THE IMPACT OF HVAC SYSTEM OPERATION AND SELECTION ON ENERGY EFFICIENCY IN OFFICE BUILDINGS IN HOT CLIMATES

BY

MOHAMMED ABDUL NAJID

A Thesis Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

ARCHITECTURAL ENGINEERING

MAY, 2010

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This thesis, written by **MOHAMMED ABDUL NAJID** under the direction of his thesis advisor and approved by his thesis committee, has been presented to and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN ARCHITECTURAL ENGINEERING.**

Thesis Committee

8/2/11

Dr. Mohammad S. Al-Homoud (Advisor)

9-2-011

Dr. Ismail M. Budaiwi (Member)

Adel Abdou 5/02/2011

Dr. Adel A. Abdou (Member)

9/2/11

Dr. Naser A. Al-Shayea
(Department Chairman)

Dr. Salam A. Zummo
(Dean of Graduate Studies)

Date: 9/2/11

DEDICATION

To those whom I have been away from most of my education

and who have waited for this day patiently,

I dedicate this research to

my grand-parents,

my parents,

my brothers and sisters,

and to my fiancé.

ACKNOWLEDGEMENTS

All praise and thanks are due to my Lord, ALLAH SUBHANAHU WA TA’ALA, for giving me the health, knowledge and patience to complete this work. I acknowledge the financial support given by Architectural Engineering Department, KFUPM, during my Master study. I appreciate the computer facilities provided by Architectural Engineering Department for this research.

I would like to express my gratitude and sincere appreciation to my thesis advisor Dr. Mohammad S. Al-Homoud for his time, patience, and extensive guidance throughout my research. I am also deeply grateful to Dr. Ismail M. Budaiwi and Dr. Adel A. Abdou for their constructive guidance and support. Thanks are also due to Dr. Baqer M. Al-Ramadan, former Chairman of ARE department for his unconditional help and support throughout my master study. I am also indebted to the Chairman of ARE department, Dr. Naser Al-Shayea. My appreciation also goes to the secretary of the ARE department, Mr. Iqbal Ghani, and all other staff members of the department who have helped me directly or indirectly.

Finally, I am deeply grateful to my grandparents, parents, brothers and sisters, and to my fiancé for their encouragement and support to pursue my graduate studies. My thanks also to my friends at KFUPM and to my friends back home in India.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

THESIS ABSTRACT

NAME : MOHAMMED ABDUL NAJID
TITLE : THE IMPACT OF HVAC SYSTEM OPERATION AND SELECTION ON ENERGY EFFICIENCY IN OFFICE BUILDINGS IN HOT CLIMATES
MAJOR : ARCHITECTURAL ENGINEERING
DATE : MAY, 2010

The global energy use has been rising at alarming rates in recent decades. The building sector, which mainly includes commercial and residential buildings, is one of the main contributors to rise in global energy use. Among these, office buildings are one of the major users of energy. Furthermore, HVAC systems contribute a major share of the total energy used in office buildings. The objective of this thesis is to present the results of studying the impact of alternative energy conservation measures (ECMs) on energy efficiency of HVAC systems in office buildings in the hot humid climate of Saudi Arabia.

In order to achieve the objectives of this research, a case study office building located in Al-Khobar, Saudi Arabia, was selected. A detailed energy audit of the selected building was performed. The audit consisted of five stages: building characteristics analysis, a walk-through survey, analysis of the electric energy utility bills, thermal comfort assessment and detailed building energy simulation. The main intent of the audit was to develop an energy use profile of the building. The analyses of the energy profile gives an indication of the components of the building in which most energy is used, leading to potential measures for energy savings.

Ten ECMs related to both operation and design of HVAC systems were evaluated using Visual-DOE energy simulation software. The evaluated ECMs were divided into three categories, zero investment, low investment and high investment measures. The zero investment category included ECMs regarding the setpoint temperature, the HVAC system operation hours and the ventilation rate. The low investment category included ECMs such as Demand Controlled Ventilation and Economizers and the high investment category included ECM related to the type of HVAC system. The annual energy savings obtained for the combination of potential zero investment ECMs was upto 13.3%, whereas the annual energy savings obtained for combination of all potential ECMs was 41.4%, for the case study building. Finally, based on the results, guidelines were developed for energy efficient design and operation of HVAC systems in office buildings in hot climates.

MASTER OF SCIENCE DEGREE
KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS
DHAHRAN, SAUDI ARABIA

ملخص الرسالة

الاسم **محمد عبد الماجد**

العنوان **أثر تشغيل واختيار نظام تكييف الهواء على كفاءة استخدام الطاقة في مباني المكاتب في المناخ الحار**

التخصص **الهندسة المعمارية**

التاريخ **مايو 2010**

إزداد استخدام الطاقة في جميع أنحاء العالم بمعدلات مثيرة للقلق في العقود الأخيرة ، و يساهم قطاع البناء والذي يتضمن المباني التجارية والسكنية بشكل رئيسي في ارتفاع معدل استهلاك الطاقة العالمية. ومن بين هذه المباني تمثل المباني المكتبية نوع من المباني المتعاظم الاستهلاك للطاقة بشكل رئيسي حيث تساهم أنظمة تكييف الهواء بها بحصة كبيرة من إجمالي الطاقة الكهربائية المستخدمة. و يهدف هذا البحث لدراسة أثر التدابير البديلة لحفظ و ترشيد استهلاك الطاقة (ECMs) على كفاءة استخدام الطاقة الكهربائية المستهلكة بواسطة أنظمة تكييف الهواء في المباني المكتبية في المناطق ذات المناخ الحار والرطب من المملكة العربية السعودية.

ومن أجل تحقيق هدف هذا البحث، تمت دراسة حالة أحد المباني المكتبية الواقعة في مدينة الخبر بالمملكة العربية السعودية. ولقد أجريت لهذا المبنى مراجعة و تدقيق سبل استهلاك المبنى للطاقة الكهربائية بشكل مفصل . ومرت هذه المراجعة على خمس مراحل هى: تحليل خصائص المبنى، جمع المعلومات اللازمة من خلال التجول و الملاحظة داخل المبنى، ودراسة وتحليل فواتير استهلاك الطاقة الكهربائية، وتقييم مستوى راحة الموظفين لدرجة الحرارة داخل المبنى وكذالك القيام بمحاكاة مفصلة لاستهلاك الطاقة الكهربائية في ذلك المبنى. وكان الغرض الرئيسي من عملية المراجعة هو الحصول على توصيف واضح عن حالة استخدام الطاقة في المبنى، و من ثم تحليل تلك الحالة لاستخلاص مؤشرات عن مكونات المبنى التي تستهلك معظم الطاقة الكهربائية، مما يؤدي إلى إيجاد التدابير البديلة والمحتملة لحفظ و ترشيد استهلاك الطاقة.

ولقد جرى تقييم عشرة تدابير بديلة لحفظ و ترشيد الطاقة (ECMs) متعلقة بتشغيل وتصميم أنظمة تكييف الهواء باستخدام برنامج محاكاة الطاقة (Visual-DOE). وُصنفت تلك التدابير البديلة لحفظ و ترشيد الطاقة إلى ثلاث فئات هي: تدابير غير مكلفة مالياً، وتدابير منخفضة التكاليف وأخرى عالية التكاليف . وتشمل الفئة الأولى على التدابير المتعلقة بتحديد بدرجة حرارة تكييف الهواء في فراغات المبنى، وساعات تشغيل نظام تكييف الهواء ومعدل التهوية. أما التدابير ذات التكلفة المنخفضة فشملت على الحاجة إلى التحكم بالتهوية، وأنظمة تقليل استهلاك الطاقة، وأما الفئة ذات التكلفة العالية فشملت على التدابير ذات الصلة بنوع نظام تكييف الهواء. و خلصت الدراسة الى أن المعدل السنوي لتوفير استهلاك الطاقة الكهربائية المستخدمة في المبنى المكتبي محل الدراسة يصل إلى13,3٪ باستخدام جميع التدابير غير المكلفة، في حين يصل المعدل السنوي لتوفير استهلاك الطاقة إلى41,4٪، باستخدام جميع التدابير المحتملة لحفظ و ترشيد الطاقة. واستنادا إلى النتائج ، تم تحديد أسس و إرشادات لمبادئ تصميم وتشغيل أنظمة تكييف الهواء ذات كفاءة عالية في استخدام الطاقة في المباني المكتبية في المناطق ذات المناخ الحار.

CHAPTER 1

INTRODUCTION

This chapter presents the background for the research subject along with problem statement, significance of research, the objectives, scope and limitations and the research methodology used.

1.1 BACKGROUND

The global energy use has been rising at alarming rates in recent decades. Latest data disclosed by the U.S. Energy Information Administration (EIA)**[1]** in 2009 reveals that the world primary energy use in the past two decades, from 1986 to 2006, has increased by 51%. Moreover, current predictions by EIA show that by 2030, there will be a further 44% increase in the global energy use, indicating an average annual increase of 1.5%**[1]**.

Furthermore, EIA also disclosed that in 2006 primary sources of energy consisted of petroleum 36.0%, coal 27.4%, and natural gas 23.0%, amounting to an 86.4% share for fossil fuels in the world primary energy use**[1]**. Non-fossil sources, which include hydroelectric 6.3%, nuclear 6.4%, and others (geothermal, solar, tide, wind, wood, and waste) 0.9%, amounted to only 13.6%**[2]**. If prevalent rates of increasing energy use are allowed to continue, the world's total fossil fuel reserves would be completely exhausted

within a few generation of a lifetime. Even if the annual rate of energy use were to remain constant, the diminishing availability of fuel would result in dreadful shortage, which would result in drastic changes in the economical and the sociological behavior.

The burning of fossil fuels produces around 21.3 billion tonnes of carbon dioxide per year. However, it is estimated that natural processes can only absorb about half of that amount, so there is a net increase of 10.65 billion tonnes of atmospheric carbon dioxide per year**[3]**. Carbon dioxide is one of the greenhouse gases that enhances radiative forcing and contributes to global warming; causing the average surface temperature of the Earth to rise in response, which causes adverse environmental issues. This has resulted in a global concern to use energy more efficiently and to reduce greenhouse gas emissions from power generation.

In addition to the above mentioned concerns, fluctuations in oil prices stimulated further interest in energy efficiency studies. In 1970 with sharp increase in oil prices, a considerable boost was given to the energy efficiency studies. As a result, energy conservation measures were developed to provide cost-effective solutions for meeting immediate short-term goals. Thereafter, in 1980, steady oil supply and low energy price had reduced people's interest in energy conservation. Further, in the late 1980 and early 1990, awareness of the close link between energy use and environmental pollution had brought energy efficiency back to front international agenda.

The various regions that have been identified as the top energy users of the world are shown in **Figure** 1.1**[3]**. As seen from **Figure** 1.1, United States uses 22.3% of the world total energy though it amounts to only 4.6% of world population, whereas Saudi Arabia uses thrice the amount of energy than its population. In addition, there are some countries which have shown relatively low energy use corresponding to their population such as China, India, Brazil and Mexico.

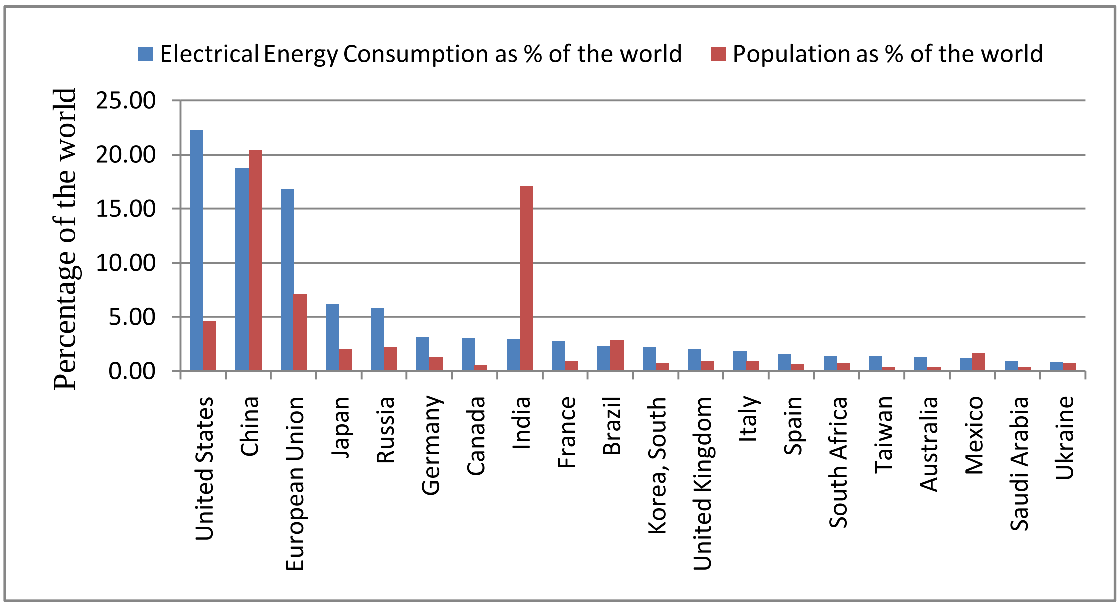


Figure 1.1: Top energy users of the world**[3]**

The building sector is one of the main contributors to rise in global energy use. The contribution from building sector towards global energy use has steadily increased, reaching figures between 20% and 40% in many countries, and has exceeded the other major sectors: industrial and transportation. Growth in population, increasing demand for

building services and comfort levels, together with the rise in time spent inside buildings, indicate that upward trend in energy demand will continue in the future**[4]**.

The building sector mainly constitutes commercial and residential sectors. The commercial sector comprises of a wide variety of building types such as offices, hospitals, schools, warehouses, hotels, shopping malls, and others. Among these, office buildings are one of the major users of energy. Data compiled by Lombard (2008)**[4]** reveals that in USA, offices accounted for about 18% of the commercial sector energy use, equivalent to a 3.2% of the total use. In Spain, they accounted for a third of the commercial sector energy use and almost 2.7% of total energy use and in the UK for 17% of energy use and 2% of total energy use. Furthermore, in Hong Kong and Malaysia, office buildings' share in the commercial sector energy use was found to be 18%**[5]** and 21%**[6]**, respectively. This shows that office buildings account for about one fifth of the commercial sector energy use in different regions of the world.

Heating, Ventilation and Air-Conditioning (HVAC) systems are one of the major users of energy in office buildings. In order to enhance the comfort and well-being of the occupants, indoor environments have been controlled with extensive and often complicated HVAC systems. The HVAC systems are no more a luxury but are becoming an integral and a necessary part of all types of facilities, including the office buildings. The primary purpose of these systems in a building is to regulate the dry-bulb air temperature, humidity and air quality by adding or removing heat energy. There are various types of HVAC systems with different mechanical design and applications. Some

of the most common types include the single zone system, variable air volume (VAV) system, Fan Coils and Individual units. These systems can also be classified as central air-conditioning systems, packaged systems, split systems and window type systems.

Studies show that HVAC systems use about half of the total energy utilized in office buildings, globally. In USA, Spain and UK, HVAC systems have contributed to about 48%, 52% and 55% of the total energy used in office buildings, respectively**[4]**. In regions like Hong Kong and Malaysia, HVAC systems' contribution towards energy use was found to be about 48%**[5]** and 57%**[6]** of the total energy used in office buildings, respectively. Additionally, some studies have shown that in hot climates such as that of Saudi Arabia, the energy utilized by HVAC systems further increases and reaches 65% of the total energy used in office buildings**[7]**. Therefore, it is necessary to analyze and improve the energy efficiency of HVAC systems. The objective of this study is to evaluate several Energy Conservation Measures (ECMs) that could help in improving the energy efficiency of HVAC systems in office buildings, especially in the hot-humid climate of Saudi Arabia.

1.2 STATEMENT OF THE RESEARCH PROBLEM

The majority of climatized comfort spaces are located in office buildings. It is of particular importance to ensure an adequate thermal comfort in such buildings as occupants usually spend their entire working day (around 8 hours) in their offices unlike other commercial buildings such as a theatre, restaurant or cinema. Furthermore, issues of

comfort in office buildings must be addressed with special attention because the type of work performed requires extra intellectual concentration**[8]**.

Office buildings usually have the same pattern of use. They are typically occupied during regular daytime hours while unoccupied or partially occupied at night and during weekends. They are also dominated by high internal loads, from lighting, equipment and people during the occupied periods. Therefore, offices are often cooled most times of the year**[9]**. This results in HVAC systems in office buildings using high amounts of energy. In locations with prevailing hot climatic conditions, like Saudi Arabia, HVAC systems tend to use bulk of the energy to cool the buildings. This HVAC load can be reduced through many means; notable among them is the proper operation and selection of HVAC systems. Therefore there is need to investigate the impact of HVAC system operation and selection on energy use in office buildings, especially in climate such as that of Saudi Arabia.

1.3 SIGNIFICANCE OF THE RESEARCH

Energy conservation and thermal comfort are vital because they are related to national economy and public health, their performance and productivity. With development, new air-tight buildings replaced old constructions and most of these new buildings are air-conditioned. Therefore, proper design and operation of HVAC systems are essential components in solving the problems of energy conservation and thermal comfort.

The whole world has given prompt attention to these problems, and the developed world has geared up to identify strategies for innovative solutions. As a result professional societies and associations like ASHRAE have established various standards and guidelines to overcome these problems. It is right time for Saudi Arabia as well to act swiftly and join the international awareness against energy use.

In Saudi Arabia, limited research has been conducted in the field of energy conservation and thermal environment control, and hence this study will be directed towards identification and evaluation of energy conservation measures for HVAC systems, thereby paving the way for healthier, productive and energy efficient environments. This research is significant for the designers as well as owners and users of office buildings for finding suitable operational and design related measures of HVAC systems.

1.4 OBJECTIVES OF THE RESEARCH

The objectives of the research are as follows:

1. To investigate the impact of HVAC system operation on energy efficiency in office buildings in hot climates.
2. To determine the type of HVAC system that can achieve required thermal comfort in the selected office building at minimum energy use.
3. To develop guidelines for energy efficient design and operation of HVAC systems for office buildings in hot climates.

1.5 SCOPE AND LIMITATIONS

The aim of this research is to minimize the annual required cooling and total electric energy use, to an acceptable level, of an office building in Saudi Arabia. However, there are a few limitations to this research, which are as follows:

- The research will focus only on the selected office building.
- The research is limited to only hot-humid climate as represented by the Dhahran city of Saudi Arabia.

1.6 RESEARCH METHODOLOGY

In order to accomplish the research objectives, a research methodology is set consisting the following phases:

Phase-1: Literature Review

This phase will include conducting a comprehensive literature review of

- Previous studies related to energy conservation in office buildings, which focus on the influence of HVAC system operation and selection on energy use of office buildings.
- The international standard requirements for human thermal comfort in office buildings.

- Available energy simulation programs and weather data.

Phase-2: Building Selection and Audit

- The criteria for the selection of the case study building
- Building data collection
  - ✓ Review of drawings and specifications
  - ✓ Information about HVAC systems, lighting, equipment and occupants
  - ✓ Utility bills for the year 2008
  - ✓ Weather data
- Walkthrough survey of the building
- Subjective evaluation through a questionnaire survey to assess the thermal comfort condition in the building
- Measurements of thermal environmental parameters in the building

Phase-3: Detailed building energy simulation using Visual-DOE program

- Modeling of the selected office building (Base Case) with the identified parameters to quantify the energy use by energy simulation program 'Visual DOE'. The results of the base case will be calibrated with the real time use obtained from the utility bills for the year 2008.
- Investigation of impact of various HVAC system operation measures on energy use of the selected office building located in hot-humid climate of Saudi Arabia.

- An investigation will also be conducted to identify the effect of use of different types of HVAC systems on energy use of the office building under study.

Phase-4: Discussion of results, preparing conclusion, recommendations and guidelines:

- Based on the results, conclusion, recommendations and guidelines will be formulated to assist designers in designing energy efficient HVAC systems for office buildings in hot climates.

A summary of the research methodology is presented in **Figure** 1.2.

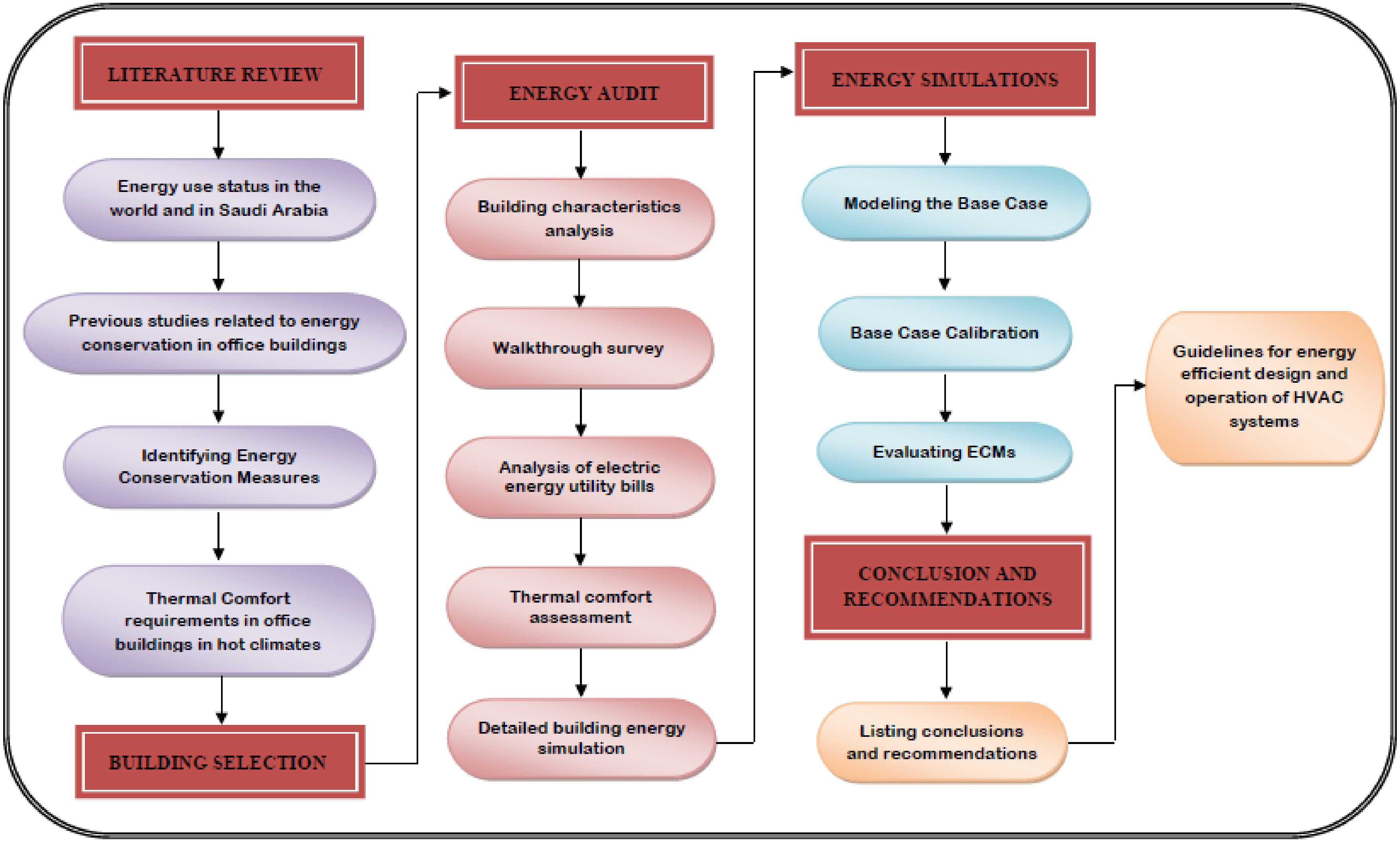


Figure 1.2: Research methodology

CHAPTER 2

LITERATURE REVIEW

This chapter provides a review of previous and ongoing research work performed by different researchers during the past decades. Knowledge gained through this review was found crucial during the simulation work of this study. Inferences from the reviewed studies are mentioned at the end of the chapter.

2.1 ELECTRICAL ENERGY USE IN SAUDI ARABIA

Saudi Arabia is very dependent on fossil fuels for generation of electric energy, which happens to be the principle form of energy delivered to buildings. Saudi Arabia has a typical desert climate of blistering hot days. Summers can be extremely hot with temperatures rising to 55ºC in some areas. Coastal cities are humid and hot year round. With the increasing standards of comfort, people prefer to spend most of their time indoor where the climate is artificially controlled to achieve the required thermal comfort level**[10]**. This has led to heavy increase in the consumption of electricity in the country. According to latest data disclosed by SEC**[11]**, during past two decades, from 1988 to 2008, electricity use has increased from 51530 GW/h to 181097 GW/h, showing a huge increase of 251%.

A major portion of the energy utilized in Saudi Arabia is used by buildings. The building segment, which mainly includes residential and commercial sectors, alone uses 63% of the total electricity generated in the country. As shown in **Figure** 2.1, another 20% is taken up by the industries, 11% by governmental agencies and a small percent (6%) in miscellaneous divisions like mosque, charity, agriculture etc.**[11]**

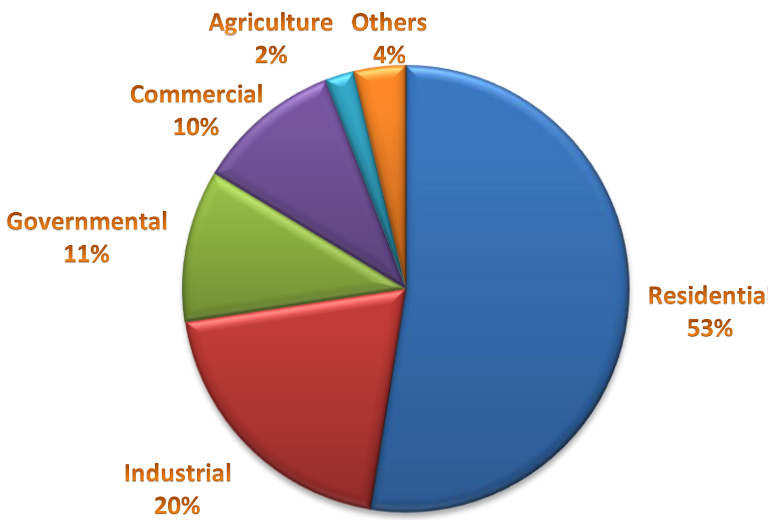


Figure 2.1: Electrical energy usage in different sectors, Saudi Arabia**[11]**

In Saudi Arabia, most of the energy utilized in buildings is used by HVAC systems to provide thermal comfort**[12]**. Several research studies have been reviewed which indicated that in most types of buildings in Saudi Arabia, HVAC systems use about **60-75%** of the total electric energy utilized in buildings. Said et. al**[7]** indicated that HVAC systems in Saudi Arabian buildings use 65% of the total energy utilized by buildings, mainly because of the extreme temperatures during summer, when the ambient

temperature frequently reaches 46°C at night. In another study, Omar and Akyurt**[13]** reported that the percentage of energy used by HVAC systems to provide cooling in buildings in a city like Jeddah, Saudi Arabia, during the summer is over 60% of the total electric energy utilized by buildings**[13]**.

Furthermore, Al-Ajlan**[14]** analyzed the data collected by Saudi Consolidated Electric Company (SCECO), which revealed that, in Saudi Arabia 65% of the electric energy utilized in buildings is used by HVAC systems, compared to 22% in the United Kingdom, 21% in the United States and 21% in Australia.

Sulaiman**[15]** performed a survey of residential-energy consumption in the eastern province of Saudi Arabia to obtain information concerning residential electrical energy-use patterns. The results revealed that a substantial 75% of the electrical energy used in the surveyed buildings was utilized for space cooling. Moreover, a study conducted at the King Fahd University of Petroleum and Minerals (KFUPM), by Zubiar et. al.**[16]**, indicated that about 70% of the total residential energy usage in the Arabian Gulf region goes towards space cooling of buildings. Furthermore, Ali**[17]** analyzed energy usage in detached houses in Dhahran, and revealed that about 65-70% of the total energy used in the buildings is utilized by the HVAC systems.

In another study at Energy Research Institute (ERI) of King Abdulaziz City for Science and Technology (KACST), Hasnain et.al**[18]**, performed energy audit of a typical Saudi

office building located in the KACST campus. It was reported that daily air-conditioning energy represents 74% of the building's total electric load during summer peak periods.

It is hence clear that, in most types of buildings in Saudi Arabia, HVAC systems use about 60-75% of the total energy utilized in buildings. Therefore, there is a need to identify and evaluate strategies that could help reduce the energy used by HVAC systems, while maintaining the required thermal comfort conditions. Hence, a number of previous studies were reviewed which focused on improving the energy efficiency of HVAC systems in buildings. The information gathered from those studies is discussed in following section.

2.2 ENERGY CONSERVATION IN OFFICE BUILDINGS: PREVIOUS STUDIES

In order to identify energy conservation measures that could help in reducing the HVAC system energy use in buildings, several previous studies were reviewed. However, since the focus of the present study is office buildings, only those studies, which dealt with energy efficiency of HVAC systems in office buildings, were reviewed.

Matthews et al.**[19]** conducted a case study aimed at developing cost-efficient HVAC control strategies to ensure optimal energy use and sufficient indoor comfort. Investigated retrofit options included air-bypass control on cooling coils, reset and setback control, improved HVAC system start-stop times, economizer cycle and CO2 control. The results indicated that, of the retrofit options investigated, improved HVAC start-stop times

together with air bypass, reset and setback control was found to be most energy efficient, with predicted annual energy savings of 66%, and a payback period of 9 months.

In another study, Adrehali and Smith**[20]** examined various operational strategies applied to older and newer-type commercial office buildings utilizing constant-air-volume-reheat and variable-air-volume-reheat HVAC systems, respectively. The operational strategies included night purge (NP), fan optimum start and stop (OSS), condenser water reset (CWR) and chilled water reset (CHWR). In the NP strategy, during the unoccupied periods, when maintaining thermal comfort is not required, outdoor air was brought into the building to cool the building mass for offsetting the cooling load at the beginning of the occupied hours. The OSS strategy included decreasing the time duration of operation of the HVAC system supply fan by delaying the start-up and by an early shutdown of the equipment. The CWR strategy included increasing of the condenser water temperature and the CHWR strategy included increasing of the chiller water supply temperature to the cooling coil. The results indicated that most energy-efficient operational strategies are the combination of OSS, CWR, and CHWR for the older-type building, which resulted in about 5% savings in energy, and OSS for the newer-type building, which resulted in about 4% energy savings.

Nurdil et.al**[21]** investigated several energy conservation opportunities, related to both envelope and HVAC system, in four different climates: hot summer and cold winter, mild, hot summer and warm winter, hot and humid summer and warm winter. An office building located in Istanbul, Turkey, was selected as the case study. Among the evaluated

opportunities, the one related to HVAC system was 'use of different ventilation rates'. Substantial energy savings, ranging from 5-25% for different climates, were obtained when different ventilation rates were used. The study concluded by indicating that the impact of the ventilation rates on the annual building energy use is significant. Furthermore, since the occupants of a typical office spend about eight hours a day indoors, there should be serious concerns about the indoor air quality and the necessary ventilation rates.

In a study conducted by Pan et al**[22]**., a base case model of a high-rise commercial building located in Shanghai, China, was developed. The building consisted of 88 floors above ground, with floors 3–50 consisting of office space and floors 53–87 consisting of hotel. The base case model was calibrated and several ECMs related to building lighting and HVAC system were evaluated. HVAC related ECMs included, ECM-1: Changing the secondary chilled water pumps and hot water pumps from constant speed into variable speed, and ECM-2: Using free cooling in winter and mild seasons (economizer cycle). The results indicated that the energy savings of the ECMs were very limited. ECM-1 was able to achieve about 5% savings in annual electrical energy use, whereas, ECM-2 (free cooling), saves only little energy due to the normally high relative humidity of outdoor air in Shanghai.

In a study conducted by Matthews et. al.**[23]**, several energy management strategies were evaluated using QUICK control energy simulation software. The evaluated strategies and corresponding energy savings achieved for each of the strategy are presented as follows:

i. Setpoint related energy management strategies

- Temperature reset – 40.6% reduction in total energy use
- Zero energy band control – 13% reduction in total energy use
- Enthalpy control – 9.2% reduction in cooling energy use, 39.3% savings in heating energy use
- Adaptive comfort control – 33.5% reduction in cooling energy use, 84.2% savings in heating energy use

ii. Schedule related energy management strategies

- Scheduling – 49.7% reduction in total energy use
- Unoccupied time setback setup – 6.1% reduction in total energy use

iii. Advanced energy management strategies

- Demand limiting – energy savings not specified
- Duty cycling – energy savings not specified
- CO_2 control (ventilation requirements based on CO_2) – 8.2% reduction in total energy use

In an experiment for testing various airflow control strategies, such as variable frequency drives, Johnson**[24]** evaluated the energy savings realized in a retrofit from CAV to VAV for an interior thermal zone of an office building. It has been shown that a 53% improvement in energy efficiency can be achieved. In another study, Adrehali et. al.**[25]** simulated various HVAC systems and reported that reduction in energy use by VAV systems, in comparison with that of CAV-RH systems, was in excess of 50%.

In addition to the ECMs stated in the above mentioned research studies, ASHRAE specifies several ECMs related to HVAC systems and equipments in its *ASHRAE Handbook of Applications***[26]**. The ECMs are listed as follows:

- Modify controls or control set points to raise and lower temperature and humidity as necessary
- Shut off or isolate all nonessential equipment and spaces
- Tune up equipment Lower thermostat set points in winter Raise chilled-water temperature
- Lower hot-water temperature (Note: Keep hot-water temperature higher than 63°C if a non-condensing gas boiler is used)
- Reduce or eliminate reheat
- Reduce (and eliminate during unoccupied hours) mechanical ventilation and exhaust airflow
- Raise thermostat set points in summer or turn cooling equipment off
- Reduce amount of re-cooling in summer
- Reduce duty cycling on HVAC systems (on later, off earlier)

In summary, it can be noted that a number of ECMs have been evaluated in recent studies, which have proved to be very effective. However, among the above mentioned ECMs, those which could be implemented to the building under study are discussed in detail in the following section.

2.3 ENERGY CONSERVATION MEASURES

The literature review in previous section was helpful in identifying several ECMs that could be implemented to reduce the energy used by HVAC systems in office buildings. However, among the various ECMs identified, only those that are feasible and could be implemented in the present study are selected, and discussed in detail. The descriptions of selected ECMs are based on Hatley et al.**[27]**

2.3.1 Space Temperature Night Setback

The energy required to maintain indoor space during unoccupied period, mostly for facilities not operating 24 hours/day, could be reduced by raising or lowering the space temperature setpoint during unoccupied hours, depending on the weather conditions**[27]**.

2.3.2 Time Scheduled Operation

This strategy consists of starting and stopping of the system based on the time and type of day. Type of the day refers to weekday, weekends and any other days that has a different schedule of operation. This is the simplest of all the ECM's function to maintain and operate and results in substantial energy savings**[27]**.

2.3.3 Start/Stop Optimization

Start/stop optimization is an improvement over time-scheduled operation strategy. The time-scheduled operation strategy is based on time-of-day, while the start/stop optimization strategy accounts for outdoor-air conditions and can include thermal storage of building mass to determine when to startup and setback the HVAC system operation. The optimized stop time permits certain HVAC systems (e.g., chillers and boilers) to be shutdown before the end of the occupied period (e.g., 10 to 15 minutes) and allows the zone temperature to float within acceptable comfort levels. Similarly, the optimized start time permits certain HVAC systems (e.g., boilers and chillers) to start just in time to allow for the zone conditions to reach the acceptable range just when the zone begins to be occupied**[27]**.

2.3.4 Economizer Controls

In cooling mode, there are a number of hours in a day when the outside air is cooler than the return-air stream. Use of “free” cooling when outside conditions are favorable is referred to as airside economizing. The cooling energy savings from use of an economizer cycle depend on the type of control for the economizer cycle employed and the climate location. The most commonly used economizer control strategies are:

i. Temperature based
ii. Enthalpy based

iii. Both temperature and enthalpy based

In the different control strategies, the outside-air condition is compared with the return-air condition. As long as the outside-air condition is more favorable, outside air is used to meet all or part of the cooling demand. An example of a favorable condition with dry-bulb temperature control would be the outside-air dry-bulb temperature being less than the return-air temperature. If the outside air alone cannot satisfy the cooling demand, mechanical cooling is used to provide the remainder of the cooling load**[27]**.

2.3.5 Thermostat Controls

Thermostats are used to control the comfort conditions. In commercial buildings, a typical HVAC zone has a number of sub-zones (rooms) all served by a single heating or cooling unit, which is controlled by a single thermostat located in only one of the sub-zones. If the internal loads (e.g., equipment in the space, number of occupants, etc.) and external envelope loads (i.e., heat gain or loss through exterior walls) are uniform across all rooms in a single HVAC zone, a single thermostat is adequate to maintain the comfort across rooms. In many cases, however, the loads are not uniform across the zone. One way to avoid hot or cold spots is to install a number of temperature sensors (wireless or wired) across the zone (e.g., one in each room) and then to use the average value of the sensed temperatures in the zone to control the HVAC equipment**[27]**.

2.3.6 Demand Limiting (Load Shed / Load Rolling)

Demand limiting is one way to control excessive demand charges. It allows for systematic shedding of electric loads when the peak demand of the building approaches a preset level. Many chillers have demand limiting features that, when triggered, limit the power to the compressor. Demand limiting supervisory controls must ensure that the desired demand limit is not exceeded at any time during the month or the season. Some advanced control features, such as building pre-cooling and pre-heating, can help alleviate uncomfortable conditions when AHU or chiller usage is limited during demand limiting periods**[27]**.

2.3.7 Duty Cycling

Duty cycling is cycling of equipment ON or OFF to control the building peak energy use while still maintaining comfort conditions. Duty cycling is one approach to demand limiting and is a means to change or control the duty cycle (i.e., the ratio of on-period to total cycle time) of on/off controlled equipment (e.g., unitary air conditioners, heat pumps, furnaces). There are a number of ways to implement duty cycling. These range from simple fixed-time-based strategies to sophisticated optimization methods. In all of these methods it is ultimately the off-period that is either fixed or adjusted in either a given reference period (typically 15 or 30 minutes), or dynamically based on temperature measurements. This results in the imposition of an equipment duty cycle that is primarily

under the control of the cycler; i.e., it overrides the "natural" duty cycle of the thermostat**[27]**.

