HVAC SYSTEM OPERATION STRATEGIES FOR ENERGY CONSERVATION AND THERMAL COMFORT IN COMMERCIAL BUILDINGS IN SAUDI ARABIA

BY

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DEDICATED IN
AFFECTION AND ADMIRATION
TO PAPPA, AMMI
AND ALL MY FAMILY MEMBERS

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All praise and thanks are due to ALLAH (SUBHAN WA TAALA) for bestowing me with health, knowledge and patience to complete this work. Thereafter, acknowledgement is due to KFUPM, Architectural Engineering Department, for the support given to this research through its tremendous facilities and granting me the opportunities to pursue graduate studies with financial support.

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NOMENCLATURE

AHU: Air Handling Unit

ASHRAE: American Society of Heating Refrigeration and Air-conditioning Engineers

CAV-RH: Constant Air Volume Reheat

CHiRP: Controlled Humidity Reduce Peak

CHWR: Chiller Water Reset

CMU: Concrete Masonry Unit

COP: Coefficient of Performance

CWR: Condenser Water Reset

DDCVP: Dual Duct Constant Air Volume System with Pretreated Outdoor air

DHW: Domestic Hot Water

DX: Direct Expansion

ECM's: Energy Conservation Measures

EIA: Energy Information Administration

EPD: Equipment Power Density

EUI: Energy Utilization Index

FCU: Fan Coil Unit

GDP: Gross Domestic Product

HVAC: Heating Ventilation Air-conditioning

I_{cl}: Clothing Insulation Value

LPD: Lighting Power Density

MIE: Ministry of Industry and Electricity

MRT: Mean Radiant Temperature

NP: Night Purge

PI: Proportional and Integral

PMV: Predicted Mean Vote

PSZ: Packaged Single Zone Unit

OSS: Optimal Start Stop

OT: Operative Temperature

RH: Relative Humidity

SDCV: Single Duct Constant Air Volume System

SDCVP: Single Duct Constant Air Volume System with Partially Reheated Air

SEC: Saudi Electricity Company

SET: Standard Effective Temperature

TLC: Time Limited Control

TPFC: Two Pipe Fan Coil

UFA: Uncontrolled Airflow

VAV: Variable Air Volume

WWR: Window Wall Ratio

THESIS ABSTRACT

NAME: **MOHAMMED FASIUDDIN**

TITLE: **HVAC SYSTEM OPERATION STRATEGIES FOR ENERGY CONSERVATION AND THERMAL COMFORT IN COMMERCIAL BUILDINGS IN SAUDI ARABIA.**

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The steady increase in energy consumption and demand will eventually require further investment in energy generation; otherwise serious shortage may occur. In most countries including Saudi Arabia, building sector consumes major portion of the electrical energy generated. Commercial buildings consume significant part of energy, yet possess great potential for energy savings due to their operational characteristics. In Saudi Arabia presence of harsh climatic conditions necessitates air conditioners. The HVAC system alone consume 65% of the total energy delivered to the building, hence implementing appropriate HVAC operation strategies can significantly reduce energy consumption. However, incorporating of improper HVAC operation strategies may help to attain energy savings, but deteriorate indoor thermal quality.

For this study shopping malls were selected to identify their building energy and thermal performance. To achieve this goal, data regarding building envelope, building systems and their operation, etc was collected from five different shopping malls located in the Eastern Province of Saudi Arabia. Also thermal analysis of present indoor conditions was evaluated by conducting comfort survey and taking measurements. Among the building surveyed a typical building was selected and modeled using Visual DOE. Further to have more reliability and acceptable results, the base model was calibrated with data from actual utility bills and thereby the model was constructed with a deviation less than 10%.

HVAC operation strategies were categorized based on their economic value. Operation strategies such as thermostat control, night setback and fan control produced energy saving of 0.5%, 7% and 10% respectively, with no investment made. Small investment can be made to control the HVAC system like the thermostat, though they generated very less savings. Since the model building had individual system installed, five central systems were also tested. TPFC produced highest saving followed by VAV whereas packaged multi zone performed the worst among different system investigated. Additionally optimal HVAC operations are investigated that can help to attain energy savings without sacrificing occupants thermal comfort.

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ملخص الرسالة

الاســـــــــــم: محمد فصيح الدين

عنوان الرسالة: إستراتجيات HVAC لتشغيل النظم للحفاظ على الطاقة والراحة الحرارية داخل المباني التجارية في المملكة العربية السعودية

التخصـــــــص: قسم الهندسة المعامرية

تاريخ التخـرج: ذو القعدة 1426 هـ

تؤدي الزيادة الثابتة في طلب و استهلاك الطاقة إلى حدوث نقص شديد في التيار الكهربائي ما لم تستثمر موارد إضافية في توليد وتوزيع الطاقة الكهربائية. ففي معظم دول العالم ومنها المملكة العربية السعودية يستهلك قطاع البناء الجزء الأكبر من الطاقة الكهربائية. حيث تستهلك المباني التجارية جزء هام من الطاقة في هذا القطاع ونتيجة للخصائص التي تتميز بها المباني التجارية عن غيرها فإنها تعتبر من أهم المصادر لترشيد الاستهلاك الكهربائي. تتميز المملكة العربية السعودية بوجود مناخ قاسي حار مما يجعل استخدام أجهزة التكييف أمرا ضروريا في معظم فصول السنة. فقد وجد أن استخدام أجهزة التكييف يستهلك ما يقارب 65 % من الطاقة المستهلكة في المباني وبالتالي فإن تطبيق استراتجيات تشغيلية مدروسة يُمْكِنُ أنْ تؤدي إلى تخفيض استهلاك الطاقة. وفي المقابل فإن استخدام استراتيجيات غير مدروسة قد تؤدي إلى تدهور نوعية الراحة الحرارية.

ففي هذه الدراسة تم باختيار مجموعه من المباني التجارية لتحديد الطاقة الكهربائية وتقييم الأداء الحراري لها. ولتحقيق الهدف المنشود من البحث, فقد قمنا بجمع المعلومات الخاصة بنوعية وخصائص الهيكل الإنشائي وأنظمة البناء وخصائص التشغيل لخمسة مجمعات تجارية في المنطقة الشرقية للملكة العربية السعودية. فقد شملت الدراسة القيام بإجراء دراسة تحليلية وعمل قياسات ميدانية ومسح استبياني للوقوف على الحالة الحرارية للجو الداخلي. ومن ثم تم اختيار نموذج مبنى تجاري من المباني الخمسة لدراسته دراسة تحليلية دقيقه باستخدام برنامج لحساب الطاقة الكهربائية والمسمى Visaual DOE. وحتى نتمكن من الوصول لنتائج عملية ودقيقة كان لا بد من القيام بمقارنة بين كمية الطاقة الكهربائية الحقيقية المستهلكة وتلك الناتجة من البرنامج, حيث كان الفرق في حدود 10% وبالتالي فإن النتيجة كانت مقبولة. صنفت إستراتيجيات تشغيل أجهزة التكييف والتبريد على أساس قيمتها الاقتصادية. فعلى سبيل المثال صنف التحكم بمقياس الحرارة والمنظم الحراري الليلي و التحكم بالمروحة من الإستراتيجيات التي لا تحتاج إلى استثمار مالي حيث أنها حققت توفير طاقة ما يقارب من 0.5% و7% و 10% من إجمالي الطاقة المستهلكة. وحيث أن المبنى التجاري في هذه الدراسة له نظام تكييف منفرد فقد تم اختبار وتقييم خمس أنظمة تكييف. من هذا التقييم وجدنا أن نظام التكييف المعتمد على نظام وحدة المروحة والمبرد بماسورتين يؤدي إلى ترشيد اكبر للطاقة يليه الوحدات المعتمدة على تغيير كمية الهواء. وفي المقابل وجدنا أن أداء أنظمة الوحدات المعلبة يستهلك كمية كبيرة من الطاقة الكهربائية. إضافة إلى ذلك فقد تم دراسة إستراتيجيات تشغيلية من شأنها ترشيد الطاقة دون التأثير السلبي على الراحة الحرارية لمستخدمي المبنى.

درجة ماجستير

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المملكة العربية السعودية

CHAPTER ONE

INTRODUCTION

1.1 Background

This chapter presents the background for the research subject along with problem statement, significance of study, the objectives, research methodology used, scope and limitation of this study and the structure of the thesis.

The present civilization is based on man's ability to harness energy and use it to his advantages. Fossil fuels have been identified as the predominant source for low cost energy generation. Nearly 85% of the world's energy consumption is based on fossil fuels (Said et al., 1990). However if prevalent rates of increasing energy consumption 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 consumption were to remain constant, the diminishing availability of fuel would result in debilitating shortage, which would result in drastic changes in the economical and the sociological behavior.

Energy is an important aspect of human life that has a significant impact on the economy of the country. Saving and using the available resources in a proper manner can help leading a country's economy out of danger from the serious consequences of various energy related problems. During the past 50 years, global consumption of commercial energy has risen more than fourfold, far outpacing the rise in population. In the period from 1970 to 1992, energy consumption in the world had increased by 66%, at the same time energy-related carbon emission had increased by 51% (EIA, 1994c). This has resulted in a global concern to use energy more efficiently and to reduce greenhouse gas emissions from power generation.

Fluctuations in oil price, stimulated unstable 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.

There was a quest for long-term energy policy and systematic measures for achieving energy efficiency. The measures designed for buildings usually aim at improving present techniques, making the best use of unexploited research results, developing new technologies and approaches for practical use (International Energy Agency, 1990). It is believed that more efficient building energy utilization is attainable and energy optimization is conceivable by using the present-day techniques effectively in building design and operation. Figure 1.1 depicts various regions of the world that have been identified as the top energy consumers of the world (Population and Natural Resources, 1998). As seen from Figure 1.1 United States consumes 25% of the world total energy though it amounts to only 5% of world population, whereas Saudi Arabia consumers twice the amount of energy than its population. Also there are some countries which have shown relatively low consumption corresponding to their population such as France and Brazil.

