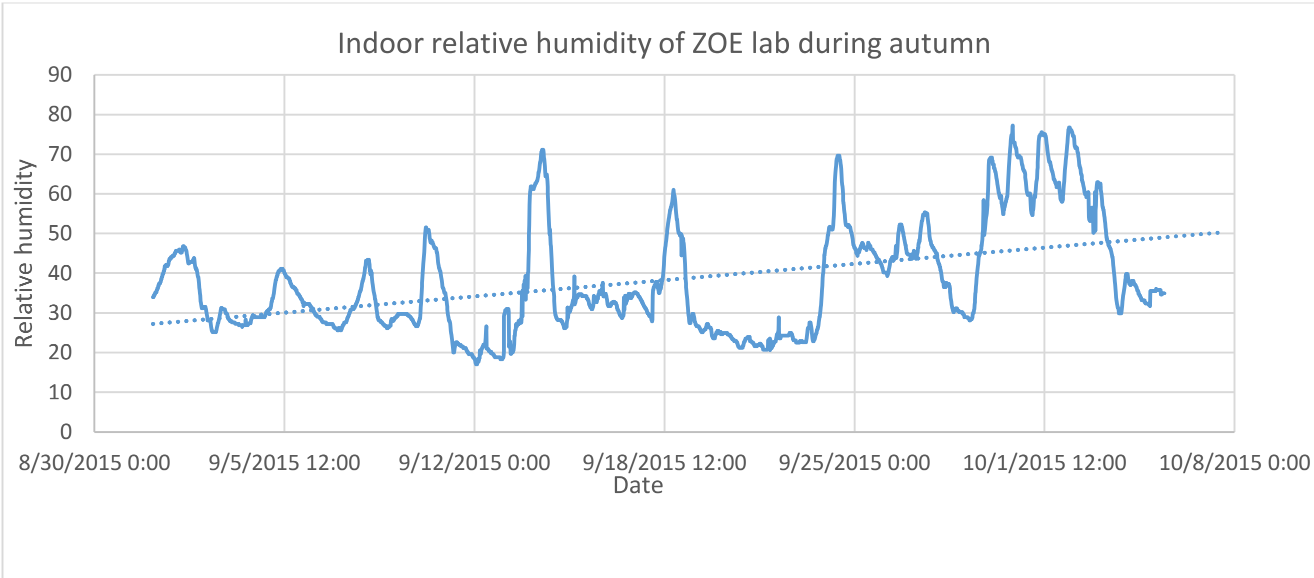

Figure 21 The indoor relative humidity during autumn

The Figure 19 shows us the original record of the indoor relative humidity of ZOE lab. It was not very clear how relative humidity changed during the whole year, as the filtered data of indoor relative humidity in Figure 20 shows. However, if we narrow down the time period to autumn in Figure 21, we can see that the range is between 30 percent and 60 percent.

4.3.5 Lighting

Table 18 Daylight calculation of ZOE lab

Day lighting calculation		
	Square feet	VLT
Floor area	1,200	
Skylight CLASS 1 & 3 ACRYLIC	90	69%
Glass Type GL-1	120	29%
Glass Type GL-2	250	20%
Glass Type GL-3	150	20%
Glass Type GL-4	150	20%
(90*69%+120*29%+250*20%+150*20%+150*20%)/1200=		0.172

Through the formula provided by LEED 2009 version, the daylight calculated value shown in table 17 is in the required range, but it is very close to the top limit.

4.4 Field test and Questionnaire response

Table 19 Questionnaire response summary

	Noise Level	Temperature	Humidity	Vibration of Wall or Floor	Freshness of Air	Daylight	Indoor Lighting System	Air Movement/Ventilation	Overall Environment
Summary 1	1	3	3	1	3	3	2	3	4
Summary 2	3	3	4	3	4	3	2	2	3
Summary 3	3	3	3	2	4	4	3	2	4
Summary 4	3	4	2	1	4	4	4	2	4
Summary 5	2	4	3	1	4	2	3	2	4
Summary 6	2	3	2	1	3	3	3	1	4
Summary 7	1	3	3	1	3	4	2	1	4
Summary 8	2	3	3	1	4	4	4	3	4
Summary 9	2	3	3	1	3	4	1	3	4
Summary 10	4	3	3	2	4	3	2	1	4
Summary 11	3	4	3	3	5	5	3	3	4
Summary 12	1	3	3	1	4	4	3	3	4
Mean	2.25	3.25	2.92	1.50	3.75	3.58	2.67	2.17	3.92
Standard Dev	0.97	0.45	0.51	0.80	0.62	0.79	0.89	0.83	0.29

In our questionnaire survey summary shown in table 18, we collected total 12 responses, which is the maximum number of occupants who are actually working in ZOE lab. Most of them spend more than 5 hours during a day and stay at least 4 to 5 days of a week in the lab. The perception of these respondents are more real than visitors'.