2.3.8 Chilled-Water Reset Function

Typically, the supply chilled-water temperature is held constant between 38°F and 44°F, which is acceptable for full-load or near full-load operation. Chillers, however, usually operate at partload conditions for significant periods. Resetting the supply chilled-water temperature to match the actual building-cooling load leads to energy savings. The supply temperature can be reset based on the outdoor-air temperature, i.e., the supply temperature can be increased as the outdoor-air temperature decreases**[27]**.

2.3.9 Condenser Water Temperature Reset

Another parameter that affects the energy use by air-conditioning system is the temperature of condenser water entering the machine. In practice, heat rejection system is designed to produce a specific condenser water temperature at peak wet bulb temperature. Optimizing of system can be attained by resetting the temperature to its initial value when the outdoor wet bulb temperature produces a lower condenser water temperature**[27]**.

2.3.10 Supply-Air Temperature Reset Function

For constant-air volume (CAV) air-handling units, the supply-air temperature can be reset based on the zone conditions. When the zones are at a “light” load condition, resetting the supply-air temperature will reduce the cooling and reheat energy use. Light load conditions can be identified two ways:

- By monitoring the return-air temperature from all zones (if return-air temperatures are close to supply-air temperature, the zone load is small); or
- By monitoring the control output of each of the terminal units

Typically, the supply-air temperature on variable-air volume (VAV) systems is held constant because the volume of the air is modulated to meet the zone load. Recent studies, however, have shown that the supply-air can be reset for VAV systems as well, although the controls sequence is more complex**[27]**.

2.3.11 Type of HVAC system

HVAC systems can be generally divided into three categories**[28]**:

- All-air systems
- All-water systems
- Air-water systems

All-air systems transfer cooled or heated air from a central plant via ducting, distributing air to the room being served. Whereas, *all water systems* transfer water from a chiller or a boiler, via pipes, to a fan-coil unit (most commonly) in the room being served. An *air-water system* is a combination of *all-air* and *all-water* system, where both air and water (cooled or heated in central plant room) are distributed to room terminals to perform cooling or heating function**[28]**.

In this study, only *all-air systems* will be evaluated. *All-water* and *air-water* systems will not be evaluated because of the following reasons:

- All-water systems are not capable of providing ventilation air to the zone being served, and hence, they will not be able to provide the requited thermal comfort conditions in the zone. Therefore, all-water systems will not be evaluated.
- Assigning an air-water system to a zone requires two different sub-systems (air-side and water-side) to be assigned to the zone. However, Visual-DOE simulation software, which will be used in this study, does not provide the scope to assign two different systems to a zone. Hence, due to this modeling difficulty, air-water systems will not evaluated.

Therefore, since only all-air systems will be evaluated in this study, they are discussed in detail in the following sections, whereas, all-water and air-water systems are not discussed.

All-air systems:

All-air systems include a number of different types of systems such as**[28]**:

- Constant Volume Reheat Fan System
- Variable Air Volume System
- Packaged Variable Air Volume System
- Multi-Zone System
- Packaged Multi-Zone System
- Packaged Terminal Air Conditioner System
- Powered Induction Unit System
- Residential System
- Single Zone Variable Temperature System

All the above-mentioned systems are described in detail as follows:

i. Constant Volume Reheat Fan System

It is a multi-zone, constant volume system served by chilled water from a central plant. Control to each of the zones served by the system is maintained by reheating the air at the zone as necessary. Supply air is typically delivered at a temperature cold enough to satisfy the cooling requirement of the warmest zone. Supply air in all the other zones is reheated, if necessary**[28]**.

ii. Variable Air Volume System

It is a multi-zone system where the primary means of controlling zone temperatures is to vary the volume of air delivered to the zone. Chilled water is provided to the air handler from a central plant. Each thermal zone has a variable air volume box that is capable of modulating the volume of air between 100% and some minimum amount, usually about 30% of the maximum. VAV boxes can also have reheat capability, especially for perimeter zones. If the zone is still cold after the supply of air has been reduced to the minimum, then the reheated air is necessary to maintain the setpoint temperature**[28]**.

iii. Packaged Variable Air Volume System

It is a multi-zone system where the primary means of controlling zone temperatures is to vary the volume of air delivered to a zone. Cooling is provided by a direct expansion air conditioner that is part of the packaged equipment. Each thermal zone has a variable air volume box that is capable of modulating the volume of air between 100% and some minimum amount, usually about 30% of the maximum. VAV boxes can also have reheat capability, especially for perimeter zones. If the zone is still cold after the supply of air has been reduced to the minimum, then the air is reheated as necessary to maintain the setpoint temperature. Several heating sources are available including hot water from a central plant, a gas furnace, an electric heat pump (reverse cycle) or electric resistance**[28]**.

iv. Multi-Zone System

It is a multi-zone system with both a heating coil and a cooling coil at the central air handler. The air handler receives chilled water or hot water from a central plant. A separate duct leaves the air handler to serve each thermal zone. Air from the hot deck and the cold deck is mixed at the central air handler to provide the necessary temperature to satisfy the need of each zone**[28]**.

v. Packaged Multi-Zone System

It is a multi-zone system with both a heating coil and a cooling coil at the central air handler. Cooling is provided by a direct expansion air conditioner that is part of the packaged equipment. A separate duct leaves the air handler to serve each thermal zone. Air from the hot deck and the cold deck is mixed at the central air handler to provide the necessary temperature to satisfy the need of each zone. Several heating sources are available including hot water from a central plant, a gas furnace, an electric heat pump (reverse cycle) or electric resistance**[28]**.

vi. Packaged Terminal Air Conditioner System

It is a single-zone system capable of providing either heating or cooling to a room or space. Units are typically installed in a window or in an opening in the wall (through-the wall). Cooling is provided by a direct expansion air conditioner with an air cooled

condenser. A variety of heating sources are available. Typical applications are hotel/motel guest rooms, hospitals, nursing homes, and office buildings. All PTAC units discharge air directly into the room with no duct work**[28]**.

vii. Powered Induction Unit System

It is a multi-zone system similar to a variable air volume system. Chilled water is provided to the air handler from a central plant. The main difference between a PIU system and a standard VAV system is that each VAV box has a small fan that can draw air from the plenum space in order to maintain a more constant flow of air into the zone**[28]**.

viii. Residential System

It is a constant volume, single-zone system typical of those used in single family homes. Unlike most of the other systems, the residential system is not capable of providing outside air. Cooling is provided by a direct expansion air conditioner. Several heating sources are available including hot water from a central plant, a gas furnace, an electric heat pump (reverse cycle) or electric resistance**[28]**.

ix. Single Zone Variable Temperature System

This system has both a heating coil and a cooling coil at the main air handler that delivers air at a temperature necessary to satisfy the central zone. This system typically serves just one zone. If other zones are served by the system, heating and cooling coils are used at the zone level to heat or cool the air as necessary to serve the needs of the additional zone**[28]**.

2.4 THERMAL COMFORT REQUIREMENTS IN OFFICE BUILDINGS

Thermal comfort is defined in *ASHRAE Standard 55***[29]** as *"that condition of mind which expresses satisfaction with the thermal environment"*. Thermal comfort is essentially a subjective response, or state of mind, where a person expresses satisfaction with the thermal environment. A person's sense of thermal comfort is primarily a result of the body's heat exchange with the environment. This is influenced by four parameters that constitute the thermal environment (air temperature, radiant temperature, humidity and air speed), and two personal parameters (clothing and activity level, or metabolic rate)**[29]**.

The majority of climatized comfort spaces are located in office buildings**[8]**. It is of particular importance to ensure an adequate thermal comfort in such buildings as occupants usually spend their entire working day (around 8 hours) in their offices unlike in other commercial buildings such as theatre, restaurant or cinema. Furthermore, issues

of comfort in office buildings must be addressed with special attention because the type of work performed requires extra intellectual concentration.

The comfort of people working in office spaces is fundamentally influenced by thermal and air quality comfort. In line with the prevailing architectural style, office buildings are currently built with large outer glass surfaces. To achieve the maximum use of area, workstations are created near the windows and the outer walls as well. Although workstations located next to windows benefit from natural lighting and a view, their occupants often experience a wider range of temperatures because of the warm or cool radiant temperatures from the window. Blinds, perimeter heating and cooling, and well-insulated windows can help minimize the problems**[30]**.

If temperature and humidity levels in the office are too high or too low, occupants can be dissatisfied with the environment, uncomfortable and less effective in their tasks. The higher density of occupants and equipment in most offices increases the amount of heat released (and thereby the cooling requirements) in the space. Thus, the air conditioning system must have the capacity to handle the internal loads, and should be operated appropriately to meet thermal requirements.

According to the comfort zone diagrams in *ASHRAE standard 55-2004***[29]**, comfortable temperatures are almost impossible to achieve when the relative humidity is high. High humidity also supports mould and bacterial growth, so ASHRAE recommends that relative humidity be maintained below 60%. There is no recommended lower level of

humidity for achieving thermal comfort, but as dry conditions can lead to increased static electricity and health problems, such as skin irritation, ASHRAE recommends relative humidity should be greater than 30%. ASHRAE's acceptable ranges of operative temperature for relative humidity levels of 30% and 60% are shown in **Table** 2.1. Occupants vary their clothing with the seasons, so recommendations for summer and winter are given to reflect the amount of "clothing insulation" (clo) that clothes provide. These ranges are valid for typical office activities and for air velocities less than 0.2 m/s (40 ft./min.)**[29]**.

Table 2.1: Acceptable operative temperature ranges based on comfort zone diagrams in ASHRAE Standard-55-2004**[29]**

Conditions	**Acceptable operative temperatures**	
	°C	**°F**
Summer (clothing insulation = 0.5 clo)		
Relative humidity 30%	24.5 – 28	76 – 82
Relative humidity 60%	23 – 25.5	74 – 78
Winter (clothing insulation = 1.0 clo)		
Relative humidity 30%	20.5 – 25.5	69 – 78
Relative humidity 60%	20 – 24	68 – 75

2.5 SUMMARY OF FINDINGS

From the literature review, it was found that the global energy use has been rising at alarming rates in recent decades. Latest data disclosed by the U.S. Energy Information Administration (EIA) in 2009 reveals that the world primary energy use in the past two decades, from 1986 to 2006, has increased by 51%. Moreover, current predictions by EIA

show that by 2030, there will be a further 44% increase in the global energy use, indicating an average annual increase of 1.5%.

Furthermore, EIA also disclosed that in 2006 primary sources of energy consisted of petroleum 36.0%, coal 27.4%, and natural gas 23.0%, amounting to an 86.4% share for fossil fuels in the world primary energy use. The burning of fossil fuels produces greenhouse gases, which are harmful to the environment. This has resulted in a global concern to use energy more efficiently and to reduce greenhouse gas emissions from power generation.

Saudi Arabia ranks 19th highest energy user in the world. Buildings use a major portion of the energy utilized in Saudi Arabia. The building segment, which mainly includes residential and commercial sectors, alone uses 63% of the total electricity generated in the country. Several research studies indicate that, in most types of buildings in Saudi Arabia, HVAC systems use about 60-75% of the total electric energy utilized in buildings. Therefore, in order to reduce the energy use in buildings, energy efficiency of HVAC systems has to be improved.

In order to identify energy conservation measures that could help in reducing the HVAC system energy use in buildings, several previous studies were reviewed. Various ECMs were identified, which, if implemented, could result in substantial reduction in HVAC system energy use. The evaluation of the ECMs, along with the results obtained, is discussed in subsequent chapters of this thesis.

CHAPTER 3

BUILDING SELECTION AND AUDIT

3.1 INTRODUCTION

In this chapter, initially, the criteria used for the selection of the case study building are presented, followed by the procedure used in conducting the energy audit of the selected building. The auditing process consisted of analysis of building characteristics, which included review of design drawings and interviews with the building maintenance personnel. This was followed by a walkthrough survey, analysis of electric energy utility bills, thermal comfort subjective and objective assessment and detailed building energy simulation that closely represents the actual profile. The main intent of the audit was to develop an energy use profile of the building. The analyses of the energy profile gives an indication of the components of the building in which most energy is used, leading to potential measures for energy savings.

3.2 BUILDING SELECTION

The building chosen, as the case study for this research, is an office building located in the hot-humid climate of Al-Khobar, Saudi Arabia. The selected building is more or less square shaped, as shown in **Figure 3.1**, with its entrance facade facing east direction. The

dimensions of the building are *30m length x 30m width x 41m height*. The building consists of nine floors, among which the first to third floors are similar; the fourth to seventh floors also have similar characteristics; while remaining floors (ground, mezzanine and eighth floor) are unique. The total floor area of the building, as obtained from building plans, is 8400 m^2. Each floor occupies an area of 862 m^2, except the mezzanine floor, which occupies an area of 642 m^2. Some pictures of the selected building are shown in **Figure 3.2**.

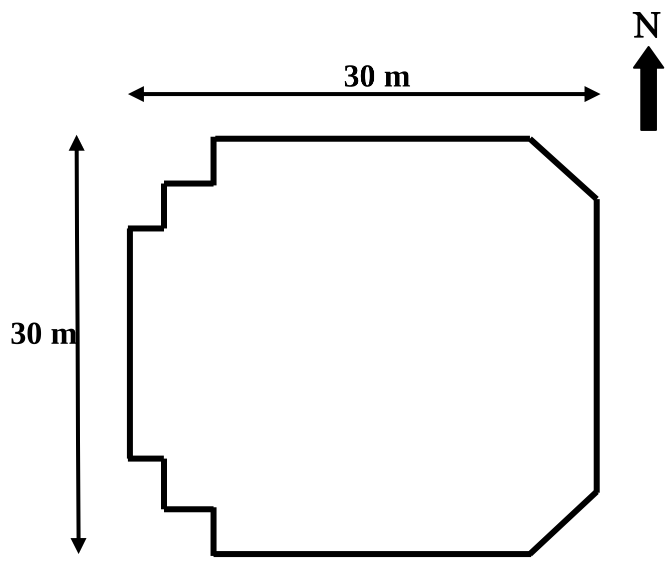


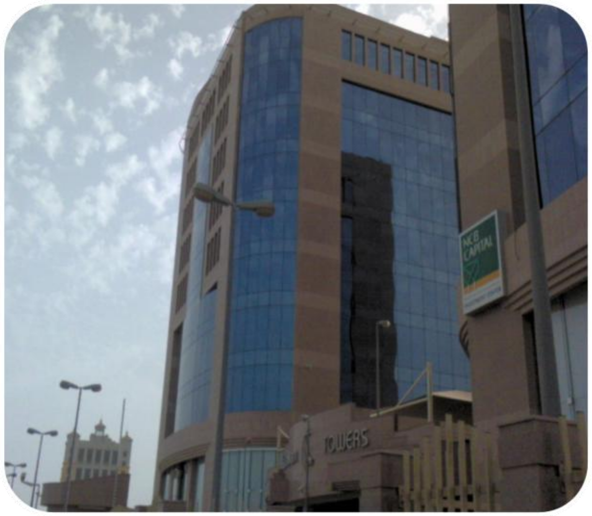
Figure 3.1: Office building basic layout

This specific building was selected in this research for the following reasons:

1. The type of HVAC system used in the selected building is *packaged single zone* (PSZ), which is the most commonly used type of HVAC system in office buildings in Al-Khobar region. The survey conducted by Al-Ashwal (2008)**[31]** showed that about 63% of the surveyed designers in Al-Khobar region use PSZ systems in their designs.

(a)

(b)



(c)

Figure 3.2: Pictures of the building;
Facade facing (a) east, (b) north-west, (c) north-east

2. The selected building is square shaped, which is one of the most common shape used by designers of office buildings in Al-Khobar**[31]**.
3. Most of the office buildings in Al-Khobar are designed between 4-10 floors**[31]**, and since the selected building is of nine floors, it lies within the range of common height of office buildings in Al-Khobar.
4. The type of glazing used in the selected building is double-glazed (clear and tinted) which is the most commonly used glazing by designers of office buildings in Al-Khobar**[31]**
5. The selected building has open plan offices, which is the commonly used type of distribution of workspaces in the office buildings in Al-Khobar**[31]**.

Apart from the building being similar to other buildings in the Al-Khobar region in many aspects, there are several other reasons that prompted the selection of this specific building for this research, which are listed as follows:

1. Information regarding the building was easily accessible and its management showed interest in implementing the recommendations, if found feasible.
2. It has simple architectural design allowing easy geometric modeling for subsequent energy simulations.
3. It is located in the hot-humid climate of Saudi Arabia where a bulk of energy is used for maintaining comfortable indoor thermal conditions, as found from literature review.

3.3 BUILDING ENERGY AUDIT PROCESS

Energy audit is a common tool to assess and study the energy profile of buildings. A systematic and detailed energy audit of the building under consideration was performed. The procedure followed in conducting the energy audit is shown in **Figure 3.3**. Each stage of the audit process is discussed in detail in the following sections:

3.3.1 Building Characteristics Analysis

The first stage of the energy audit process was to determine the physical and operational characteristics of the building. The physical characteristics of the building were obtained from review of design drawings. The operational characteristics of the building were obtained from interviews with the building maintenance personnel.

3.3.1.1 Review of Design Drawings

This stage of the building energy audit process consisted of review of architectural, mechanical and electrical drawings of the building to obtain data regarding building envelope, HVAC systems and equipment, and lighting fixtures. The floor plans of the building obtained from design drawings of the building are shown in **Figure** 3.4. Information obtained during this stage of the audit process is presented in the following sections.

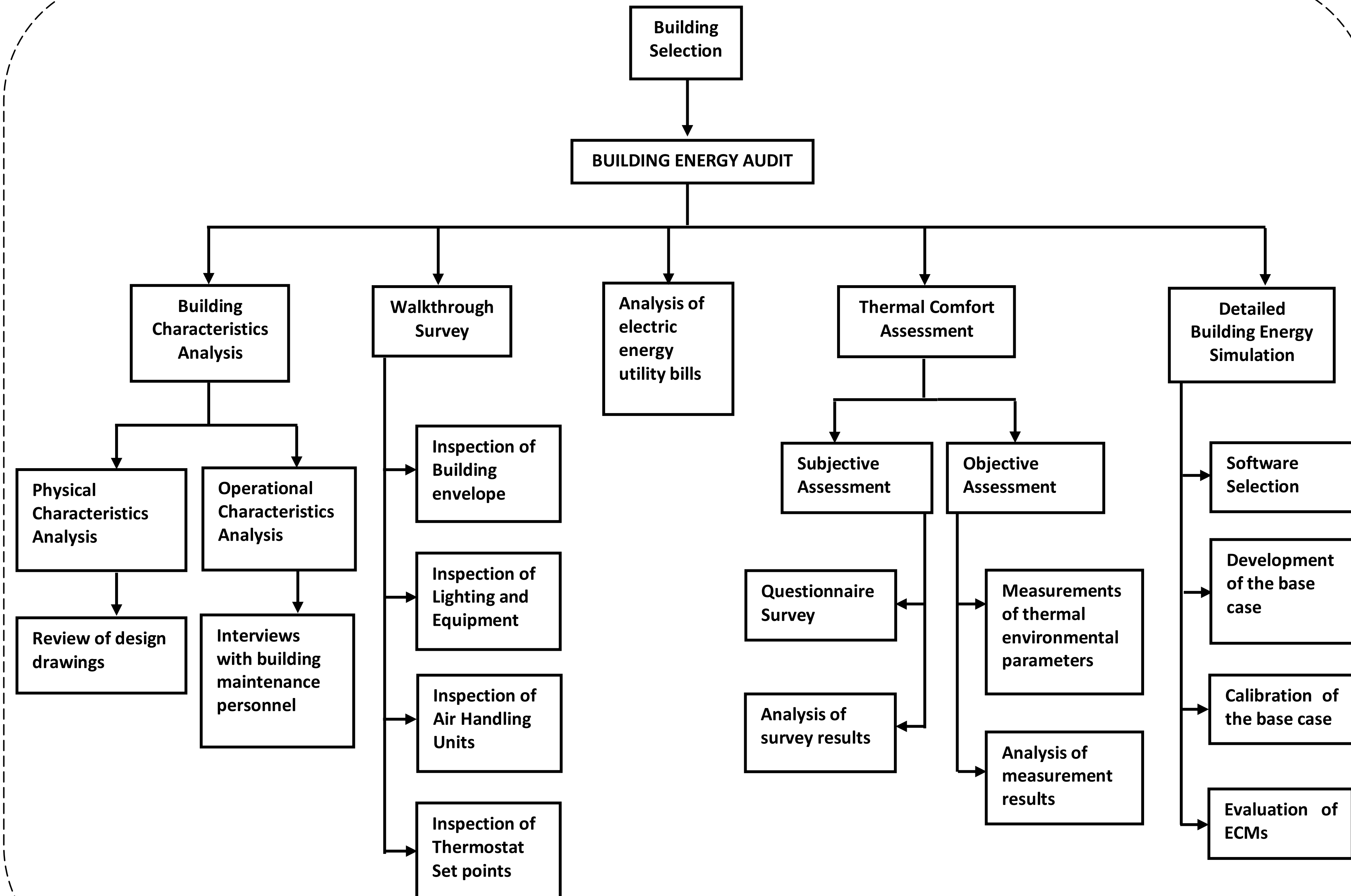


Figure 3.3: The energy audit process

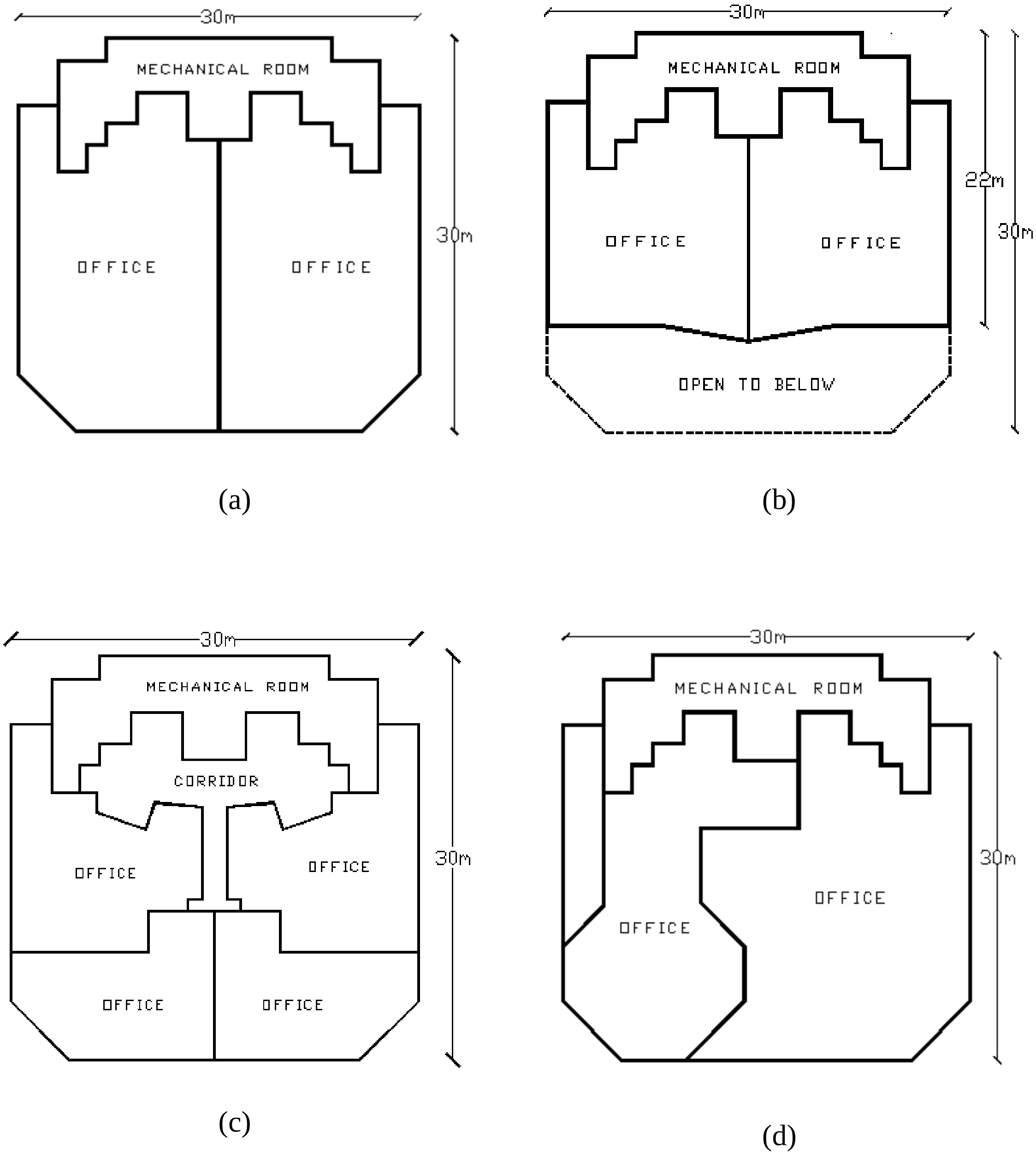


Figure 3.4: Floor plans of the building (a) Ground floor, (b) Mezzanine floor, (b) Typical first to seventh floors, (d) Eighth floor

i. Envelope details

A building envelope constitutes the barrier between the interior and the exterior environment of a building. It serves as the outer shell to protect the indoor environment from harsh climatic conditions. The main components of building envelope are walls, roof, windows, and doors. The envelope details of the building under study were obtained from the architectural drawings. The components of the walls include granite cladding on the outside, followed by concrete hollow block, gypsum board and paint on the interior side. It is to be noted that the walls do not contain any insulation. The overall U-value of the wall, calculated using Visual-DOE software, is 2.68 W/m^2.°C. The cross-section of the wall, reproduced based on drawings, is shown in **Figure 3.5**.

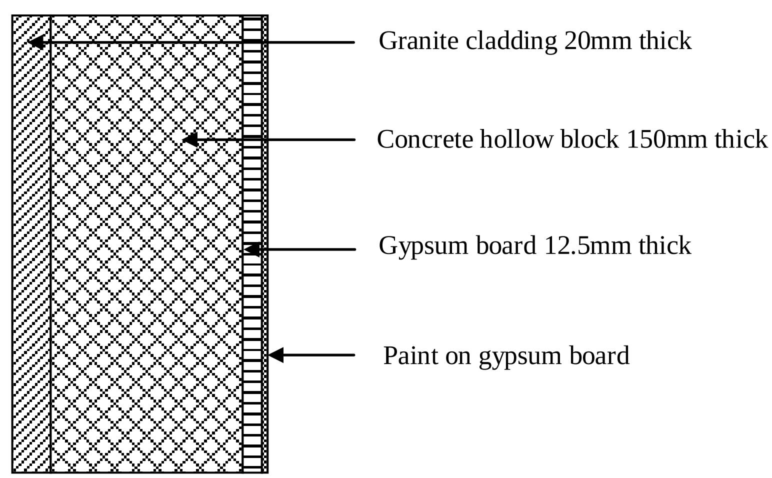


Figure 3.5: Wall cross-section

The roof of the building consists of 200mm thick reinforced concrete slab with asphalt tiles on the outside and cement plaster on the inside. The overall U-value of the roof,

calculated using Visual-DOE software, is 4.01 $W/m^2.°C$. The floor of the building is a slab-on-grade floor. The cross-sections of roof and floor, drawn based on drawings, are shown in **Figure 3.6 and 3.7,** respectively.

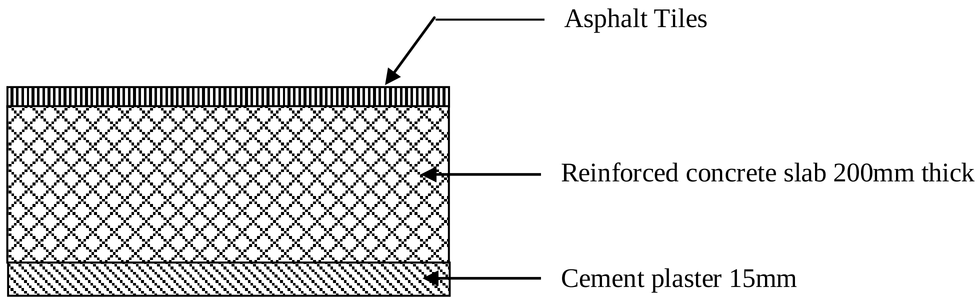


Figure 3.6: Roof cross-section

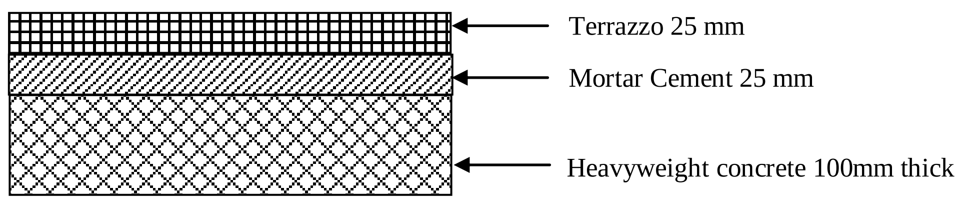


Figure 3.7: Floor cross-section

The exterior doors of the building are made of double clear glass. Two different types of glazing are used in windows throughout the building. In the ground and mezzanine floors, double clear glass is used while reflective-tinted double glazing is used in the first to the eighth floors. The window-to-wall ratios (WWR) are 4% and 51% for the west and east facades, respectively. On the north and south facades, the WWR ratios are 41% each. The building envelope details are summarized in **Table** 3.1.

Table 3.1: Building envelope details

Characteristics	Description
Plan shape	Square
Total height of the building	41 m
Gross floor area	8400 m^2
Gross wall area	4690 m^2
Glazing area	2040 m^2
Overall WWR	43.5 %
Type of glazing	Double Glazed-Clear 6/6/6 mm, Reflective Double Glazed-Tinted 6/6/6 mm
External walls	Granite cladding 20mm thick, Concrete hollow block 150mm thick, 12.5mm thick Gypsum Board, , Paint on gypsum board
Roof	15mm Cement Plaster, 200mm Thick Reinforced Concrete Slab, Asphalt Tiles
Floor	100 mm Heavyweight Concrete, 25 mm Mortar Cement, 25 mm Terrazzo

ii. HVAC system details

The main purposes of a heating, ventilation, and air-conditioning (HVAC) system are to provide thermal comfort and to help maintain good indoor air quality. An important aspect of determining the details of HVAC system is to determine building thermal zoning. Thermal zoning is the subdivision of spaces inside the building that have varying thermal conditions. However, for the building under study the information regarding thermal zoning was not available from drawings. Hence, the area served by each HVAC system was assumed as a zone. The thermal zoning of different floors in the building is shown in **Figure** 3.8.

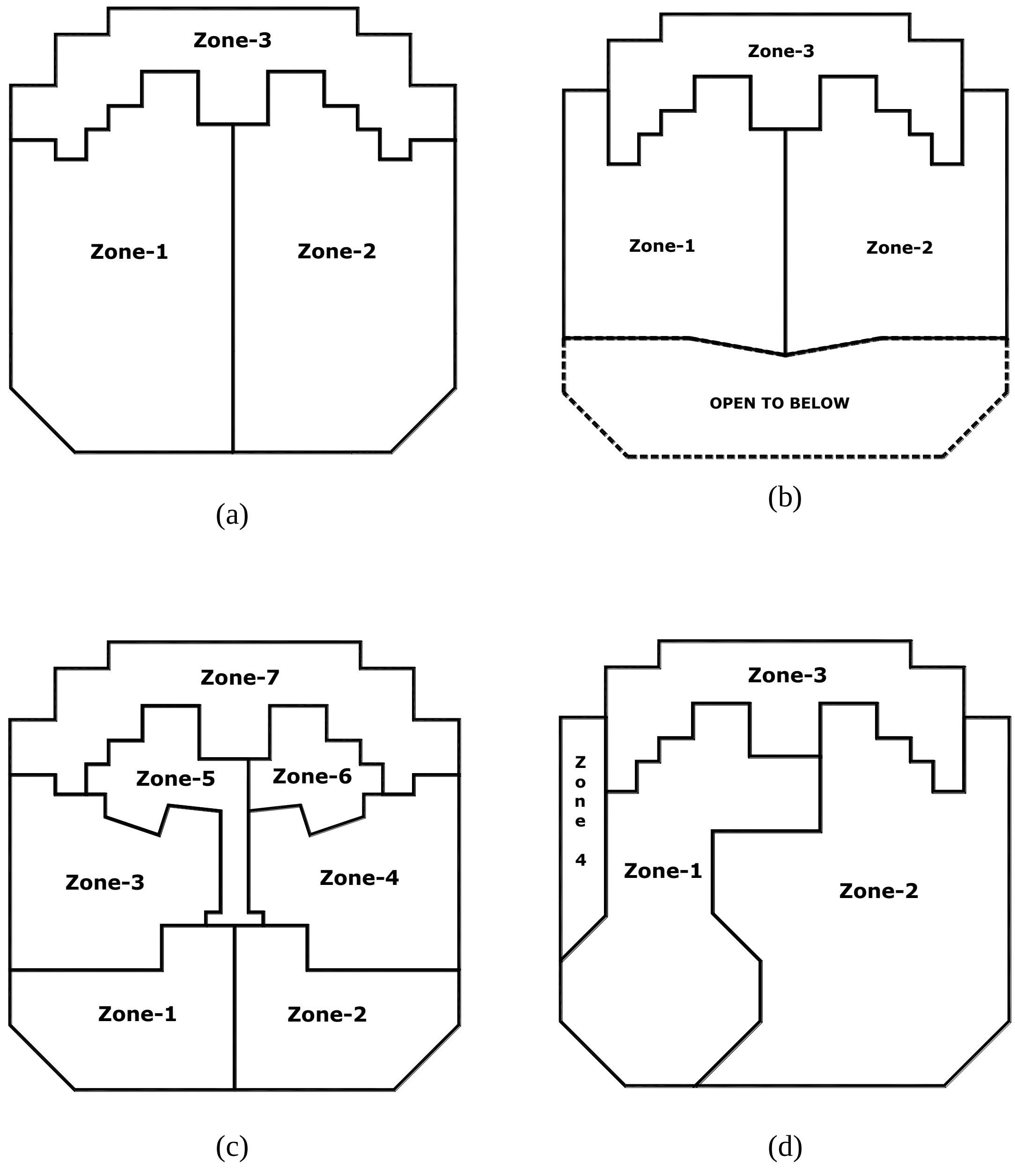


Figure 3.8: Thermal zoning of (a) Ground floor, (b) Mezzanine floor, (c) Typical first to seventh floors, and (d) eighth floor

Review of mechanical drawings of the building indicated that two types of HVAC systems, packaged single zone (PSZ) units and fan coil units (FCUs) serve the building. PSZ units serve all the office zones while corridors are served by FCUs. The capacities of the available HVAC systems along with supply and ventilation air flow rates are presented in **Table** 3.2. Furthermore, the building under study is assumed to be *tight*, and therefore, based on ASHRAE *Handbook of Fundamentals***[32]**, the infiltration rate is assumed to be 0.38 ACH, for outdoor design conditions of 43°C, 7.5 mph wind speed and indoor temperature of 24°C**[32]**.

Table 3.2: HVAC system details

Floor	Zone	Type of system	Capacities		Supply air flow		Ventilation	
			Tons	KW	cfm	l/s	cfm	l/s
Ground floor	Zone-1	PSZ	30	105.50	10,500	4955.17	794.5	375
	Zone-2	PSZ	30	105.50	10,500	4955.17	794.5	375
	Zone-3	Unconditioned zone						
Mezzanine floor	Zone-1	PSZ	30	105.50	10,500	4955.17	794.5	375
	Zone-2	PSZ	30	105.50	10,500	4955.17	794.5	375
	Zone-3	Unconditioned zone						
Typical first to seventh floor	Zone-1	PSZ	15	52.73	7,500	3539.41	381.3	180
	Zone-2	PSZ	15	52.73	7,500	3539.41	381.3	180
	Zone-3	PSZ	15	52.73	7,500	3539.41	381.3	180
	Zone-4	PSZ	15	52.73	7,500	3539.41	381.3	180
	Zone-5	FCU	3.5	12.33	1,400	660.69	0	0
	Zone-6	FCU	3.5	12.33	1,400	660.69	0	0
	Zone-7	Unconditioned zone						
Eighth floor	Zone-1	PSZ	30	105.50	10,500	4955.17	530	250
	Zone-2	PSZ	30	105.50	10,500	4955.17	178	84
	Zone-3	Unconditioned zone						
	Zone-4	Unconditioned zone						

iii. Lighting details

The lighting details were determined by reviewing the electrical drawings of the building. The different types of fluorescent lighting fixtures used in the building along with wattage for each type of fixture are shown in **Table** 3.3. The lighting power density (LPD) for each zone in the building was calculated by multiplying the number of fixtures of each type by wattage of lamps in each type of fixture. The LPD calculated for different zones in the building is summarized in **Table** 3.4.

Table 3.3: Types of lighting fixtures used in the building

Description	Wattage	Voltage
Fluorescent light with above mirror, rapid start	20	127
Wraparound fluorescent fixture with prismatic diffuser, rapid start	40	127
Wraparound fluorescent fixture with prismatic diffuser, rapid start	2x40	127
Industrial Type wraparound fluorescent fixture with prismatic diffuser	2x40	127
Fluorescent fixture with fully anodized louver	4x18	127
Spot light with ring	50	127

Table 3.4: Building lighting power density

Floor	Zone	LPD(W/m^2)
Ground floor	Zone-1	11.2
	Zone-2	10.9
	Zone-3	21.5
Mezzanine floor	Zone-1	14.6
	Zone-2	14.6
	Zone-3	21.5
Typical first to seventh floor	Zone-1	13.6
	Zone-2	13.6
	Zone-3	15.3
	Zone-4	15.3
	Zone-5	20.2
	Zone-6	24.6
	Zone-7	21.5

Eighth floor	Zone-1	18.8
	Zone-2	12.1
	Zone-3	21.5
	Zone-4	0.0

3.3.1.2 Interviews with Building Maintenance Personnel

The building maintenance personnel were interviewed in order to collect information about the operational characteristics of the building, which could not be obtained from design drawings. The information regarding operation of the building is usually available with the building facility manager. However, for the building under consideration, there is no facility manager appointed and all the information regarding building operation was obtained from the maintenance personnel. The key maintenance personnel were informed about the purpose of the audit and were taken into confidence by informing them that the information obtained will be used strictly for research purposes only. The information obtained during this stage of the audit process is discussed below.

i. Building operation and occupancy schedules

Building operation and occupancy follow the same pattern during both summer and winter seasons. Building occupancy starts at 7:00 am in the morning until 5:30 pm in the evening, with a break of half hour for lunch, from 12:00 noon to 12.30 pm. However, during the holy month of Ramadan, the occupancy schedule changes. During Ramadan, occupancy starts as usual at 7:00 am but about 65% of the people leave 2 hours earlier than usual, i.e., at 3.30 pm instead of 5.30 pm and the remaining 35% of the people

follow regular working hours. The representative occupancy profiles for the building users and schedules for different building systems are shown in **Table** 3.5.

ii. HVAC system operation schedule

Interviews with building maintenance personnel indicated that the HVAC systems in the building are operated 24 hrs a day during summer (April to November) to maintain required indoor conditions. However, during winter (December to March), from 9pm to 6am, the HVAC system fans are set to turn off automatically from 9:00 pm to 6:00 am if the zone temperature is below 28°C. In addition, the setpoint temperature adopted in the building is 21°C for summer and 24C for winter. The operation profile for setpoint temperatures and fans are shown in **Table** 3.5.