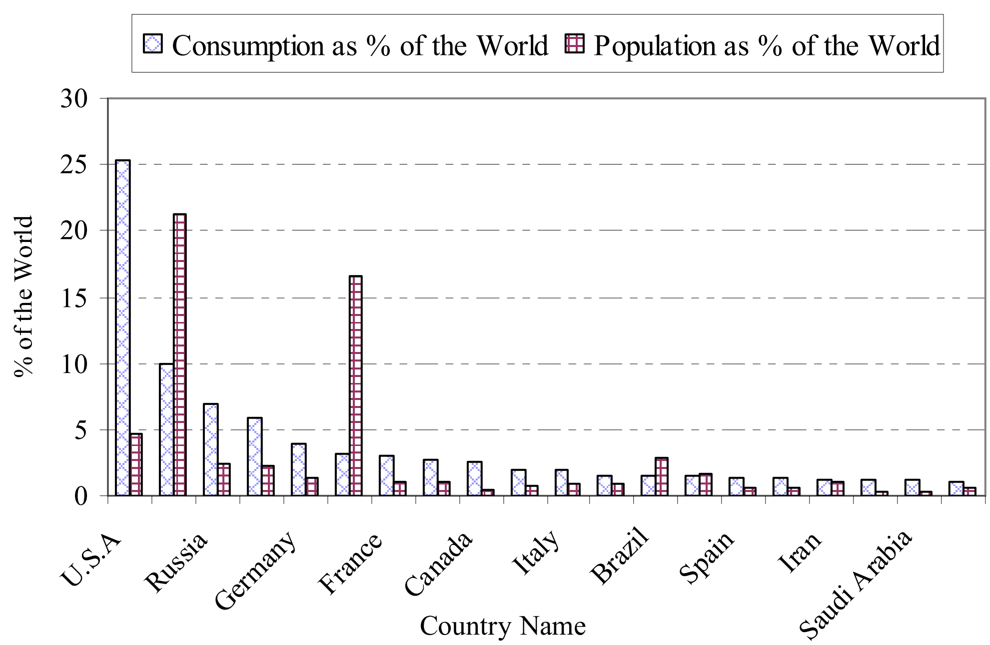

Figure 1.1 Top Energy Consumers of World, (Population and Natural Resources, 1998)

With the trend of energy showing sharp and sustained increase, due to economic development and increased standard of living, energy conservation has become an important aspect that matters to individuals and government. Energy is one of the most basic human needs, which have been a fundamental ingredient for all economic systems (ASHRAE, 1990b).

The awareness towards the need for energy conservation worldwide has helped majority of people to gain knowledge about dwindling reserves of fossil fuels. There is still considerable scope to further reduce the energy consumption in buildings. Efficient use of energy is important since the reserves of our global energy resources are finite and depleting and adversely effect the environmental as a result of power generation. Among the different energy end-use sectors, the building sector is often considered having large potential for substantial energy savings (Alliance to Save Energy, 1993). Buildings alone in United States account to about 75% of the electrical energy and about 40% of natural gas usage, and commercial buildings consume an approximate of 1/6th of total energy used in which 1/3rd of it is electrical energy (Max and Hal, 1996). The energy consumption trend in United Kingdom follows the same trend, it has been observed that the energy demand in the commercial sectors from 1973-1996 has grown at three times faster rate than domestic sectors as identified by Scrase (Scrase, 2001). In United Kingdom, buildings account to 40%-50 % of the total energy produced for creating and maintaining internal environment (Sherratt, 1976). The Asian regions are not left far behind; the commercial sector in Hong Kong in the year 1991 has shown to consume 44% of the total electricity produced (Lam and Hui, 1993). Although the present energy technology for building components promises to reduce energy demands (Bevington and Rosenfeld, 1990), there is a lack of real understanding with respect to energy performance of buildings, especially for air-conditioned premises in hot-humid climate.

During the past decades, building designers have been searching for a systematic way to measure, analyze and assess the building energy performance. Although efforts have been made on this subject, building energy performance remains an enigma to most people. Energy use in buildings at present is ill-conceived and not well understood because the parameters involved are complex, diverse and insubstantial in nature. Attempt to achieve energy-efficient design of buildings is often hindered by the lack of appreciation of the way buildings respond to the climate and the various environmental and design factors.

To tackle this difficulty, computer simulation models have been developed to help the building designers and energy analysts in conducting detailed building energy analysis. Through a couple of decades, these models have been accepted as the most powerful and flexible tools for investigating building energy performance, and have been used extensively in the world for supporting the development of modern building energy standards (Dubin and Long, 1978; Deringer and Busch, 1992; Wilcox, 1991; SRC Australia Pty Ltd, 1993c). Despite the growing implications of computer building energy simulation, application of the simulation tools and techniques is problematic. There is a gap between the technology as applied using computer and what is being adopted and understood by the practicing building designers.

With a growing concern regarding energy efficiency, developing countries have begun to investigate and develop their own building energy standards. But the tasks are often hindered by the breadth of the subject and the complexity of building energy analysis (Hui and Lam, 1991b). Efforts to investigate energy performance of buildings are usually impeded by the lack of suitable local climatic data and the insufficient recognition of the properties of energy analysis and simulation techniques.

1.1.1 Other Issues Related to Electricity Generation

Electricity is clean energy at the point of use. One way or another, all this energy comes from natural resources – whether fossil fuels, living resources, nuclear fuel, or renewable resources. A generation ago, there was concern that fossil fuels would run out, plunging the world into an energy crisis. Today the fear is that their continued use might be wrecking the global climate by CO, CO_2, SO_X, NO_X and particulates depending on the fuel properties and composition, operating conditions and plants efficiency. These emissions contribute to air pollution, acid rain and global warming. This anxiety is substantially increased in view of the considerable unmet demands for energy in the developing world. Therefore, control of the overall energy consumption in buildings is necessitated.

In most countries at the community level, by reduction in the energy demand, excessive dependence on imported fuels can be avoided and the resources for generating and supplying energy can be minimized. Government-initiated control measures have been developed to stimulate energy efficiency improvements and the formulation of building energy standards is of primary concern. Economic and environmental factors are also causing the prospective building owners and developers to be increasingly concerned with energy costs and to transmit this concern to the building designers through a demand for more energy-efficient buildings.

Among the different forms of energy, electricity is the most convenient and important for general use (Fickett, et al., 1990). To ease environmental pressures and meet the world growing energy service needs, improving electricity end-use efficiency is very essential. The potential for electricity savings is probably greatest in commercial buildings where a significant portion of the energy demand is expended by heating, ventilating and air-conditioning (HVAC) systems (Bevington and Rosenfeld, 1990). A number of technologies and opportunities such as energy efficient buildings and lighting system have been identified and studied in developed countries (Holtz, 1990; Morse, 1990; Geller, 1988), but their applicability and effectiveness in developing countries, like Saudi Arabia, are seldom evaluated extensively.

1.1.2 HVAC System and Energy Conservation

In order to enhance the comfort and well being of the occupants, indoor environments have been controlled with extensive and often complicated heating, ventilating and air-conditioning (HVAC) systems. The Heating Ventilation and Air Conditioning (HVAC) systems are no more a luxury but are becoming an integral and a necessary part of all types of facilities, including residential, commercial, institutional or industrial, to maintain acceptable indoor environment. 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. The capital investment of air-conditioning system also represents a major expense in the construction of commercial buildings. Considerable saving potentials for energy and cost-effective building design can be anticipated.

The amount of attention given by the designers while selecting HVAC system may satisfy the peak load and budget constraints with little or no consideration towards energy efficient management and indoor environmental quality. Sometimes in-order to satisfy energy conservation issues, like the incorporation of incorrect HVAC operation strategies, changes in the design of HVAC systems so as to reduce energy consumption and maintenance cost, may result in poor thermal comfort quality. Proper design, commissioning, operation and maintenance of these systems and good HVAC system control could be vital to ensure thermal comfort and is the most cost-effective way to improve the energy efficiency of an air-conditioned building.

Unfortunately very little consideration has been given towards energy-conscious design in the past. The new buildings though purposeful and attractive, are not necessarily cost-effective in energy terms. The building designers and consultants are now considering building and other codes on HVAC equipment and lighting installation. But there is a lack of detailed technical knowledge about how the regulation can achieve the objectives and what measures are needed for improvement. Detail research studies are needed to provide systematic methods for evaluating building performance and to help designers achieve the efficiency goal.

1.1.3 Need for Energy Conservation in Commercial Buildings in Saudi Arabia

Saudi Arabia is totally 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 and cool nights. Summers can be extremely hot with temperatures rising to 55ºC in some areas. The higher inland areas are cooler. Coastal cities are humid and hot year round. Sandstorms blow in many regions in the country, some lasting for days. 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. The following Table 1.1 reveals the electric production and consumption over a period of 10 years from 1990 to 2000 (Earth Trends, 1999). Total Energy Consumption is defined as the total amount of primary energy consumed from all sources in the year specified.

Table 1.1 Energy Productions and Consumption in Saudi Arabia (1990-2000).

Energy Production and Consumption (in thousand metric tons of oil equivalent)	
Total Energy Production, 2000	487,889
% Change since 1990	-8 %
Energy Import, 1997	4
Energy Export, 1997	386,792
Total Energy Consumption, 1999	84,907
Electricity Consumption, 1999	8,181
Energy Consumption per capita, 1997	5.05
% Change since 1990	28%
Energy Consumption per GDP, 1999	404
% Change since 1990	11%

Energy consumption per capita, is the total amount of energy consumed per person, in each country in the year specified. This variable includes energy from all energy sources. The percentage change since 1990 shows the percentage change in per capita energy consumption between 1990 and the specified year: in this case, 1997 which in the present case is 28 %. Energy consumption per GDP indicates the amount of energy consumed per unit Saudi Riyal of income generated by the country's economy. The change since 1990 shows the percentage change in energy consumption per GDP between 1990 and the specified year: in this case, 1999 accumulating to 404 Metric ton.

Figure 1.2 is the graphical representation of Table 1.1. It reveals that the total consumption for the year 1999 in comparison with 1970 has drastically increased over a 30 year period. However the energy consumption per capita and energy consumption per GDP appears to remain constant after gradually increasing for 10 years.