For all the study parameters, the perception of temperature, humidity, freshness of air and overall environment satisfaction is close. However, the perception of noise level, vibration of wall or floor, day light and indoor lighting system is at variance. First of all, these responses are subjective and independent. Second, the total respondent number is sufficient. Third, the questionnaire survey is random for the respondents.

4.5 Comparison

Vibration

According to the field test result, the geothermal system generates the most local vibration in the mechanical room, which reached 4.583 mg. Figure5 shows two shaded bands representing two ranges of peak acceleration: 5–7mg for residential buildings and 9–12mg for office buildings with one year return period, which means the acceleration level in mechanical room is still acceptable. Moreover, refer to Table 4, when the acceleration level is below 0.315 m/s^2, occupants do not feel any uncomfortable. This pointed out that this kind of level of local vibration in mechanical room is completely acceptable for that standard.

Meanwhile, based on the questionnaire analysis the average scale of the perception of occupants for vibration is 2.25 out of 5, but the standard deviation is up to 0.97, which means our respondents have widely different perceptions for the vibration, and most of them think vibration of wall or floor is weak. According to simple statistical analysis, people at least actually felt a little bit of vibration, which matches with the result of the field test.

Noise

By comparing 51 dB in working room, the noise level summarized from the field test was relatively high, which reached 72 dB when the geothermal system was working in the mechanical room. Both of the background noise levels of HVAC system did not satisfy the requirement of LEED, which should be 35 dB or less. They also were not acceptable for the U.S. EPA standard, which recommended 45 dB for residential area and 55 dB for office area.

In addition, when only the geothermal system turned off, the average sound levels were approximately 40 dB in mechanical room and 43 in the working room, which can indicate the rest of noise came from the working room. This kind of level of sound is acceptable for the U.S. EPA though.

Outside of the lab, all the recorded sound levels were approximately 55 dB whether it was daytime or nighttime, and the sound level outside the lab was acceptable for the U.S. EPA standard, which recommends 55 dB sound level outdoors. Moreover, the wind turbine did not make lots of noise outdoors let alone indoors based on our field test result.

Even with this kind of noise level in the lab, by comparing the questionnaire results, the occupants in the survey felt comfortable, and their average scale was 2.25 out of 5.

Temperature

According to the field test result analysis of indoor temperature of ZOE lab, we found that the range of indoor temperature of ZOE lab was around 70 °F to 75 °F, which is within suggested range of temperature of 68 °F to 75.2 °F (ASHRAE 55 2010), and that is also an accepted comfort range for most occupants (ISO 7730) [57].

In addition, this indoor temperature range also was reasonable based on the study of Wai (2011), who suggested in office environment the air-conditioning temperature be no lower than 75 °F to 77 °F [57], and Sharharon, who recommended the optimum comfortable workplace temperature in the range of 68 °F to 78.8 °F should be maintained in office [58]. However, except for the timeframe of work, the temperature of the rest of the day varied widely, with some periods of time that were not acceptable by the standards.

Based on the questionnaire survey we conducted, the average scale of occupants was around 3.25 out of 5, which meant the respondents were feeling a little bit hot for the temperature inside of ZOE lab, which represented the field test result.

Humidity

In Figure 19 and Figure20 regarding to data analysis of original and filtered indoor relative humidity of ZOE lab, we found that the range of indoor relative humidity of ZOE lab was between 20% and up to 90%, which is too wide to tell the main range of indoor relative humidity; therefore, it is not clear enough to decide if it is acceptable for the LEED and other standards.

However, since we conducted our survey during September, we tried to narrow down the time period to autumn. In Figure21, we can see that the range is between 30 percent and 60 percent, which is within the recommended level of maintaining indoor relative humidity levels between 30 percent and 60 percent [57]. In addition, this range also accorded with the suggested range of Wei and Sharharon [57-58].

Based on the questionnaire survey we conducted, the average scale of occupants for indoor relative humidity was around 2.92 out of 5, which meant the respondents felt balanced about the humidity level inside of ZOE lab, which represented the field test result during autumn.