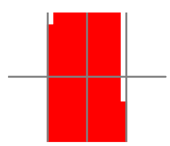
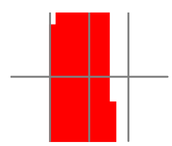
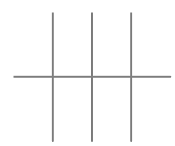
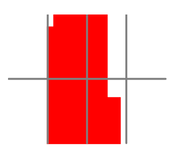
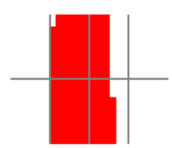
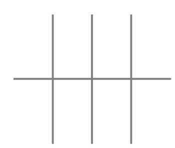
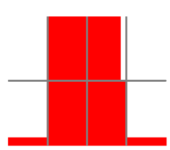
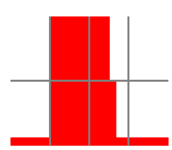
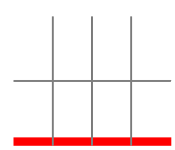
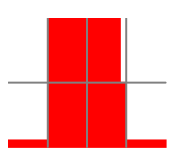
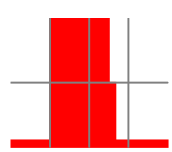
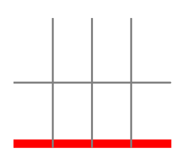
iii. Lighting operation schedule

Most of the lighting in the building is operated during the occupancy periods, from 7:00 am to 5.30 pm; where 100% of the lights are switched on to maintain required illumination levels. During unoccupied hours, 95% of the lighting is switched off and about 5% is kept switched on for security purposes. The lighting occupancy schedule is shown in **Table** 3.5.

iv. Equipment operation schedules

The equipments in the building mainly include desktop computers, small and large printers and photocopying machines. The operation schedules for equipments in the building are shown in **Table** 3.5. To calculate equipment power density (EPD) for different zones in the building, average heat gain values for different types of equipments were estimated based on ASHRAE *Handbook of Fundamentals***[32]** and are shown in **Table** 3.6. The EPD calculated for different zones in the building is shown in **Table** 3.7.

Table 3.5: Building operation and occupancy schedules

		Saturday to Tuesday	**Wednesday**	**Thursday-Friday**
Occupancy schedule	Regular months (Jan-1 to Aug-31 and Oct-1 to Dec-31)	 Normal Operation	 Normal Operation	 0% Occupancy
	Ramadan Months (Sep-1 to Sep-30)	 Normal Operation	 Normal Operation	 0% Occupancy
Lighting schedule (all year round)		 Unocc. – 5% Occ. – 100%	 Unocc. – 5% Occ. – 100%	 5%
Equipment schedule (all year round)		 Unocc. – 5% Occ. – 100%	 Unocc. – 5% Occ. – 100%	 5%

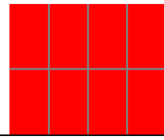
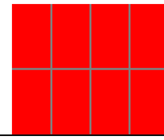
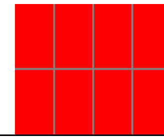
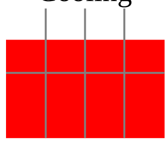
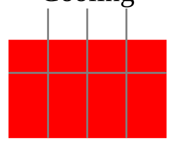
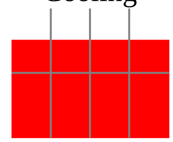
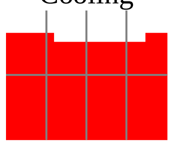
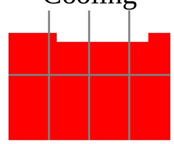
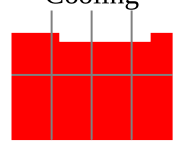
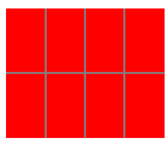
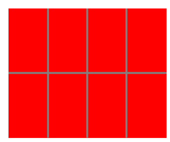
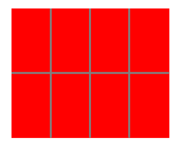
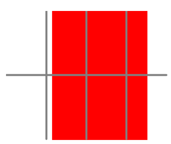
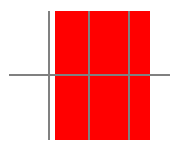
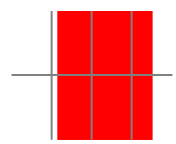
Infiltration (all year round)			
Space Temp (summer)	Cooling  21 °C all time	Cooling  21 °C all time	Cooling  21 °C all time
Space Temp (winter)	Cooling  24 °C (7am to 8pm) 28 °C (9pm to 6am)	Cooling  24 °C (7am to 8pm) 28 °C (9pm to 6am)	Cooling  24 °C (7am to 8pm) 28 °C (9pm to 6am)
Fan Profile (summer)	 100% On all time	 100% On all time	 100% On all time
Fan Profile (winter)	 Turned off from 9pm to 6am if temp is below 28°C	 Turned off from 9pm to 6am if temp is below 28°C	 Turned off from 9pm to 6am if temp is below 28°C

Table 3.6: Recommended heat gain from typical office equipments

Equipment	Type	Continuous (W)	1 page per min. (W)	Idle (W)
Laser Printers	Small Desktop	130	75	10
	Desktop	215	100	35
	Small Office	320	160	70
	Large Office	550	275	125
Copiers	Desktop	400	85	20
	Office	1100	400	300
Computers	Average Value	55	-	-
Monitor	Medium (16 to 18 inch)	70	-	-

Table 3.7: Building equipment power densities

Floor	Zone	EPD, (W/m^2)
Ground floor	Zone-1	15.7
	Zone-2	14.9
	Zone-3	0
Mezzanine floor	Zone-1	10.9
	Zone-2	10.1
	Zone-3	0
Typical first to seventh floor	Zone-1	24.6
	Zone-2	24.6
	Zone-3	19.8
	Zone-4	19.8
	Zone-5	0
	Zone-6	0
	Zone-7	0
Eighth floor	Zone-1	9.7
	Zone-2	5.4
	Zone-3	0
	Zone-4	0

3.3.1.3 Summary of the Collected Building Information

During the fist stage of the energy audit process, information regarding building characteristics was collected by review of design drawings and interviews with building maintenance personnel. The information included physical and operational characteristics of the building, the HVAC system, lighting and equipments. All the information gathered during this stage of the audit process is summarized in **Table** 3.8.

3.3.2 Walkthrough Survey

The second stage of the energy audit process was a walkthrough survey of the building under study. The walkthrough survey was conducted in order to confirm the information collected from design drawings and interviews with maintenance personnel. The walkthrough survey was performed in all the floors of the building except mezzanine floor and eighth floor, as access was not granted to visit those floors for security reasons. A checklist was formulated to document the observations made during the walkthrough survey. The checklist included information regarding building glazing, lighting, equipment and HVAC systems. The observations made during the walkthrough survey are shown in **Table** 3.9.

Table 3.8: Building physical and operational characteristics

Characteristics	**Description**
Location	Al-Khobar, Saudi Arabia
Type of building	Office
Plan shape	Square
Total height	40.730 m
Gross floor area	8400 m^2
Gross wall area	4690 m^2
Window area	2040 m^2
Overall WWR	43.5 %
Type of glazing	Double Glazed-Clear 6/6/6 mm, Reflective Double Glazed-Tinted 6/6/6 mm
Total no. of people	400
Operating hours	Ramadan: 7:00am to 3.30pm on all working days for 65% of occupants, Remaining 35% of occupants- Sat. to Tue.-7:00am to 5.30pm, Wed.-7:00am to 3:30pm. Normal Days: Sat. to Tue.-7:00am to 5.30pm, Wed.-7:00am to 3:30pm
External walls	Granite cladding cut to size 20mm thick, Concrete hollow block 150mm thick, 12.5mm thick Gypsum Board, , Paint on gypsum board
Roof	15mm Cement Plaster, 200mm Thick Reinforced Concrete Slab, Asphalt Tiles
Floor	100 mm Heavyweight Concrete, 25 mm Mortar Cement, 25 mm Terrazzo.

		Ground Floor			**Mezzanine Floor**			**Typical First to Seventh Floor**							**Eighth Floor**			
		Zone1	**Zone2**	**Zone3**	**Zone1**	**Zone2**	**Zone3**	**Zone1**	**Zone2**	**Zone3**	**Zone4**	**Zone5**	**Zone6**	**Zone7**	**Zone1**	**Zone2**	**Zone3**	**Zone4**
Occupant density (m^2/person)		23.5	23.5	-	35.3	35.3	-	24.5	24.5	20	20	-	-	-	51	80	-	-
Lighting Power Density (LPD) (W/m^2)		11.2	10.9	21.5	14.6	14.6	21.5	13.6	13.6	15.3	15.3	20.2	24.6	21.5	18.8	12.1	21.5	0
Equipment Power Density (EPD) (W/m^2)		15.7	14.9	0	10.9	10.1	0	24.6	24.6	19.8	19.8	0	0	0	9.7	5.4	0	0
HVAC system type		PSZ	PSZ	PSZ	PSZ	PSZ	PSZ	PSZ	PSZ	PSZ	PSZ	FCU	FCU	PSZ	PSZ	PSZ	PSZ	PSZ
Supply Temperature (°C)		13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13
Thermostat Setpoint temperature (°C)	Summer	21	21	-	21	21	-	21	21	21	21	21	21	-	21	21	-	-
	Winter	24	24	-	24	24	-	24	24	24	24	24	24	-	24	24	-	-
Total ventilation air flow rate for each zone (l/s)		375	375	0	375	375	0	180	180	180	180	0	0	0	250	84	0	0

Legend: WWR=Window to Wall Ratio; PSZ = Packaged Single Zone; FCU = Fan Coil Unit

Table 3.9: Checklist for walkthrough survey of the building

	Checklist	Information from drawings and interviews	On-site observation
1	Glazing	• Double clear for ground and mezzanine floors • Double glazed, reflective tinted for first to eighth floors	Same as designed
2	Lighting	100% switched-on during working hours	• All the lights were switched on at the time of inspection • However, some lights were not working, resulting in low illumination in some workstations.
3	Equipment details	• Types of equipments: o Desktop computers o Printers o Photocopying machines o Scanners	• The type of equipments listed by the maintenance personnel were available • Most of the computers were working during occupied hours. • Some of the computers were at times not used if the staff may be out to visit a project site • The photocopying machines and printers were used as need arises
4	HVAC systems	All units operating 24 hours	• All units were operating at the time of inspection • However, the ventilation dampers were completely closed for some units, as shown in **Figure** 3.9. This might cause a deviation in ventilation rates from the designed values.
5	Thermostat readings (checked during summer)	21 °C for all zones	Same as designed
6	Accessibility of thermostats to occupants	Not applicable	Easily accessible

Figure 3.9: Ventilation damper completely closed in one of the air-handling units

3.3.3 Analysis of Electric Energy Utility Bills

The third stage of the energy audit process was to analyze the building electric energy utility bills in order to determine the energy use pattern of the building. The utility bills of the building for the year 2008 were obtained from the building management. However, the data obtained was in terms of the amount of money paid each month for the electric energy used. The obtained data had to be converted into kWh units for further analysis. To accomplish this, the cost per kWh of energy used was obtained from the Saudi Electric Company and necessary conversions were made. The monthly energy use pattern

of the building obtained after conversion is shown in **Figure** 3.10. The annual energy use of the building was found to be 2,989,508 kWh (355.9 kWh/m^2/yr).

It can be seen from the Figure 3.10 that the maximum electric energy is used by the building in the month of July, which is considered to be the peak summer month in the eastern province of Saudi Arabia. The utility bills data obtained in this stage were useful in the later stage of the energy audit process for the calibration of the base case model of the building.

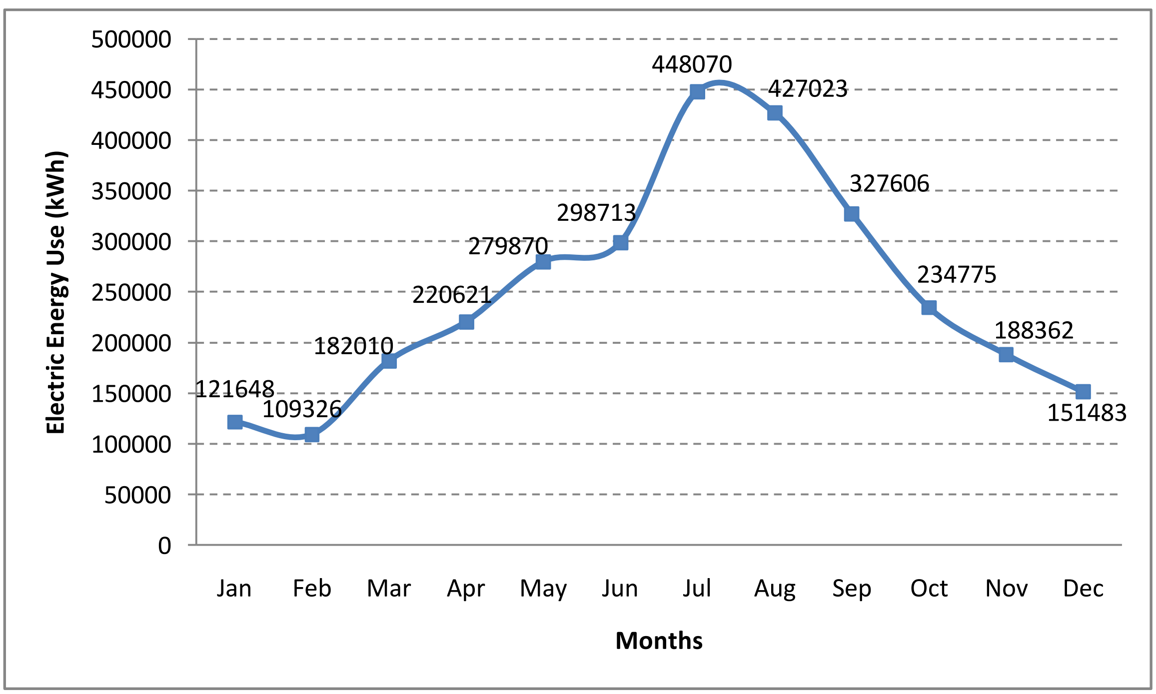


Figure 3.10: Building electric energy use pattern for the year 2008 obtained from utility bills

3.3.4 Assessment of Building Thermal Comfort Conditions

The fourth stage of the energy audit process was the assessment of building thermal comfort conditions. Thermal comfort is defined by *ASHRAE Standard 55* as *"that condition of mind which expresses satisfaction with the thermal environment"***[29]**. Thermal comfort is essentially a subjective response, or state of mind, where a person expresses satisfaction with the thermal environment. A person's sense of thermal comfort is primarily a result of the body's heat exchange with the environment. This is influenced by four parameters that constitute the thermal environment (air temperature, radiant temperature, humidity and air velocity), and two personal parameters (clothing and activity level, or metabolic rate)**[29]**.

The ASHRAE *Standard* 55**[29]** also reveals that in order to assess if an environment is thermally acceptable, there are two methods that can be implemented. The first method is to perform subjective assessment of the environment by conducting a survey to determine occupant's perception of thermal environment. The second is to perform objective assessment by conducting measurements of key environmental variables at different locations in the space.

For the building under study, both subjective and objective assessments were conducted. Since it was not practical to assess every single zone in the building, representative zones were selected. The nine floors of the building were divided into four groups, as shown in **Table** 3.10, and among each group, one floor was selected as representative of the group

for carrying out the thermal comfort assessment. Among ground and mezzanine floors, the ground floor was selected, among the typical first to third floors, the second floor was selected and among the typical fourth to seventh floors, the fourth floor was selected. However, the eighth floor in group-4 was not selected for carrying out assessment, as access to visit the floor was not granted. In summary, among the nine floors, thermal comfort assessment was carried out for the ground, the second and the fourth floors as representatives of the whole building.

Table 3.10: Floors selected for typical thermal comfort assessment

Groups	**Floors**	**Selected Floors**
Group-1	Ground and Mezzanine floors	Ground floor
Group-2	Typical first to third floors	Second floor
Group-3	Typical fourth to seventh floors	Fourth floor
Group-4	Eighth floor	No floor selected

3.3.4.1 Thermal Comfort Subjective Assessment

The ASHRAE *Standard* 55**[29]** defines an acceptable thermal environment as one in which atleast 80% of the occupants are comfortable with the environmental conditions. One effective way to evaluate the environmental conditions is to survey the occupants. To conduct the survey, a questionnaire form was developed, which focused mainly on occupant's perception of air temperature, air humidity and air velocity (movement) and other related issues at their workplaces. A sample of the questionnaire form is illustrated in **Appendix-A**.

The questionnaire was divided into two sections. The first section was designed with the aim of acquiring general information regarding the occupants such as name, job title, age, location in the building and the period for which the person has been working in the building. The second section consisted of questions regarding occupant's perception of the thermal environmental parameters such as air temperature, air humidity, air movement and ventilation. Other information such as the effect of thermal discomfort on productivity, adequacy of ventilation and usage of pedestal fan was also included in the questionnaire.

The survey was conducted in the month of July, which is considered to be one of the peak summer months in the eastern province of Saudi Arabia While conducting the survey, the occupants of the building were first introduced to the objectives and importance of the research to be performed. The occupants were assured that the information obtained from the questionnaire survey would be kept confidential and for the sole purpose of the study. The questionnaires forms were distributed to all the occupants present in the office at the time of distribution of forms. All the distributed seventy-six (76) survey questionnaire forms were received with response rate of 100%. The total occupancy of the assessed floors of the building along with the number of occupants who took part in the survey is shown in **Figure** 3.11.

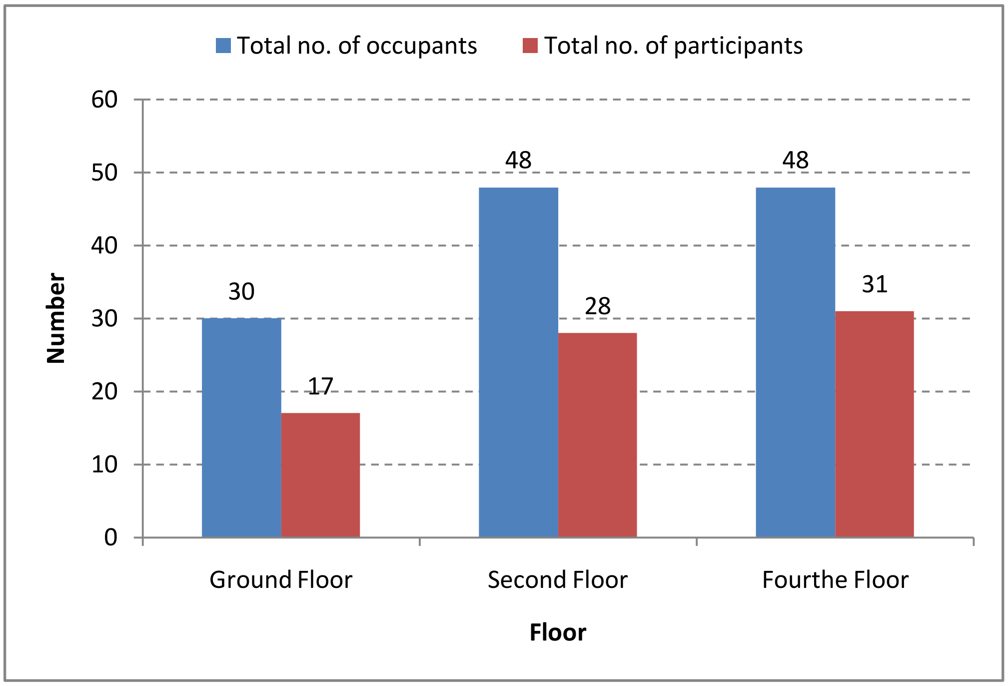


Figure 3.11: Comparison between total occupancy and number of respondents to the questionnaire in different floors of the building

3.3.4.2 Analysis of Subjective Assessment Results

For the subjective assessment of thermal comfort, as discussed in earlier sections of this chapter, the questionnaire forms were distributed to the occupants in the representative ground, second and fourth floors of the building. In order to get a realistic response from the occupants, great care was taken in the design and distribution of questionnaire. As mentioned earlier, the survey was conducted in the month of July, which is considered to be one of the peak summer months in the eastern province of Saudi Arabia. The analysis of the survey results obtained for different zones in each of the selected floors is discussed in detail in the following sections.

i. Ground Floor

The ground floor is divided into three thermal zones among which, zones 1 and 2 are occupied while zone 3 is unoccupied. The questionnaire forms were distributed to the occupants in zones 1 and 2. The survey results of different zones of the ground floor are discussed as follows.

Survey Results of Zone 1

In zone-1, out of the total occupancy of fifteen people, nine participated in the survey. Among the nine respondents, only five (55.5%) indicated that they feel comfortable with air temperature at their workplace 'most of the time'. Another four (44.4%) pointed out that they feel 'slightly warm' and are only 'sometime' comfortable with the air temperature at their workplace. However, about six (66.6%) respondents out of nine indicated that they feel comfortable with air humidity at their workplace 'most of the time', and an additional two (22%) indicated that they feel comfortable 'all the time'. Therefore, the total percentage of respondents comfortable with air humidity is 88.8%. Furthermore, about seven respondents (77.7%) out of nine expressed that they are comfortable with air movement at their workplace 'most of the time', and merely two respondents (22.2%) expressed that they are only 'sometime' comfortable with the air movement at their workplace. A summary of the survey results is shown in **Figure** 3.12.

It can be seen from the survey results of zone 1 that among the three thermal environmental parameters, air humidity and air movement were found to be satisfactory

by a majority of the respondents. However, about 44% of respondents indicated that they feel ‘slightly warm’ with air temperature at their workplace. The reason for this could be the fact that this zone is exposed to south and east orientations, which receive high solar heat gains. In addition, the structural glazing used in ground floor is double clear, which allows most of the unwanted solar radiation into the zone, causing the occupants to feel warm. Usage of shading devices such as venation blinds to prevent the solar radiation from entering the zone, could help in improving the thermal comfort condition in the zone.

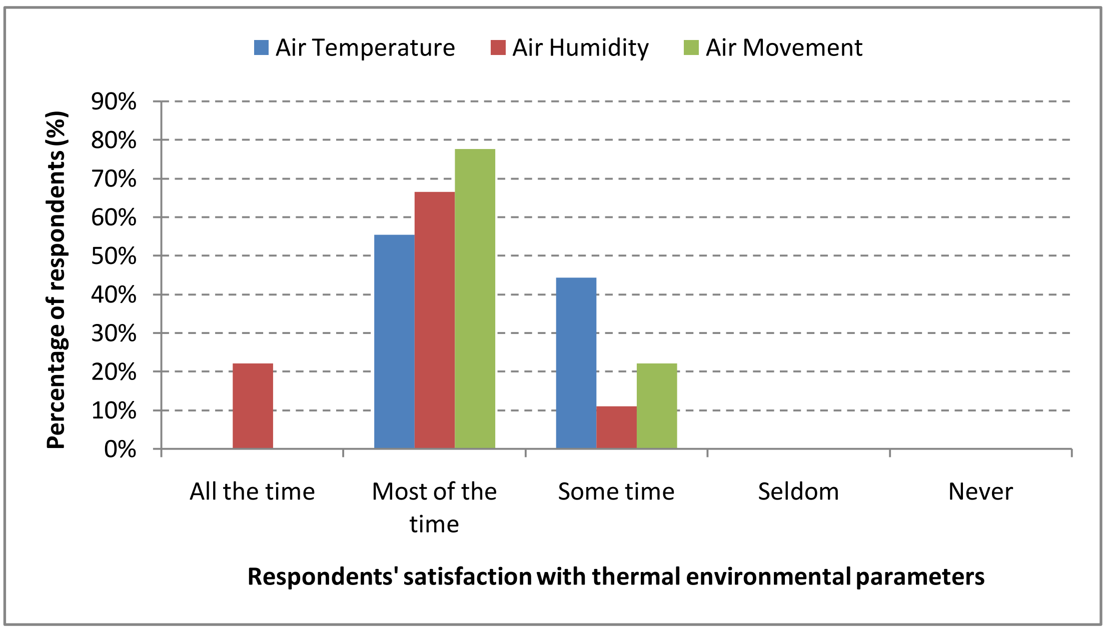


Figure 3.12: Survey results of zone-1 of ground floor

Survey Results of Zone 2

In zone-2, out of the total occupancy of fifteen people, eight participated in the survey. Among the eight respondents, only three (37.5%) indicated that they feel comfortable

with air temperature at their workplace ‘most of the time’, while four (50%) indicated that they feel ‘slightly warm’ and are only ‘sometime’ comfortable with the air temperature at their workplace. The thermal discomfort could be due to the transmitted solar radiation from the glass as most of the surveyed respondents in zone-2 were seated near the exterior wall that comprised mainly of double clear glass. Furthermore, five out of eight respondents, about 62.5%, specified that they feel comfortable with air humidity at their workplace ‘most of the time’, and two respondents (25%), pointed out that they only ‘sometime’ feel comfortable with air humidity at their workplace. In addition, seven out of eight respondents, about 87.5%, showed that they are comfortable with air movement at their workplace ‘most of the time’. The survey results are summarized in **Figure** 3.13.

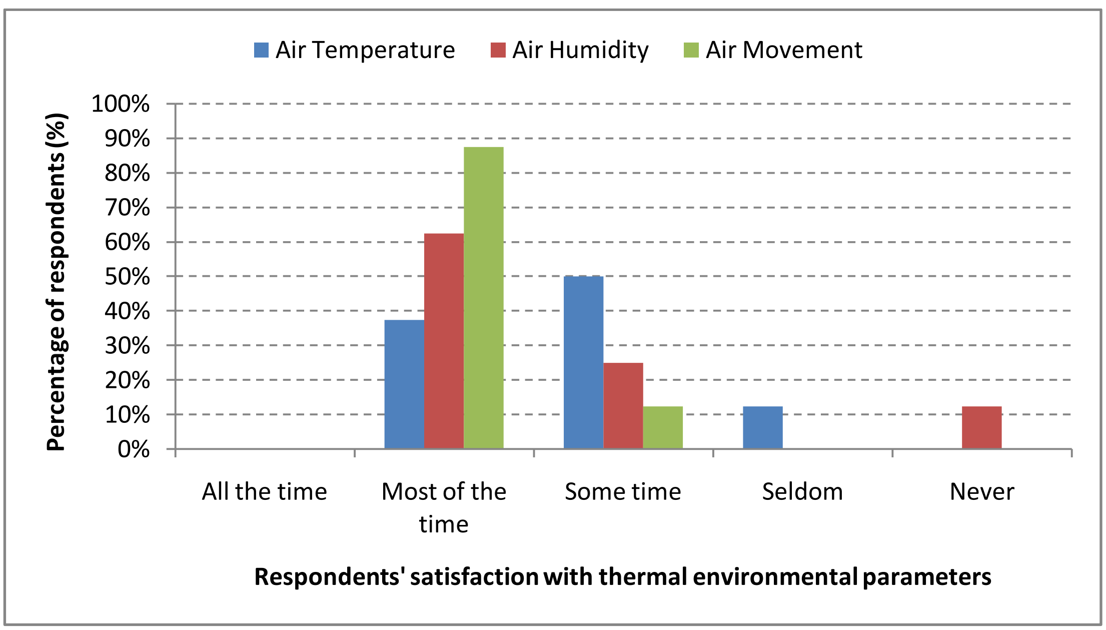


Figure 3.13: Survey results of zone-2 of ground floor

It can be seen from the survey results of zone 2 that about half of the respondents feel 'slightly warm' and are only 'sometime' comfortable with air temperature. The thermal discomfort could be mainly attributed to the solar heat gains from the un-shaded double-clear glazing.

Overall, in the ground floor, a majority of respondents indicated that they felt comfortable with air humidity and air movement, while a few respondents found air temperature unsatisfactory. It is interpreted that the discomfort is mainly due to the solar heat gain from the glazing. Shading the glazing in the ground floor could help alleviate the problem.

ii. Second Floor

The second floor is divided into seven thermal zones, out of which four zones (zones 1 to 4) are occupied and remaining three (zones 5 to 7) are unoccupied. The questionnaire forms were distributed to the occupants in zones 1 to 4. The total number of occupants in each of the four occupied zones is twelve.

Survey Results of Zone 1

Out of the twelve occupants in zone-1, eight participated in the survey. Among the eight respondents, four (50%) expressed that they feel 'slightly warm' and are comfortable with the 'air temperature' at their workplace only 'sometime', and three respondents (37.5%) expressed that they 'seldom' feel comfortable with 'air temperature' at their

workplace. However, a majority of respondents, about 75%, expressed that they feel comfortable with 'air humidity' at their workplace 'most of the time'. A similar percentage of respondents (75%) have also expressed that the 'air movement' at their workplace is comfortable 'most of the time'. The survey results are shown in **Figure** 3.14.

It can be observed from the survey results of zone-1 that a majority of respondents expressed satisfaction with air humidity and air movement whereas the air temperature was reported as unsatisfactory. Although the design setpoint temperature in this zone is 21°C, which is 2°C cooler than the lower limit of ASHRAE specified thermal comfort range (23-25.5°C), about 50% of the respondents expressed that the overall thermal comfort condition at their workplace is 'slightly warm'. The reason for this could be the fact that this zone is exposed to two orientations, south and east; both considered orientations receiving high solar heat gains. In addition, the window-to-wall ratios on the facades facing both orientations is large (about 50%), which further enhances solar heat gains.

Survey Results of Zone 2

In zone-2, out of the twelve occupants, six participated in the survey. Out of the six respondents, three (50%) indicated that they feel comfortable with air temperature at their workplace 'most of the time'; while two respondents (33.3%) pointed out that air temperature at their workplace is comfortable only 'sometime' and they feel 'slightly cold'. This could be attributed to the fact that design setpoint temperature is about 2°C

cooler than the ASHRAE specified comfort range. However, air humidity and air movement was reported as satisfactory 'most of the time' by about 83.3% of respondents. The results are summarized in **Figure** 3.15.

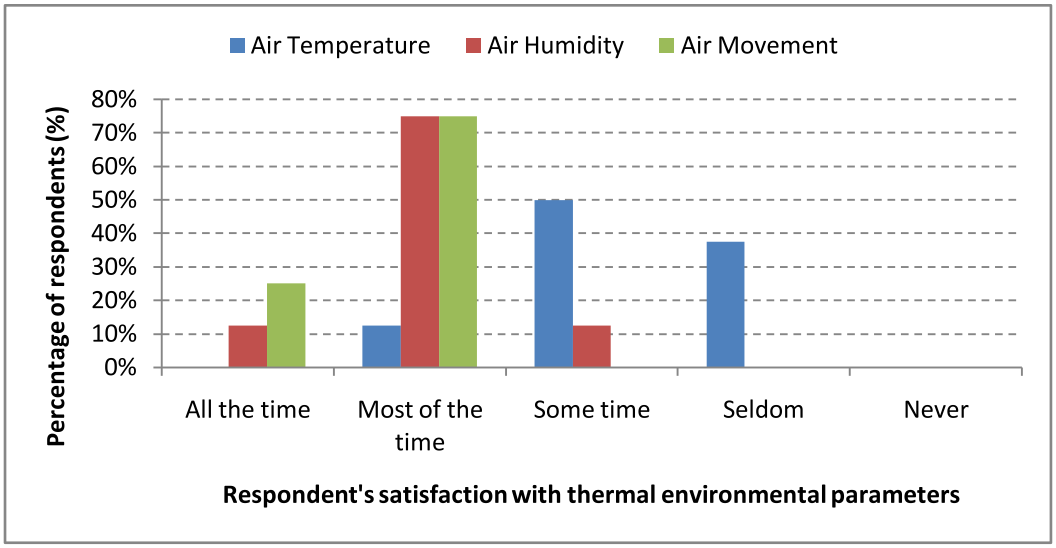


Figure 3.14: Survey results of zone-1 of the second floor

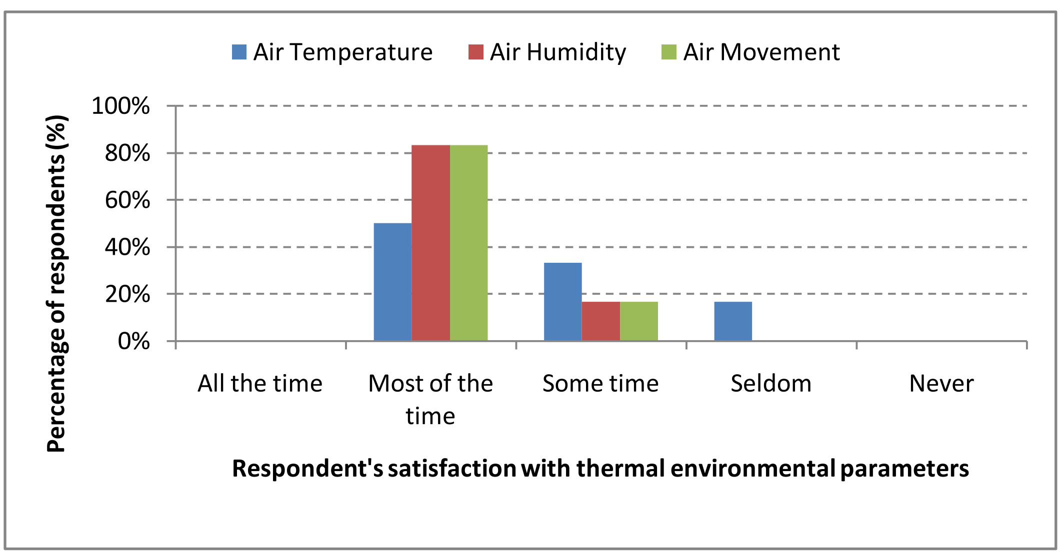


Figure 3.15: Survey results of zone-2 of the second floor

Survey Results of Zone 3

In zone-3 of second floor, four respondents (57.2%) out of seven revealed that they feel comfortable at their workplace 'most of the time', and remaining three respondents (42.8%) revealed that they feel 'slightly cold' and are comfortable at their workplaces only 'sometime'. Whereas, about 71.4%, indicated that they feel comfortable with air humidity at their workplace 'most of the time'. A larger percentage of respondents, about 86%, indicated that the air movement at their workplaces is comfortable 'most of the time'. The survey results are summarized in **Figure** 3.16.

A review of the survey results of this zone reveals that a slightly higher percentage of respondents expressed satisfaction with air temperature when compared to zones 1 and 2. However, the respondents who felt that the temperature is unsatisfactory revealed that they feel 'slightly cold', which could mainly be because of the low setpoint temperature.

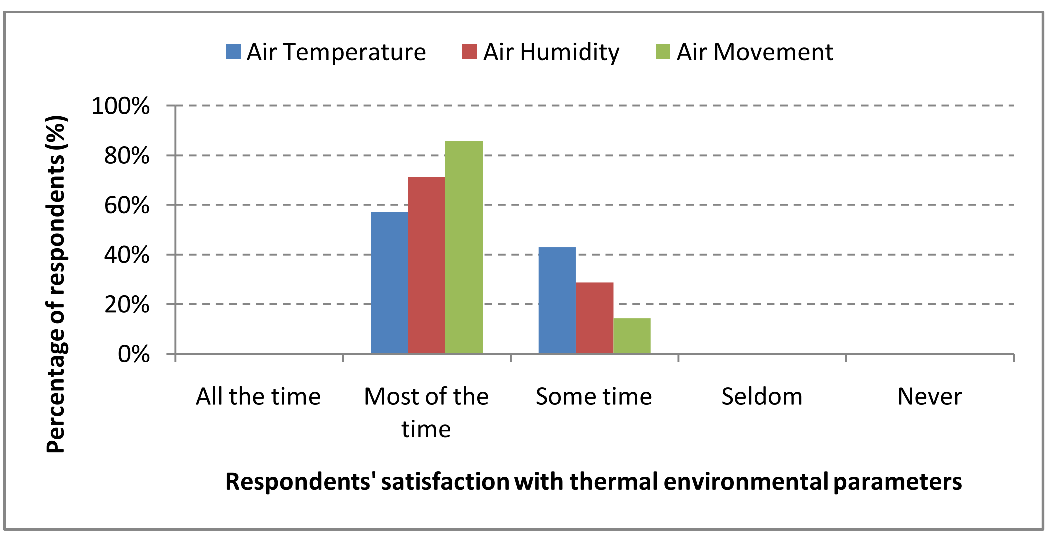


Figure 3.16: Survey results of zone-3 of the second floor

Survey Results of Zone 4

In zone 4, five respondents (71.5%) out of seven expressed that they feel comfortable with air temperature at their workplace 'most of the time'; while the remaining 28.5% indicated that, they feel 'slightly cold' at their workplaces. Furthermore, all the seven respondents (100%) in zone 4 have pointed out that they feel comfortable with air humidity at their workplace 'most of the time'. Moreover, about 86% indicated that the air movement at their workplaces is comfortable 'most of the time'. In summary, as shown in **Figure** 3.17, majority of the respondents in this zone expressed satisfaction with all the three environmental parameters and there were lesser complaints about air temperature in this zone when compared to other zones of second floor.