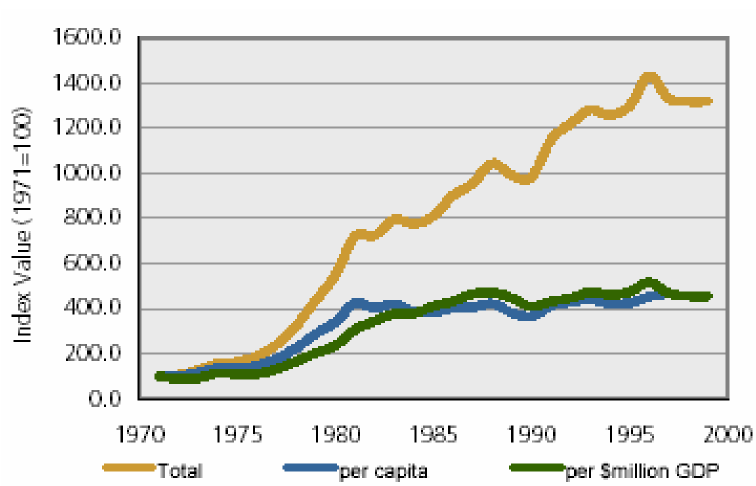

Figure 1.2 Electric Consumption: Relative Trend, Saudi Arabia, (Earth Trends, 1999)

Factors such as climatic conditions and those required to maintain indoor environmental condition at acceptable level consume bulk amount of energy. The demand for energy has increased by an average of 13% annually over the decades, with peak load demand of 848 MW/ years in 1975, which has now reached to 21451 MW/year in the year 2000 and is expected to be 59000 MW by 2023 (Abdulrahman, 2001). The present electricity consumption accounts to 13 Trillions KWh which may rise to 60 Trillions KWh by year 2050 (Abdulrahman, 2001).

Commercial buildings in Saudi Arabia have evolved with rapid development over the past twenty years (Al-Sulaiman and Zubair, 1996). Energy in commercial buildings is generally used to perform various types of functions, such as heating and cooling, mechanical drives, lighting and many other special applications. In Saudi Arabia the commercial building consume about 9% of total energy generated (Aftab Ahmed and Elhadidy, 2002). A typical breakdown of relative energy used in commercial building in United States is shown in Figure 1.3 (Ronald et al., 1998). It can be seen that major portion of the total electrical energy delivered to the facility is consumed by lighting load which impacts the cooling load, thereby consuming additional energy for maintaining thermal comfort. The second one to lighting in energy consumption is air conditioning and refrigeration which amount to almost 40% of the total energy. The past pattern of energy usage in commercial building and their intermittent operation suggests that there can be a fertile area and a potential candidate for energy conservation.

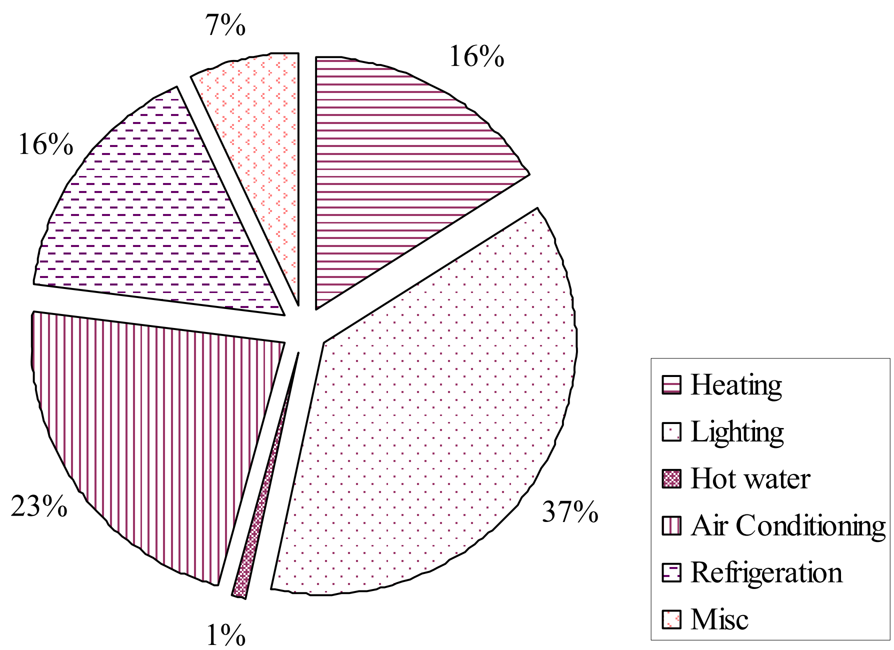

Figure 1.3 Energy Use in Commercial Buildings in U.S.A. (Ronald et al., 1998)

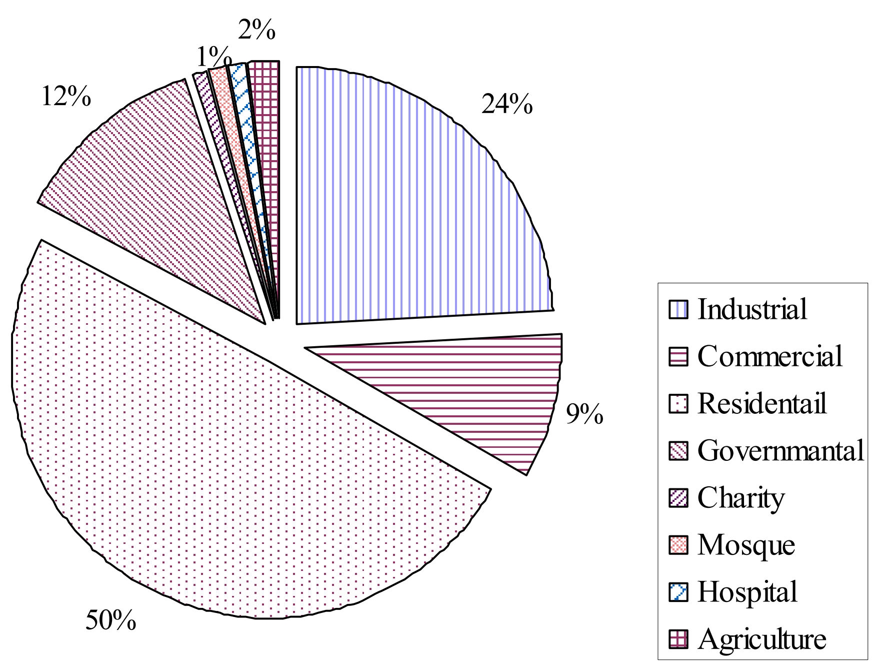

Figure 1.4 Electrical Energy Usage in Different Sectors, Saudi Arabia

Figure 1.4 reveals the electrical energy consumption sector-wise in Saudi Arabia. The building sector including residential and commercial are major consumers of energy in Saudi Arabia, these sectors alone consume 60% of the total energy generated in the kingdom. Another, 25% energy is taken up by the industries, 12% by hospital and medical facilities and a small percent (5%) in miscellaneous divisions like mosque, charity agriculture etc. Figure 1.5 below shows comparison of the total energy consumption for various regions of the Middle East from 1980-2000. It can be seen that even from the early period of 80's Saudi Arabia has always surpassed other nations in electricity consumption.

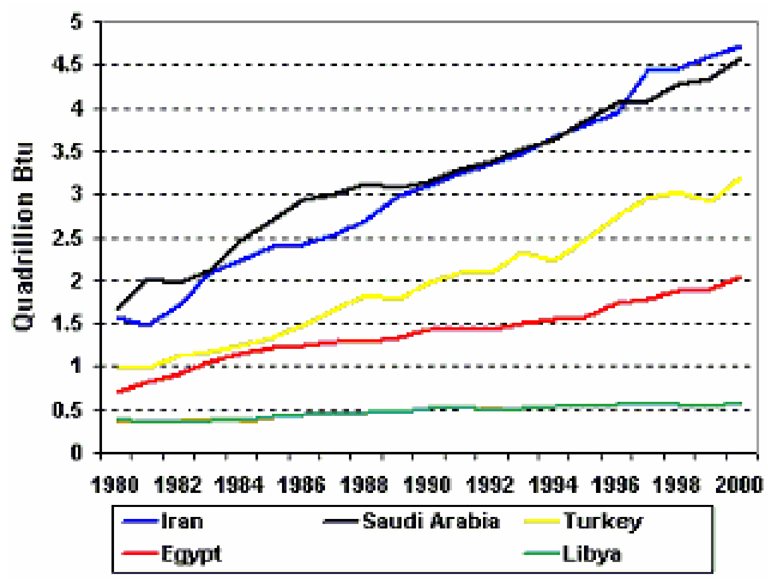

Figure 1.5 Comparison of Total Energy Consumption in the Middle East, (Said et al., 1990)

The data published by the MIE, Saudi Arabia revealed that the largest portion of the total energy sold to the country is consumed by the building sector. It is believed that a significant portion of the electricity energy in buildings of Saudi Arabia is used for air-conditioning during the summer months. The analysis of the data by the SEC showed that the air-conditioning requires about 65% of the total energy delivered to the building sector (Aftab Ahmed and Elhadidy, 2002).

1.2 Statement of Research Problem

Commercial buildings have been identified as major consumers of electrical energy because of their continuous operation of HAVC system to maintain indoor comfort conditions. Prominence towards energy conservation and energy management have resulted in energy efficient systems, most of which compromise with the indoor thermal quality. Some of the most common techniques adopted globally for energy conservation are the reduction in the ventilation rate, control of temperature and humidity that may result in unsatisfactory thermal environment. This attitude of designer should be rectified as poor indoor conditions can lead to lower productivity and rising health-care cost. Therefore there is need to investigate the impact of HVAC system operation on energy consumption relative to thermal comfort being achieved. Impact of such HVAC system operation strategies in Saudi Arabian towards commercial buildings is not known and needs to be identified.

1.3 Significance of Study

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 and air-conditioned buildings replaced old constructions and most of these buildings are air-conditioned. Therefore, proper design, operation and maintenance of HVAC systems are essential components in solving the problems of energy conservation and thermal comfort.

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 to the evaluation and improvement of indoor space conditions, thereby paving the way for productive and healthier environments. The whole world has given prompt attention to these serious 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 to act swiftly and join the international awareness against energy consumption in different types of buildings. It is also vital to know the common operation practices of HVAC system.