Lighting

We measured the floor area, side window size and top window size of ZOE lab. According to the formula given by LEED 2009 version, we achieved a value of 0.172, which is within the range from 0.150 and 0.180, and the formula is calculated as the product of the visible light transmittance (VLT) and window-to-floor area ratio (WFR) of daylight zone. However, the calculated value is very close to the top limit, which means the window area is relatively large compared to the floor area as the VLT of windows meet the minimum requirement.

According to the response of questionnaire survey, the average scale of occupants for daylight was around 3.58 out of 5, which means the respondents were satisfied with the daylight inside of ZOE lab, which represented the field test result for daylight parameter.

CHAPTER 5 IMPLICATION FOR GREEN BUILDING DESIGN AND ASSESSMENT

Based on the building environment parameters' field test result and their comparison with LEED or other standard and questionnaire survey feedback in chapter 4, in this chapter, the discussion about whether there is an impact of the green design elements shown in Table 9 on these building environment parameters will be presented below.

5.1 Vibration comfort

As table 9 shows, the green designs and technologies including wind turbine, rainwater harvesting system, post storage tank filtration, vertical closed loop heat exchanger and geothermal heat pumps have a potential impact on generation or reinforcement of vibration.

According to the basic theory of vibration discussed in chapter 3, the vibration in our case was mechanical vibration, which was caused by equipment rotating and friction force. Our field test result showed that wind turbine and rainwater harvesting system had almost no impact on the vibration due to this equipment located outside, and the ground vibration we collected was pretty low.

However, all of the post storage tank filtration system, vertical closed loop heat exchanger system and geothermal heat pumps are involved in the heating and water pump system, which was located in the mechanical room. Based on our field test result and standard, even the local vibration level is acceptable and occupants feel a little uncomfortable about it, and these green designs and technologies were the sources of vibration. Specially, the geothermal system contributed most of the local vibration in the mechanical room and even strengthened the vibration. Therefore, these green designs and technologies have a slight impact on the vibration comfort in this building.

5.2 Noise pollution

Similarly, potential sources of noise pollution are wind turbine, post storage tank filtration system, vertical closed loop heat exchanger system and geothermal heat pump system. Since the filtration system, heat exchanger system and geothermal heating system are installed in the mechanical room, and wind turbine is located outside of the lab, our data receiving spots are in the mechanical room, working room and outside of the lab. According to the discussion about the field test result analysis in chapter 4, it is obvious that the mechanical room contributed most of the noise, and heating and water pumps were proven to be the primary noise makers due to the heat exchanger system being underneath steel concrete foundation. For wind turbine outside, it is a surprise that it was extremely quiet, based on the data analysis. Therefore, as we can see some of these green designs and technologies are potential noise makers in our case study and have strong influence on the noise pollution, but it does not mean this finding represents all the cases.

Unlike vibration comfort, the noise level in the working room is above the required background noise level of LEED standard and almost over the acceptable level of other standard. Even though it is totally unacceptable for the noise level in mechanical room, it can be ignored because there were so few occupants who need to work in this room.

In our case, that is because the size of the lab is relatively small, so that we can detect the noise from the mechanical room that is just right next to the working and living area. Even though the perception of respondents for noise level is not negative in our case, the insulation level still needed to be increased and the central room needs to be separated away from the working area in other case to improve the noise level.

5.3 Temperature and humidity

As ZOE lab has its own indoor environment monitoring system, every 15 minutes the indoor temperature and humidity were recorded in the system. By reviewing the discussion in chapter 4, the indoor temperature and humidity is acceptable by the LEED and other standards during working time. However, in the other period of time they were very varied that the temperature was too high or low. The green designs and technologies related to this building environment element include low- emission windows, solar chimney (Passive ventilation), energy recovery ventilation (ERV) and control system shown in table 9. ZOE lab is state of the art sustainable and high efficient building, and its task is to try to balance the energy production and energy saving. So first of all, the control system would not allow energy waste, which causes some time the indoor heating or cooling needed to be sacrificed to chase this goal. Secondly, the heating and cooling depend on the advanced equipment like geothermal, vertical closed loop heat exchanger, ERV, etc., so if this equipment is not sensitive or high efficient enough that will delay the adjustment of temperature or humidity. Then last but not least, the special design of applying amounts of skylight and side windows or other energy efficiency designs aiming to gain more daylight like low emission window or other sustainable ventilations have indirect impact on the temperature or humidity, for example, the temperature will increase or drop faster when the building has a large window area. This also can explain why there are varied indoor temperature and humidity during some periods of time.