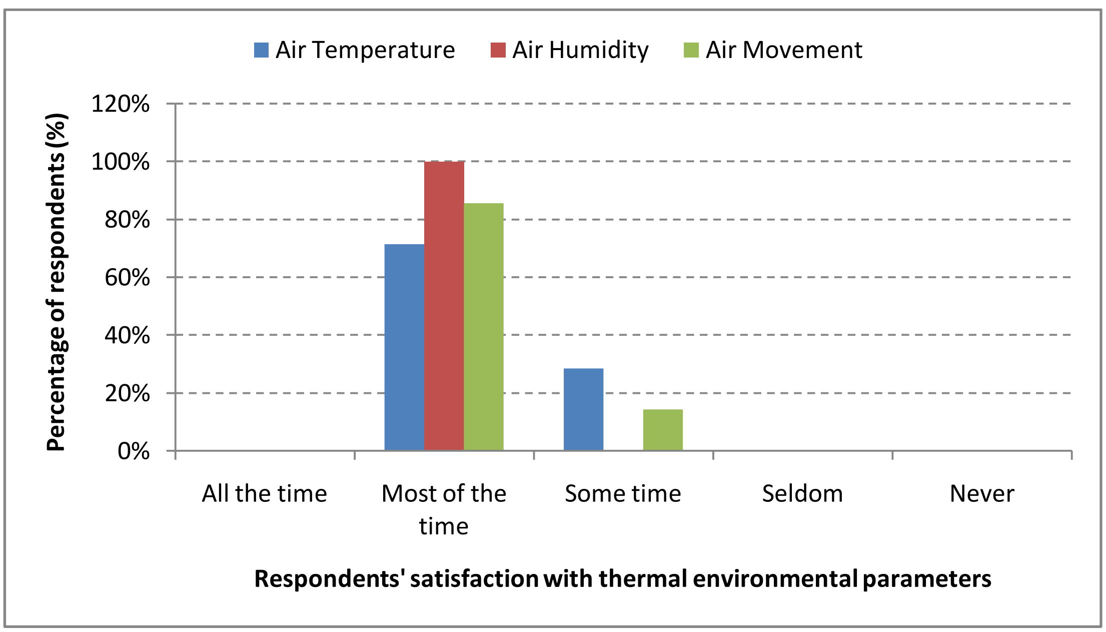


Figure 3.17: Survey results of zone-4 of the second floor

Overall, air humidity and air movement in the second floor were found to be satisfactory by most of the occupants, whereas there were some complaints about air temperature. In zone-1 where the occupants reported that they feel ‘slightly warm’; shading devices such as venetian blinds could be used to shade the glazing from solar radiation. In zones 2, 3 and 4, where the occupants indicated that they feel ‘slightly cold’, the setpoint temperature could be increased from the existing 21°C to a value within the ASHRAE specified comfort range (23-25.5°C).

iii. Fourth floor

The fourth floor is divided into seven thermal zones, out of which zones 1 to 4 are occupied and zones 5 to 7 are unoccupied. The questionnaire forms were distributed to the occupants in zones 1 to 4. The total number of occupants in each of the four occupied zones is twelve.

Survey Results of Zone 1

Out of the twelve occupants in zone-1, six participated in the survey. Among the six respondents, only one respondent (16.6%) expressed that the temperature at his workplace is comfortable ‘most of the time’; while four (66.6%) respondents expressed that, they feel ‘slightly warm’ and are ‘seldom’ comfortable with the air temperature at their workplace. Whereas, 83.3% of respondents indicated that they are comfortable with air humidity at their workplace ‘most of the time’, and the remaining 16.6% pointed out that they feel comfortable with the air humidity at their workplaces only ‘sometime’.

Furthermore, 83.3% of the respondents indicated that the air movement at their workplace is comfortable ‘most of the time’. The survey results of this zone are shown in **Figure** 3.18.

In summary, a majority of respondents in this zone have expressed that they are not comfortable with air temperature at their workplaces. About 66.6% indicated that they feel ‘slightly warm’. The reason here could be the same as that of zone-1 of second floor. This zone is also exposed to two orientations, south and east, which receive high solar heat gains, and window-to-wall ratio of the facades facing both the orientations of this zone is high (about 50%).

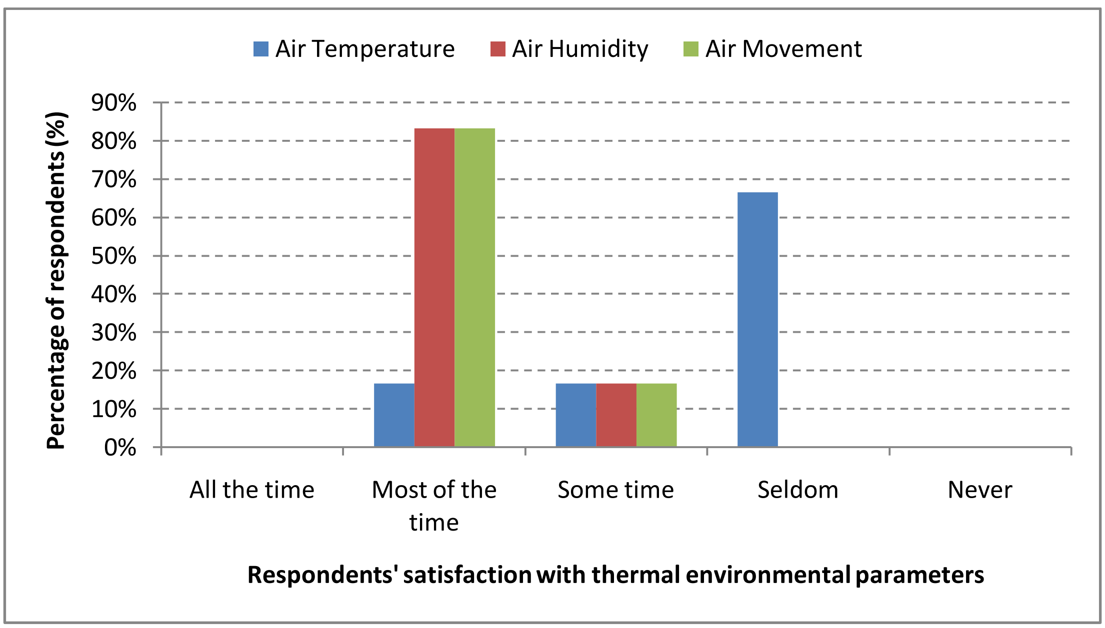


Figure 3.18: Survey results of zone-1 of the fourth floor

Survey Results of Zone 2

In zone 2, five out of eight respondents (62.5%), indicated that they feel comfortable with the air temperature at their workplaces 'most of the time'. In addition, 12.5% indicated that they feel comfortable with air temperature 'all the time', which makes the total percentage of respondents who are satisfied with air temperature, 75%. Furthermore, air humidity and air movement was reported as comfortable 'most of the time' by about 75% of the respondents. It can be noted from the results shown in **Figure** 3.19 that in this zone a majority of respondents expressed satisfaction with all the three thermal environmental parameters.

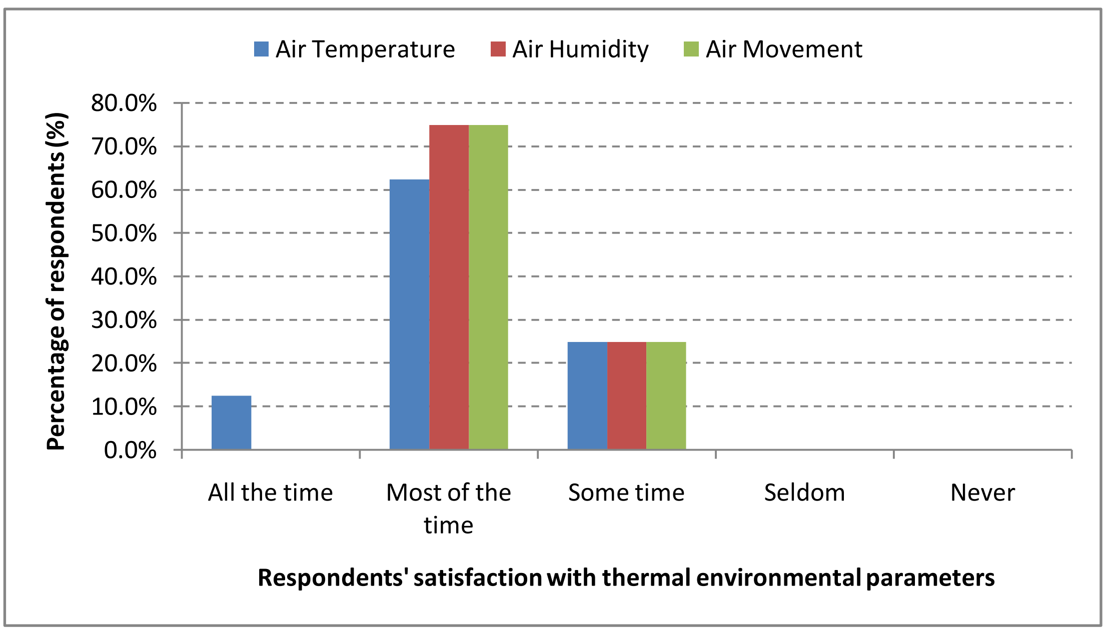


Figure 3.19: Survey results of zone-2 of the fourth floor

Survey Results of Zone 3

In zone 3, merely three out of eight respondents (37.5%), indicated that they feel comfortable with the air temperature at their workplaces 'most of the time' whereas about

four (50%) indicated that they feel comfortable with air temperature at their workplace only ‘sometime’. Within these 50%, about 25% indicated that they feel ‘slightly cold’; while the remaining 25% indicated that, they feel ‘slightly warm’. It can be seen that the feedback of the respondents regarding air temperature was very diverse. Additional interviews with the occupants of this zone during the objective assessment process indicated that as the thermostat is easily accessible to all the occupants, the temperature setting in the zone is disturbed frequently, resulting in varied temperature in the zone. However, air humidity and air movement were reported as satisfactory ‘most of the time’ by 87.5% of the respondents. A summary of survey results of zone 3 is shown in **Figure** 3.20.

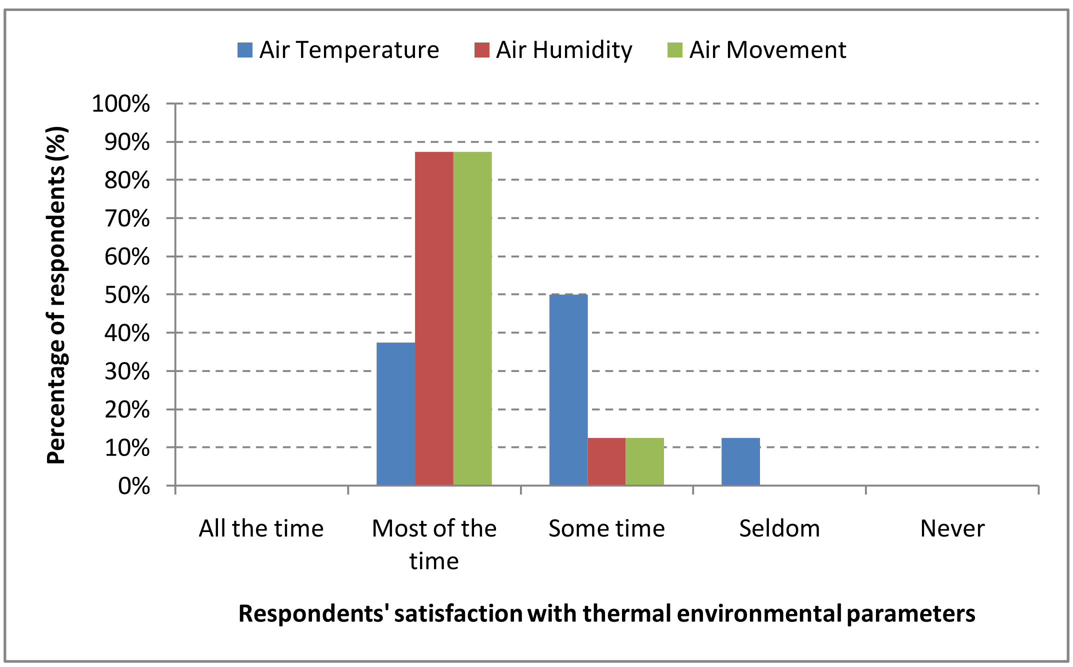


Figure 3.20: Survey results of zone-3 of the fourth floor

Survey Results of Zone 4

In zone 4 of the fourth floor, six out of nine respondents, about 66.6%, revealed that they feel comfortable with air temperature at their workplace 'most of the time'. Furthermore, about 22.2% of the respondents indicated that the air temperature at their workplace is comfortable only 'sometime' and they feel 'slightly cold'. However, about 77.7% respondents pointed out that, they are comfortable with air humidity at their workplace 'most of the time', while about 22.2% of the respondents have pointed out that they are comfortable with air humidity only 'sometime'. Furthermore, about 88.8% of the respondents have indicated they are comfortable with air movement at their workplace 'most of the time'. A summary of the survey results is shown in **Figure** 3.21.

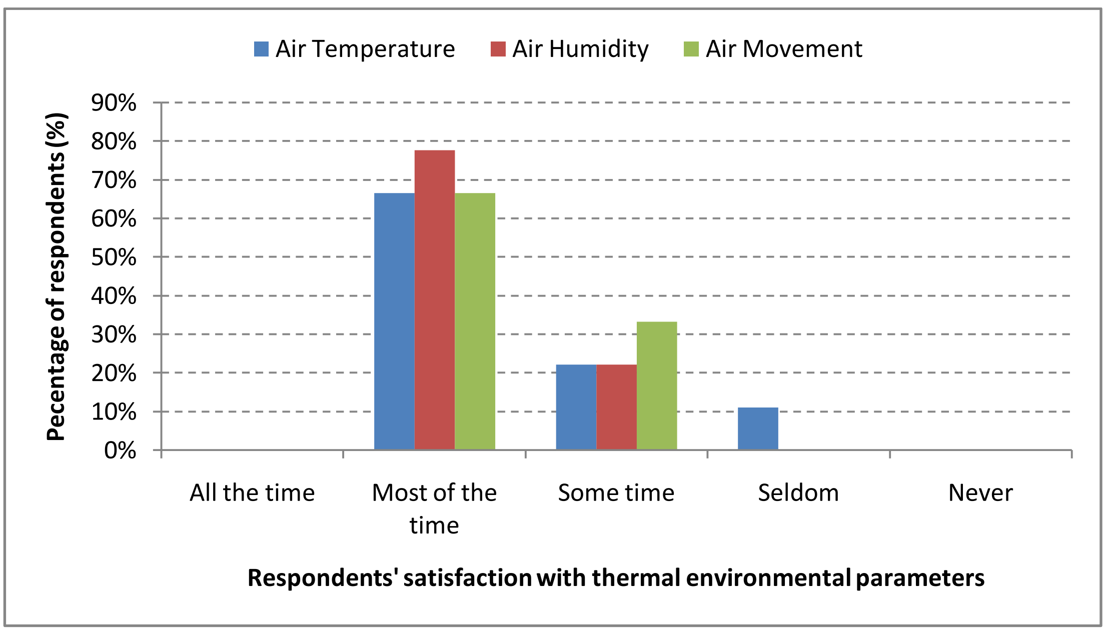


Figure 3.21: Survey results of zone-4 of the fourth floor

In this zone as well, a majority of the respondents reported satisfaction with air humidity and air movement whereas, a few respondents have expressed dissatisfaction with air temperature and indicated that they feel ‘slightly cold’. As mentioned earlier, this could again be attributed to the fact that the design setpoint temperature is cooler than the comfort range specified by ASHRAE.

In summary, the fourth floor survey results are similar to second floor, where, air humidity and air movement were found to be satisfactory by most of the occupants, whereas the respondents reported few concerns about air temperature. The remedial measures for the concerns of the air temperature in fourth floor are similar to second floor. In zones where the occupants reported that, they feel ‘slightly warm’; shading devices such as venetian blinds could be used to shade the glazing from solar radiation. In zones where the occupants indicated that they feel ‘slightly cold’, the setpoint temperature could be increased from the existing 21°C to a value within the ASHRAE specified comfort range (23-25.5°C).

Overall, the results of the subjective assessment indicated that air humidity and air temperature were found to be satisfactory by most of the occupants, in all the zones selected for survey. However, most of the complaints by the respondents were regarding air temperature. In zone-1 of all the three selected floors, most of the occupants indicated that they felt slightly warm. As explained earlier, this could be because of the fact that this zone is exposed to two orientations south and east, which tend to receive high solar heat gains. In addition, the window to wall ratio of the facades on these orientations is

about 50%, which further increases the solar heat gains. It is recommended that shading devices should be used to shade the glazing on these facades from solar radiation, which may help alleviate the problem.

In other zones where respondents indicated that they feel slightly cold, the setpoint temperature can be increased from the existing 21°C to a value within the ASHRAE specified thermal comfort range (23-25.5°C). Furthermore, although in few zones the occupants indicated that they are comfortable, the existing setpoint temperature of 21°C is not energy efficient. Since the ASHRAE comfort range is 23 to 25.5°C, the setpoint can be increased by 2-5°C, which could result in tangible energy savings.

3.3.4.3 Thermal Comfort Objective Assessment

The second method for evaluating the thermal comfort conditions is to perform measurements of environmental parameters that include air temperature, air humidity and air velocity, at different locations in the occupied spaces of the building. However, although air velocity is a very important parameter which affects the thermal environment, measurements of air velocity could not be conducted. It was initially planned to take measurements of temperature and humidity on one day and perform the air velocity measurements on the next day. However, this decision turned out to be mistake as access to make any more measurements on the next day was not granted, because of complaints from occupants of the building, who felt uneasy with loggers being installed at their workstations. From this experience, it is recommended that if a

researcher has access concerns, the measurement activities should be pre-planned and full use should be made of the available opportunities to access the building. Therefore, in this study, the objective assessment was carried out by taking measurements only for air temperature and humidity.

The data logger used for air temperature and humidity measurements is shown in **Figure** 3.22. The logger can be adjusted to record parameters at various sample intervals ranging from ‘10 second intervals’ to ‘24 hour intervals’**[33]**. For this study, the data loggers were set to measure the parameters at ‘five minute’ intervals in order to obtain detailed profile of the temperature and humidity in the building.

Figure 3.22: Dickson temperature and humidity logger**[33]**

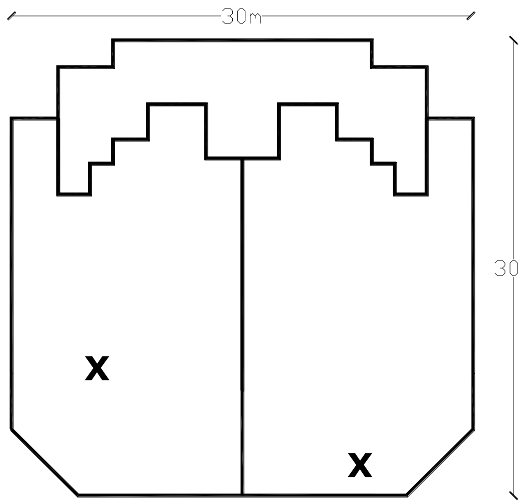
ASHRAE *standard* 55**[29]** specifies that measurements shall be made in occupied zones of the building at locations where the occupants are known to spend their time. The standard specifies the measurement locations to be in the center of the room and at 1.0 m

inward from the center of each of the room's walls. The measurement heights from the ground specified by the standard are 0.1, 0.6, and 1.1 m levels for sedentary occupants. However due to limited number of data loggers, the measurements were made only in the center of the zone and at 1.1m height from the ground.

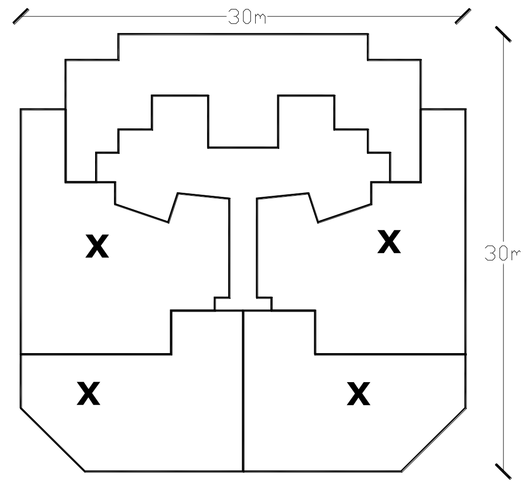
As discussed earlier, the loggers were installed only in the occupied zones of the representative floors in the building. In the ground and the second floors, the loggers were installed in all the occupied zones, but in the fourth floor, one of the zones was left out due to limited number of loggers. The approximate locations of the data loggers in the ground, second and fourth floors of the building are shown in **Figure** 3.23. The location of data loggers in each zone is represented by a 'X' mark. It is to be noted that the loggers were not installed exactly in the centre of the zone but at an appropriate place as close to centre as possible, depending upon the availability of a position at which the logger can be placed securely and without disturbance by the movement of people inside the zone. In addition, it is also to be noted that in order to determine the prevailing thermal conditions close to the perimeter, in zone-2 of the ground floor, the logger was intentionally installed close to the east facade, which is essentially made of double clear glass.

The measurements of air temperature and humidity were done for 15 consecutive days in the month of July (14 July to 28 July 2009), which represents the peak summer month in the Eastern Province in Saudi Arabia. The measurements of the indoor environmental conditions in the building were performed in the same week in which the occupants were

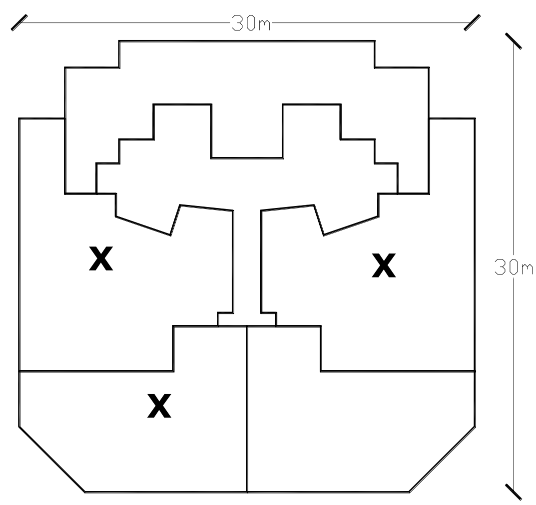
asked to complete the thermal comfort questionnaire in order to relate the occupant's perception to the actual environmental conditions.



(a)



(b)



(c)

Figure 3.23: Locations of data loggers in (a) Ground floor, (b) Second floor, and (c) Fourth floor

3.3.4.4 Analysis of Objective Assessment Results

To perform the analysis of objective assessment results, the temperature and humidity readings recorded by the data loggers were transferred from the loggers to the computer. To facilitate the analysis, graphs were developed from the collected data. The analysis of the obtained data for different floors of the building is discussed as follows.

i. Ground floor

In zone-1 of the ground floor, the temperature was found to be within the comfort zone, especially during office working hours, as shown in **Appendix B.1**. The average of the recorded temperatures in the zone was 22.5°C, which is only 0.5°C cooler than the lower limit of ASHRAE specified thermal comfort zone (23-25.5°C) for summer. However, objective assessment results were not consistent with the subjective assessment results. The survey results revealed that about 44.4% of respondents pointed out that they feel 'slightly warm' and are only 'sometime' comfortable with the air temperature at their workplace. This could be attributed to the fact that this zone is exposed to south and east orientations, which receive high solar heat gains. In addition, the structural glazing used in ground floor is double clear, which allows most of the unwanted solar radiation into the zone, causing the occupants to feel warm.

Nevertheless, the humidity levels in zone-1 were found to be within the comfort range of 30% to 60%**[29]**, as shown in **Appendix B.2**. The subjective assessment results also

indicate the same, where, 88.8% of respondents indicated that the overall humidity condition at their workplace is ‘comfortable’.

In order to see the effect of glazing on the comfort conditions in the workstations located near the perimeter, in zone-2 the data logger was installed close to the structural glazing on the east side of the building,. Although the average temperature in the zone was about 24°C, it was found that during the office working hours, the air temperature reaches upto 27°C for all the days, as shown in **Appendix B.2**. This shows that the occupants located near the glazing on the east side of the building were uncomfortable because the temperature in this area goes well beyond the ASHRAE specified thermal comfort range. This is consistent with the results obtained in the subjective assessment in this zone, where about 50% of respondents indicated that they feel ‘slightly warm’ at their workplaces. However, the humidity levels in the zone were found to be within the comfort range and the respondents indicated the same; where about 62.5% of the respondents expressed that they feel comfortable with air humidity at their workplaces ‘most of the time’.

ii. Second floor

In zone 1 of the second floor, although the average temperature was found to be 24.4°C, it can be seen in **Appendix B.3** that the temperature during working hours for most of the days was higher than the thermal comfort range**.** This is in agreement with the results obtained in the subjective assessment, where about 50% of the surveyed respondents in

the zone have specified that they feel 'slightly warm' at their workplaces. Furthermore, the relative humidity measurement results for zone-1 indicate that the humidity levels remains within the ASHRAE specified levels, as shown in **Appendix B.3**. This is supported by the fact that about 75% of the respondents indicated that overall humidity condition at their workplace is 'comfortable'.

On the other hand, in zone 2, the average temperature was found to be 22°C, as seen in **Appendix B.4**, which is only 1°C cooler than the lower limit of ASHRAE specified comfort range (23-25.5°C). The survey results are in agreement with measurements results, where only 16.6% of the respondents have shown that they feel 'slightly cold' and a majority, about 66.6%, have indicated that they feel 'comfortable' at their workplaces. The humidity levels in zone-2 go above the recommended level, as shown in **Appendix B.4**. Nevertheless, all the respondents (100%) have indicated that overall humidity condition at their workplaces is 'comfortable'.

In zone 3 of the second floor, as shown in **Appendix B.5**, the temperature always stays below the thermal comfort range, with an average temperature of 20.3°C. The subjective assessment results complement the objective assessment results, where 42.8% of the respondents indicated that they feel 'slightly cold' at their workplaces. Furthermore, the humidity in zone 3 stays above the recommended levels, as shown in **Appendix B.5**. However, 71.4% of the respondents indicated that they feel 'comfortable' and only 28.6% of the respondents indicated that overall humidity condition at their workplaces is 'slightly humid'.

In zone 4, the average temperature was found to be 22.4°C, which is only 0.6°C less than the lower limit of temperature range recommended by ASHRAE, as shown in **Appendix B.6**. About 71.5% of the respondents indicated that they feel ‘comfortable’ at their workplaces ‘most of the time’, and only 28.6% indicated that they feel ‘slightly cold’. The measurement results for humidity revealed that for most of the days, humidity levels were within the comfort range, as shown in **Appendix B.6**. This is consistent with the subjective assessment results where all the respondents of zone 4 indicated that the overall humidity condition at their workplaces is ‘comfortable’.

iii. Fourth floor

In zone-1 of the fourth floor, although the average air temperature in the zone was found to be low (21.9°C), it can be seen from **Appendix B.7** that the temperature during working hours for most of the days stays within the thermal comfort zone. In contrast, the survey results showed that 66.6% of the respondents indicated that they feel ‘slightly warm’ at their workplaces. As mentioned during the analysis of the subjective assessment results, the reason for inconsistency here could be due to the fact that this zone is exposed south and east orientations, which receive high solar heat gains and the window-to-wall ratio for these orientation is high, which further increases solar heat gains. Thus, about 66.6% of the occupants expressed that they feel ‘slightly warm’ whereas, the measurements indicated that the temperature readings are well within the comfort range.

The relative humidity level in zone-1 was found to be within the ASHRAE specified levels as shown in **Appendix B.7**, except for few days where the humidity values reached upto 70%. This is in conformity with the subjective assessment results, where about 83.3% of the respondents have indicated that the humidity at their workplaces is comfortable 'most of the time'.

In zone-3 of the fourth floor, the air temperature in the zone has shown large fluctuations, as seen in **Appendix B.8**. The survey results were also a diverse response where, 25% of the occupants indicated that they feel 'slightly cold', 50% indicated that are comfortable and remaining 25% indicated that they feel 'slightly warm'. Interviews with occupants of zone 3 revealed that the reason for large fluctuations in temperature could be the fact that temperature setting is disturbed quite frequently in the zone, as the thermostat is easily accessible to all occupants. The humidity levels in zone 3 goes beyond 60% for some days, as shown in **Appendix B.8**. However, the survey results indicated that only 12.5% of the respondents in zone 3 indicated that the humidity condition at their workplace is 'slightly humid'; while a majority of respondents indicated that, they feel 'comfortable'.

In zone-4, as shown in **Appendix B.9**, although the average temperature was found to be 22.5C°, it can be seen that the air temperature mostly stays within comfortable zone during working hours. This is in conformity with the subjective assessment results where 66.6% of respondents have indicated that they feel 'comfortable' with air temperature at their workplace. Furthermore, as shown in **Appendix B.9**, the humidity levels in zone 4 have always stayed within the ASHRAE specified comfort levels. The subjective

assessment of zone 4 also shows the same results, where about 77.7% of the respondents have indicated that the overall humidity condition at their workplaces is ‘comfortable’.

In conclusion, the results of the objective thermal comfort assessment indicated that in most of the zones the thermal conditions are maintained within the comfort levels except for a few zones in which the air temperature and humidity go beyond the ASHRAE recommended range. The deviations between the measured and designed thermal conditions were incorporated in the base case model during the calibration process, in order to bring the base case model as close to the real building as possible. The formulation of the base along with the calibration process is discussed in the following sections of the energy audit process.

3.3.5 Detailed Building Energy Simulation

The fifth stage of the energy audit process is the detailed building energy simulation. This stage consists of following three sub-stages:

- Development of the base case model
- Calibration of the base case model
- Evaluation of alternative energy conservation measures

In this section, the first and second sub-stages, development and calibration of the base case model, are discussed in detail and the third sub-stage, evaluation of energy

conservation measures, is discussed separately in Chapter-4 of this thesis. This is because the evaluation of alternative energy conservation measures is a very extensive process and is worthy of being discussed as a separate chapter.

3.3.5.1 Development of the Base Case Model

The main purpose of this step is to develop a base case model that closely represents the reality of the existing energy use and operating conditions of the building. This model was used as a reference to estimate the energy savings incurred from appropriately selected energy conservation measures. The base case model was developed using Visual DOE 4.1 hourly energy simulation program, which uses DOE-2.1 as its calculation engine**[34]**. The Visual DOE 4.1 was selected as simulation tool in this study for the following reasons:

- It is a detailed hourly energy simulation program using hourly weather data.
- It covers all major building components, including building envelope, lighting, daylighting, water heating, HVAC and central plant, and is especially useful for studies of envelope and HVAC design alternatives.
- It uses DOE-2.1E simulation tool as its calculation engine, which is one of the most widely used simulation tool that has been validated in several studies, Neymark et al. (2002)**[35]**, Pasqualetto et al (1998)**[36]**, Meldem and Winkelmann (1998), Vincent and Huang (1996), and Lomas et al. (1994)**[37]**.

- DOE-2.1E is also recognized by several standards such as ANSI/ASHRAE Standard 140-2004, *"Standard Method of Test for the Evaluation of Building Energy Analysis and Computer Programs"***[38]** and ANSI/ASHRAE/IESNA Standard 90.1-2007, *"Energy Standard for Buildings Except Low-Rise Residential Buildings"***[39]**, as an acceptable simulation tool.
- It is easily available commercially, supported by graphical Windows interface allowing easy geometric modeling.

The base model was developed from data accumulated in earlier stages of the audit process, through review of design drawings, interviews, and surveys. However, the gathered data is often inconsistent or incomplete for simulation needs. Therefore, certain assumptions had to be made to select and determine the necessary inputs for the investigated building. The assumptions made in developing the base case model are listed as follows:

- The building internal walls were assumed as adiabatic, with no heat transfer between different zones.
- The building thermal zoning was not available from drawings. Hence, the area served by each HVAC system was assumed as a zone.
- Electric loads from exterior lighting were not considered as part of building energy use.

- The weather file used for performing the simulations was for the city of 'Dhahran', which has similar climatic conditions and is located very close to the actual location of the building in 'Al-Khobar'
- The weather file for the year 2002 was used due to unavailability of the latest weather files.

The annual energy use of the building, obtained from initial simulation run, was found to be 3,123,380 kWh (371.8 kWh/m^2/yr). A comparison between the simulation results of the base case model and the actual annual electric energy use of 2,989,508 kWh obtained from utility bills yielded a deviation of 4.3%. Although this deviation is low, it can be observed from the **Figure** 3.24 that the deviation in monthly electric usage is very high. The largest deviation of 43.7% was observed in the month of February. Therefore, in order to have more reliability and acceptable results, the base case model has to be calibrated. The calibration of the base case model is discussed in the following section.

3.3.5.2 Calibration of the Base Case Model

There are three standards that specify the criteria for a simulation model to be considered calibrated – these are ASHRAE Guideline 14 2002, the International Performance Measurement and Verification Protocol (IPMVP) and the Federal Energy Management Program (FEMP) Monitoring and Verification Guide**[40]**. However, none of these standards prescribes a methodology to actually perform the calibration**[40-43]**. Nevertheless, one of most common method of calibration that has been used in recent

years in several research studies is calibration by comparison of simulation results with actual monthly utility bills data **[22, 43, 44]**. The simulation results are compared to monthly utility bills data and the deviation between the two is minimized by varying the key input parameters.

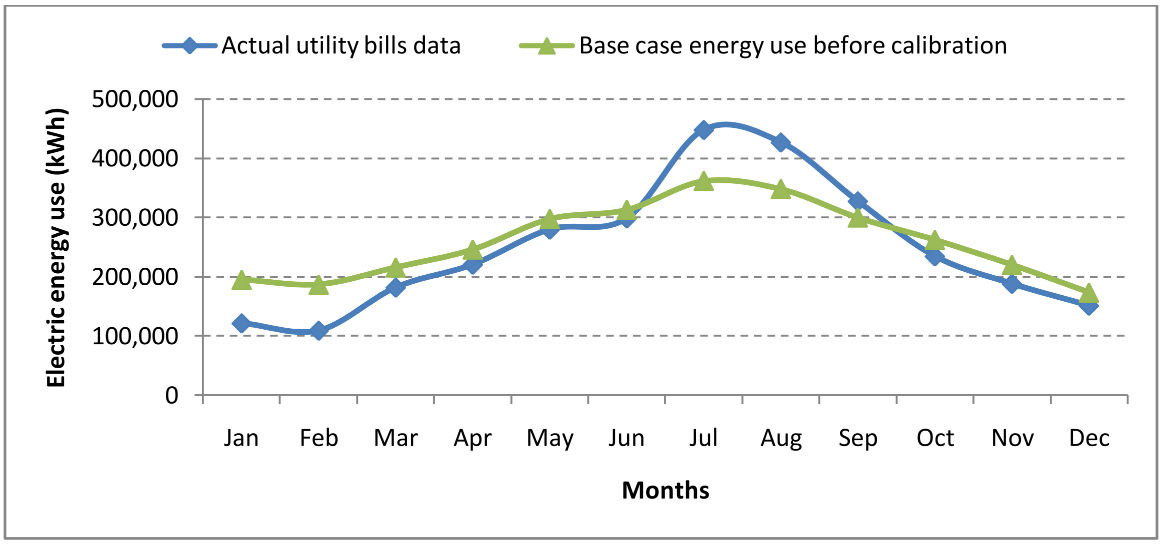


Figure 3.24: Comparison between actual utility bills data and base case energy use before calibration

ASHRAE Guideline-14 specifies that models are declared to be calibrated if the simulation results are within 15% of the actual monthly utility data**[45]**. An observation of the energy use profile of the base case model indicates that the deviation between actual utility bills data and base case energy use is more than 15% in the winter months of January, February and March, and in summer months of July and August. To determine the cause of the variation, the building maintenance personnel were contacted again to verify the input data, especially the HVAC operation schedule. After several communications, it was found that during winter (December to March), the HVAC

systems were being switched off from 9pm to 6am and the on/off setting of the HVAC system during this time was such that the system would start working if the zone temperature goes beyond 28°C. Using this information, the model was calibrated during winter (December to March). However, no specific reason could be found for the deviation observed in the months of July and August., except that there was an increase in the occupancy by 50 additional occupants. Incorporating this data into the base case model increases the energy use only slightly. In addition, an attempt was also made to obtain the weather data for Dhahran for the year 2008 to verify the weather file utilized for simulation. However, due to unavailability of the weather data for Dhahran, the weather file could not be verified. Therefore, the base case model was finalized with a deviation of 23% in July and 22% in August. Nevertheless, for the rest of the months, the deviation was well within 15% of the utility bills data. Therefore, it can be concluded that the model is reliable for evaluating the effects of energy conservation measures for the building under study.

The annual electric energy use obtained for the base case model after performing the calibration was 2,953,614 kWh (351.6 kWh/m^2/yr). An overall comparison between the actual utility bills data and simulation results before and after calibration is shown in **Figure** 3.25. Furthermore, the breakdown of the annual electrical energy use revealed that about 67% of the total energy is used for cooling (including fans), followed by 15% for lighting and 18% for equipments. The breakdown of the electrical energy use is shown in **Figure** 3.26.