1.4 Objectives of Study

The main purpose of this study is to identify those operation strategies for HVAC system that can help to attain energy savings without sacrificing thermal comfort conditions. It is expected that the research can draw useful information to HVAC designers in Saudi Arabia for analyzing and designing HVAC system and operation for commercial building to achieve energy efficiency.

The main objectives of this study are as follows:

1. To investigate the impact of HVAC system various operation strategies on energy conservation and thermal comfort in commercial malls in Saudi Arabia.
2. Identify HVAC system operation strategies to obtain thermal comfort at reduced energy consumption for shopping malls in hot-humid climate.

1.5 Research Methodology

This section describes the methodology adopted to investigate Heating Ventilation and Air Conditioning System (HVAC) operation strategies and their impact on energy conservation and thermal comfort. Strategies used by various investigators show an inconsistency; therefore a need to employ multidisciplinary approach of achieving energy saving and thermal comfort simultaneously has been recognized. This approach includes gathering information about selected number of existing commercial building including their characteristic. Furthermore HVAC system operation, available occupants' comfort level and their perception about indoor environment are obtained from the facilities managers of a number of shopping malls in the Eastern Province of Saudi Arabia as it has been identified as the potential area for energy saving.

The means of collecting information for the research includes review of relevant literature, personal interview with the facilities managers and questionnaire survey for thermal comfort analysis with the building users, review of engineering drawings and field measurement of certain environmental parameters that are indicative of thermal comfort conditions and energy consumption in the space. Figure 1.6 illustrates the various components constituting in the research methodology. The research methodology is designed to comprise different phases. These phases include extensive literature review of the subject, followed by data collection of commercial malls and assessment of thermal comfort status. Formulation of a case study through the process of calibration via an energy modeling and simulation tool, investigating impact of various operation strategies on thermal comfort and energy consumption and finally identifying best HVAC system operation strategies to achieve energy conservation and required level of thermal comfort.

Phase I: Extensive literature review is carried out to acquire in-depth understanding of the issues related to energy conservation, thermal comfort level and HVAC system operation strategies in commercial buildings. This phase helps to build the foundation for the research work and explore potential area for energy problems that are associated with the topic in the Kingdom of Saudi Arabia. This exercise further helps in developing the data collection forms and questionnaire for thermal comfort analysis.

Phase II: The next step towards the investigation of the energy problem is to interact with the facility managers and the users of sample commercial buildings in the Eastern Province of Saudi Arabia. This phase emphasizes on conducting personal interview with the managers to acquire useful information pertaining to the physical building characteristics, occupant's density, lighting requirement, thermal comfort level adopted, electric energy consumption etc. The as-built drawings are reviewed to gather information about the thermal zoning and construction systems. Thermal comfort survey questionnaire is distributed to the building users to obtain their perception on thermal environmental conditions.

Phase III: During this phase of research the information obtained from the above two phases is used in the selection of model building to form a real case study. Using the acquired data for the selected building a base case is formulated in Visual DOE energy simulation program. The results of the base case are calibrated with the real time consumption obtained from the utility bills for the year 2002. Calibration of the base case is essential to improve the accuracy of the strategies to be implemented in the later phase.

Phase IV: There are numerous HVAC operation strategies that can be implemented to conserve electrical energy and thermal comfort, but all of them don't help to attain both goals at same time. In this phase impact of different operation strategies for HVAC system on energy conservation and thermal comfort is investigated. Employing new strategies might reduce the energy consumption but on the other hand may or may not be able to maintain the desired thermal comfort. Such variations in energy consumption and thermal comfort with changing HVAC operation strategies are studied in detail under this phase.

Phase V: In this phase among the strategies investigated in earlier phase only those strategies are selected that helps to achieve thermal comfort conditions in the building at reduced consumption. Based on the final outcome recommendation and guidelines are suggested for the facility managers of the shopping malls.

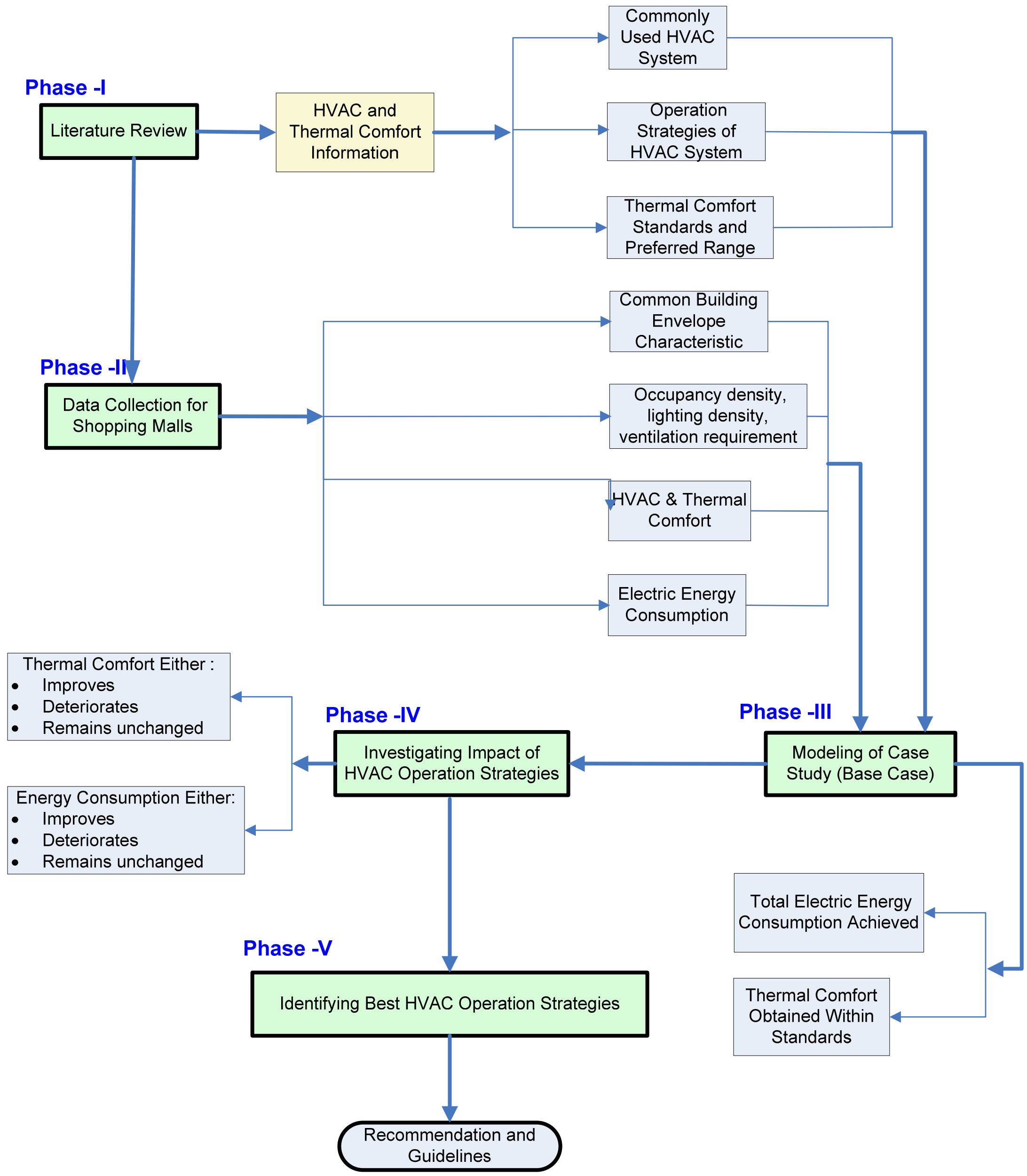

Figure 1.6 Flowchart Showing Different Phases of the Research Methodology

1.6 Scope and Limitation

This research will help to identify the commercial building performance in Saudi Arabia; however there are few limitations of this work which are mentioned here.

1. This thesis primarily focuses on air-conditioned buildings located in the Eastern Province of Saudi Arabia, since this sector has largest volume of construction and energy consumption.
2. Improving the energy efficiency of these building is a major issue as most of them have profligate energy use towards cooling system.
3. This study will concentrate on different operation strategies of HVAC system and their intimate relationship to energy consumption and thermal comfort in shopping malls only.
4. Unavailability of weather data for current year, 2002 weather file is used to perform computer simulations for energy analysis.

1.7 Organization of the Thesis

This thesis explicates the energy crises problem with emphasis on role of commercial buildings towards it, also follows an investigation to identify the key factors for energy savings in commercial buildings. The primary aim is to identify potential HVAC operation strategies that can help conserve electrical energy. At the same time the impact of these strategies on thermal comfort for air-conditioned commercial buildings represented by shopping malls in Saudi Arabia is investigated.

This thesis is documented into six chapters on the basis of proposed research methodology of study. The introduction of the current work, its importance and the research methodology has been discussed in the chapter 1.

Chapter 2: Provides the necessary background for the research problems being undertaken and explains the current developments and related understanding. It highlights the approach to energy conservation opportunities, energy and thermal comfort aspects in commercial buildings. HVAC operation strategies and energy analysis through simulation program and the selection of the simulation program for the present study are also described.

Chapter 3: Presents the analysis of the data collected from various commercial buildings through personal interviews with different facility managers, drawings and measurements. Also an energy index is developed from the information of energy from different buildings. It describes the present status of thermal comfort range found in the shopping mall in Saudi Arabia.

Chapter 4: Presents the criteria for selection of the model building and an overview of the building for the formulation of base case of shopping mall model in Dhahran weather via a detailed VisualDOE 4.0 simulation program. Validation of the selected base case with the real time energy consumption data taken from SEC Dammam, Saudi Arabia is performed.

Chapter 5: Investigates the impact of different HVAC operation strategies on the energy consumption in the selected shopping mall. Sensitivity analysis is carried out to examine the impact of HVAC operation on energy consumption and thermal comfort. Comfort trends obtained in the present study are compared to the standard values given in ASHRAE and Fanger Charts.

Chapter 6: Summarizes the key research findings, explains the significance and limitations of this study. It recommends future research work for enhancing energy conservation and thermal comfort in commercial buildings.

CHAPTER TWO

LITERATURE REVIEW

The energy problems in building arise due to lack of theoretical framework and uncertainty towards building design and energy analysis methods. This chapter outlines the existing problems, the ongoing developments in achieving energy savings and better understanding of the field of energy simulation.