5.4 Lighting

In ZOE lab, the building was designed with top skylight windows and many side windows, which acquire maximum daylight. In chapter 4, the daylight calculation result showed the daylight design of ZOE lab met the requirement of LEED, and this design has a positive impact on lighting in the daytime. However, although the energy efficient lighting system was used to prevent wasting energy, this design might also degrade the user experience based on the questionnaire response. In this case study, the interior lighting system was not tested, but the feedback of the survey is not positive enough (mean=2.67). We assume that maybe there is not enough lighting equipment installed in ZOE lab.

CHAPTER 6 SUMMARY AND FUTURE WORK

6.1 SUMMARY

Our case study, Zero Energy lab in UNT, is a classic energy sustainable building where installed many different advanced energy efficient equipment and applied lots of state of the art sustainable technologies. As we know, the design principle of a sustainable building is to pursue the maximum energy reduction and keep balancing the energy output and input, and ZOE lab is an excellent example for this goal. This kind of sustainable building is highly possible to spread everywhere in the future and just as normal as the residential buildings nowadays. However, we need to remember that the fundamental purpose of a building is to provide a safe and comfortable environment to the residents. Even the green building has a lot of environment friendly advantages, we still need to make a building comfortable. In our case study, through our field measurement and questionnaire survey, we can say all these green design elements met the LEED standard or other standards and the occupants feel comfortable about these designs and technologies in ZOE lab.

6.2 Future work in this case study

6.2.1 Option selection

In the future, we want to be able to design a building by choosing green design elements and checking not only their effect on energy efficiency or LEED scoring, but also on the building environment. For instance, wind turbine. We only have one wind turbine in this case study, but we should have multiple choices of selecting wind turbine in the future. If we design a new building, we would choose from several wind turbines or other the renewable energy application not only based on how much the energy they produced, but their impact on the building environment.

6.2.2 Questionnaire survey

In our case study, the number of survey is not enough to do the statistical analysis, in order to perform a sound statistical analysis of what factor influence people's overall comfort with the building environment, in the future, we want to get a greater sample size of this building. In other words, what we want to do is to create a more comprehensive survey. For example, we design the questionnaire then give it to greater sample size and get an appropriate response rate (like n=100, RR=0.3-0.6), in that way we would be able to tell what is the influence of each building environment factor on overall comfortable and which is the factor needed to be improved or concerned.

6.2.3 Noise control

In our case study, even though we obtained a very high noise level in the mechanical room in ZOE lab, more study on how occupants' perception for the noise level in mechanical room should be done in the future. In addition, since the questionnaire survey conducted in our case showed occupants have varied perceptions about this parameter, a survey on why there is a high standard deviation about noise level should be conducted as well in the future.

6.2.4 Future work of lighting

As the field test shows, the calculated value (1.78) based on the formula given by LEED 2009 version was very close to the top limit (1.8). We explained this was because the total size of all windows in ZOE lab was pretty large, which led to the situation that daylight quality bases on the weather conditions. Moreover, according to the questionnaire, the average scale of perception of interior lighting system was below 3 and the standard deviation was very high (0.89). We assume there is a correlation between the daylight and interior lighting, and a more study plan and questionnaire survey should be conducted on this in the future.

6.2.5 Conclusion

As we can see in the questionnaire survey summery table, many building environment parameters had a high standard deviation. Even though, the sample size in our case study was not enough, there should be more future works needed to explain why the occupants have varied opinions about these parameters.

APPENDIX 1

Survey on perception of occupants for working in Zero Energy Lab in UNT

Section A

Please circle the number.

Gender:

1 Female

2 Male

Age:

1 20 years or below

2 21-30 years

3 31-40 years

4 41-51 years

5 51-60 years

What do you do in Zero Energy Lab?

1 Student Researcher

2 Visitor

3 Faculty

4 Other

How often you stay in Zero Energy Lab?

1. Everyday
2. Couple days a week
3. Couple days a month
4. Few

Section B

Please circle a number to rate your perception of the Zero Energy Lab on each of the following scales from 1 to 5.

Noise Level:	very quiet	1	2	3	4	5	very noisy
Temperature:	very cold	1	2	3	4	5	very hot
Humidity:	very dry	1	2	3	4	5	very humid
Vibration of Wall or Floor:	very weak	1	2	3	4	5	very strong
Freshness of Air:	very stale	1	2	3	4	5	very fresh
Daylight:	very dim(poor)	1	2	3	4	5	very bright
Indoor Lighting System:	very dim	1	2	3	4	5	very bright
Air Movement/Ventilation:	very still/slow	1	2	3	4	5	very drafty/fast
Overall Environment:	very uncomfortable	1	2	3	4	5	very comfortable

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