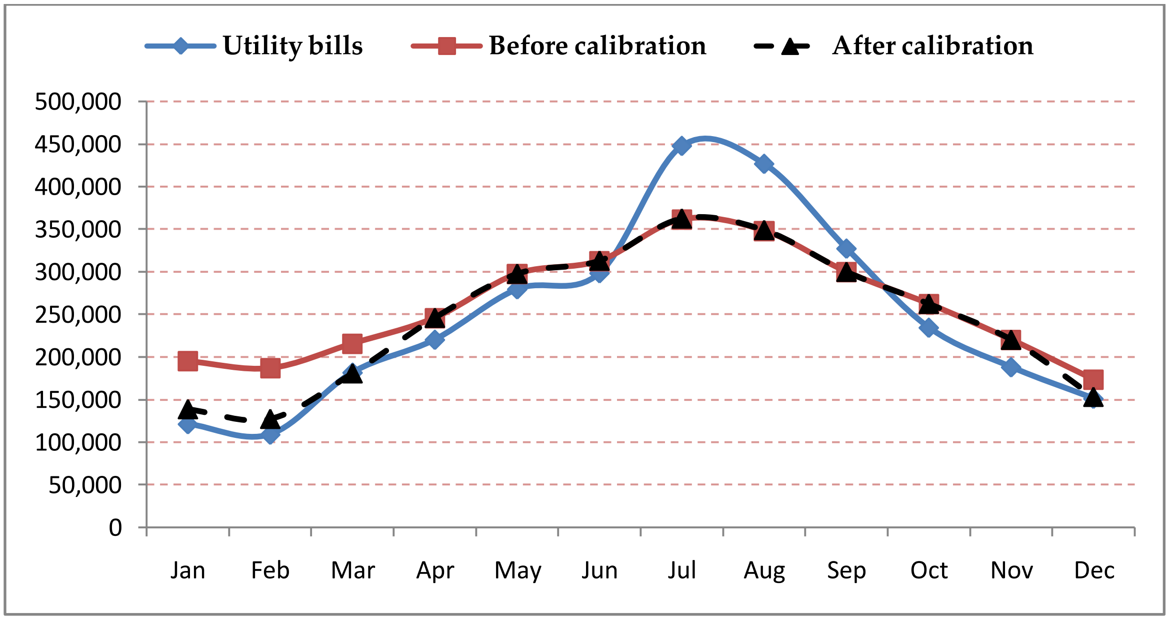


Figure 3.25: Comparison between actual utility bills data and base case simulation results before and after calibration

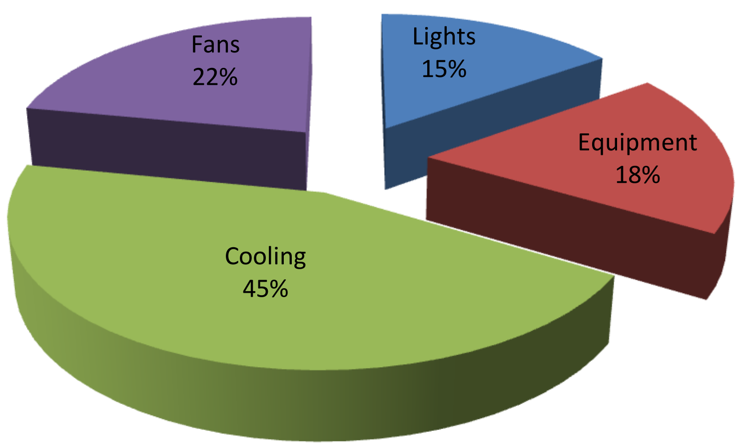


Figure 3.26: Electrical energy use breakdown of the base case after calibration

In conclusion, the energy audit process revealed that for the building under study, 67% of the electric energy is used by HVAC system (45% for cooling and 22% for fans). It is believed that a bulk of the energy can be saved if HVAC systems are properly operated. Changes such as increasing the setpoint temperature to a higher value within the thermal

comfort range, changing the schedule of operation of HVAC system from the present 24-hour operation to operation only during occupied hours, could help save a lot of energy. Additionally, usage of a ‘variable air volume’ (VAV) system could help achieve required thermal comfort at relatively low energy use.

Furthermore, towards the end of this chapter, few suggestions are also made regarding the maintenance of the building systems. It is recommended that, to improve the thermal comfort conditions in the building, it should be made sure that all the units are operating at design ventilation rates, as it was found that during the walkthrough audit, the ventilation dampers for some of the air-handling units were completely closed. Moreover, it is also necessary that some of the lamps that were not working be replaced in order to achieve designed illumination levels in the building.

In addition to the above mentioned actions, several other energy conservation measures (ECM) were tested in order to identify the amount of energy that can be saved for the building under study. The evaluation of ECMs is presented in the following chapter of this thesis.

CHAPTER 4

EVALUATION OF ALTERNATIVE ENERGY CONSERVATION MEASURES

4.1 INTRODUCTION

This chapter presents the evaluation of selected alternative energy conservation measures (ECMs). Among the ECMs discussed in the literature review, only those, which can be implemented to the building under study, were selected. The selected ECMs were divided into three categories based on the economic interest. The categories are as follows:

i. Zero Investment ECMs
ii. Low Investment ECMs
iii. High Investment ECMs

The detailed grouping of the ECMs is depicted in the **Table** 4.1. The ECM's are implemented on the base case model while maintaining all other parameters same. The evaluation of ECMs is discussed in the following sections.

Table 4.1: List of Energy Conservation Measures

Economic Interest	**Energy Conservation Measures**		**Description**
Zero Investment	ECM # 1	Setpoint temperature reset	Setpoint temperature is reset from 21°C to 24°C during summer
	ECM # 2	Night time setback	During unoccupied periods, a range of temperatures from 28°C to 32°C is tested
	ECM # 3	Combination of ECM # 1 and 2	Combination of ECM # 1 and 2
	ECM # 4	Time scheduled operation	During unoccupied hours, HVAC system is switched off
	ECM # 5	Ventilation air reset based on ASHRAE Standard 62.1	Old and new ventilation standards are implemented to the base case and comparison between the two is made
	ECM # 6	Combination of ECM # 1, 2 and 5	Combination of ECM # 1, 2 and 5
Low Investment	ECM # 7	Air Side Economizers	‘Temperature’, ‘Enthalpy’ and ‘Temperature-Enthalpy’ economizers are tested
	ECM # 8	Demand Controlled Ventilation	Ventilation is provided only during occupied hours
High investment	ECM # 9	Type of HVAC system	Five different types of all-air HVAC systems are tested
	ECM # 10	Combination of ECM # 1, 2, 5,8 and 9	Combination of all potential ECMs

4.2 ZERO INVESTMENT ENERGY CONSERVATION MEASURES

This set of energy conservation measures do not require any investment or modification to be done in the existing HVAC system. They require simple adjustments to be made in the operational strategies of the existing HVAC system.

ECM # 1: Set point temperature reset

In the building under study, the existing design setpoint temperature is 21°C during summer (April to November) and 24°C during winter (December to March). However, during winter, from 9pm to 6am, the HVAC system fans are set to turn off automatically if the zone temperature is below 28°C.

The ASHRAE *Standard* 55-2004 recommends a temperature range of 20-24°C for winter and 23-25.5°C for summer (for 60% relative Humidity). In order to verify whether the building requires heating during winter, the HVAC system in the base case model of the building was switched off for January 21, since January is considered one of the peak winter months in Eastern Province of Saudi Arabia. The temperature profiles for all the occupied zones of the building for Jan-21 were generated, as shown in **Figure** 4.1. It can be seen from the temperature profiles in **Figure** 4.1 that the temperature in all the zones of the building stays above 25°C for most of the time during occupied hours, indicating that even during winter season, the building requires cooling.

In this ECM, a setpoint temperature of 24°C, with a throttling range of 2°C, was set for the base case for summer and its effect on energy use was determined. Implementation of ECM#1 resulted in annual electric energy saving of 1%. To further investigate the effect of different indoor set-point temperatures on energy use, set-point temperatures ranging from 23°C to 26°C were tested in increments of 1°C. This evaluation was performed to determine the energy savings that can be achieved per degree (°C) increase in indoor

setpoint temperature. The results indicated that for one degree (°C) increase in setpoint temperature, on an average, there was an increase of 0.4% in the annual electric energy savings. The results are shown graphically in **Figure** 4.2.

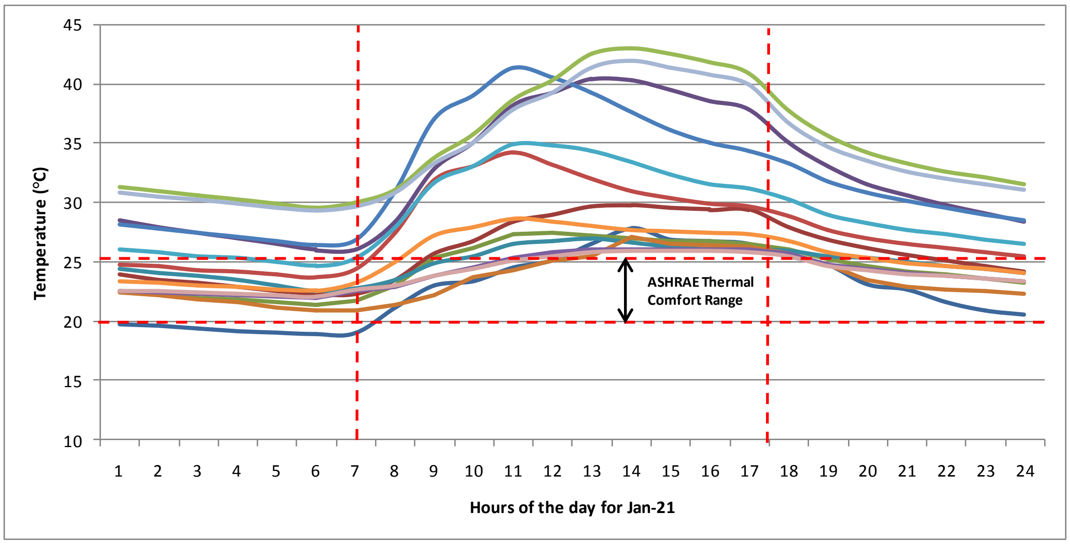


Figure 4.1: Temperature profiles in different zones of the building when HVAC system is switched off

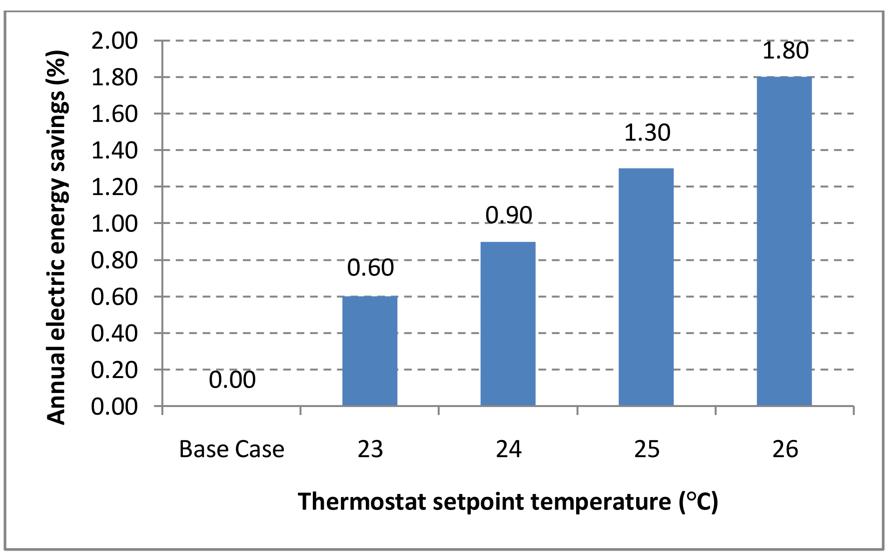


Figure 4.2: Electric energy savings per degree (°C) increase in setpoint temperature for ECM#1

In order to determine whether, after implementation of ECM#1, the temperature in occupied zones of the building remains within the comfort zone specified by ASHRAE, temperature profiles for the occupied zones were generated, as shown in **Figure** 4.3. It can be seen from **Figure** 4.3 that when ECM-1 is implemented to the base case, the temperature profiles indicate that the zone temperature stays close to the desired setpoint temperature of 24°C and also well within the ASHRAE specified thermal comfort zone for summer (23-25.5°C).

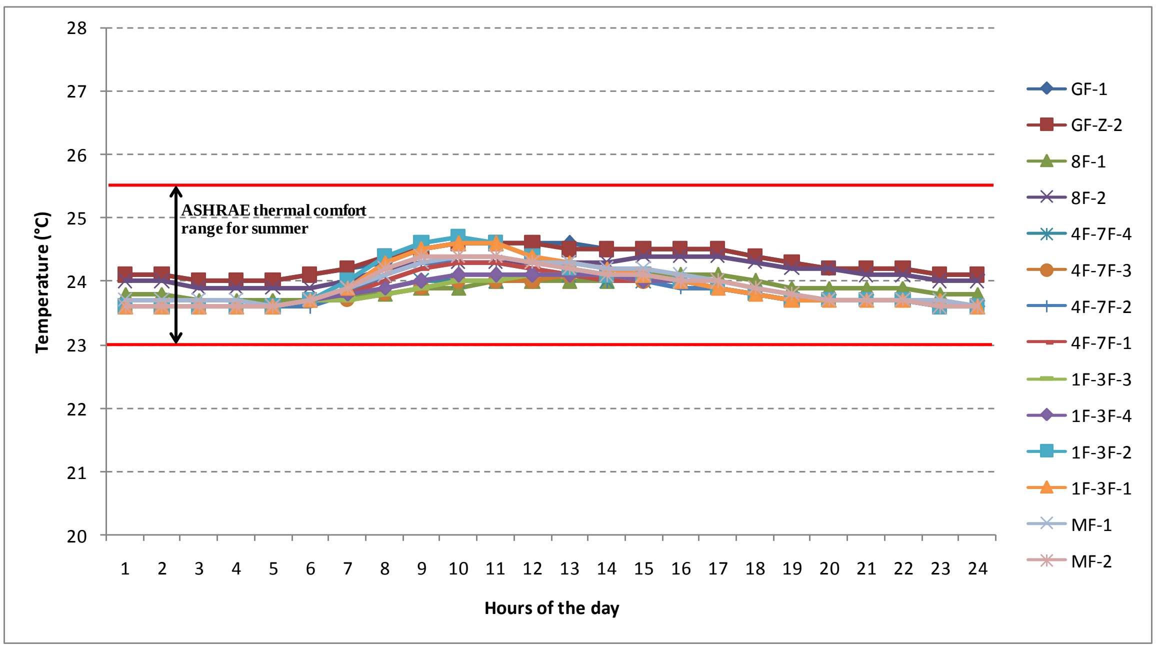


Figure 4.3: Temperature profile for different zones in the building after implementation of ECM-1

Furthermore, it is to be noted that in all the *temperature profile graphs*, the zone names are mentioned as abbreviations. For example, *GF-1* was used as an abbreviation to represent *zone-1 of the ground floor*. This was done because some of the zone names are

large and mentioning the entire name in the graph would make the graph congested. The detailed descriptions of the abbreviations used to represent different zones are presented in **Table** 4.2.

Table 4.2: Description of the abbreviations used in legends of all the temperature profile graphs

Abbreviation	**Description**
GF-1	Ground floor zone-1
GF-2	Ground floor zone-2
MF-1	Mezzanine floor zone-1
MF-2	Mezzanine floor zone-2
1F-3F-1	Representing zone-1 in typical first to third floors
1F-3F-2	Representing zone-2 in typical first to third floors
1F-3F-3	Representing zone-3 in typical first to third floors
1F-3F-4	Representing zone-4 in typical first to third floors
4F-7F-1	Representing zone-1 in typical fourth to seventh floors
4F-7F-2	Representing zone-2 in typical fourth to seventh floors
4F-7F-3	Representing zone-3 in typical fourth to seventh floors
4F-7F-4	Representing zone-4 in typical fourth to seventh floors
8F-1	Eighth floor zone-1
8F-2	Eighth floor zone-2

ECM # 2: Night Time Setback

In this ECM, the indoor temperature setting was adjusted for unoccupied periods to reduce the demand for electric energy during this time. The unoccupied periods for the

building under study are from 6 PM to 6 AM next day. During this period, set-point temperatures ranging from 28°C to 32°C were tested. The implementation of this ECM resulted in annual electric energy savings ranging from 3.9% to 7.4% for temperature settings of 28°C to 32°C, respectively. Furthermore, for one degree (°C) increase in setpoint temperature during unoccupied period, on an average, there was an increase of 0.9% in the annual electric energy savings, as shown in **Figure** 4.4.

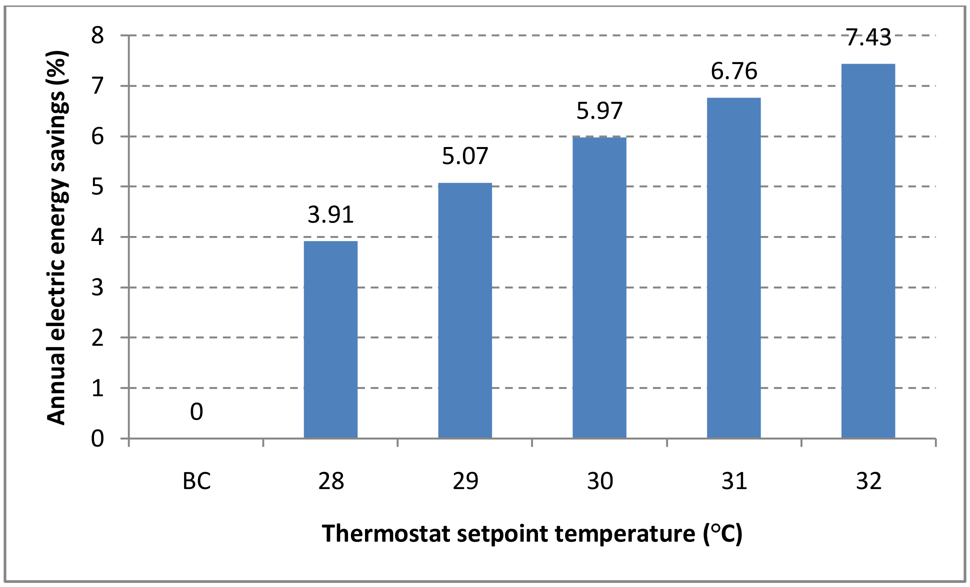


Figure 4.4: Annual electric energy savings for ECM#2

The temperature profiles generated after implementation of ECM#2 are shown in **Appendix C.1**.

ECM # 3: Combination of ECM # 1 and 2

In this combined ECM, during occupied periods the temperature was fixed to 24°C for both summer and winter seasons and during unoccupied period, temperature set-points

ranging from 28°C to 32°C were tested. As shown in **Figure** 4.5, this resulted in annual electric energy savings of 7.1 to 11% for temperature settings of 28°C to 32°C, respectively. In addition, for each degree (°C) increase in setpoint temperature during unoccupied periods, on an average, there is an increase of 1% in annual electric energy savings.

The temperature profiles generated after implementation of ECM#3 are shown in **Appendix C.2**. It can be seen from the profiles that the temperature during occupied hours in all the zones stays well within the ASHRAE comfort range for summer. This indicates that increasing the set-point temperature to the values mentioned in ECM#3, results in considerable energy savings (7.1% to 11%), more importantly, without sacrificing required thermal comfort conditions.

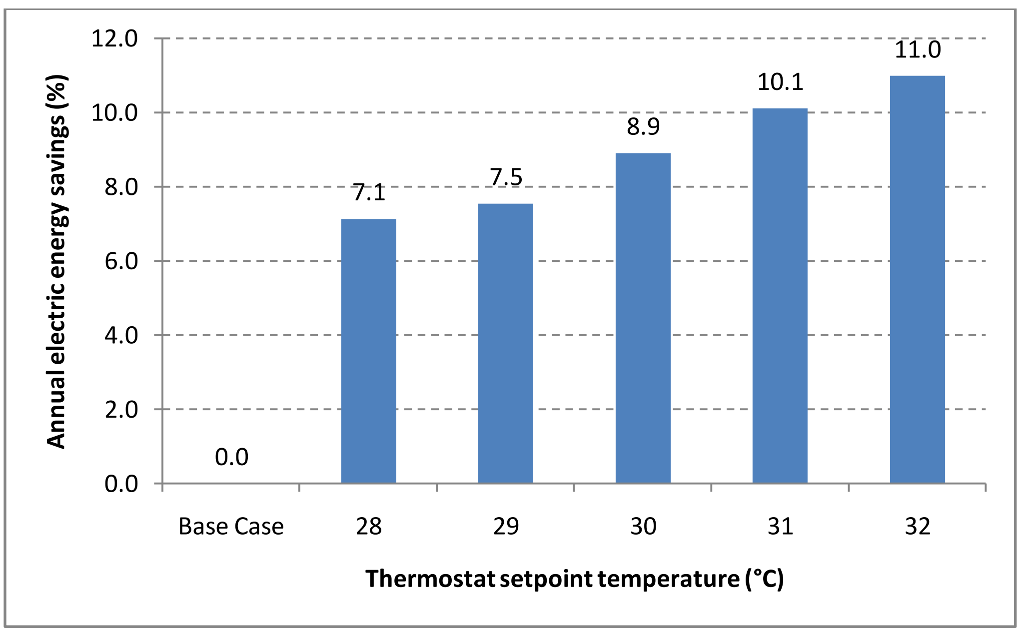


Figure 4.5: Annual electric energy savings for ECM#3

ECM # 4: Time Scheduled Operation

In this ECM, the HVAC system is turned-off during unoccupied periods for both summer and winter seasons. However, there are several alternatives for scheduling the start-up timing of the system on the next day. The HVAC system can be switched-on on the next day either before or at the start of occupancy. The alternative which resulted in the highest electric energy saving of 27.8% was the one in which the HVAC system is turned-on at the start of occupancy. On the other hand, if the system is turned on one hour before the start of occupancy, about 26.2% saving in the annual electric energy is achieved. This corresponds to a decrease of 1.6% in the annual electric energy saving from previous case. Similarly, for each hour increase in start-up time, on an average, there is an extra energy penalty of 1.4%. However, although there is an energy penalty for starting the system early, it should be noted that early start ensures pre cooling of the building to be ready for occupancy. The summary of energy savings for ECM # 4 is illustrated in **Figure** 4.6.

The temperature profiles generated for different zones, after implementation of ECM#4, are shown in **Appendix C.3**. It can be noted from the temperature profiles that switching off the HVAC systems during unoccupied hours increases the temperature upto 37°C during this time. This may cause damage to documents, furniture and equipments in the building. Therefore, this ECM should be implemented only after careful thought.

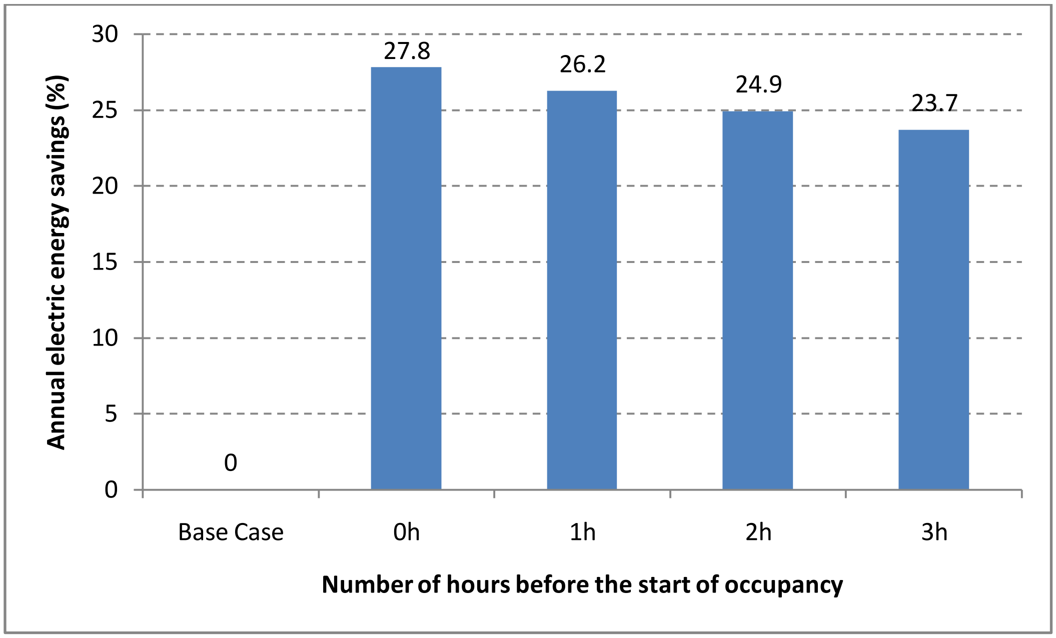


Figure 4.6: Annual electric energy savings for ECM#4

The temperature profiles shown in Appendix C.3 also indicate that after implementation of ECM#4, during occupied hours, the temperature in few zones stays within the comfort range, whereas in few zones, stays below the lower limit of the comfort range. This is because the setpoint temperature during occupied hours is set to 21°C, which is 2°C lower than the lower limit of ASHRAE comfort range.

ECM # 5: Implementing ASHRAE ventilation standard 62.1

ANSI/ASHRAE Standard 62.1, *Ventilation for Acceptable Indoor Air Quality*[46], specifies minimum ventilation rates and indoor air quality requirements for commercial and institutional buildings. First published in 1973, Standard 62.1 is updated on a regular basis and the latest edition of the standard was published in 2007[46].

Historically, for office spaces, standard 62.1 based ventilation requirements on the number of occupants regardless of the area of the space. The ventilation rate for an office space in earlier versions of the standard was specified as 10 L/s-person. However, the revised standard published in the year 2004 indicated that the breathing zone ventilation rate must include an occupancy-related component as well as an area-related component. Now, the outdoor air requirement for an office space is 5 L/s-person plus 0.3 L/s-m^2. The latest edition of the standard published in the year 2007 retains the same ventilation rates for office spaces as in 2004**[46]**.

The average ventilation air flow rate in the base case building is 22 L/s-person. In this ECM, the ventilation rates of base case were reset to 10 L/s-person as prescribed by the versions of standard 62.1 prior to 2004. This resulted in annual electric energy savings of 3.9%. Furthermore, the ventilation rates of the base case were again reset to the values prescribed by the latest version of standard 62.1 published in 2007. It can be noted from the results shown in **Figure** 4.7 that implementation of standard 62.1-2007 resulted in annual electric energy savings of 5.3% when compared to the base case and 1.4% increase in annual electric energy savings when compared to previous versions of the standard.

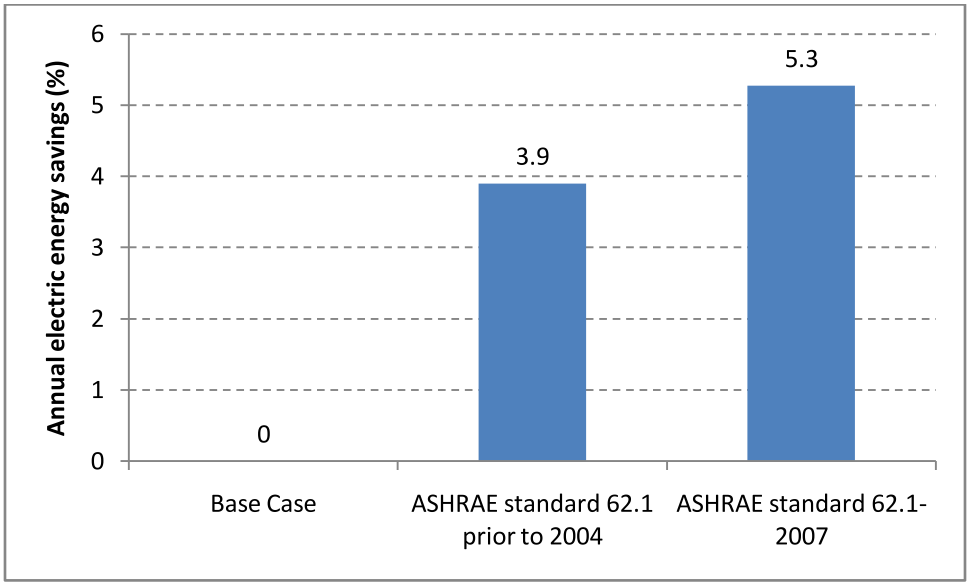


Figure 4.7: Annual electric energy savings for ECM#5

ECM # 6: Combination of ECM # 1, 2 and 5

In this combined ECM, combinations of potential zero investment ECMs (ECM # 1, 2 and 5) were tested. The combination included resetting the indoor setpoint temperature from existing 21°C to 24°C (for summer) during occupied hours and testing temperatures from 28°C to 32°C during unoccupied hours, in addition to resetting the ventilation rates based on ASHRAE Standard 62.1-2007. This combination of ECMs resulted in electric energy savings ranging from 9.8% to 13.3%, as shown in **Figure** 4.8. It is to be noted again that the substantial annual energy savings achieved for this combined ECM does not require any investment or modification to be done in the existing HVAC system. It is the saving achieved entirely by making simple adjustments in the operational strategies of the existing HVAC system.

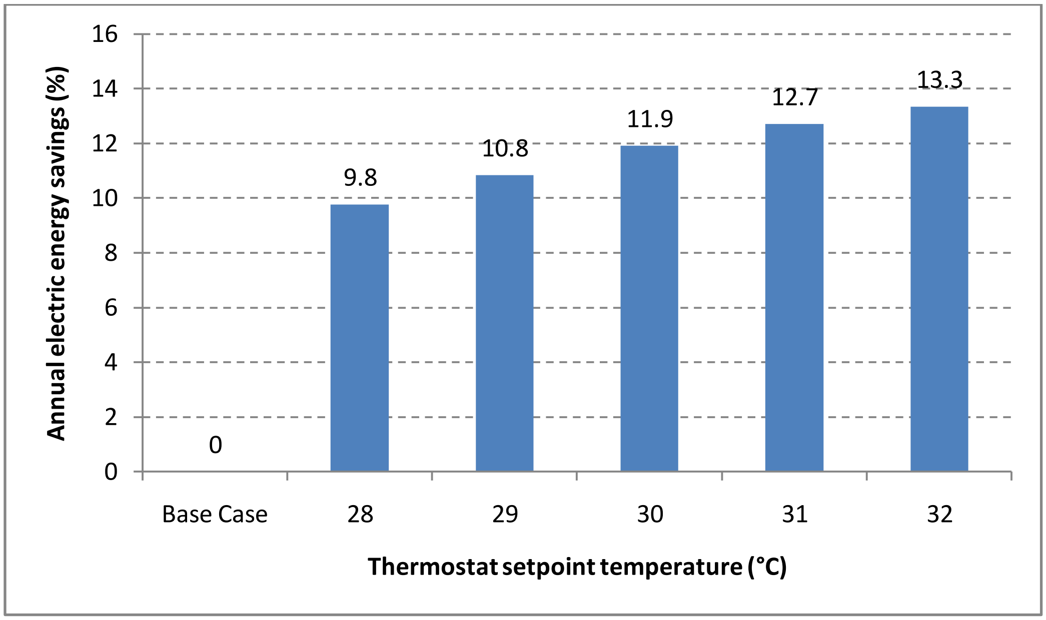


Figure 4.8: Annual electric energy savings for ECM#6

4.3 LOW INVESTMENT ENERGY CONSERVATION MEASURES

These ECMs require minor modifications to be done to the existing HVAC system and hence require some investment to be made.

ECM # 7: Air Side Economizers

"An air side economizer is a collection of dampers, sensors, actuators, and controls that work together to determine how much outside air to bring into the building to reduce, or eliminate, the need for mechanical cooling during mild and cold weather conditions"**[39]**. However, usage of economizer needs installation of additional sensors to compare the

conditions of the return air to the outside air. Hence, implementation of the economizer strategy requires some investment to be made.

In this study, three types of economizers, *Temperature*, *Enthalpy* and *Temperature and Enthalpy* were tested. It can be seen from the results presented in **Figure** 4.9 that with the use of *Temperature Economizer,* annual energy saving of 3.8% was achieved compared to the base case with no economizer. Usage of *Enthalpy economizer* resulted in an annual electric energy saving of 2.7%, and usage of *Temperature and Enthalpy* economizer resulted in an annual electric energy saving of 2.6%.

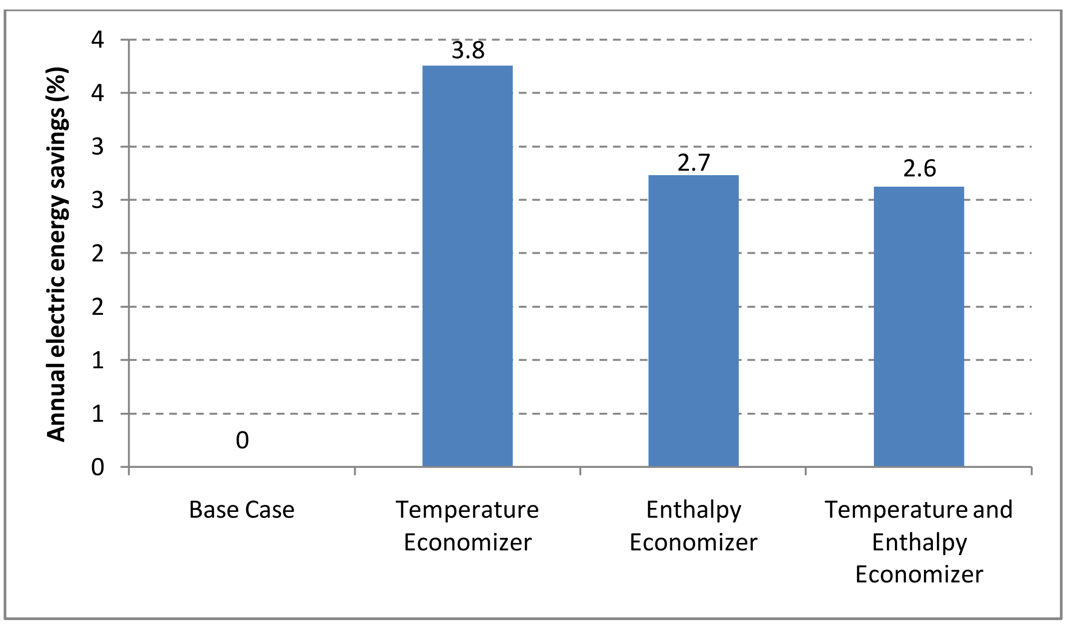


Figure 4.9: Annual electric energy savings for ECM#7

ECM # 8: Occupancy based demand controlled ventilation (DCV)

DCV is a ventilation control strategy in which the amount of outside air is adjusted based on the number of occupants and the ventilation demands that those occupants create while still ensuring adequate levels of outdoor air ventilation. By providing ventilation only during occupancy and based on the occupancy level, DCV tends to reduce the energy penalties caused due to over-ventilation of the zones during unoccupied periods. However, implementation of DCV strategy requires installation of sensors, which can detect occupancy patterns. Some of the available options include *CO_2-based sensors*, which measure the buildup of CO_2 from the occupants present, and *occupancy sensors*, which use infrared light and sound to detect occupants.

In this ECM, DCV is implemented by providing ventilation only during the occupancy periods and closing ventilation during unoccupied periods. The implementation of this ECM to the base case resulted in an annual energy saving of about 5.4%. Furthermore, when DCV is combined with ECM-5, i.e., implementation of ASHRAE standard 55-2007, the annual energy savings increase to 7.8%.

4.4 HIGH INVESTMENT ENERGY CONSERVATION MEASURES

The ECM tested in this section involves evaluation of several types of HVAC systems to determine which type of HVAC system could achieve the required thermal comfort

conditions at minimum possible energy use. Implementation of this ECM requires considerable amount of investment to be made.

ECM # 9: Type of HVAC system

The HVAC systems can be generally divided into three categories**[28]**:

i. All-air systems

ii. All-water systems

iii. Air-water systems

All-air systems transfer cooled or heated air from a central plant via ducting, distributing air to the room being served. Whereas, *all water systems* transfer water from a chiller or a boiler, via pipes, to a fan-coil unit (most commonly) in the room being served. An *air-water system* is one in which both air and water (cooled or heated in central plant room) are distributed to room terminals to perform cooling or heating function**[28]**. In this study, only *all-air systems* were evaluated. *All-water* and *air-water* systems are not evaluated because of the following reasons:

- All-water systems are not capable of providing ventilation air to the zone being served, and hence, they will not be able to provide the requited thermal comfort conditions in the zone. Therefore, all-water systems were not evaluated.
- Air-water systems were not evaluated because, in order to assign an air-water system to a zone, two different sub-systems (air-side and water-side) have to be assigned to single a zone. However, Visual-DOE does not provide the scope to assign two

different systems to a zone. Hence, due to this modeling difficulty, air-water systems were not evaluated.

Five different types of *all-air* HVAC systems, namely, variable air volume (VAV), packaged variable air volume (PVAV), constant air volume - reheat (CAV-RH), multi-zone (MZ), and packaged multi-zone (PMZ), were evaluated in this ECM. Annual electric energy used by each system is compared to the base case and results after comparison are shown in **Figure** 4.10.

The type of HVAC system used in the base case is packaged single zone (PSZ). As the name implies, PSZ system is a single-zone system, and hence, in the original design, each unit of the PSZ system was assigned to serve one zone. However, all the five systems that were evaluated are multi-zone systems and therefore, each unit has to be assigned to serve more than one zone. There are several options of doing this, where one unit can be assigned to serve two zones, three zones, or the whole floor. However, in order to make the analysis simple, it was opted to assign one unit to serve each floor. The cooling capacities and airflow rates of the units serving the whole floor were the sum of the cooling capacities and airflow rates of all the individual units serving different zones in the floor. Furthermore, it is to be noted that since heating is not provided in the base case, it was not provided in all the evaluated systems as well.

It can be seen from the **Figure** 4.10 that the highest annual electric energy saving of 26.9% was achieved with the usage of VAV system, followed by the PVAV system,

which resulted in 14.9 % annual electric energy savings. Other systems such as CAV-RH, MZ and PMZ use about 21.3%, 17.9% and 21.8% more electric energy than the base case, respectively.

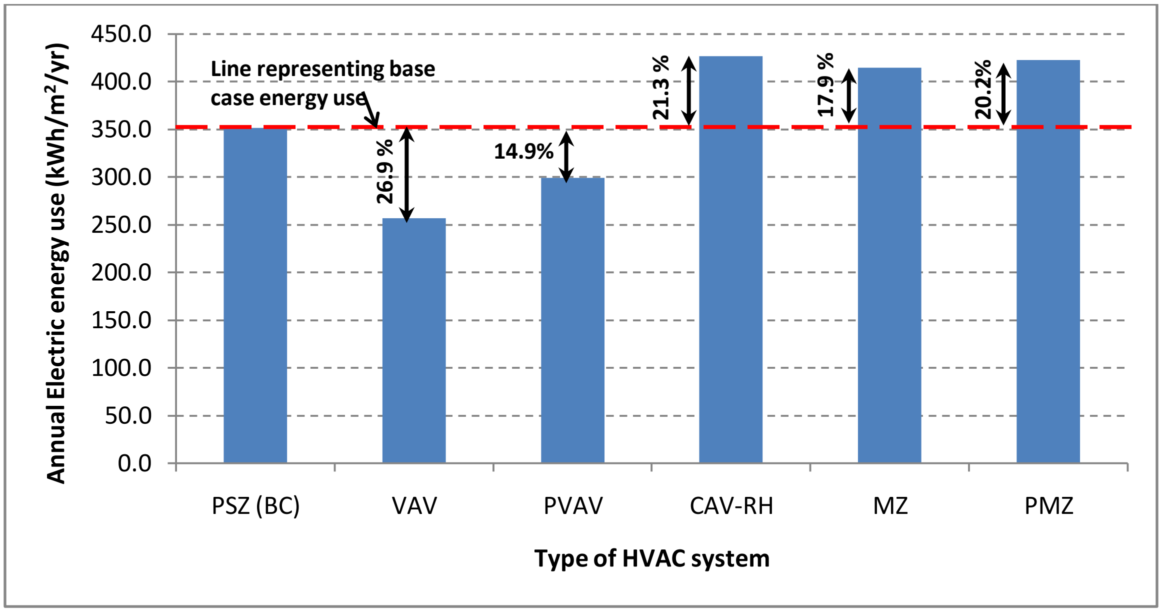


Figure 4.10: Comparison between energy use of base case and different types of *all- air* HVAC systems

VAV system airflow control alternatives:

Among the evaluated HVAC systems, usage of the VAV system, with variable speed drives (VSDs) as flow control option, resulted in annual electric energy savings of 26.9%. In addition to VSDs, the other available airflow control alternatives include *inlet vanes* and *discharge dampers*. In order to investigate the effect of these airflow control alternatives on energy use, comparisons were made between the annual energy usage of VAV system with VSDs, inlet vanes and discharge dampers. The results revealed that annual energy usage increases by 17% when inlet vanes are used and by 33% when

discharge dampers are used. The comparison between the three alternative control options is shown in **Figure** 4.11.