2.1 Thermal Comfort Requirements in Commercial Buildings

A positive definition of comfort is the feeling of well being. The principle purpose of a HVAC system is to provide conditions for human thermal comfort. A widely accepted definition of the thermal comfort is "that condition of mind which expresses satisfaction with the thermal environment" (Ronald et al., 1998).

A comfortable environment is created by simultaneously controlling temperature that includes mean radiant temperature and air temperature, humidity, air cleanliness and distribution within the occupant's vicinity. In addition to these factors, behavioral factors like clothing level, activity, posture and location, opening a window, etc also affect the feeling of thermal comfort (ASHRAE Fundamentals, 2001). Though wide variation exists in the climatic conditions, living conditions and cultures throughout the world, the temperature preferred by the people under such conditions of clothing, activity, humidity and air movement have been found to be similar (ASHRAE, 1993).

A laboratory study revealed parameters to describe the environment in terms of thermal comfort. These indices are generally sub-divided into three groups: direct, rationally derived, and empirical. Direct indices include dry-bulb temperature, relative humidity, dew point temperature, wet-bulb temperature and air velocity. Rationally derived indices include mean radiant temperature, operative temperature and humid operative temperature. Empirical indices include effective temperature, black globe temperature, corrective effective temperature, wet bulb globe temperature and wind-chill index. Among the above mentioned indices the most commonly used are dry-bulb temperature, relative humidity, air velocity and mean radiant temperature as they are the key factors behind the thermal comfort conditions of a space.

Tanabe and Kimura (1994) investigated the effect of similar air temperature, air movement and humidity on thermal comfort for people with different clothing and activity level during summer and winter in hot humid conditions. Higher air velocities were recommended for occupants working under high temperature and humidity. Also it was found that sine-wave air movement produced better comfort conditions than constant air movement with same mean air velocity.

2.2 Energy Conservation in Commercial Building: Research and Case Study

The energy trend data and literature shows that there is significant potential to improve energy performance of commercial buildings. Based on well established experience, cost-effective measures can be used to reduce the energy consumption in commercial buildings by at-least 20-30%. Such techniques to name a few include: Building Envelope Design, Energy Efficient lighting System, HVAC Design, Operation and Maintenance, Building Control and Efficient Operation and Retrofit of Existing Building and Operation. Approaches taken for energy efficiency in new buildings differ from those taken for existing buildings. For new projects the move is to build energy-efficient and self-powered buildings. For the old and existing buildings the approach taken is efficiency improvement, such as good energy management practices and/or energy auditing is recommended to identify possible areas for improvement. Some of the most important and established energy efficiency improvement trends are to employ good operation and maintenance practices, replacement, retrofit, fuel substitution and co-generation.

2.2.1 Energy-Efficient Design

John Radford et al., (2000) described and demonstrated the new design alternative for state building to assess the energy and cost associated with them. These cases were simulated using PowerDOE building energy simulation software and later compared with the ASHRAE 90.1.1989 base case. Analysis showed saving of $6,139,125 achieved over the reference base case with an investment of $4,002,000.

2.2.2 Building Envelope

Energy-efficient buildings are the result of not only a responsible attitude toward energy but also how successfully the designer is able to apply energy technology and energy analysis tools during the design process. Building envelope may be defined as barrier between the controlled indoor environment and outdoor. It includes exterior walls, windows, doors, floor, ceiling and roof. The performance of the building envelope impacts different sub-systems such as HVAC systems, plumbing and electrical systems. Building envelope through its components plays a major role by gaining or loosing heat to the surroundings. This heat loss or gain can be translated into cooling or heating load used in the design of HVAC system.

A. Wall System

Numan and Al-Mazaid (1994) demonstrated the effect of envelope on energy performance with variation in parameters like plan, facades, glazing etc. with respect to orientation and surrounding configuration using PC-DOE. Building orientation of ±15%

to the south or north was found to be optimal. Plan proportion of 1:2 was considered to be appropriate, with two sides glazing rather than all side for orientation NE or SE. Obstruction from neighboring buildings was another factor towards reduction of energy consumption.

B. Fenestration System

Glazing is the weakest spot of the building envelope from the point of view of thermal transfer; therefore it is one of the most important parameters to be considered with regard to energy conservation in buildings. Klainsek et al., (1996) studied the influence of glazing and their shape on energy consumptions in commercial buildings. Energy consumption for horizontal and vertical glazing separated by opaque area was evaluated. For traditional wall with colorless glazing energy consumption was reduced from 0.78% - 0.92% and 0.16% - 0.18% during summer and winter months respectively. However use of curtain walls further reduced the consumption between 0.3% - 0.39%. Further the results showed that energy consumption was high for vertical discontinuous windows than continuous horizontal of same area.

Carriere et al., (1999) in their study on commercial buildings evaluated the energy conservation potential through window glazing, occupancy sensors and cold deck temperature set point and ventilation air. They found that cold deck temperature setpoint and ventilation air as an attractive option with investment of no cost. Energy savings from the use of occupancy sensors and window glazing were substantial and economical.

Hunn et al., (1993) identified the effect of shading devices on energy usage in residential and non- residential buildings using DOE 2.0. It was concluded that for the best shading device performed better in residential buildings. The interior window attachment generated more saving then exterior fixed shading. Subsequently greater energy saving can be obtained for commercial buildings when the HVAC system is resized with shading strategies.

2.2.3 Lighting System

All enclosed spaces require either daylight or artificial lighting. In modern buildings artificial lighting is a significant contributor to the electric consumption and air-conditioning load. Electrical energy required for artificial lighting contributes to 15% towards peak power and 20% of annual energy consumption. Therefore lighting is an important factor to reduce the electric consumption especially in commercial buildings as it is more widely used than any other type of buildings. Use of energy-efficient lighting system not only reduces the cooling load but also minimizes the electric consumption. Saving electrical energy through lighting system is simple and cost efficient as it is visible.

Dina and Gopal (1998), in their cost benefit analysis of energy efficient lighting estimated the saving that could be obtained through the use of energy efficient fixtures, compact fluorescent lamps and electronic control. Use of locally manufactured fixtures performed in same manner as those imported from USA, however use of large reflectors produced uniform distribution and higher level of light intensity. Compact fluorescent lamps reduced energy consumption up-to 80% compared to normal incandescent lamps.

Larry (2002) demonstrated the use of occupancy sensor for reduction in energy consumption depending on occupancy and daylight using ENER-WIN. Results showed 40% reduction in lighting energy and when used with motion sensors to control ventilation can produce 50% savings.

2.2.4 HVAC System

The main purpose of heating ventilation and air-conditioning system is to create a comfortable and healthy indoor environment, by controlling the indoor temperature, humidity level, air circulation and air quality. Creating and monitoring comfortable, healthy environment within buildings has been a sustained occupant's requirement and a challenge to HVAC designers and operators. The impact of the quality of indoor environment on the performance, efficiency, quality and morale of individuals are significantly important factors that needs prompt consideration. Further a well-designed

HVAC system is an essential component of efficient performance of buildings. Poor design is frequently cited as a primary cause of all major problems. Most of the HVAC systems in use today have been designed for temperature control, with little or no consideration towards energy saving. HVAC systems in the USA alone consume more than 25% of the total primary energy in commercial building as reported by Westphalen and Koszolinski (2001). Due to the harsh climatic conditions in Saudi Arabia the HVAC systems consume more than 60% of the energy delivered to the building (Al-Azhari et al., 2002). Therefore there is an urgent need for energy efficient design.

Sekhar and Chung (1998) employed simulation to evaluate five most commonly used HVAC systems in commercial buildings based on their thermal and energy performance. Two coil induction unit had lowest consumption and performed better in providing thermal comfort, followed by VAV system with small fluctuation over the building. CAV system consumed 10% more than VAV system at the same time gave degraded performance. Packaged system had highest consumption and was least satisfactory.

Charles et al., (1996) describes the impact of uncontrolled air flow and pressure differential on energy use, and indoor comfort in commercial buildings. Duct leakages were identified as the main source of UFA in most facilities. With an average investment of $455 per year the cooling energy usage was reduced by 15%.

Thomas (2003) revealed the strategies for terminal VAV system in commercial building. Research has shown that use of floating supply temperature offered improved comfort conditions and energy performance. Use of cooling effect dampers rather than conventional box dampers to modulate the air flow has shown better comfort and operation stability. Further use of multiple space temperature sensors and incorporating them with lighting and occupancy sensors improved the comfort conditions of the building.

2.3 Operation Strategies of HVAC System

HVAC Operation plays a major role in the control of indoor environment and energy management. There are numerous available strategies applicable to the HVAC system of interest depending on the facility occupancy. Below mentioned are a few strategies discusses by Manuel (1983) for energy management and control of indoor environment.

2.3.1 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.

2.3.2 The Outside Air Temperature Cut-off

This strategy should stops the flow of cooling media upon the fall of outside air temperature to within 5^0 F of the inside design temperature. Similarly in event of provision of heating in the facility this function helps to cut-off the flow of heating media with the rise of outside air temperature to within 5^0 F of the inside design temperature.

2.3.3 Duty Cycling

This strategy involves shutdown of system for pre-determined short periods of times during normal operating hours. It is based on the principle that HVAC system seldom operates at peak output; thus if the system is shut off for a time, it has enough capacity to overcome the slight temperature drift that occurs during the shutdown. This function also helps to reduce the outside air cooling and heating load as the outside air damper is closed when the system is OFF.

2.3.4 Demand Limiting Start / Stop

This strategy helps in the reduction of electrical load that would add to setup peak electrical demand. There are numerous ways of accomplishing this task. Generally electrical loads are continuously monitored and predictions are made. When these predictions exceed the preset limits certain scheduled electrical loads are shut off to reduce the rate of consumption and predicted peak demand. The loads are turned off on priority basis, if the initial load drop action does not sufficiently reduce the peak demand.

2.3.5 Warm-Up / Night Cycle

The thermal load from the outside air used for ventilation contributes a substantial percentage of the total heating and cooling requirement for the building. This strategy helps to control the outside air damper when outside air is introduced during warm-up and cool down cycles prior to the occupancy and when the building is unoccupied.