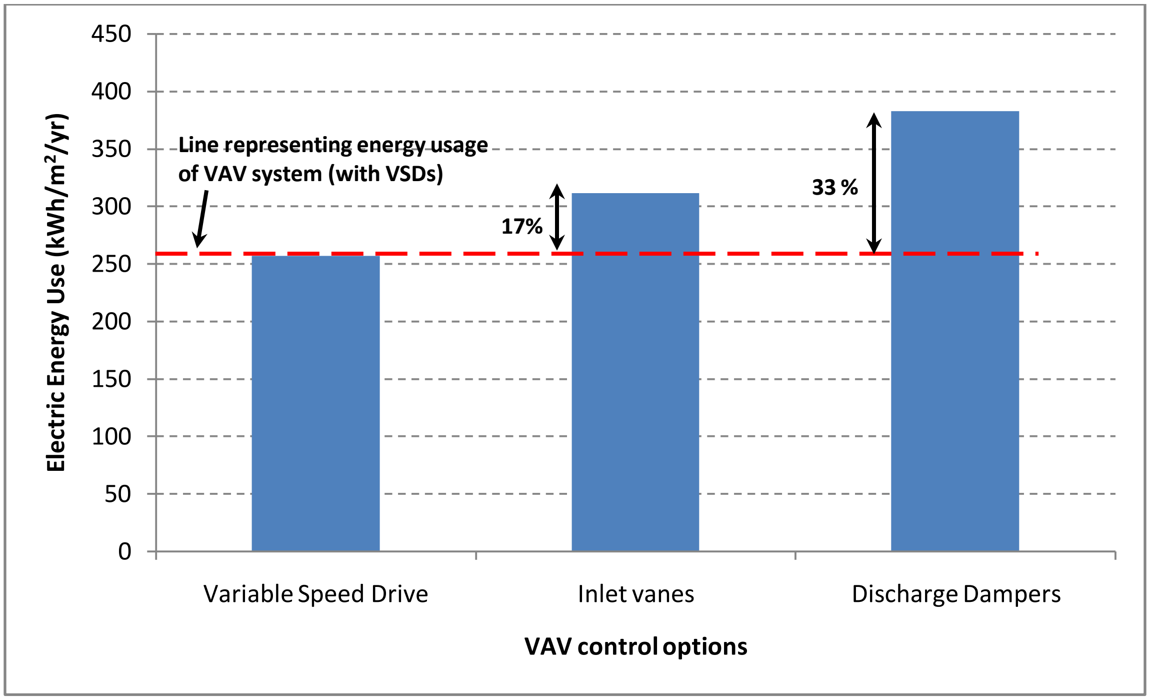


Figure 4.11: Comparison between energy usage of alternative airflow control options in VAV system

Size of HVAC system:

In order to evaluate the energy penalties of over-sizing the HVAC systems, the sizes of HVAC systems in base case were *auto-sized* and the results obtained were compared to the original base case. It was found that the required thermal comfort conditions could be achieved at about 22% lower equipment sizes on average, which corresponds to about 15.9% annual electric energy savings. This indicates that, over-sizing the HVAC systems can result in substantial energy penalties. Furthermore, if the auto-sized systems are operated at setpoint temperature of 24°C, the energy savings increase slightly by 0.5%.

The temperature profile graphs obtained for these evaluations are shown in **Appendix-C.4**.

Moreover, for further analysis, the base case and all five types of HVAC systems were *auto-sized* and a comparison was made between the annual electric energy used by the base case and the evaluated alternatives. The results, as shown in **Figure** 4.12, indicated that VAV system again resulted in the highest annual electric energy savings of 21%.

In addition, analysis was also made by keeping the base case HVAC system of original size and *auto-sizing* the five alternative types of HVAC systems. As expected, the highest annual electric energy saving of 33.6% was achieved when VAV system is used, followed by 22.7% when PVAV system is used, as shown in **Figure** 4.13. It is also to be noted that CAV, MZ and PMZ systems, which were previously using about 25% more electric energy than base case, are now using energy almost equal to the base case. This again shows that over-sizing of the HVAC systems results in considerable energy penalties.

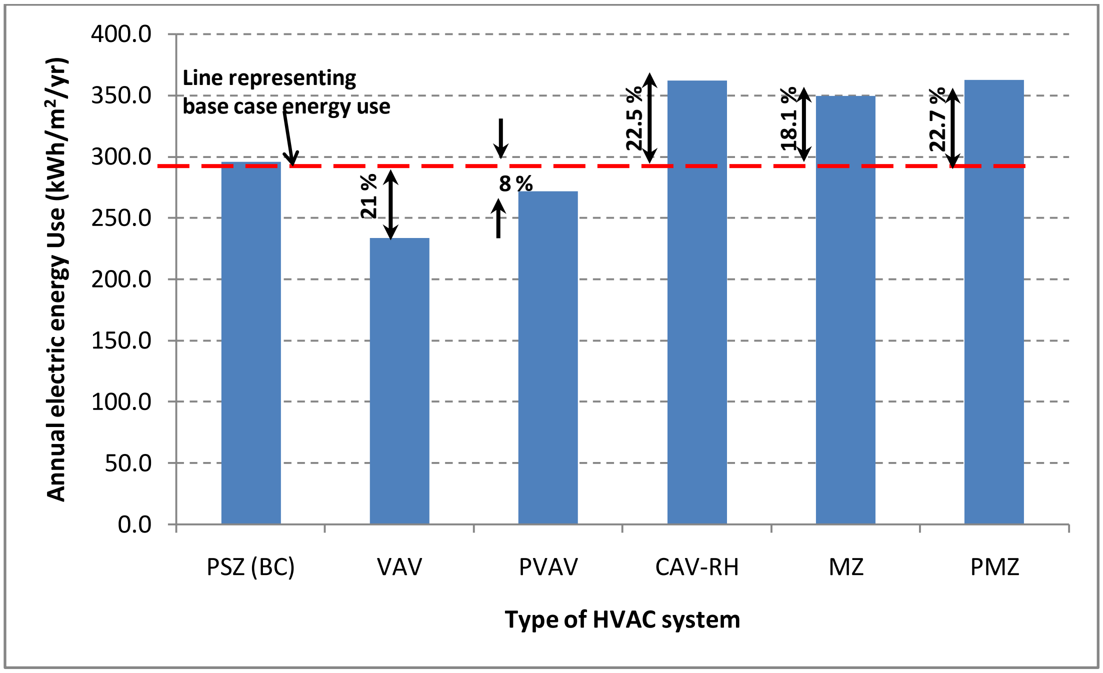


Figure 4.12 Comparison between energy use of base case and different types of HVAC systems, when all the systems are auto-sized

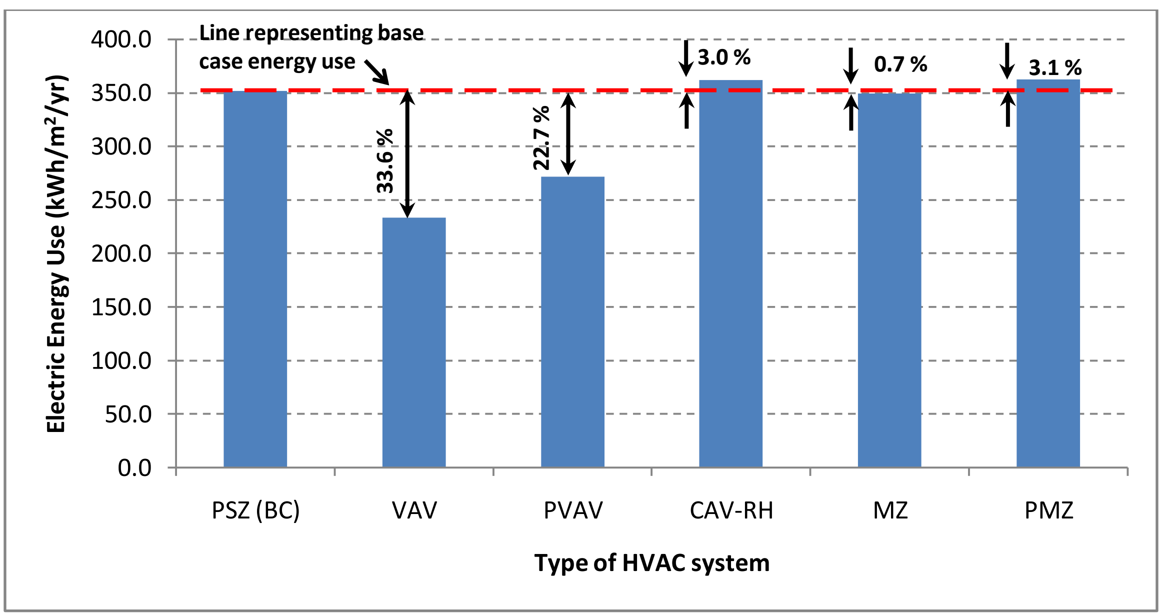


Figure 4.13: Comparison between energy use of base case and different types of HVAC systems, when base case is of original size and all other systems are auto-sized

ECM # 10: Combination of potential ECMs

In this ECM, potential ECMs have been combined in order to determine cumulative energy savings. The combination included ECM#1, 2, 5 and 8 and 9, which consisted of

- ECM-1: Resetting the indoor setpoint temperature from existing 21°C to 24°C for occupied hours during summer,
- ECM-2: Resetting the indoor setpoint temperature to 28°C during unoccupied hours,
- ECM-5: Resetting ventilation rates based on *ASHRAE ventilation standard 62.1-2007*,
- ECM-8: Implementing occupancy based demand controlled ventilation (DCV),
- ECM-9: Usage of VAV system (cooling capacities and airflow autosized) with variable speed drive as airflow control option

The cumulative energy saving achieved for ECM-10 was **41.4%**. The temperature profile graphs obtained after implementation of this ECM are shown in **Appendix-C.5**. A summary of annual electric energy savings achieved for all potential ECMs along with the cumulative energy saving is shown in **Figure** 4.14.

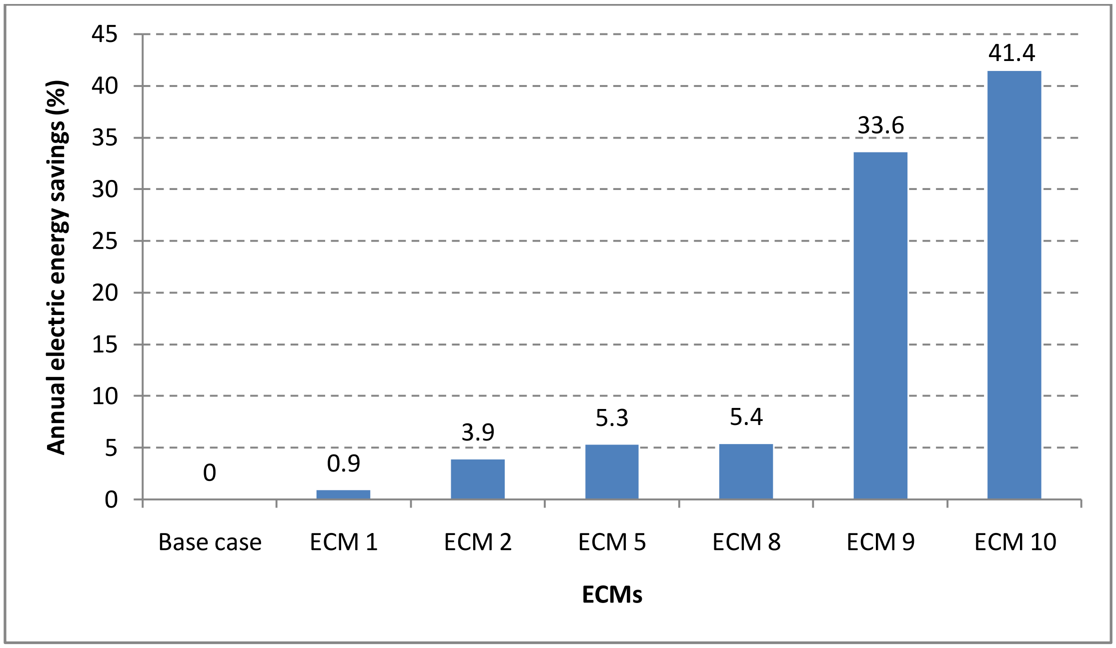


Figure 4.14: Annual electric energy savings for all potential ECMs along with cumulative energy savings (ECM-10)

4.5 SUMMARY OF ALL EVALUATED ECMs

In conclusion, a summary of annual electric energy savings achieved for all the evaluated ECMs is presented in **Table** 4.3. The highest annual electric energy saving of **41.4%** was achieved when all the potential ECMs were combined. In addition, it is worth mentioning again that the combination of potential *zero investment* ECMs resulted in savings of upto **13.3%**.

Table 4.3: Summary of all tested ECMs

ECM No.	Description	Comments	Level of Investment	Annual Electric Energy Savings (%)
ECM 1	Setpoint temperature reset	Setpoint temperature in all the zones is reset from 21°C to 24°C for both summer and winter seasons	Zero	0.6 – 1.8
ECM 2	Night time setback	During unoccupied periods, setpoint temperatures ranging from 28°C to 32°C are tested	Zero	3.9 – 7.4
ECM 3	Combination of ECM # 1 and 2	Combination of ECM # 1 and 2	Zero	7.1 – 11.0
ECM 4	Time scheduled operation	During unoccupied hours, HVAC system is switched off	Zero	23.7 – 27.8
ECM 5	Implementing ASHRAE ventilation standard 62.1	Ventilation air is reset based on old and new ASHRAE Standard 62.1	Zero	3.9 – 5.3
ECM 6	Combination of ECM # 1, 2 and 5	Combination of ECM # 1, 2 and 5	Zero	9.8 – 13.3
ECM 7	Air Side Economizers	Temperature, Enthalpy and Temperature-Enthalpy economizers are tested	Low	2.6 – 3.8
ECM 8	Occupancy Based DCV	Ventilation is provided only during occupied hours	Low	5.4
ECM 9	Type of HVAC system	Five different types of HVAC systems were evaluated	High	Upto 33.6
ECM 10	Combination of potential ECMs	Combination of ECMs # 1, 2, 5, 8 and 9	High	41.4

CHAPTER 5

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 SUMMARY AND CONCLUSIONS

This research has been carried out in different phases to achieve its objectives. In the initial stage, extensive literature was reviewed to determine the status of energy use in buildings in Saudi Arabia. It is evident that buildings use a major portion of the energy utilized in Saudi Arabia. Within buildings, HVAC systems have shown to use a large portion of the energy, contributing to about 60-75% of the total use. Therefore, in order to identify strategies that could help in reducing the energy used by HVAC systems, several recent studies were reviewed. Among the various identified strategies, few strategies, which were feasible, were selected to be implemented to the building under study.

The building chosen, as the case study for this research, is an office building located in the hot-humid climate of Al-Khobar, Saudi Arabia. Prior to implementation of the ECMs to the selected building, a detailed energy audit of the building was performed. The audit consisted of five stages: building characteristics analysis, a walk-through survey, analysis of the electric energy utility bills, thermal comfort assessment and detailed building energy simulation.

The first stage, *building characteristics analysis*, included review of design drawing to obtain physical characteristics of the building, and interviews with building maintenance personnel to obtain operational characteristics of the building. The data obtained during this stage of the audit process was crucial in development of the base case model of the building under study. The second stage of the energy audit process was a *walkthrough survey* of the building. This walkthrough survey was conducted to obtain additional data regarding the building. Several important observations were made during the survey, which were very helpful in base case development.

The third stage of the energy audit process was to analyze the *building electric energy utility bills* in order to determine the energy use pattern of the building. The utility bills of the building for the year 2008 were obtained from the building management. The data obtained in this stage was useful in the later stage of the energy audit process, for the calibration of the base case model of the building.

The fourth stage of the energy audit process was *thermal comfort assessment* of the building. The thermal comfort assessment included both subjective and objective assessments. The results of the subjective assessment indicated that air humidity and air temperature were found to be satisfactory by most of the occupants, in all the zones selected for survey. However, most of the respondents' complaints were regarding air temperature. In zone-1 of all the three selected floors, most of the occupants indicated that they felt slightly warm. As explained earlier, this could be because of the fact that this zone is exposed to two orientations south and east, which tend to receive high solar

heat gains. In addition, the window to wall ratio of the facades on these orientations is about 50%, which further increases the solar heat gains. It was recommended that shading devices should be used to shade the glazing on these facades from solar radiation, which may help alleviate the problem.

In other zones where respondents indicated that they feel slightly cold, the setpoint temperature could be increased from the existing 21°C to a value within the ASHRAE specified thermal comfort range (23-25.5°C). Furthermore, although in some zones the occupants indicated that they are comfortable, the existing setpoint temperature of 21°C is not energy efficient. Since the ASHRAE comfort range is 23 to 25.5°C, the setpoint can be increased by 2-5°C, which could result in tangible energy savings, while still maintaining required thermal comfort.

The results of the objective thermal comfort assessment indicated that in most of the zones, the thermal conditions are maintained within the comfort levels except for a few zones in which the air temperature and humidity go beyond the ASHRAE recommended range. The deviations between the measured and designed thermal conditions were incorporated in the base case model during the calibration process, in order to bring the base case model as close to the real building as possible.

The fifth stage of the energy audit process consisted of *detailed building energy simulation*. The base case model of the building was developed using Visual-DOE hourly energy simulation program. Ten ECMs were evaluated in this study. The ECM#1,

setpoint temperature reset, included resetting the setpoint temperature to 24°C during summer. This resulted in annual electric energy saving of about 1%. Furthermore, temperatures ranging from 23°C to 26°C were tested in increments of 1°C. The results indicated that for one degree (°C) increase in setpoint temperature, on an average, there was an increase of 0.4% in the annual electric energy savings. In ECM#2, *night-time setback*, the setpoint temperature during unoccupied hours was raised to 28°C. This resulted in annual electric energy savings of 3.9%. In addition to 28°C, temperature values ranging from 29°C to 32°C were also tested. This indicated that for each degree (°C) increase in setpoint temperature, there is an increase of 0.9% in annual electric energy savings.

The ECM#3 is a combination of ECM#1 and 2. In this combined ECM, the setpoint temperature during occupied hours was set to 24°C and during unoccupied hours, temperature values ranging from 28°C to 32°C were tested. This resulted in annual electric energy savings of 7.1 to 11%. The ECM#4, *time scheduled operation*, included switching off HVAC system during unoccupied hours and switching-on on the next day either before or at the start of occupancy. This resulted in savings ranging from 23.7 to 27.8%. However, although ECM-4 is able to achieve high energy savings annually, it is to be noted that it involves switching off HVAC system during unoccupied hours, which may not be feasible in some cases, as it may result in thermally uncomfortable environment.

The ECM#5 included resetting the ventilation rates based on the values prescribed by ASHRAE standard 62.1. The implementation of the version of the standard prior to 2004 resulted in annual electric energy savings of 3.9% and the implementation of the latest version of the standard released in 2007 resulted in 5.3% annual electric energy savings. The ECM#6 was combination of potential zero investment ECMs. The combination included ECM 1, 2 and 5. The results indicated that the annual electric energy savings ECM#6 range from 9.8 to 13.3%. It is worth mentioning that the substantial savings achieved for ECM#6 does not require any investment or modification to be done in the existing HVAC system. It is the saving achieved entirely by making simple adjustments in the operational strategies of the existing HVAC system.

In ECM#7 three types of economizers, *Temperature*, *Enthalpy* and *Temperature and Enthalpy* were tested. The results indicated that with the use of *Temperature Economizer,* annual energy saving of 3.8% was achieved compared to the base case with no economizer. Usage of *Enthalpy economizer* resulted in an annual electric energy saving of 2.7%, and usage of *Temperature and Enthalpy* economizer resulted in an annual electric energy saving of 2.6%. In ECM#8, DCV is implemented by providing ventilation only during the occupancy periods and closing ventilation during unoccupied periods. The implementation of this ECM to the base case resulted in an annual energy saving of about 5.4%.

In ECM#9, five different types of *all-air* HVAC systems, namely, variable air volume (VAV), packaged variable air volume (PVAV), constant air volume - reheat (CAV-RH),

multi-zone (MZ), and packaged multi-zone (PMZ), were evaluated. Among the evaluated systems, highest annual electric energy saving of 33.6% was achieved for the VAV system (autosized and with the usage of VSDs). In ECM#10, potential zero investment ECMs were combined in order to determine the cumulative energy savings. The combination included ECM 1, 2, 5, 8 and 9. The results indicated that about 41.4% annual electric energy savings could be achieved when the above-mentioned ECMs are combined.

In conclusion, among the evaluated ECMs, energy saving of upto 13.3% was obtained for ECM #6, which is a combination of potential zero investment ECMs. It is to be noted that, this substantial annual energy saving of 13.3% achieved for the ECM#6, does not require any investment or modification to be done in the existing HVAC system. It is the saving achieved entirely by making simple adjustments in the operational strategies of the existing HVAC system. Conclusively, the combination of all potential ECMs resulted in substantial 41.4% annual energy savings.

5.2 RECOMMENDATIONS

Based on the analyses of the results of this study, the below recommendations are made. Although the recommendations are based on results obtained for the specific office building under study, most of the recommendations are equally applicable to similar buildings operated in the same or similar climates.

1. The set-point temperature during occupied hours should be maintained within the ASHRAE specified thermal comfort range of 23-25.5°C, as it can result in annual electric energy savings ranging from 0.6 to 1.8%, compared to slight deviation from the lower limit of such range. Furthermore, for each degree (°C) increase of setpoint temperature from the lower limit of comfort range, on an average, there is an increase of 0.4% in the annual electric energy savings.

2. It is highly recommended that night-time setback in setpoint temperature is implemented. Increasing the setpoint temperature during unoccupied hours is a very efficient means to save valuable electric energy. Energy savings upto 7.4% can be achieved by implementation of night-time setback strategy. Furthermore, for one degree (°C) increase in setpoint temperature during unoccupied period, on an average, there is an increase of 1% in the annual electric energy savings.

3. The operation of the HVAC system should follow a time schedule. Switching off HVAC system during unoccupied periods can result in annual electric energy savings ranging from 23.7 to 27.8%, as opposed to continuous operation. If switching off HVAC system during unoccupied hours is not practical, then night-time setback should be implemented, as the savings can be 1% per 1°C increase from the regular setpoint temperature.

4. The outside air ventilation rate should be designed based on latest ASHRAE ventilation standard 62.1-2007, as it takes into account the zone area as well as the

zone occupancy for calculating the ventilation rate, as opposed to only the occupancy related component in previous standards. The implementation of the standard results in annual electric energy saving of about 5.3%.

5. The usage of the economizer system requires some amount of investment to be made for installation of additional sensors, while the savings achieved are relatively low, 3.8% for temperature economizer, 2.7% for enthalpy economizer and 2.6% for temperature-enthalpy economizer. Hence, economizer system should be used in hot and humid climates after careful thought.

6. Demand Controlled Ventilation (DCV) strategy, although requires investment to be made for installation of additional sensors, can be used and may result in energy savings of upto 5.4%.

7. VAV system has shown to produce the highest energy savings of 33.6% in the investigated office building. Accordingly, it could be the best choice for office buildings. Furthermore, it is recommended to use variable speed drives to control airflow in VAV systems, as they are the most energy efficient option when compared to inlet vanes and discharge dampers.

8. Avoid over sizing the HVAC system as over-sizing can result in substantial energy penalties. For the case study, it was found that the required thermal comfort

conditions could be achieved, on average, at about 22% lower equipment sizes. The over-sizing resulted in about 15.9% more energy usage annually.

9. HVAC systems should be maintained on a regular basis to ensure energy efficient operation. The maintenance personnel should periodically inspect the air-handling units, including the dampers, diffusers and grills, as it was found in the building under study that the ventilation dampers in some of the AHU's were completely closed. This could result in thermal discomfort to the occupants in the building.

10. The result of thermal comfort assessment conducted in this study indicated that most of the thermal discomfort was observed in the zones facing south-east orientation. Therefore, shading the glazing on the facades facing these orientations is highly recommended, as solar heat gains from the south-east orientation contributes substantially to the cooling load.

5.3 GUIDELINES FOR ENERGY EFFICIENT DESIGN AND OPERATION OF HVAC SYSTEMS IN OFFICE BUILDINGS

Based upon the analysis of the results, outcome from the analyses of the questionnaire and walkthrough survey, the guidelines have been formulated for energy efficient design and operation of HVAC systems in hot humid climate universally and particularly for the climate of Saudi Arabia. The proposed guidelines are illustrated as follows:

1. Type of HVAC system

In office buildings, consider using VAV system, as it is more energy efficient when compared to other all-air systems such as PSZ, PVAV, CAV-RH, MZ, and PMZ. For example, for the investigated building VAV system proved to achieve the required thermal comfort conditions at 118.1 kWh/m^2/yr lesser energy usage when compared to PSZ system. This corresponds to 33.6% annual electric energy savings. Additional savings might even be achieved for other buildings.

Air Flow Control:

Consider using variable speed drives for controlling airflow in VAV systems, as they are more energy efficient when compared to discharge dampers and inlet vanes. For example, for the investigated building VSDs were able to achieve energy savings of 54 kWh/m^2/yr when compared to inlet vanes, equivalent to 17% annual energy savings. When compared to discharge dampers, VSDs were able to achieve savings upto 126 kWh/m^2/yr, corresponding to 33% annual energy savings.

2. Size of HVAC system

Ensure that HVAC equipment is properly sized for the intended application, as oversized equipment results in more energy usage. For example, the HVAC equipment in the investigated building was found to be 22% oversized, based on calculations performed

using Visual-DOE software. Resizing the equipments resulted in annual electric energy savings of upto 15.9%. This corresponds to energy savings of 56 kWh/m^2/yr.

3. Outside air ventilation:

Consider determining the ventilation rate based on ASHRAE standard 62.1-2007, as it takes into account the zone area as well as the zone occupancy for calculating the ventilation rate, as opposed to only the occupancy related component in previous standards. The implementation of the standard may result in annual electric energy savings of about 18.5 kWh/m^2/yr, equivalent to 5.3% annual energy savings.

In addition, outdoor air supply systems can be equipped with motorized dampers that will automatically close when the spaces served are not in use, as closing ventilation during unoccupied period results in energy savings of upto 19.1 kWh/m^2/yr (5.4% annually) , when compared to providing continuous ventilation.

4. Air-side economizers

Air-side economizers are not very effective in hot-humid climates such as that of Al-Khobar. For example, for the three types of economizers evaluated for the case study, merely 3.8% annual electric energy saving was achieved for *temperature* economizer, only 2.7% for *enthalpy* economizer and barely 2.6% for *temperature-enthalpy*

economizer. The savings are equivalent to 13.2, 9.6 and 9.2 kWh/m^2/yr, for temperature, enthalpy and temperature-enthalpy economizers, respectively.

In addition to achieving low energy savings, another factor which could limit the use of economizers is the fact that they require additional investment to be made for the installation of extra sensors needed for their operation. Therefore it is not practical to utilize economizers in hot humid climates, especially the temperature economizer, which in addition to the above drawbacks, does not provide humidity control.

5. Set-point temperature

- During occupied hours, consider using set point temperature within the ASHRAE specified thermal comfort range of 23-25.5°C. Each degree (°C) increase in set point temperature from lower limit of such range results in energy savings of 2 kWh/m^2/yr, corresponding to annual energy savings of 0.4%, on average. For example, during summer, an increase from 21°C to 24°C in the investigated building resulted in annual energy savings of 1%, corresponding to energy savings of 3.5 kWh/m^2/yr.

- During unoccupied hours, reduction in energy use can be achieved by raising the set point temperature to a higher value outside of the comfort range. Each degree (°C) increase in set point temperature from the higher limit of comfort range (25.5°C) results in energy savings of 3.2 kWh/m^2/yr, corresponding to 0.9% annual energy savings. For example, for the investigated case study building, setting the thermostat

temperature to 28°C during unoccupied hours resulted in energy savings of 13.7 kWh/m^2/yr, corresponding to 3.9% energy savings, annually.

6. Window shading

Consider shading the glazing, especially on south and east orientations, as it was found during the thermal comfort assessment survey that, on average, 50% of the respondents located in zones facing south and east orientations indicated that they felt slightly warm at their workplaces.

7. Air handling unit (AHU) maintenance

Energy efficient operation of HVAC system totally depends on continuous maintenance of each of its component. However, during the walkthrough survey conducted for the case study building, it was observed that the outside air dampers of some of the air handling units were completely closed, which indicates lack of proper maintenance. Therefore, based on this observation, it is recommended to ensure proper maintenance of the following components of the AHUs:

- ✓ Supply/outside air dampers
- ✓ Ductwork
- ✓ Diffusers/grills
- ✓ Fans

REFERENCES

1. Energy Information Administration (2009), *"International Energy Outlook"*, U.S. Department of Energy, Washington, D.C.

2. U.S. Department of Energy (2009), Independent statistics and analysis on greenhouse gases.

3. CIA (2009), *"The World Factbook"*, Central Intelligence Agency, USA.

4. Lombard, L. P., Ortiz, J. and Pout, C. (2008), *"A review on buildings energy consumption information"*, Energy and Buildings, P.394-398.

5. Chao, C. Y. H. and Kwong, P. C. W. (2004), *"Energy in buildings in Hong Kong - A lesson for the mainland"*, Department of Mechanical Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong.

6. Saidur, R. (2009), *"Energy consumption, energy savings and emission analysis in Malaysian office buildings"*, Energy Policy, Vol.37, P.4104-4113.

7. Said, S. A. M., Habib, M. A. and Iqbal, M. O. (2003), *"Database for building energy prediction in Saudi Arabia"*, Energy Conversion and Management, Vol.44, P.191–201.

8. Kajtar, L., Erdosi, I. and Bako-Biro, Z. (2000), *"Thermal and air quality comfort of office buildings based on new principles of dimensioning in Hungary"*, Periodica Polytechnica Ser. Mech. Eng., Vol.44, No.2, P.265-274.

9. Al-Homoud, M. S. (1997), *"Optimum thermal design of office buildings"*, International Journal of Energy Research, Vol.21, P.941-957.

10. Al-Rubaih, M. S. (2008), *"Energy efficient envelope design for schools in Saudi Arabia"*, M.S. Thesis, KFUPM.

11. Saudi Electricity Company (2008), Annual Report.

12. Al-Arfag, K. A. (2002), *"Thermal insulation in buildings and its contribution to conserve electrical energy consumption"*, Proceedings of the first Symposium on Energy Conservation and Management in Buildings Conference, Saudi Arabia, 5-6 February, Vol.1, P.49-58.

13. Al-Rabghi, O. M. and Akyurt, M. M. (2004), *"A survey of energy efficient strategies for effective air conditioning"*, Energy Conversion and Management P.1643–1654.

14. Al-Ajlan, S. A., Smiai, M. S. and Elani, U. A. (1998), *"Effective tools toward electrical energy conservation in Saudi Arabia"*, Energy Converison and Management, Vol.39, No.13, P.1337-1349.

15. Al-Sulaiman, F. A. and Zubair, S. M. (1996), *"A survey of energy consumption and failure patterns of residential air-conditioning units in eastern Saudi Arabia"*, Energy and Buildings, Vol.21. , No.10, P.967-975.

16. Zubair, S. M., Bahel, V., Abdel-Nabi, D. Y. and Abdelrahman, M. A. (1989), *"A case study for improving performance and life expectancy of air-conditioning systems at a university campus"*, ASHRAE Transactions, Vol.95, No.1, P.349.

17. Ali, A. M. and Aftab, A. (1991), *"Cost-effective use of thermal insulation in hot climates"*, Building and Environment, Vol.26, No.2, P.189-194.

18. Hasnain, S. M., Alawaji, H. S., Al-Ibrahim, A. M. and Smiai, S. M. (2000), *"Analysis of electric energy consumption in an office building in Saudi Arabia"*, ASHRAE Transactions, ProQuest Science Journals, Vol.106, P.173.

19. Matthews, E. H., Botha, C. P., Arndt, D. C. and Malan, A. (2001), *"HVAC control strategies to enhance comfort and minimize energy usage"*, Energy and Buildings, Vol.33, P.853-863.

20. Ardehali, M. M. and Smith, T. F. (1997), *"Evaluation of HVAC system operational strategies for commercial buildings"*, Energy Conversion and Management, Vol.38, No.3, P.225-236.

21. Nurdil, E. and Turkmen, H. (2008), *"Analysis of annual heating and cooling energy requirements for office buildings in different climates in Turkey"*, Energy and Buildings Vol.40 P.763–773.

22. Pan, Y., Huang, Z. and Wu, G. (2007), *"Calibrated building energy simulation and its application in a high-rise commercial building in Shanghai"*, Energy and Buildings Vol.39 P.651–657.

23. Mathews, E. H. and Heerden, E. V. (1999), *"A tool for integrated HVAC building energy and control analysis, Part2: Control simulations with QUICKcontrol"*, Building and Environment, Vol.34, P.451-467.

24. Johnson, G. A. (1984), *"Retrofit of a constant volume air system for variable speed fan control"*, ASHRAE Transactions Vol.90(2B), P.201-211.

25. Ardehali, M. M. and Smith, T. F. (1996), *"Evaluation of variable volume and temperature HVAC system for commercial and residential buildings"*, Energy Conversion and Management, Vol.37, No.9, P.1469-1479.

26. ASHRAE (2008), *"Handbook of Applications"*, American Society of Heating Refrigeration and Air-conditioning Engineers, Atlanta, GA, USA.

27. Hatley, D. D., Meador, R. J., Katipamula, S., Brambley, M. R. and Wouden, C. L. (2005), *"Energy Management and Control System: Desired Capabilities and Functionality"*, Pacific Northwest Laboratory for The United States Department of Energy (US-DOE).

28. Howell, R. H., Sauer, H. J. and Coad, W. J. (2005), *"Principles of Heating, Ventilation and Air-Conditioning"*, American Society of Heating Ventilation and Air-Conditioning Engineers, Inc.

29. ASHRAE (2004), *"ANSI/ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy"*, American Society of Heating Refrigeration and Air-conditioning Engineers, Atlanta, GA, USA.

30. IRC (2003), COPE Project Research Reports, Institute for Research in Construction, National Research Council of Canada.

31. Al-Ashwal, N. T. (2008), *"Energy efficient window design through the integration of daylighting and artificial lighting in office buildings"*, Master Thesis, KFUPM.

32. ASHRAE (2009), *"Handbook of Fundamentals"*, American Society of Heating Refrigeration and Air-conditioning Engineers, Atlanta, GA, USA.

33. User Manual, Dickson D200 Temperature and Humidity Data Logger.

34. VisualDOE User Manual (2004), Architectural Energy Corporation.

35. Neymark, J., Judkoff, R., Knabe, G., Le, H. T., Durig, M., Glass, A. and Zweifel, G. (2002), *"Applying the building energy simulation test (BESTEST) diagnostic method to verification of space conditioning equipment models used in whole-building energy simulation programs"*, Energy and Buildings, Vol.34, P.917–931.

36. Pasqualetto, L., Zmeureanu, R. and Fazio, P. (1998), *"A Case Study of Validation of an Energy Analysis Program: MICRO-DOE2.1 E"*, Building and Environment, Vol.33, No.1, P.2141.

37. Sullivan, R. (1998), *"Validation studies of the DOE-2 builidng energy simulation program"*, Building Technology Department, Lawrence Berkeley National Laboratory, University of California, Berkeley, USA.

38. ASHRAE (2004), *"ANSI/ASHRAE Standard 140-2004: Standard Method of Test for the Evaluation of Building Energy Analysis and Computer Programs"*, American Society of Heating, Refrigeration and Air-Conditioning Engineers, Atlanta, GA, USA.

39. ASHRAE (2007), *"ASHRAE Standard 90.1-2007: Energy Standard for Buildings Except Low-Rise Residential Buildings"*, American Society of Heating Ventilation and Air-conditioning Engineers, Atlanta, GA, USA.

40. Raftery, P., Keane, M. and Costa, A. (2009), *"Calibration of a detailed simulation model to energy monitoring system data: A methodology and case study"*, Eleventh International IBPSA Conference, Glasgow, Scotland, July 27-30.

41. Reddy, A. T. (2006), *"Literature review on calibration of building energy simulation programs: Uses, problems, procedures, uncertainity and tools"*, ASHRAE Transactions, Vol.112, P.226.

42. Reddy, S. N., Hunn, B. D. and Hood, D. B. (1994), *"Determination of retrofit savings using a calibrated building energy simulation model"*, Proceedings of the ninth symposium on improving building systems in hot and humid climates, Arlington, TX, May 19-20.

43. Yoon, J., Lee, E. J. and Claridge, D. E. (2003), *"Calibration procedure for energy performance simulation of a commercial building"*, Journal of Solar Energy Engineering, Vol.125, P.251-257.

44. Michael, J. C., Walker, C. E. and Franconi, E. (2001), *"Determining baseline energy consumption and peak cooling loads of a 107-year-old science museum using DOE-2.1E"*, Seventh International IBPSA Conference, Rio de Janeiro, Brazil, August 13-15.

45. ASHRAE (2002), *"ASHRAE guideline 14: Measurement of energy and demand savings"*, American Society of Heating Ventilation and Air-Conditioning Engineers, Atlanta, GA, USA.

46. ASHRAE (2007), *"ASHRAE Standard 62.1-2007: Ventilation for Acceptable Indoor Air Quality"*, American Society of Heating Ventilation and Air Conditioning Engineers, Atlanta, GA, USA.

APPENDIX – A

Sample Thermal Comfort Assessment Questionnaire

Thermal Comfort Assessment Survey

Section 1: General Information

Name (Optional)		Location (Floor)		Age (Optional):
Job title (Optional)		Working since		

Section 2: Thermal Comfort

Please mark (✓) at the appropriate box

	Statements	Scale					N/A
		All the time	Most of the time	Some time	Seldom	Never	
1	I feel comfortable with **air temperature** at my workplace						
2	I feel comfortable with **air humidity** at my workplace						
3	The **air movement** at my workplace is satisfactory						
4	I feel **inadequate ventilation** for performing my work						
5	My working productivity is adversely effected due to thermal discomfort						
6	I have frequent complaints about air conditioning at my workplace						
7	I use pedestal fan for more cooling at my workplace						
8	I feel warm in summer during office hours because my workplace is exposed to outside (near exterior walls)						

The overall **thermal comfort condition** at my workplace is						
☐ Too cold	☐ Cold	☐ Slightly cold	☐ Comfortable	☐ Slightly warm	☐ Hot	☐ Too hot

The overall **humidity condition** at my workplace is						
☐ Too humid	☐ Humid	☐ Slightly humid	☐ Comfortable	☐ Slightly dry	☐ dry	☐ Too dry

The overall **air movement** at my workplace is						
☐ Too high	☐ High	☐ Slightly high	☐ Comfortable	☐ Slightly low	☐ Low	☐ Very low

I feel thermally uncomfortable at my workplace during:	Summer ☐	Winter ☐	Both ☐	None ☐

Please add any additional comments

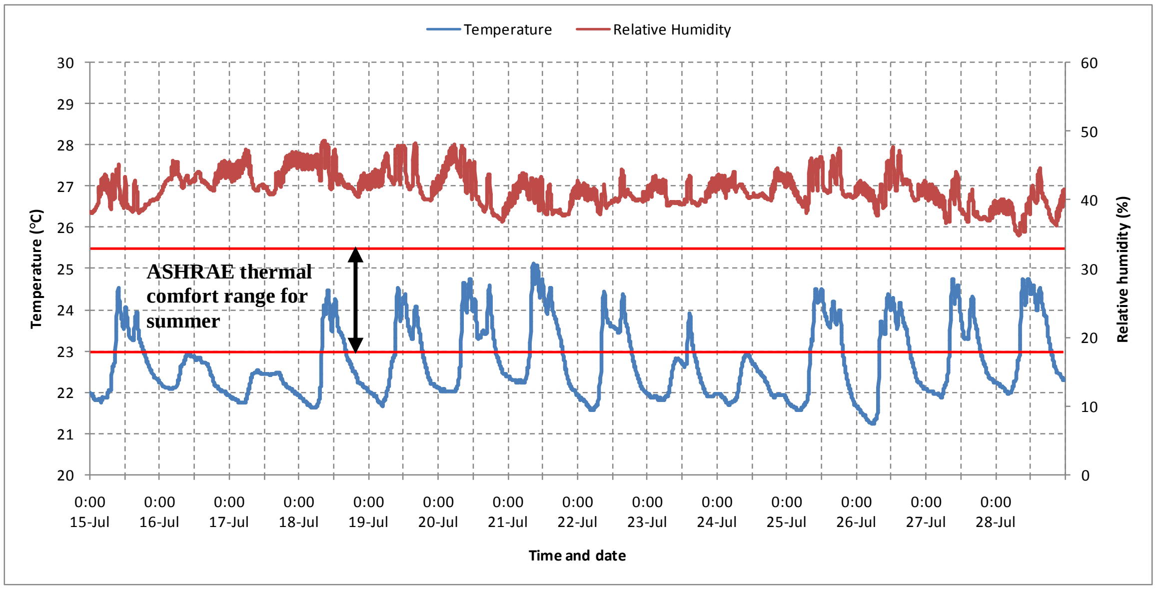
....

....

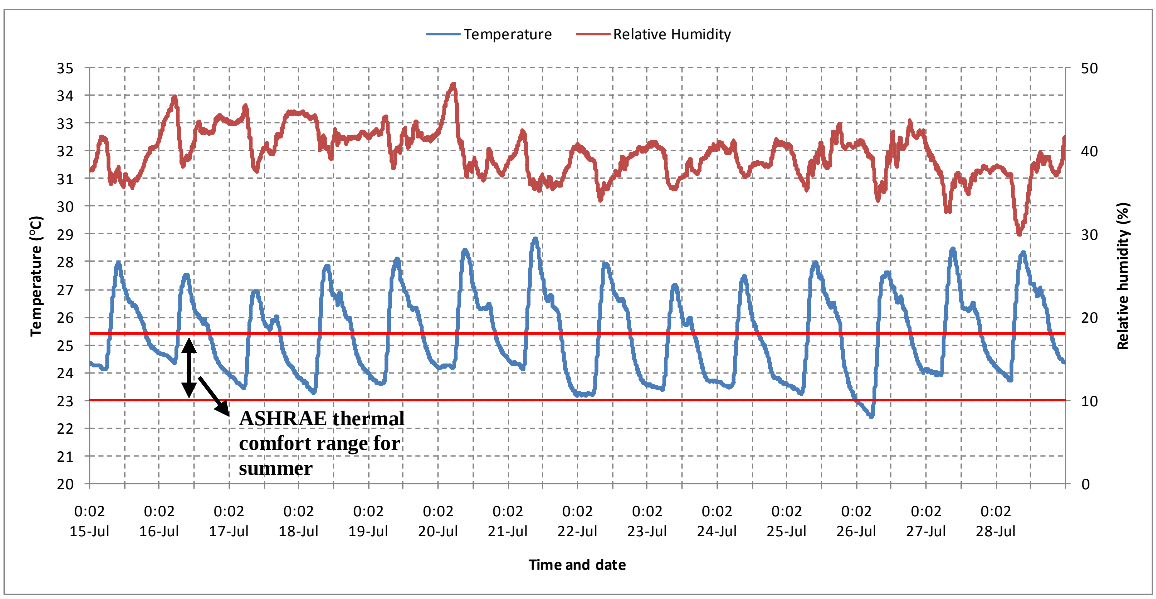
....

APPENDIX – B

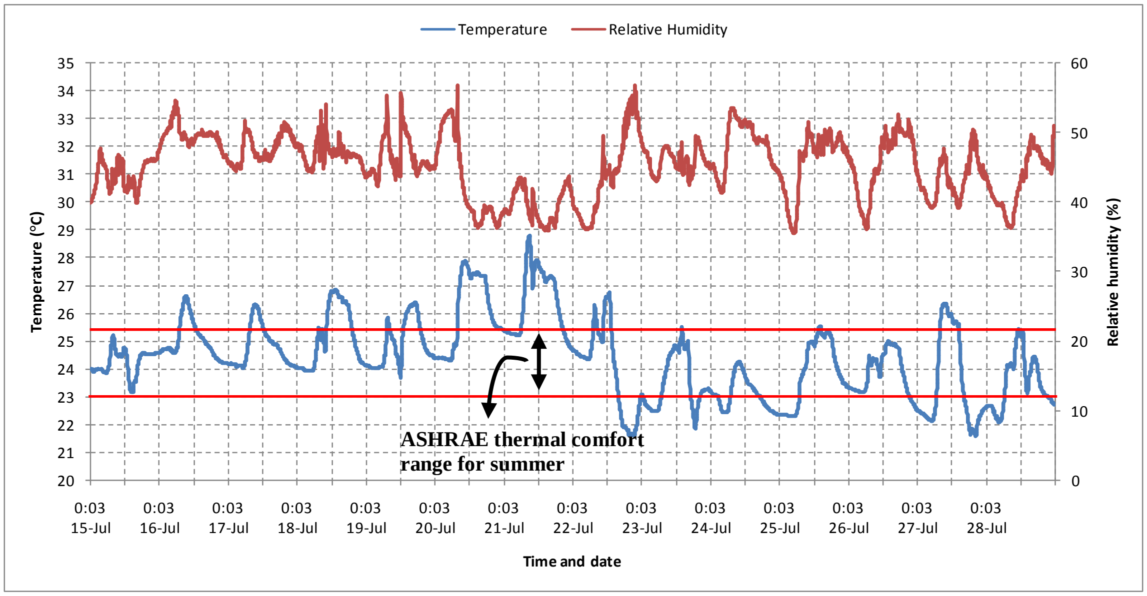
Objective Thermal Comfort Assessment Results



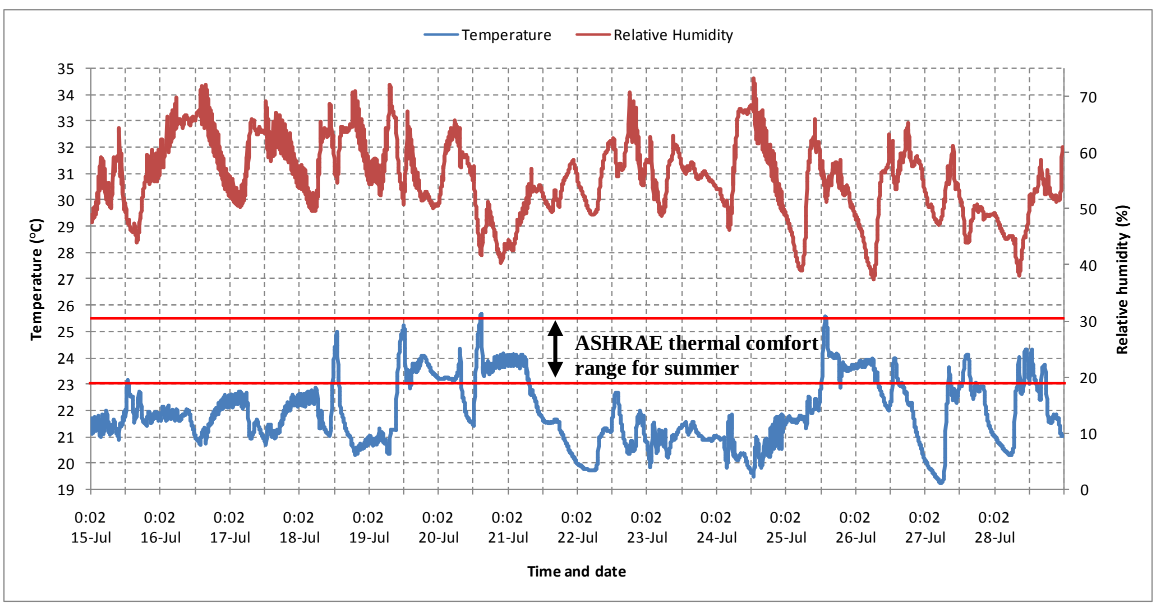
Appendix B.1: Air temperature and relative humidity profiles for zone-1 of ground floor



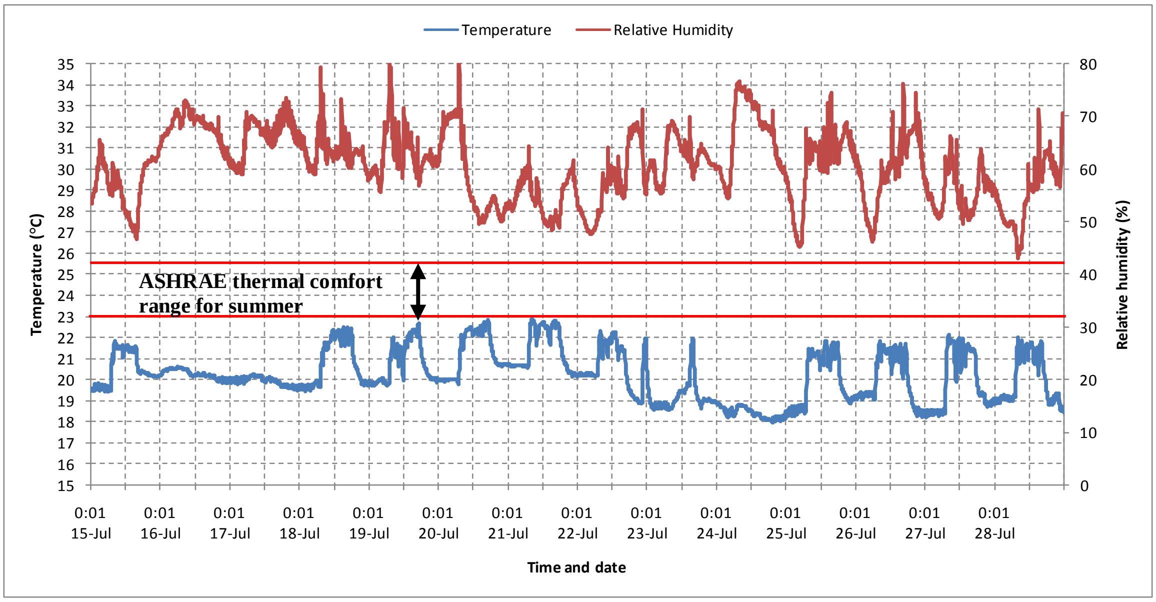
Appendix B.2: Air temperature and relative humidity profiles for zone-2 of ground floor



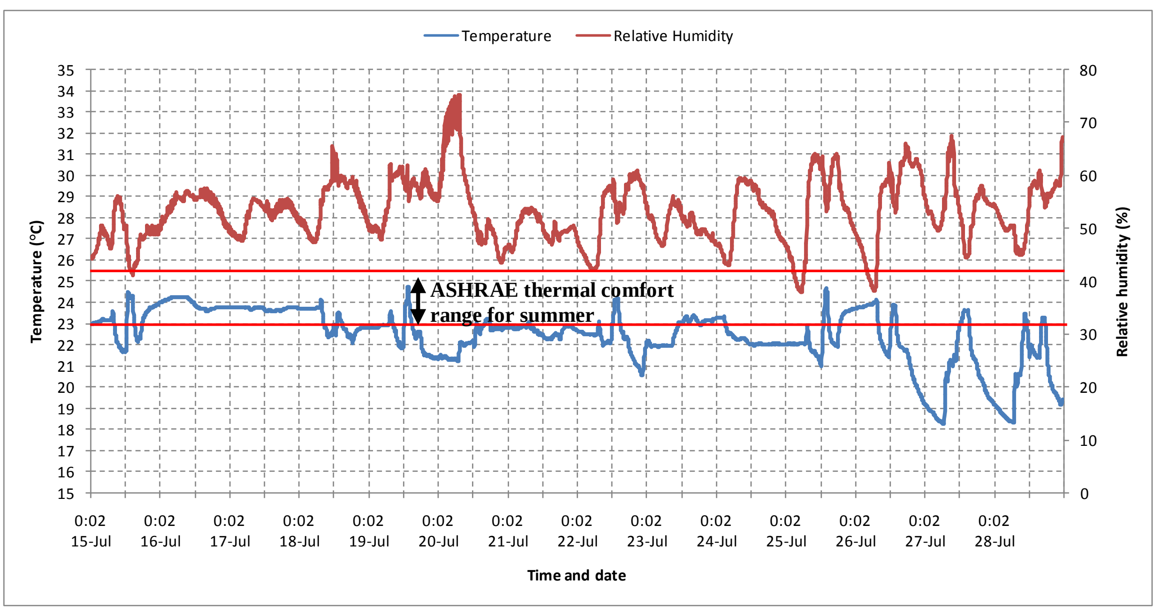
Appendix B.3: Air temperature and relative humidity profiles for zone-1 of second floor



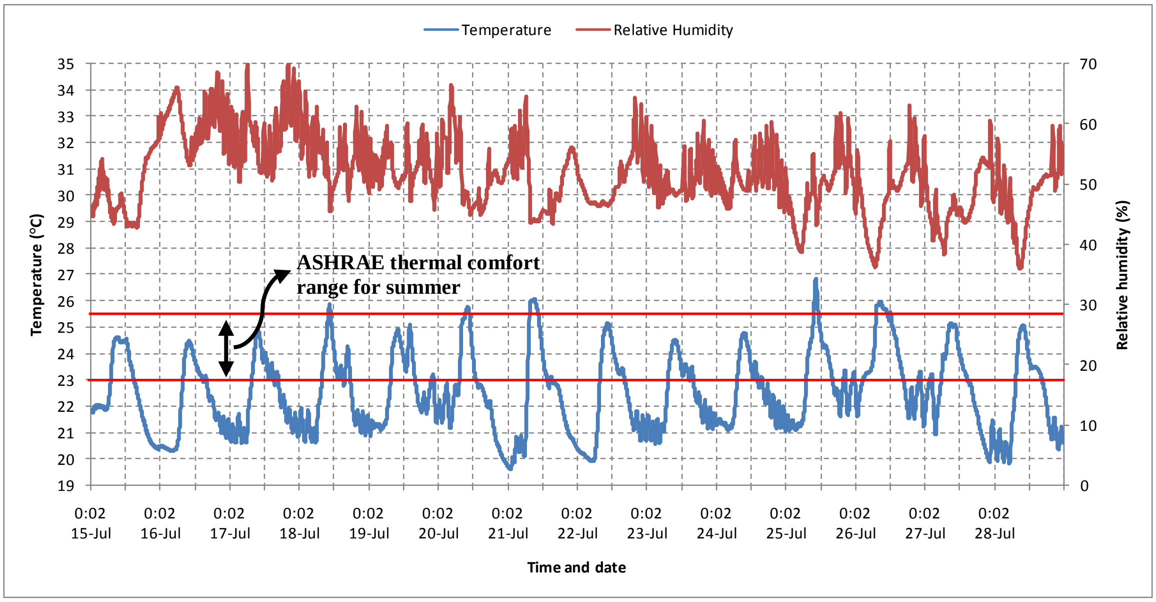
Appendix B.4: Air temperature and relative humidity profiles for zone-2 of second floor



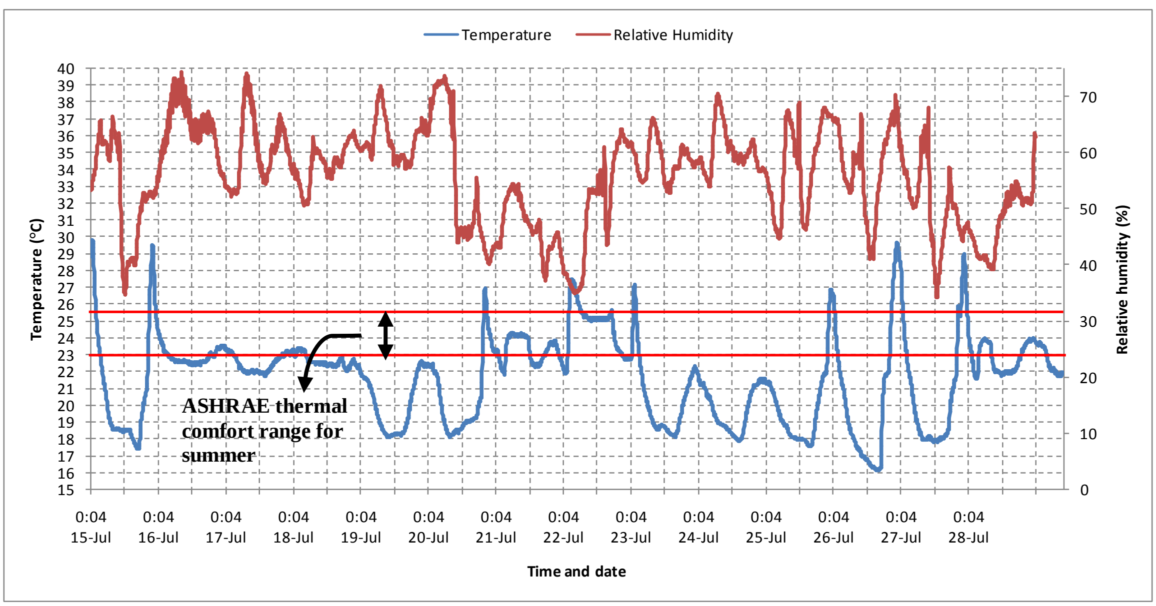
Appendix B.5: Air temperature and relative humidity profiles for zone-3 of second floor



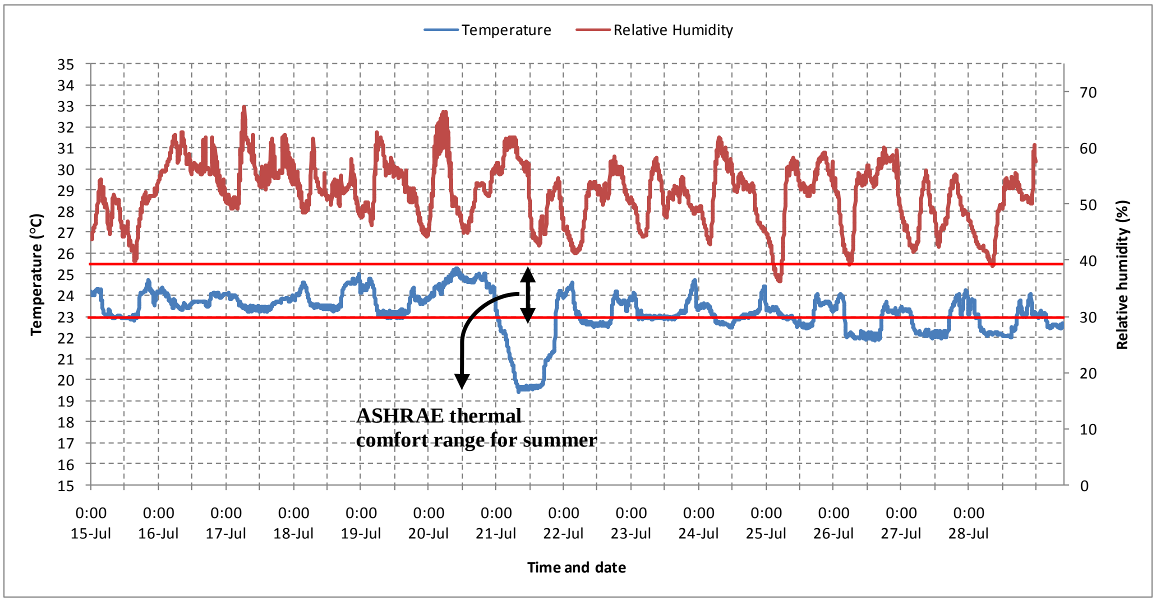
Appendix B.6: Air temperature and relative humidity profiles for zone-4 of second floor



Appendix B.7: Air temperature and relative humidity profiles for zone-1 of fourth floor



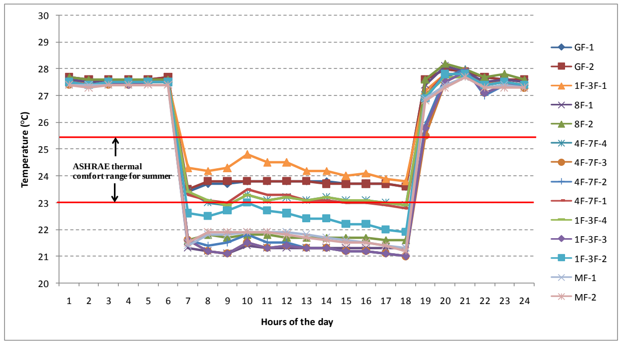
Appendix B.8: Air temperature and relative humidity profiles for zone-3 of fourth floor



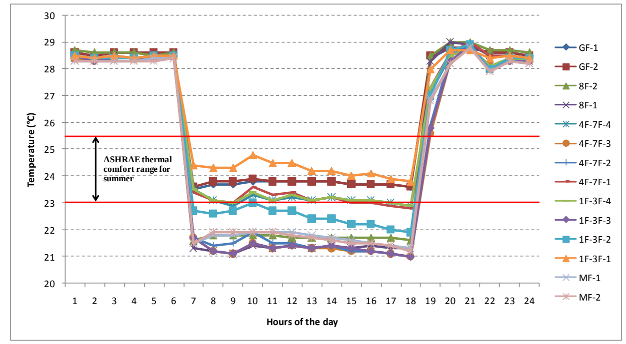
Appendix B.9: Air temperature and relative humidity profiles for zone-4 of fourth floor

APPENDIX – C

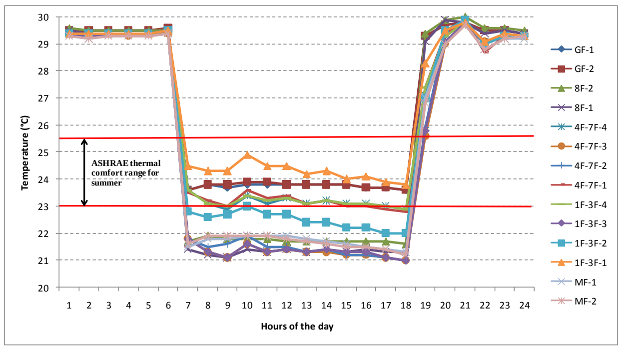
Temperature profiles generated after implementation of alternative ECMs



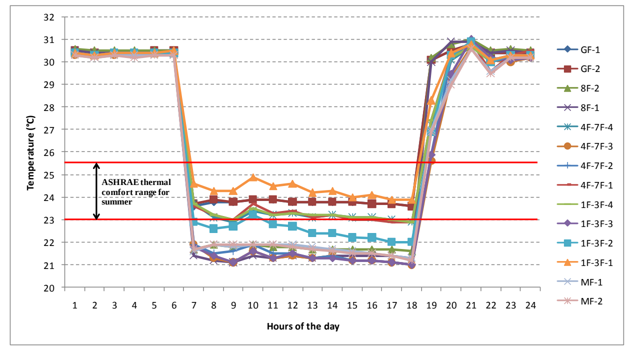
(a)



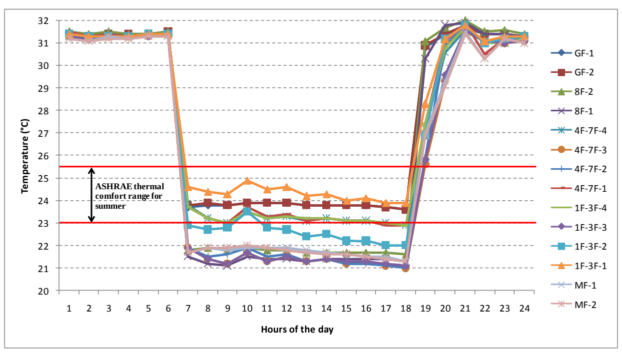
(b)



(c)

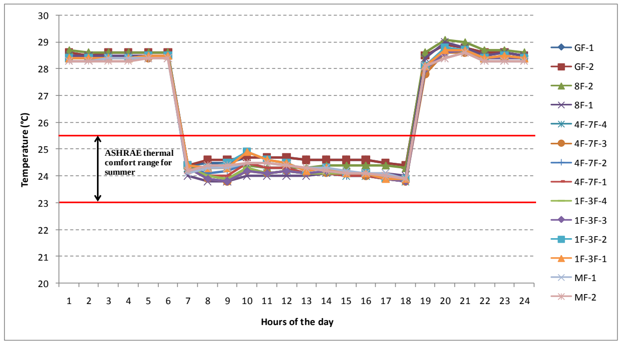


(d)

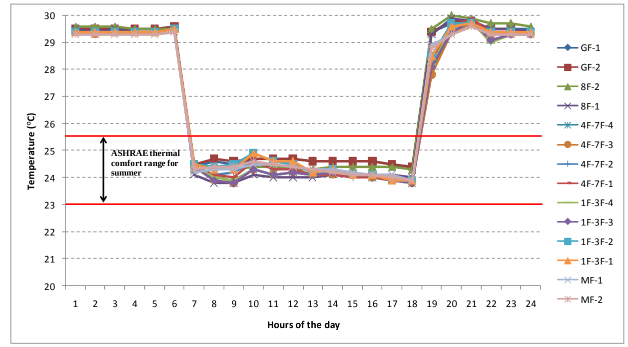


(e)

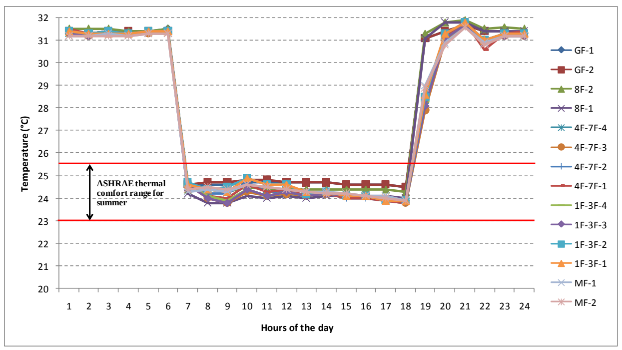
Appendix C.1: Temperature profiles for July-21 for different zones in the building after implementation of ECM-2; (a) 28°C, (b) 29°C, (c) 30°C, (d) 31°C, and (e) 32°C



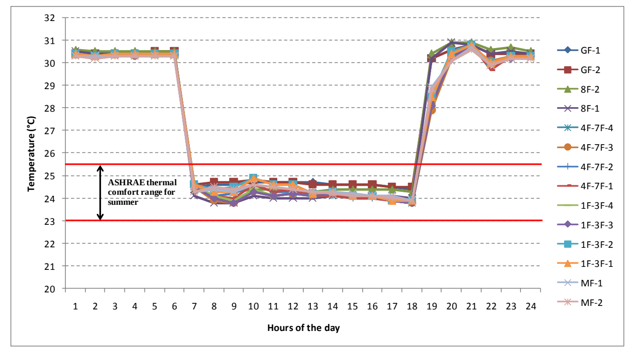
(a)



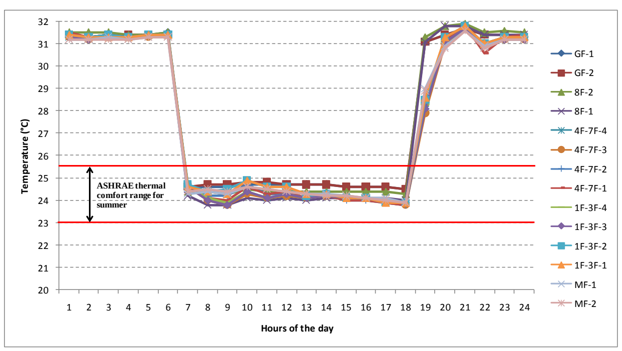
(b)



(c)

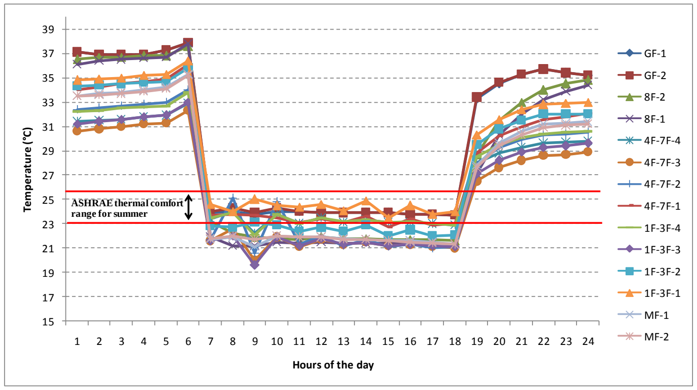


(d)

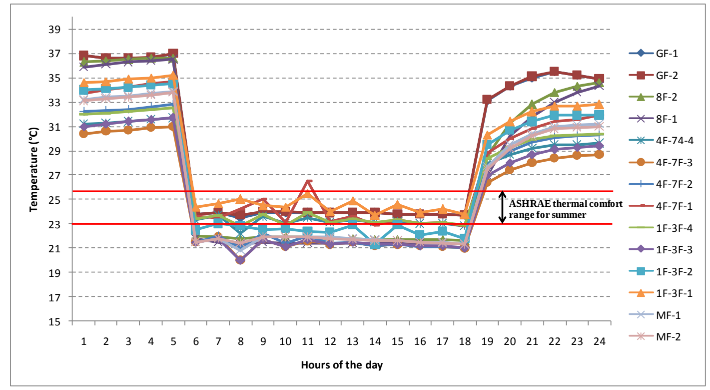


(e)

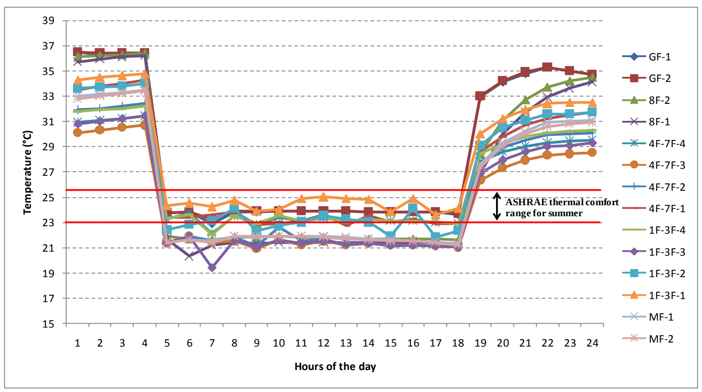
Appendix C.2: Temperature profile for July-21 for different zones in the building after implementation of ECM-3 (a) 28°C, (b) 29°C, (c) 30°C, (d) 31°C, and (e) 32°C



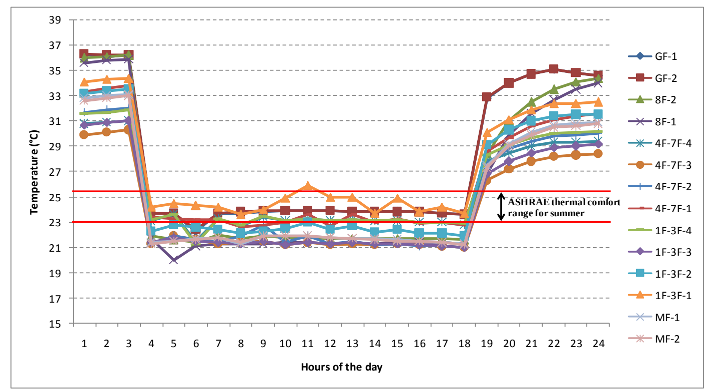
(a)



(b)

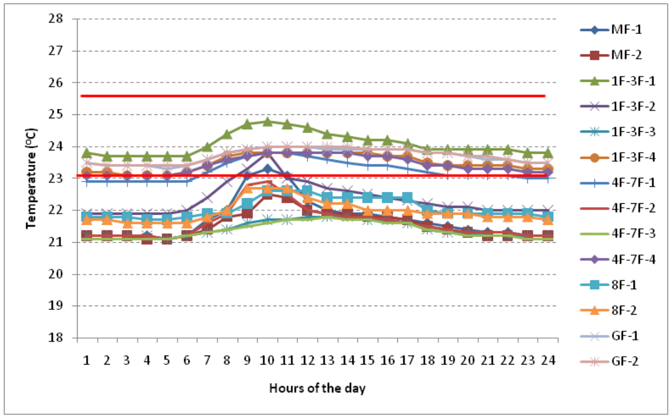


(c)

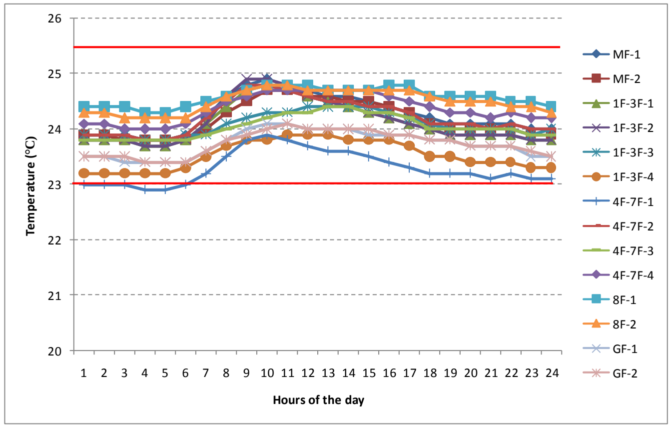


(d)

Appendix C.3: Temperature profile for July-21 for different zones in the building after implementation of ECM-4 (a) 0h, (b) 1h, (c) 2h, (d) 3h

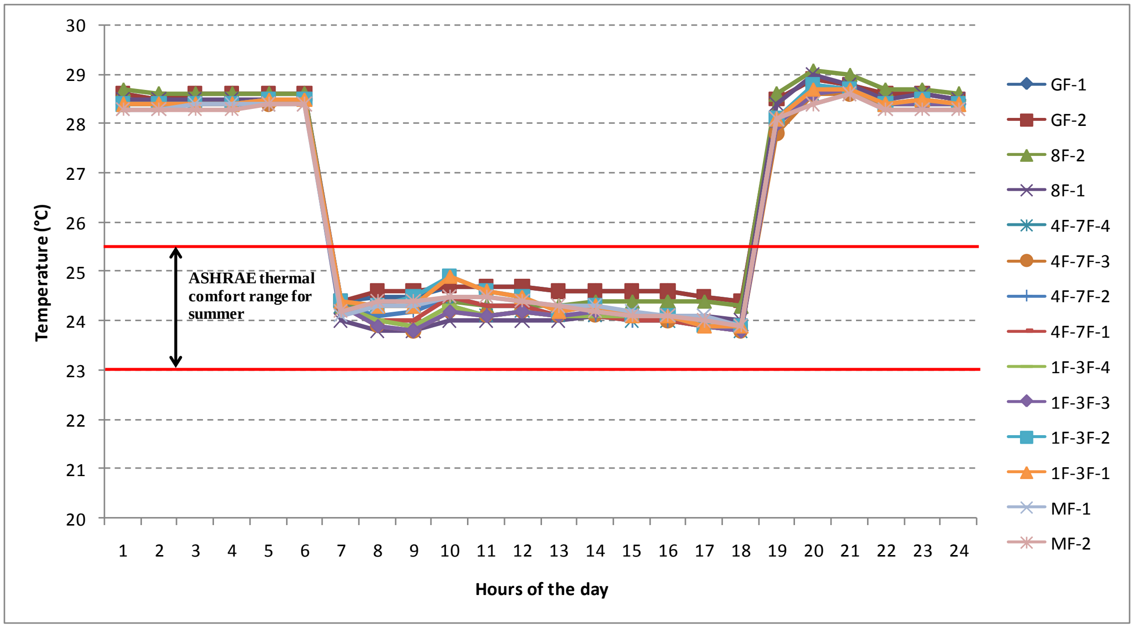


(a)



(b)