2.3.6 Enthalpy Economizer

This strategy of using outside air economizer cycle can be a cost-effective energy conservation measure. This strategy utilizes the outside air to satisfy all or portion of the building cooling requirement when the enthalpy (total heat content) of the outside air is less than the return air from the space. The outside air is introduced into the building through the mechanical system during the cooling cycle in replacement for the recirculation air.

2.3.7 Space Temperature Night Setback

The energy required to maintain indoor space during unoccupancy, mostly for facilities not operating 24 hours/day can be reduced by raising or lowering the space temperature setpoint, depending on the weather conditions.

2.3.8 Chilled Water Reset

The energy required to generate chilled water in a reciprocating or centrifugal electric driven machines are influenced by number of parameters including the temperature of chilled water leaving the system. As chilled water temperature is selected for peak design times, in absence of effective humidity control, this temperature can be elevated during operating hours, in-order to satisfy the greatest cooling requirement.

2.3.9 Condenser Water Temperature Reset

Another parameter that affects the energy consumption 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.

2.3.10 Start/Stop Optimization

Another feature of time-scheduled operation of mechanical system serving areas not occupied 24 hours of days is the optimized start/stop. Mechanical system installed in buildings not operating 24 hrs should be shut down during unoccupancy and restarted prior to occupancy in order to cool down or heat up depending upon the requirements on a fixed schedule. This feature has the capability to automatically start and stop the system to minimize energy required to maintain the desired environmental conditions during occupied hours.

2.4 Applications to Operation Strategies to HVAC Systems

2.4.1 Single-zone Air Handler

Single-zone air handler provides conditioned air to one or several spaces with single thermostat controlling the temperature of all the spaces served. The air handler provides either cooling or heating based on the thermostat requirements; however there is no simultaneous cooling and heating in this type of system.

ECM’s that can be applied to single zone air handler are as follows:

1. Time Schedule Operation Strategy.
2. The Space Night Setback Strategy.
3. The Start/Stop Optimization Strategy.
4. The Duty Cycle Strategy.
5. The Enthalpy Economizer Strategy.
6. The Warm up / Night Cycle Strategy.

2.4.2 Single-zone Split System

Single-zone split system consists of single zone air handler utilizing DX cooling supplied by a dedicated air-cooled condensing unit. The air handler and condensing unit operates in together, providing conditioned air to one or several spaces with single thermostat controlling the temperature of all the spaces served. The air handler is capable of providing either cooling or heating based on the thermostat requirements.

ECM’s that can be applied to single-zone split system are as follows:

1. Time Schedule Operation Strategy.
2. The Space Night Setback Strategy.
3. The Start/Stop Optimization Strategy.
4. The Enthalpy Economizer Strategy.
5. The Warm up / Night Cycle Strategy.

2.4.3 Multi-zone Air Handler

Multi-zone air handler provides conditioned air to different spaces with individual thermostat control for each space or group of spaces that controls zone mixing damper in the duct. The cooling and heating coils in the air handler are controlled by discharge air controller to provide air streams of constant temperature. These airstreams are mixed by the zone mixing dampers to supply air at desired temperature called by the thermostat. This unit has the capability of serving some zones with cooling requirement and others that require heating at the same time.

ECM's that can be applied to Multi-zone air handler are as follows:

1. Time Schedule Operation Strategy.
2. The Space Night Setback Strategy.
3. The Start/Stop Optimization Strategy.
4. The Duty Cycle Strategy.
5. The Demand Limiting Start/Stop Strategy.
6. The Enthalpy Economizer Strategy.
7. The Warm up / Night Cycle Strategy.

2.4.4 Two Pipe Fan Coil System

A two pipe fan coil system consists of individual room fan coil unit/s served by a common piping system transferring either cold or hot water depending on the season. Each fan coil unit is controlled by an individual thermostat located in the space it serves.

The media being supplied to the fan coil units is usually selected by a two position valve, which is controlled manually or based on the outside air temperature.

ECM's that can be applied to TPFC system are as follows:

1. Time Schedule Operation Strategy.
2. The Outside Air Temperature Cut-off Strategy
3. The Space Night Setback Strategy.
4. The Start/Stop Optimization Strategy.
5. The Duty Cycle Strategy.
6. The Demand Limiting Start/Stop Strategy.

2.4.5 Air-cooled Chillers

An air-cooled chiller provides air conditioning refrigeration by cooling a chilled water loop, while rejecting the heat from the loop through an air-cooled condenser. The chiller and condenser may be mounted together as a packaged unit or separately. This unit serves several AHU utilizing chilled water coils. The unit operation is controlled by a temperature controller maintaining constant temperature for the water leaving the chillers.

ECM's that can be applied to air-cooled chillers are as follows:

1. Time Schedule Operation Strategy.
2. The Start Optimization Strategy
3. The Demand Limiting Start/Stop Strategy.
4. Chiller Water Temperature Reset Strategy.

2.4.6 Water-cooled Chiller

A water-cooled chiller provides air-conditioning refrigeration by cooling a chilled water loop, while rejecting the heat from the loop through water cooled condenser and cooling tower. The chiller and pumps are mounted together in a mechanical room, while the cooling tower is remotely located. This unit serves several AHU utilizing chilled water coils. In order to maintain a constant temperature for the water leaving the chiller, the unit operation is controlled by a temperature controller. Also there is a temperature controller available for maintaining constant condenser water temperature.

ECM’s that can be applied to water-cooled chillers are as follows:

1. Time Schedule Operation Strategy.
2. The Demand Limiting Start/Stop Strategy.
3. Chiller Water Temperature Reset Strategy.
4. Condenser Water Temperature Reset.
5. The Start Optimization Strategy

2.4.7 Air-cooled DX Unit

Air-cooled DX unit is an air conditioning refrigeration compressor system utilizing an air cooled condenser. The compressor and the condenser may be mounted in same frame or separately. The unit might serve several AHU utilizing direct expansion cooling coils.

ECM's that can be applied to air-cooled DX system are as follows:

1. Time Schedule Operation Strategy.
2. The Start/Stop Optimization Strategy.

2.4.8 Water-cooled DX Unit

Water-cooled DX unit is an air-conditioning refrigeration compressor system utilizing a water cooled condenser and cooling tower. The unit might serve several AHU utilizing direct expansion cooling coils.

ECM's that can be applied to water-cooled DX system are as follows:

1. Time Schedule Operation Strategy.
2. The Start/Stop Optimization Strategy.

2.5 Case Studies

Hunchu et al., (1996) focused on reduction in the energy consumed by the fan in VAV system through experimental work. Different control strategies such as conventional PI, adaptive and optimal control were employed to correlate their responses to duct pressure & energy consumption. Implementation of these strategies resulted in increase of pressure, thereby less energy consumption at all times. Approximately 30% energy saving was achieved with use of PI technique. Table 2.1 summarizes the application of different operation strategies depending on the system of interest under study.

Table 2.1 Summary of Operation Strategies and their Applicability

Operation Strategies/ Systems	Single-zone Air handler	Single-zone Split	Multi-zone Air handler	TPFC unit	Air-cooled Chillers	Water-cooled Chillers	Air-cooled DX	Water-cooled DX
Time Schedule	X	X	X	X	X	X	X	X
Night Setback	X	X	X	X				
Start Stop Optimization	X	X	X	X	X	X	X	X
Duty Cycling	X		X	X				
Demand Limiting			X	X	X	X		
Enthalpy Economizer	X	X	X					
Warm up/ Night cycle	X	X	X					
Outside air temperature cut				X				
Chilled Water Reset					X	X		
Condenser Water Reset						X		

Budaiwi (2003) investigated the impact of ventilation and temperature strategies for energy conservation and thermal comfort. Different case were studied, initially start of ventilation two hours before occupancy resulted in little change in cooling energy & 3% reduction in heating energy. Further delaying the start of ventilation for two hours after the occupancy have started resulted in significant reduction in both cooling and heating energy. Control of temperature only during working period rather than all day produced 25% & 35% reduction in CE & HE respectively. With temperature controlled over working hours and floating during low occupancy resulted in further savings.

Ardehali & Simit (1997) examined HVAC operation strategies for CAV-RH & VAV-RH system using TRACE energy simulation program for newer & old commercial buildings. The different strategies evaluated were NP, OSS, CWR and CHWR. For old facilities NP was least & OSS most effective. For chillers with multi stage unloading characteristic CWR & CHWR in combination produced reasonable saving. Further savings could be achieved with OSS, CWR & CHWR when all the three were applied together. However for new buildings though OSS was most effective, CWR showed highest consumption because of cooling tower fan.

Andrews et al., (1993) evaluated CHiRP and TLC strategy in a test chamber for small buildings. The CHiRP is designed to provide significant peak load reduction while maintaining temperature & humidity within acceptable limit. It further involves precooling of the building before the onset of peak, maintaining humidity rather than temperature. TLC involves low set point temperature being imposed on the air conditioning system for fraction of ON-Time during peak load, enabling the system to perform its best. Results showed that CHiRP reduced the on-peak energy usage but not the on-peak demand, whereas TLC reduces both parameters by an average of 35%.

Mingsheng et al., (1995) identified the means energy savings in non-residential buildings by resetting the cooling deck and heating deck temperature with respect to the ambient conditions without compromising with thermal comfort. Three different systems were evaluated in this study namely, DDCVP, SDCV and SDCVP. The simulations were performed in LoanSTAR program. The results showed that 19% energy savings are achieved with the newly improved strategies; further the savings attained was similar to case of replacing CAV with VAV.

Tham (1993) explored energy conservation measures and their impact on thermal environment in office buildings. Daylight and high efficiency lighting system utilization produced saving of 15% & 13% respectively. Chiller COP, thermostat setpoint, throttling range and minimum air flow were also found to have significant impact on energy. Energy saving at higher setpoint temperature can be achieved by using higher velocity of supply air.

Methews et al., (2001) determined comfort enhancement and energy saving potentials adopting new control strategies using QUICK Control energy simulation program. Various strategies such as air by-pass, reset control, set back control, improved start-stop times, economizer control and CO_2 were investigated and compared in-terms of indoor comfort. Improved HVAC system start-stop times together with air by-pass, reset control and set back control were found to be more lucrative and helped in achieving 30% reduction of total building energy consumption.