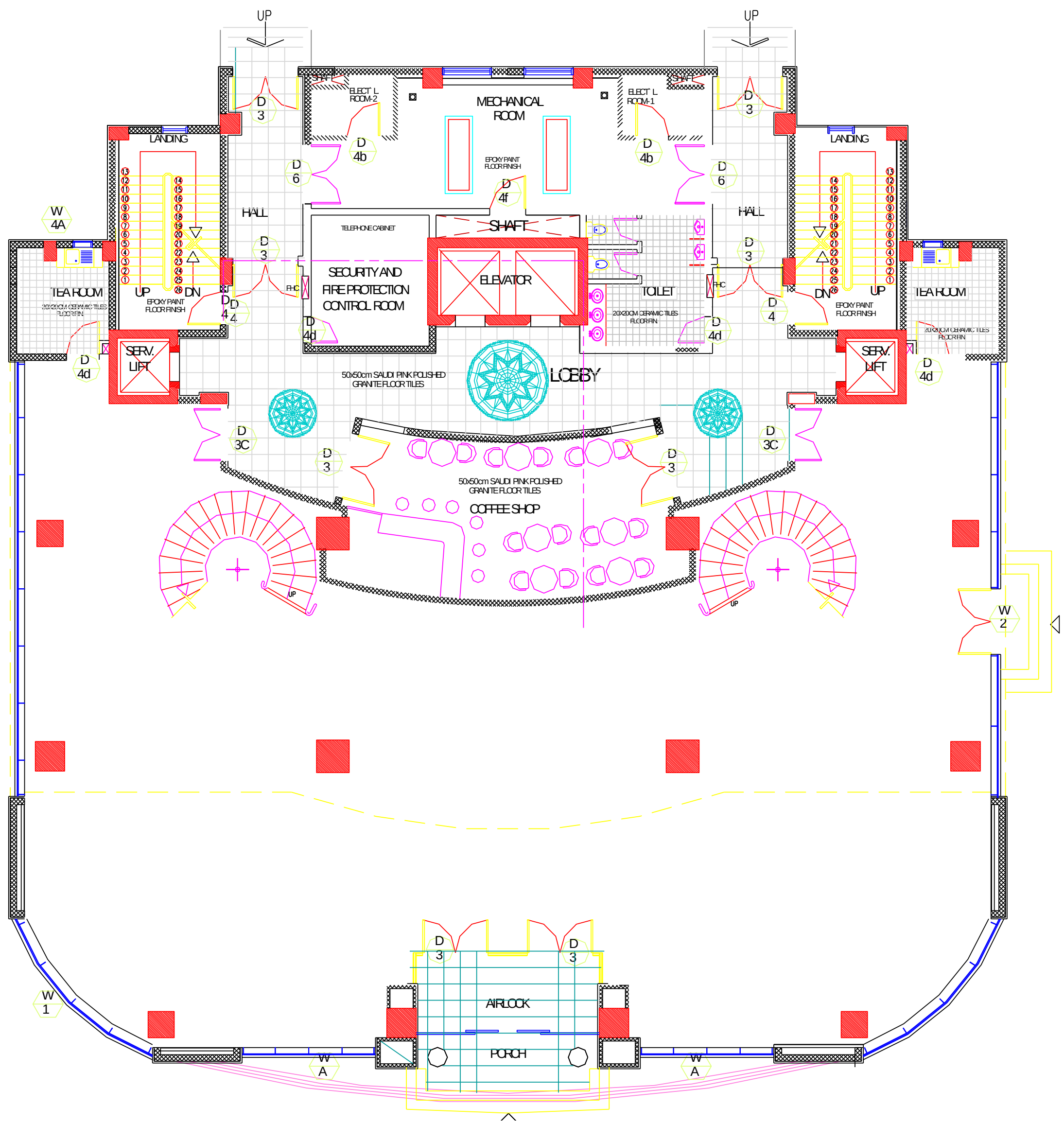
Appendix C.4: Temperature profile for July-21 for different zones in the building after implementation of ECM-9: PSZ autosized (a) 21°C (b) 24°C



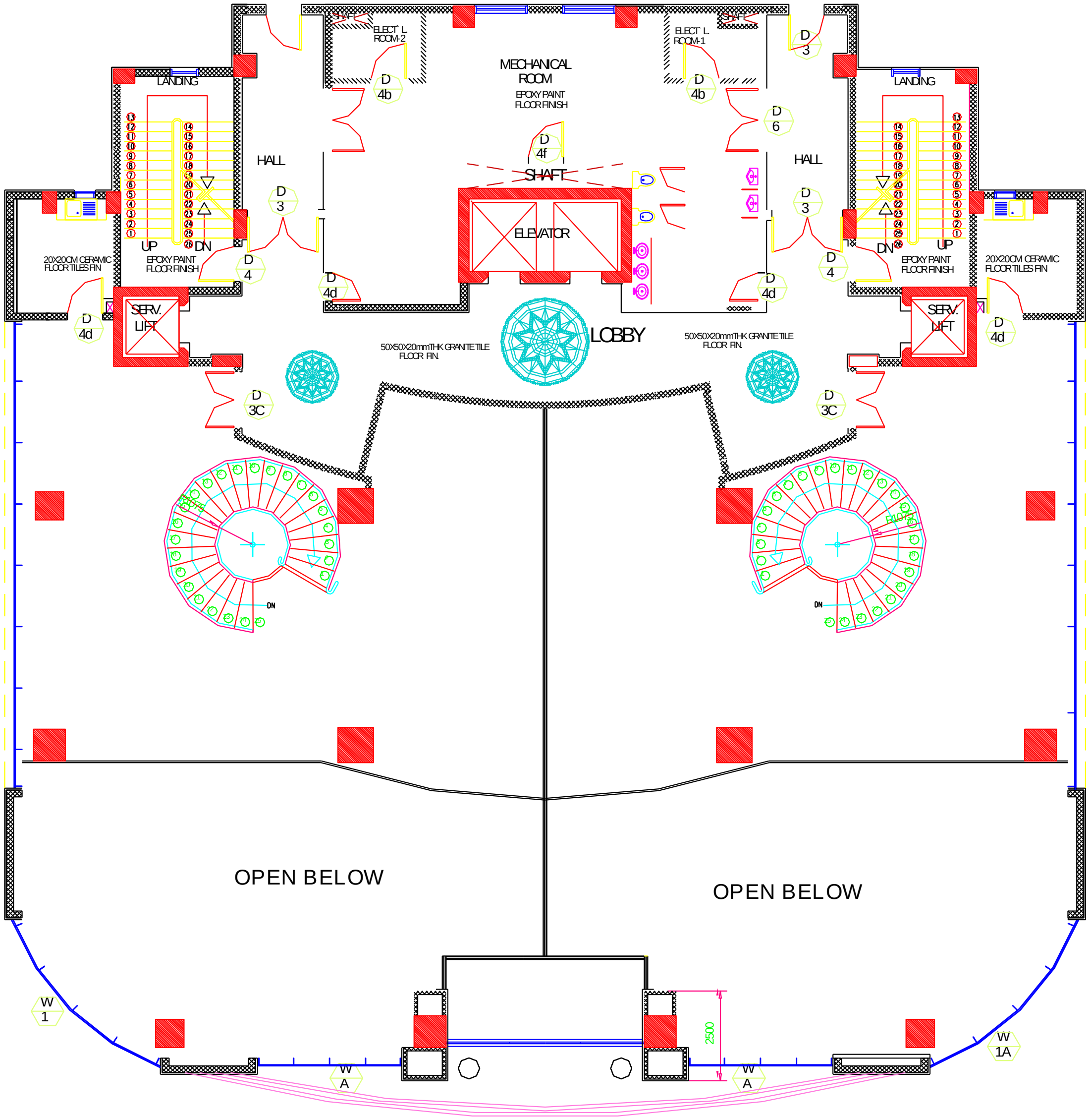
Appendix-C.5: Temperature profile for July-21 for different zones in the building after implementation of ECM-10

APPENDIX – D

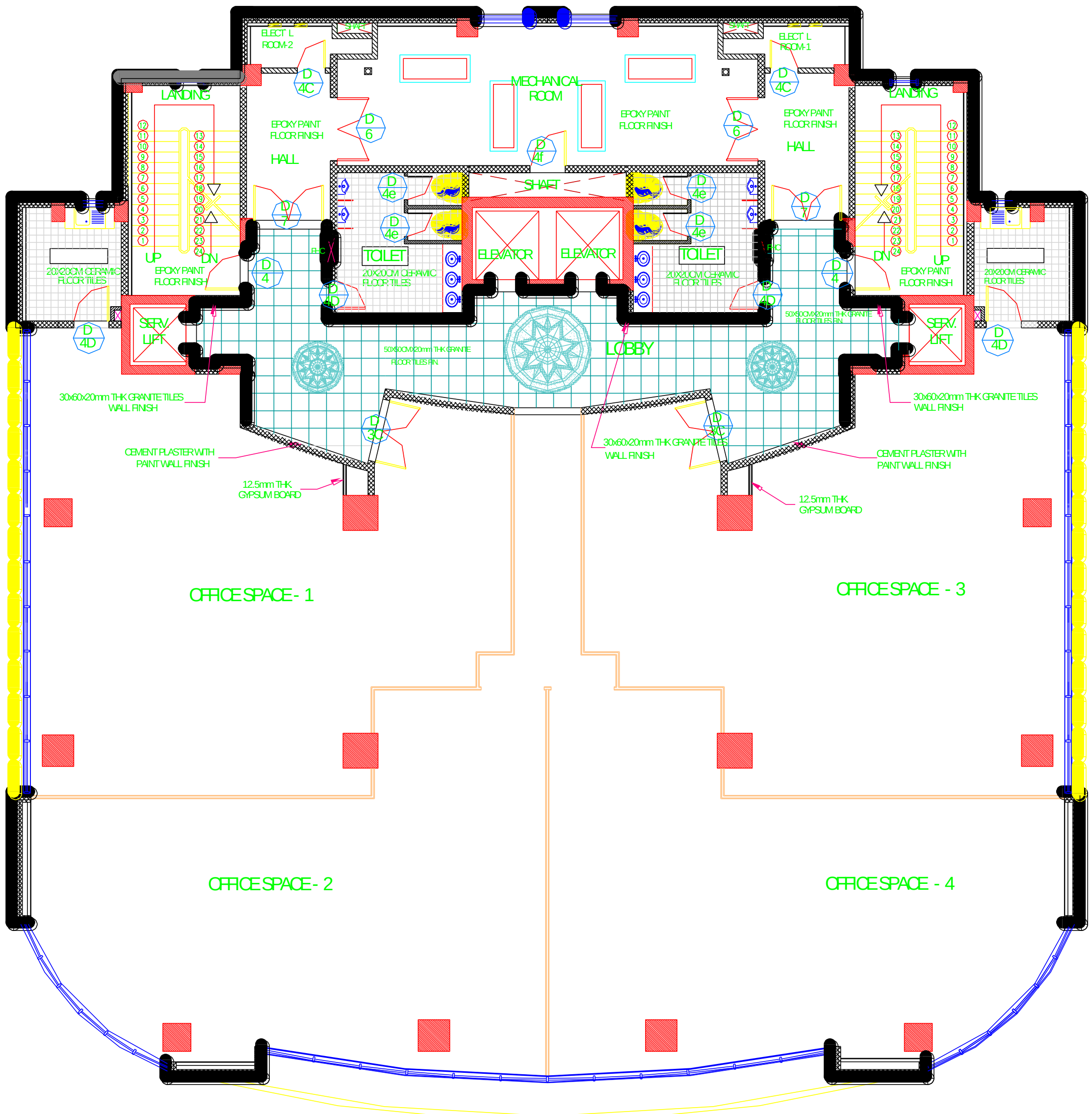
Detailed building floor plans



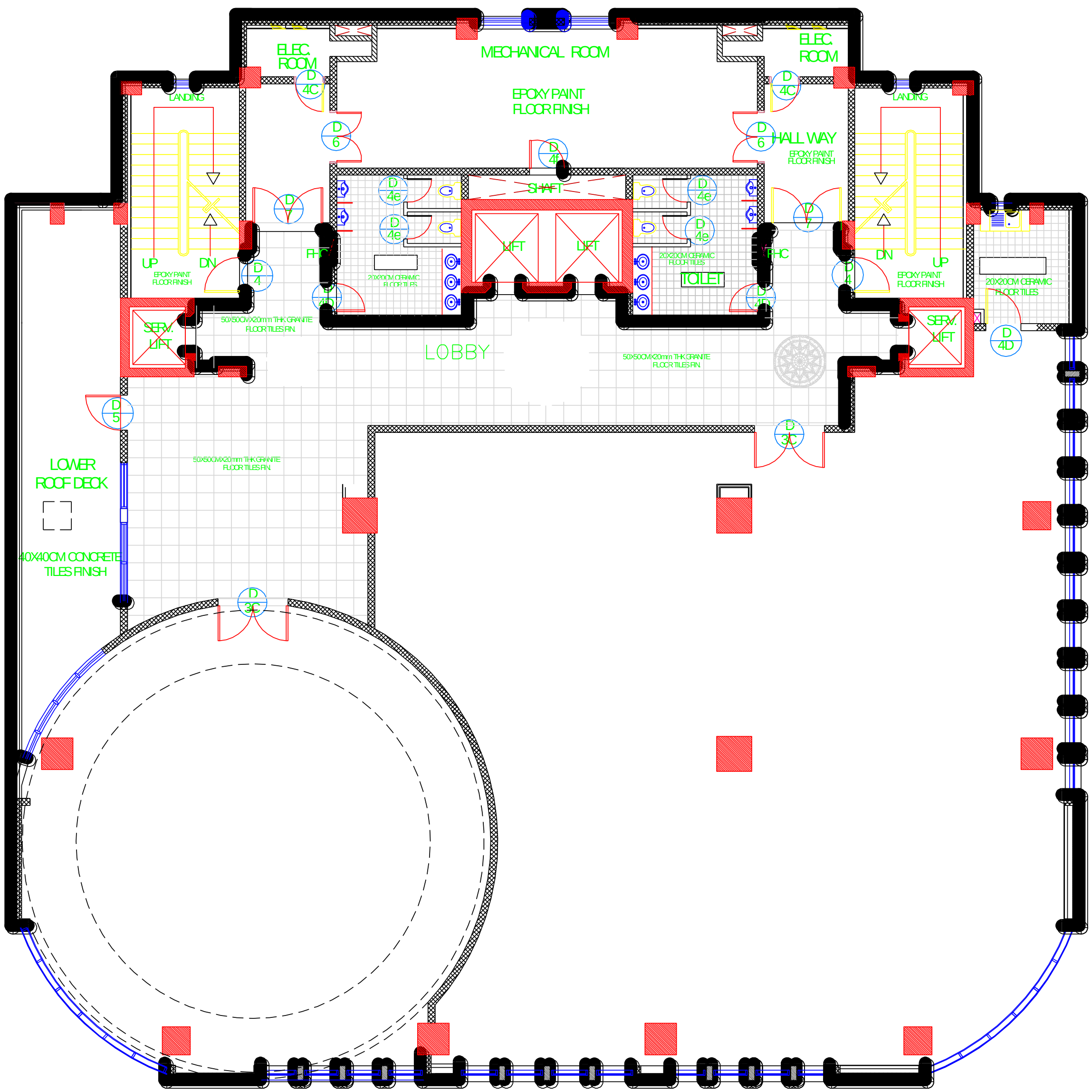
Appendix D.1: Ground floor plan



Appendix D.2: Mezzanine floor plan



Appendix D.3: Typical first to seventh floor plan



Appendix D.4: Eighth floor plan

APPENDIX – E

Sample simulation input report

SAMPLE ARCHITECTURAL DETAILS

Name: Karawan Tower
Address: KFUPM
Description: DEFAULT SI UNIT TEMPLATE
Analysis done by: Najid @ King Fahd University of Petroleum & Minerals
Gross Area: 8,625 m²
Conditioned Area: 8,625 m²
Project File: c:\docume~1\najid\desktop\newbas~1\afterc~1.gph
Case Name: Base Case
Case Description: Base Case
Number of Blocks: 5

Block 1, Level 2: Block_2

Block Information	
Shape	CUSTOMBLK
Zoning	Custom
Number of Zones	6
Number of Facades	0

Ceiling and Plenum Heights	
Floor to Floor Height	4.5 m
Plenum Height	0.75 m
Number of Floors	1

Block Dimensions

Coordinates (m)		Point	X (m)	Y (m)
X	0	Pt. 1	3.08	25.14
Y	0	Pt. 2	3.08	28.57
Z	4.5	Pt. 3	6.7	28.57
		Pt. 4	6.7	30.36
		Pt. 5	23.83	30.36
		Pt. 6	23.83	28.57
		Pt. 7	27.46	28.57
		Pt. 8	27.46	25.14
		Pt. 9	30.53	25.14
		Pt. 10	30.53	4.4
		Pt. 11	26.13	0.0
		Pt. 12	15.27	0.0
		Pt. 13	4.4	0.0
		Pt. 14	0.0	4.4
		Pt. 15	0.0	25.14

Block Constructions

Construction	Description	U-Factor (W/m²-°C)	HC (kJ/m²-K)
Roof	Karawan Roof	3.575	404.9
Ceiling	Gyp. bd. ceiling	4.229	10.6
Floor	Karawan Floor	3.366	277.3
Int. Floor	Karawan Internal Floor	1.417	452.6
Interior Wall	Partition	2.196	21.3

Facade Dimensions

Name	Bay Width (m)	Window Height (m)	Window Width (m)
Surface_MF_W2	Custom	n.a.	n.a.
Surface_MF_W3	Custom	n.a.	n.a.
Surface_MF_W4	Custom	n.a.	n.a.
Surface_MF_N1	Custom	n.a.	n.a.
Surface_MF_NE	Custom	n.a.	n.a.
Surface_MF_E1	Custom	n.a.	n.a.
Surface_MF_E1	Custom	n.a.	n.a.
Surface_MF_E2	Custom	n.a.	n.a.
Surface_MF_E2	Custom	n.a.	n.a.
Surface_MF_SE	Custom	n.a.	n.a.
Surface_MF_S1	Custom	n.a.	n.a.
Surface_MF_W1	Custom	n.a.	n.a.

Facade Shading

Name	Window Recess (m)	Interior Shading	Exterior Shading	Overhang Distance (m)	Overhang Projection (m)	Side Fin Distance (m)	Side Fin Projection (m)
Surface_MF_W2	0	No	No	n.a.	n.a.	n.a.	n.a.
Surface_MF_W3	0	No	No	n.a.	n.a.	n.a.	n.a.
Surface_MF_W4	0	No	No	n.a.	n.a.	n.a.	n.a.
Surface_MF_N1	0	No	No	n.a.	n.a.	n.a.	n.a.
Surface_MF_NE	0	No	No	n.a.	n.a.	n.a.	n.a.
Surface_MF_E1	0	No	No	n.a.	n.a.	n.a.	n.a.
Surface_MF_E1	0	No	No	n.a.	n.a.	n.a.	n.a.
Surface_MF_E2	0	No	No	n.a.	n.a.	n.a.	n.a.
Surface_MF_E2	0	No	No	n.a.	n.a.	n.a.	n.a.
Surface_MF_SE	0	No	No	n.a.	n.a.	n.a.	n.a.
Surface_MF_S1	0	No	No	n.a.	n.a.	n.a.	n.a.
Surface_MF_W1	0	No	No	n.a.	n.a.	n.a.	n.a.

Facade Constructions

Name	Window Construction	U-Factor (W/m²-°C)	SC	VLT	Wall Construction	U-Factor (W/m²-°C)	HC (kJ/m²-K)
Surface_MF_W2	customized	n.a.	n.a.	n.a.	karawan Wall	2.490	229.9
Surface_MF_S2	n.a.	n.a.	n.a.	n.a.	karawan Wall	2.490	229.9
Surface_MF_W5	n.a.	n.a.	n.a.	n.a.	karawan Wall	2.490	229.9
Surface_MF_N3	n.a.	n.a.	n.a.	n.a.	karawan Wall	2.490	229.9
Surface_MF_W3	customized	n.a.	n.a.	n.a.	karawan Wall	2.490	229.9
Surface_MF_N2	n.a.	n.a.	n.a.	n.a.	karawan Wall	2.490	229.9
Surface_MF_S3	n.a.	n.a.	n.a.	n.a.	karawan Wall	2.490	229.9
Surface_MF_W4	customized	n.a.	n.a.	n.a.	karawan Wall	2.490	229.9
Surface_MF_N1	customized	n.a.	n.a.	n.a.	karawan Wall	2.490	229.9
Surface_MF_NE	customized	n.a.	n.a.	n.a.	karawan Wall	2.490	229.9
Surface_MF_E1	customized	n.a.	n.a.	n.a.	karawan Wall	2.490	229.9
Surface_MF_E1	customized	n.a.	n.a.	n.a.	karawan Wall	2.490	229.9
Surface_MF_E2	customized	n.a.	n.a.	n.a.	karawan Wall	2.490	229.9
Surface_MF_E2	customized	n.a.	n.a.	n.a.	karawan Wall	2.490	229.9
Surface_MF_SE	customized	n.a.	n.a.	n.a.	karawan Wall	2.490	229.9
Surface_MF_S1	customized	n.a.	n.a.	n.a.	karawan Wall	2.490	229.9
Surface_MF_W1	customized	n.a.	n.a.	n.a.	karawan Wall	2.490	229.9

SAMPLE ARCHITECTURAL INPUT SUMMARY

Project Information
Name: Karawan Tower
Address: KFUPM
Description: DEFAULT SI UNIT TEMPLATE
Analysis done by: Najid @ King Fahd University of Petroleum & Minerals
Project File: c:\docume~1\najid\desktop\newbas~1\afterc~1.gph
Case Name: Base Case
Case Description: Base Case
Gross Area: 8,625 m²
Conditioned Area: 8,625 m²
Window-Wall-Ratio: 43.5%
Skylight-Roof-Ratio: 0.0%
Number of Blocks: 5
Note: This report includes floor multipliers

Occupancies Summary

Name	Area (m²)	Avg. LPD (W/m²)	Avg. EPD (W/m²)
Karawan Occupancy	2,756	21.19	8.07
Occ for Unconditioned	1,612	29.01	2.69
Karawan Occupancy-23	1,707	21.21	8.07
Occ-4F-Z-3	644	21.21	8.07
Occ-4F-Z-4	644	21.21	8.07
Occ-2F-Z-3	483	21.21	8.07
Occ-2F-Z-2	389	21.21	8.07
Occ-2F-Z-1	389	21.21	8.07
Building Totals & Averages	8,625	22.66	7.07

Constructions Summary

Name	Net Area (m²)	U-Factor (W/m²-°C)	HC (kJ/m²-	Absorptance	Type	Category	Layers
Partition	4,134	2.19	21.3	0.3	Partitions	Light	3
Gyp. bd. ceiling	8,625	4.23	10.65	0.7	Ceilings	Light	1
Karawan Roof	862	3.57	404.92	0.7	Roofs	Light	3
Karawan Floor	862	3.36	277.34	0.7	Floors	Light	3
Karawan Internal Floor	17,062	1.42	452.6	0.7	Floors	Light	4
karawan Wall	2,649	2.49	229.95	0.5	Walls	Light	3

Fenestrations Summary

Name	Ucog (W/m²-°C)	SHGC	Tvis	North (m²)	East (m²)	South (m²)	West (m²)	Total (m²)	No.
kARAWAN STRUCT GLS_GF_N-S	3.160	0.695	0.781	119	0	119	0	239	4
kARAWAN STRUCT GLS_GF_NE	3.160	0.695	0.781	0	47	47	0	93	4
KARAWAN WEST	2.979	0.249	0.162	0	0	0	13	13	18
KARAWAN WEST	2.979	0.249	0.162	0	0	0	35	35	22
KARAWAN STRUCT GLS_GF_E1	3.160	0.695	0.781	0	73	0	0	73	4
KARAWAN STRUCT GLS_GF_E4	3.160	0.695	0.781	0	50	0	0	50	4
KARAWAN STRUCT GLS_GF_E5	3.160	0.695	0.781	0	86	0	0	86	8
kARAWAN STRUCT GLS_GF_NE1	3.160	0.695	0.781	0	157	157	0	314	16
KARAWAN STRUCT GLS_GF_E-1-3	3.160	0.695	0.781	0	204	0	0	204	6
kARAWAN STRUCT GLS_GF_N-S1	3.160	0.695	0.781	414	0	414	0	827	16
KARAWAN-3F-7F	2.979	0.249	0.162	0	93	0	0	93	40
KARAWAN-3F-7F_1	2.979	0.249	0.162	0	12	0	0	12	4
Building Totals & Averages	3.147	0.661	0.734	533	722	737	48	2,040	146

SAMPLE ZONE INPUT SUMMARY

Project Information
Name: Karawan Tower
Address: KFUPM
Description: DEFAULT SI UNIT TEMPLATE
Analysis done by: Najid @ King Fahd University of Petroleum & Minerals
Project File: c:\docume~1\najid\desktop\newbas~1\afterc~1.gph
Case Name: Base Case
Case Description: Base Case
Number of Blocks: 5

Zone Loads

Name	Area (m²)	LPD (W/m²)	EPD (W/m²)	Occupancy	Occupant Density (m²/person)	Daylight Control	Illuminance (lux)	Control Fraction	Infiltration (ach)	SS-G Max Cl/Ht (kW)
Room_MF_3	157	15.07	.006	Occ for Unconditioned	156.6	None	n.a.	n.a.	0.2	n.a./n.a.
Room_MF_2	353	10.23	10.159	Karawan Occupancy	35.3	None	n.a.	n.a.	0.2	n.a./n.a.
Room_MF_1	353	10.23	10.978	Karawan Occupancy	35.3	None	n.a.	n.a.	0.2	n.a./n.a.
Room_1F-3F_1	389	9.548	24.627	Occ-2F-Z-1	10.8	None	n.a.	n.a.	0.2	n.a./n.a.
Room_1F-3F_2	389	9.548	24.648	Occ-2F-Z-2	10.8	None	n.a.	n.a.	0.2	n.a./n.a.
Room_1F-3F_5	222	14.18	.014	Karawan Occupancy	74.0	None	n.a.	n.a.	0.2	13.56/n.a.
Room_1F-3F_6	152	17.26	.02	Karawan Occupancy	50.7	None	n.a.	n.a.	0.2	7.62/n.a.
Room_1F-3F_7	470	15.07	.006	Occ for Unconditioned	156.6	None	n.a.	n.a.	0.1	n.a./n.a.
Room_1F-3F_3	483	10.766	19.814	Occ-2F-Z-3	13.4	None	n.a.	n.a.	0.2	n.a./n.a.
Room_1F-3F_4	483	10.766	19.829	Karawan Occupancy-23	13.4	None	n.a.	n.a.	0.2	n.a./n.a.
Room_4F-7F_1	518	9.54	24.627	Karawan Occupancy-23	10.8	None	n.a.	n.a.	0.2	n.a./n.a.
Room_4F-7F_2	518	9.54	24.648	Karawan Occupancy	10.8	None	n.a.	n.a.	0.2	n.a./n.a.
Room_4F-7F_5	296	14.18	.014	Karawan Occupancy	74.0	None	n.a.	n.a.	0.2	13.26/n.a.
Room_4F-7F_6	203	17.20	.02	Karawan Occupancy	50.7	None	n.a.	n.a.	0.2	n.a./n.a.
Room_4F-7F_7	626	15.071	.006	Occ for Unconditioned	156.6	None	n.a.	n.a.	0.2	n.a./n.a.
Room_4F-7F_3	644	10.76	19.814	Occ-4F-Z-3	13.4	None	n.a.	n.a.	0.2	n.a./n.a.
Room_4F-7F_4	644	10.76	19.829	Occ-4F-Z-4	13.4	None	n.a.	n.a.	0.2	n.a./n.a.
Room_8F_1	257	13.22	9.709	Karawan Occupancy	51.3	None	n.a.	n.a.	0.2	n.a./n.a.
Room_8F_3	157	15.07	.006	Occ for Unconditioned	156.6	None	n.a.	n.a.	0.2	n.a./n.a.
Room_8F_4	46	.015	.022	Occ for Unconditioned	46.4	None	n.a.	n.a.	0.2	n.a./n.a.
Room_8F_2	403	8.42	5.462	Karawan Occupancy	80.6	None	n.a.	n.a.	0.2	n.a./n.a.

Room_GF_3	157	15.071	.006	Occ for Unconditioned	156.6	None	n.a.	n.a.	0.2	n.a./n.a.
Room_GF_2	353	7.60	14.978	Karawan Occupancy-23	23.5	None	n.a.	n.a.	0.2	n.a./n.a.
Room_GF_1	353	7.85	15.793	Karawan Occupancy-23	23.5	None	n.a.	n.a.	0.2	n.a./n.a.

Supply Air

Name	Total Flow (l/s)	Flow/Area (l/s/(m²))	Air change/hour	Min. Flow Ratio	Cool/Heat Cap. (kW)
Room_MF_3	AutoSized - 1033.611	0	0	1	n.a.
Room_MF_2	4955	14.0452	13.4834	1	n.a.
Room_MF_1	4955	14.0337	13.4723	1	n.a.
Room_1F-3F_1	3540	27.3114	31.213	1	n.a.
Room_1F-3F_2	3540	27.3349	31.2399	1	n.a.
Room_1F-3F_5	661	8.9318	10.2078	1	37.0 / 17.9
Room_1F-3F_6	661	13.0469	14.9107	1	37.0 / 23.9
Room_1F-3F_7	AutoSized - 1111.667	0	0	1	n.a.
Room_1F-3F_3	3540	21.9736	25.1127	1	n.a.
Room_1F-3F_4	3540	21.9908	25.1323	1	n.a.
Room_4F-7F_1	3540	27.3114	31.213	1	n.a.
Room_4F-7F_2	3540	27.3349	31.2399	1	n.a.
Room_4F-7F_5	661	8.9318	10.2078	1	50.0 / 23.9
Room_4F-7F_6	661	13.0469	14.9107	1	n.a.
Room_4F-7F_7	AutoSized - 1144.722	0	0	1	n.a.
Room_4F-7F_3	3540	21.9736	25.1127	1	n.a.
Room_4F-7F_4	3540	21.9908	25.1323	1	n.a.
Room_8F_1	4955	19.3049	22.0628	1	n.a.
Room_8F_3	AutoSized - 1071.667	0	0	1	n.a.
Room_8F_4	AutoSized - 1486.667	0	0	1	n.a.
Room_8F_2	4955	12.3029	14.0605	1	n.a.
Room_GF_3	AutoSized - 1720.556	0	0	1	n.a.
Room_GF_2	4955	14.0452	13.4834	1	n.a.
Room_GF_1	4955	14.0337	13.4723	1	n.a.

Outside Air

Name	Total Flow (l/s)	Flow(cfm)/Person	Air change/hour	Fraction Supply Air
Room_MF_3	n.a.	n.a.	0.01	n.a.
Room_MF_2	375	n.a.	n.a.	n.a.
Room_MF_1	375	n.a.	n.a.	n.a.
Room_1F-3F_1	n.a.	15	n.a.	n.a.
Room_1F-3F_2	n.a.	15	n.a.	n.a.
Room_1F-3F_5	n.a.	1	n.a.	n.a.
Room_1F-3F_6	n.a.	1	n.a.	n.a.
Room_1F-3F_7	n.a.	n.a.	0.01	n.a.
Room_1F-3F_3	n.a.	15	n.a.	n.a.
Room_1F-3F_4	n.a.	15	n.a.	n.a.
Room_4F-7F_1	n.a.	15	n.a.	n.a.
Room_4F-7F_2	n.a.	15	n.a.	n.a.
Room_4F-7F_5	n.a.	1	n.a.	n.a.
Room_4F-7F_6	n.a.	1	n.a.	n.a.
Room_4F-7F_7	n.a.	n.a.	0.01	n.a.
Room_4F-7F_3	n.a.	15	n.a.	n.a.
Room_4F-7F_4	n.a.	15	n.a.	n.a.
Room_8F_1	250	n.a.	n.a.	n.a.
Room_8F_3	n.a.	n.a.	0.01	n.a.
Room_8F_4	n.a.	n.a.	0.01	n.a.

Room_8F_2	84	n.a.	n.a.	n.a.
Room_GF_3	n.a.	n.a.	0.01	n.a.
Room_GF_2	n.a.	25	n.a.	n.a.
Room_GF_1	n.a.	25	n.a.	n.a.

Name	Thermostat Type	Throttling Range (°C)	PIU Type	Zone Fan Volume (l/s)	Fan Power (W)
Room_MF_3	Reverse Action	2	No PIU	n.a.	n.a.
Room_MF_2	Reverse Action	2	No PIU	n.a.	n.a.
Room_MF_1	Reverse Action	2	No PIU	n.a.	n.a.
Room_1F-3F_1	Reverse Action	2	No PIU	n.a.	n.a.
Room_1F-3F_2	Reverse Action	2	No PIU	n.a.	n.a.
Room_1F-3F_5	Reverse Action	2	No PIU	n.a.	n.a.
Room_1F-3F_6	Reverse Action	2	No PIU	n.a.	n.a.
Room_1F-3F_7	Reverse Action	2	No PIU	n.a.	n.a.
Room_1F-3F_3	Reverse Action	2	No PIU	n.a.	n.a.
Room_1F-3F_4	Reverse Action	2	No PIU	n.a.	n.a.
Room_4F-7F_1	Reverse Action	2	No PIU	n.a.	n.a.
Room_4F-7F_2	Reverse Action	2	No PIU	n.a.	n.a.
Room_4F-7F_5	Reverse Action	2	No PIU	n.a.	n.a.
Room_4F-7F_6	Reverse Action	2	No PIU	n.a.	n.a.
Room_4F-7F_7	Reverse Action	2	No PIU	n.a.	n.a.
Room_4F-7F_3	Reverse Action	2	No PIU	n.a.	n.a.
Room_4F-7F_4	Reverse Action	2	No PIU	n.a.	n.a.
Room_8F_1	Reverse Action	2	No PIU	n.a.	n.a.
Room_8F_3	Reverse Action	2	No PIU	n.a.	n.a.
Room_8F_4	Reverse Action	2	No PIU	n.a.	n.a.
Room_8F_2	Reverse Action	2	No PIU	n.a.	n.a.
Room_GF_3	Reverse Action	2	No PIU	n.a.	n.a.
Room_GF_2	Reverse Action	2	No PIU	n.a.	n.a.
Room_GF_1	Reverse Action	2	No PIU	n.a.	n.a.

APPENDIX – F

Sample simulation output report

REPORT- BEPU BUILDING ENERGY PERFORMANCE SUMMARY (UTILITY UNITS)   WEATHER FILE- DHAHRAN SAUDI ARABIA

ENERGY TYPE:	ELECTRICITY	NATURAL-GAS
SITE UNITS:	KWH	M3
CATEGORY OF USE		
AREA LIGHTS	196170.	0.
MISC EQUIPMT	293103.	0.
SPACE HEAT	0.	0.
SPACE COOL	1667253.	0.
VENT FANS	918053.	0.
DOMHOT WATER	0.	0.
TOTAL	3074579.	7384.

TOTAL ELECTRICITY   3074579. KWH   3.077 KWH   / M2 -YR GROSS-AREA   3.077 KWH   / M2 -YR NET-AREA

PERCENT OF HOURS ANY SYSTEM ZONE OUTSIDE OF THROTTLING RANGE = 0.1
PERCENT OF HOURS ANY PLANT LOAD NOT SATISFIED = 0.0

REPORT- PS-E MONTHLY ENERGY END-USE SUMMARY WEATHER FILE- DHAHRAN SAUDI ARABIA

0ELECTRICAL END-USES IN KWH

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
0 AREA LIGHTS	7506.	6824.	14813.	14728.	14260.	29210.	30474.	28294.	11663.	11295.	12000.	15091.	196158.
MAX KW	27.3	27.3	49.7	49.7	49.7	98.1	98.1	98.1	42.2	41.0	41.0	59.7	98.1
DAY/HR	1/ 7	2/ 7	2/ 7	1/ 7	1/ 7	1/ 7	1/ 7	3/ 7	1/ 7	5/ 7	2/ 7	1/ 7	
0MISC EQUIPMT	13084.	4047.	4451.	10386.	12679.	4451.	83630.	83630.	56652.	6744.	7081.	6272.	293108.
MAX KW	39.3	16.9	16.9	39.3	39.3	16.9	112.4	112.4	112.4	28.1	28.1	28.1	112.4
DAY/HR	1/ 7	2/ 7	2/ 7	1/ 7	1/ 7	1/ 7	1/ 2	1/ 2	1/ 7	5/ 7	2/ 7	1/ 7	
0 SPACE COOL	40184.	43731.	89101.	118587.	178580.	197761.	253996.	253524.	187030.	152248.	93136.	59378.	1667254.
MAX KW	202.8	236.2	286.3	370.2	434.5	438.9	535.7	586.5	476.3	534.7	341.7	262.9	586.5
DAY/HR	6/11	25/11	27/11	29/14	25/12	27/12	24/15	14/13	28/12	5/ 2	2/12	11/ 1	
0 VENT FANS	62891.	57130.	79274.	82815.	85576.	82815.	85576.	85576.	72733.	71713.	76514.	75493.	918104.
MAX KW	115.0	115.0	115.0	115.0	115.0	115.0	115.0	115.0	115.0	115.0	115.0	115.0	115.0
DAY/HR	1/ 1	2/ 1	1/ 8	1/ 1	1/ 2	1/ 2	1/ 2	1/ 2	1/ 2	5/ 2	1/ 8	1/ 1	
0 TOTAL KWH	123665.	111732.	187639.	226516.	291094.	314238.	453675.	451023.	328078.	242000.	188731.	156234.	3074625.

CURRICULUM VITAE

Name	:	MOHAMMED ABDUL NAJID
Nationality	:	Indian
Date of Birth	:	30 October 1984
Marital Status	:	Single
Place of Birth	:	Hyderabad, India
E-mail	:	manajid@kfupm.edu.sa mohd_najid2000@yahoo.com

EDUCATIONAL HISTORY

King Fahd University of Petroleum & Minerals, 2007-2010
Address : Dhahran, Eastern Province, Saudi Arabia
Major : M.S.in Architectural Engineering

Muffakham Jah College of Engineering and Technology (Osmania University), 2002-2006
Address : Hyderabad, India
Major : Mechanical Engineering

Sri Chaitanya Junior Kalasala, 2000-2002
Address : Hyderabad, India
Class 11 and 12

Gyan Vatika High School, 1990-2000
Address : Hyderabad, India
Class 1 to 10