2.6 Energy Analysis Using Simulation Methods and Techniques

Nowadays computer simulation is the most popular and flexible building energy analysis tool. Figure 2.1 gives a general picture of the major elements of building energy simulation (Clarke, 1982; Clarke and Irving, 1988). Building design parameters are the input; indoor environmental conditions and energy performance are the output.

The climate is the boundary condition of the simulation system and forms the basic driving potential for the variation of building loads. Building simulation allows us to see the effects of all kinds of changes in a fraction of the time. It takes to study the same alternative in realities and at a much smaller cost (International Energy Agency, 1990). Computer simulation programs and methods required to carry out building energy simulation are described in the next section.

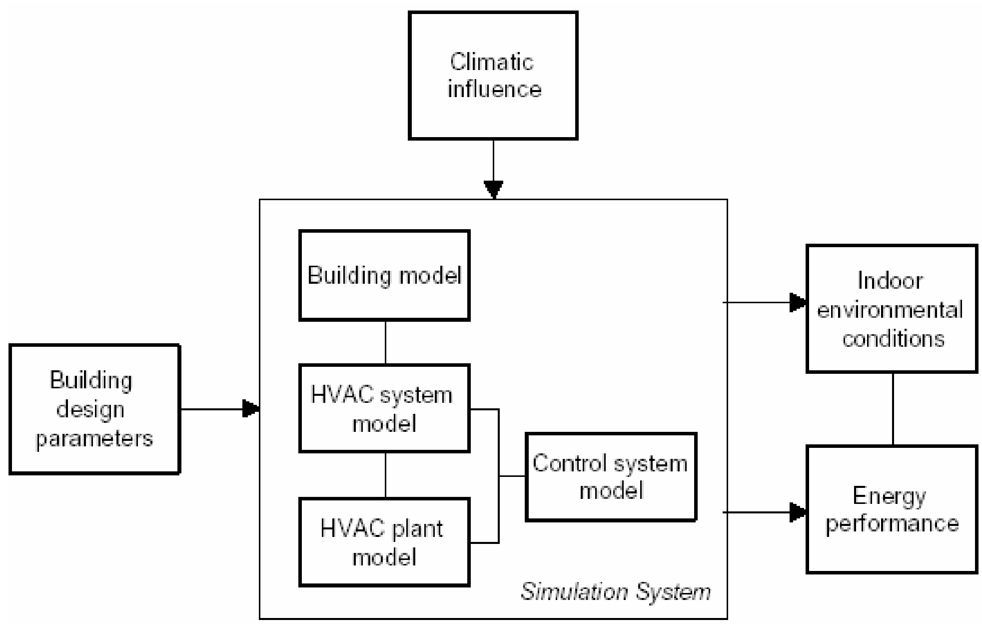

Figure 2.1 Major Elements of Energy Simulation (Clarke and Irving, 1988)

2.6.1 Simulation Programs

Computer programs designed for energy modeling and analysis of buildings are generally known as building energy simulation programs. These programs are intended for modeling of large, multi-zone building and their HVAC systems (ASHRAE, 1993). The interactions in buildings are by their nature very complex. While some simplified design tools and guidelines exist to help designers understand the phenomena involved, more elaborate, often computer-based tools are required for detailed analysis.

Despite the great potential the building energy simulation program hold for optimizing energy use, it is often difficult for the designers and clients alike to justify the extra time and expense that their use entail. Some of the most compelling argument for more widespread use of these programs in the design process comes to light in application where they have enabled cost saving opportunities. Various energy studies discuss implementation of various design strategies, which contoured local standard architectural and engineering practice. Without the use of energy simulation programs it is doubtful that the improvements would have been made.

Energy simulation programs have increased the individual user's level of understanding the building performance, helped them to better identify potential cost saving measures and improved their ability to affect truly integrative approach to energy conservative design. In this light, DOE simulation program has been an important tool for individual education and professional advancement for achieving higher quality results.

2.6.2 Existing program

Most of the building energy analysis programs are developed in USA and Europe; directories and lists of energy analysis software have been published to show people what is available in the market, such as AEE (1991), ASHRAE (1991d), Williams (1992), Degelman (1987) and Weiss and Brown (1989). There are more than 200 programs in

USA and 100 programs in Europe and elsewhere (Seth, 1989b), but only a handful of them are frequently used by building designers (Bloomfield, 1989b). Table 2.2 gives a list of the programs commonly used nowadays. A list of the programs common in Europe can also be found in Goulding et at., (1992).

These software packages have different levels of detail and input requirements; they may come from research institutions, equipment manufacturers or private consulting firms; some of them are public domain programs and some are proprietary programs. Procedures established from recognized professional bodies are often used in their algorithms, such as G. K. Yuill and Associates Ltd. (1990), ASHRAE (1976), ASHRAE (1975b) and Petherbridge (1985).

Table 2.2 A Lists of Common Building Energy Simulation Programs (Goulding , 1992)

Programs	Reference sources	Country	Remarks
APEC ESP-II	Wickham, 1985	USA	Detailed Program
ASEAM 2.1	Ohadi, Mever and Pollington, 1989	USA	Simplified
BESA	BESA, 1993	Canada	Detailed
BLAST	BLAST, 1991	USA	Detailed and Public domain
BUNYIP	Moller and Wooldridge, 1985	Australia	Utilizing Bin Weather file
Carrier HAP	Carrier Corporation, 1990	USA	Simplified and Commercialized
DOE-2.0	Birdsall, et al., 1990 LBL, 1981	USA	Detailed and Public domain
ESP-r	Clarke, 1993	USA	Detailed
HVACSIM+	Clark, 1985	USA	Detailed and Public domain
TRACE 600	Trane Company, 1992a and b	USA	Simplified and Commercialized
TRNSYS	TRANSYS, 1988	USA	Detailed

Apart from energy analysis, many of them also allow for standard HVAC design load calculations. It is believed that each program has its own areas of application and it is difficult to determine which one is the best for a specific job. Generally, the detailed simulation programs (such as BLAST (BLAST, 1991), DOE-2 (LBL, 1981) and ESP-r (Clarke, 1993)), which perform calculations for every hour of a year (8,760 hours), are considered more accurate and capable than those programs using simplified procedures. But a lot more input efforts are usually required by the detailed programs.

Recently Energy PLUS has been added to the list of energy simulation programs. It is an energy simulation program for modeling building heating, cooling, lighting, ventilating, and other energy flows. While it is based on the most popular features and capabilities of BLAST and DOE-2, it includes many innovative simulation capabilities such as time steps of less than an hour, modular systems and plant integrated with heat balance-based zone simulation, multi-zone air flow, thermal comfort, and photovoltaic systems. Further it is a stand alone simulation program without user friendly graphical interface.

2.6.3 Development trends

Building energy analysis programs have undergone a slow evolution since arrival over a decade ago (Beranek and Lawrie, 1989). The simulation techniques are rapidly changing with decreasing cost and increasing flexibility of computer systems. In the 1970, the cost of conducting an energy analysis was high (Rubin, 1973); most energy programs in those days were developed on mini- or mainframe computers and so, due to the cost of these machines, were inaccessible to the vast majority of potential users (Mac Randal, 1988). In the 1980 and 1990, profligate of microcomputers and emergence of microcomputer versions of the simulation programs made it more affordable and accessible to carry out detailed energy studies. Many of the current simulation programs are succeeding generations of some previous ones. Experience suggests that only a few of the many models will survive over time while others may fall, some will be replaced by new generations (Radford, 1993). Care must be taken to keep abreast of the latest development and updates of the programs. In other engineering disciplines, such as civil and structural, simulation tools have been used extensively and routinely for design. But in the building industry, designers are often reluctant to use simulation tools. Simplified and commercialized packages are now been gradually accepted in design offices, but the detailed simulation programs are very seldom used. The variety and diversity of simulation tools give rise to a practical need for evaluating the applicability and credibility of the existing programs.

2.6.4 Comparing Different Programs in Perspective

Since different programs are developed by different bodies based on different approaches to the modeling problem, it is very difficult to compare them on a common basis. The input requirements, output quality, simulation capability and user supports of these programs vary significantly. No program is likely to satisfy all users and the requirements of all projects. To choose the simulation tools for this research, the common building energy simulation programs have been reviewed. Based on their capabilities and usage by other researchers, five detailed simulation programs which met the requirements of detailed research studies have been examined. Table 2.3 gives a brief comparison of them showing their program designs, input and output features, weather files used and simulation approaches.

As discussed most validation studies of the simulation programs are found to be inconclusive. Deviations resulting from inadequacy of the programs and their solution techniques are often masked by uncertainties in the input data. Even though much effort is taken to eliminate possible errors, the various programs, when applied to the same problem, can produce quite different results which are very difficult, if not impossible, to verify. Any comparison of the simulation results is an assessment not only of the program itself but also of the model interface, which is susceptible to user skills and input uncertainty. It is believed that the performance of a detailed simulation program will depend more on implementation and use than their design. The ability of a user to use the program effectively and to understand the implications of each item of input data is of prime importance. As long as the program can model the required features and give reasonable results, it is considered suitable for the application.

Table 2.3 Comparisons of Different Detail Simulation Programs (Hui, 1996)

Programs/ Attributes	SIMULATION PROGRAMS					
	BESA	BLAST	BUNYIP	DOE		ESP-r
				DOE 2.0	Visual DOE	
Country	Canada	USA	Australia	USA	USA	UK
Version	2.0	3.0	3.0	2.1 E	4.1	Version 8
Weather Data Required	Fully Hourly	Fully Hourly	Pinned Weather	Fully Hourly	Fully Hourly	Fully Hourly
Weather File Processor	EW_WTH	UFE	NA	OE2WTH	OE2WTH	SPclm climate database management
Calculation Method	Not known	Heat balance	Finite difference	Weighting factor	Weighting factor	Finite difference
Input Method	Menu driven input forms	TEXT or ASCII file	UNYIS input system	ASCII file	ASCII file	SPimp input management
Input Checking	Internal	BLAST error check	UNYED error detect	BDL error check	BDL error check	Internal
Output Method	Forms, Graphs	ASCII file report writer	UNREP report spreadsheet output	ASCII file	ASCII file	Spout
Parametric Runs	NA	NA	Limited	Limited	Limited	Limited
Users Manual	Acceptable	Good	Poor	Fair	Well developed	Fair
Manual	NA	NA	Not available	Yes	Yes	Yes
Accepted	ASHRAE 90.1.1989	ASHRAE 90.1.1989	-	ASHRAE 90.1.1989	ASHRAE 90.1.1989	As reference in Europe

2.6.5 Simulation programs

ASHRAE (1993) and NSW Public Works (1993) have provided some general considerations for selecting energy analysis programs. However, it is hard to judge which program is suitable and adequate for an application since there are no definite criteria to select the programs wisely in all situations. Generally speaking, each program has its particular features and limitations. The decision for selection often depends on previous experience of the user, popularity of the program, computer hardware available to run them and specific requirements of the application (Evans, 1987).

Visual DOE 4.0 was selected as simulation tool in this research for the following reasons:

- It is widely used simulation programs and its results are generally accepted as reasonable for different building types.
- It can offer wide range of simulation features for a detailed whole building energy performance analysis.
- To some degree, DOE has been validated. Extensive studies have been conducted for DOE-2, such as Diamond et al., (1985 and 1986), Diamond and Hunn (1981), Diamond et al., (1981 and 1985), Bahel et al., (1989) and USDOE (1984).
- DOE-2 have been used by many researchers and governments for developing building energy standards, such as California Title 24,

ASHRAE 90.1, ASHRAE 90.2 and the OTTV standards in Hong Kong and ASEAN.

- DOE is recognized by the ASHRAE Standard 90.1-1989 as an acceptable simulation tools (ASHRAE, 1989c).
- DOE-2 is a public-domain program
- DOE-2 seems to be the most widely adopted simulation program nowadays.

2.6.6 Simulation and Modeling

As explained by Matko et al., (1992), simulation and modeling are inseparable procedures used to analyze the complex behavior of real processes. Modeling deals primarily with the relationships between actual dynamic processes and models; simulation refers above all to the relationship between the model and the simulation tool.

Figure 2.2 shows the crucial stages of a computer modeling and simulation cycle as suggested by Matko et al., (1992) and Neelamkavil (1987).

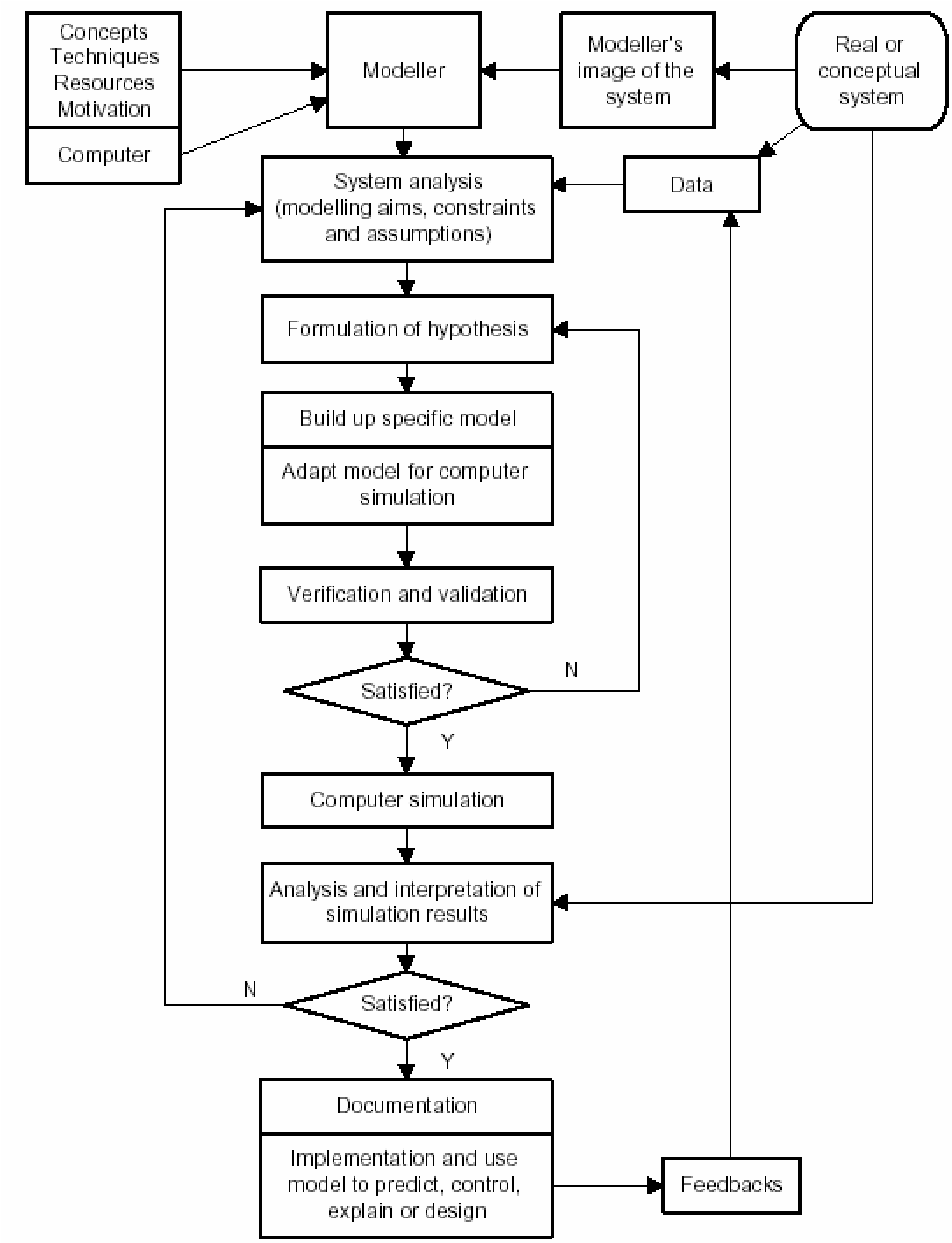

Figure 2.2 Simulation and Modeling Cycle (Neelamkavil, 1987).

CHAPTER THREE

ENERGY AND THERMAL COMFORT STATUS OF SELECTED COMMERCIAL BUILDINGS IN THE EASTERN PROVINCE, SAUDI ARABIA

3.1 Introduction

The second phase of the thesis focuses towards the investigation of energy problem, involves the collection of data from commercial building as they have been found to be potential source of energy saving. The data collected from the survey along with the literature reviewed help in selected the building modeling and formulation of the base case. Literature review provides sound background about the universally adopted building characteristics and standards prescribed by different international organizations, whereas the data collection reveals the current construction practices, and building system information for Saudi Arabia

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The commercial building data collection was emphasized for Shopping Mall located at Al-Khobar and Dammam in the Eastern Province of Saudi Arabia. Efforts were made to target typical shopping mall so that they could be used as a model to other buildings of similar characteristic and operation. The shopping malls were characterized on the basis of floor area. The data collection forms were separately designed for large, medium and small malls as detailed and general respectively. For each facility the data collection was carried out in two different stages. In the initial stage information related to building physical and operation characteristic was collected through personal interview with the facility managers and maintenance engineers. This includes information on wall and roof assembly, openings, fenestration, HVAC System, operation of the facility, energy consumption data etc. Review of as-built drawings and other relevant documents obtained from the management to acquire additional information, this helped to develop the base model in close proximity to the real building. In the second stage thermal comfort assessment was performed involving the building users to obtain their view regarding the current thermal comfort conditions. Series of air temperature, relative humidity, air velocity and dew point measurements were conducted at different location in the building to get an insight about the actual conditions being sensed.

3.1.1 Outline of Data Collection Form

The data collection form was divided into four sections. First section deals with the general information pertaining to the mall location, gross floor area, maximum capacity, conditioned and un-conditioned areas, year of construction, respondent details and available number of thermal zones. Second section is comprised of details about the building and its components, such as wall and roof assemblies, fenestration and openings details, operation of the facility etc. Third section contains information about the different building systems installed, including lighting and electrical system and the HVAC system, their operation schedule, area of the zone served, thermostat setting and the details for the central plant in the event of centralized air-conditioning system etc. Last section includes information for the operation of the mall, maximum capacity it could accommodate, variation of occupancy density during the operation, electrical consumption and other applicable factors. During the data collection and thermal comfort survey and measurement apart from the two climatic seasons, summer and winter emphasis was given to the holy month of Ramadan during which the occupancy and operation of facility undergoes a drastic change. More details of the data collection form; thermal comfort survey and measurement are mentioned in the Appendix-A

3.2 Analysis of the Data Collected

Due to time constraints only five buildings were selected to conduct the survey and were nominated as representative buildings for the other commercial buildings situated in Eastern Province of Saudi Arabia. The buildings were characterized into 3 types based on their total gross floor area. Those malls with area less than 20,000 m^2 were defined as small; those with area in-between 20,000-50,000 m^2 were termed as medium-size and those with area of 50,000 m^2 and above were categorized as large buildings. Amongst the buildings selected for the survey one is large, another one is medium and three others are small. Each selected building was reviewed for its envelope characteristics which include the wall and roof system details, fenestration and opening details, the operation of facility, the building systems and their operations. The different wall and roof assemblies were studied to gain an insight of the construction materials used. It was found that most of the buildings were constructed using precasted material. Only one or two shopping malls operated from morning to night, where as for others had a break of 4 hrs during afternoon.

An important fact worth considering is that only two malls have centralized air-conditioning system while others have either residential type system or packaged units installed. As no flexibility exists in unitary systems to manage high latent heat gain or changed sensible heat ratio, and therefore do not have good humidity control. Also air cleaning quality is minimal achieved because the filter removes only large particles in order that the resistance to air flow is maintained low. Another disadvantage of using unitary type of system in multi-room building is high maintenance cost and burdensome, along with waste of energy as they cannot modulate capacity (Edward, 2003). Therefore it can be concluded that neither the designers nor the owners are energy conscious and aware if they are using the appropriate air conditioning system.

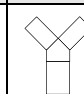
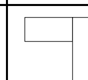
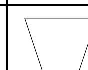
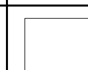
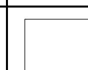
3.2.1 General Information

The general information pertaining to the representative shopping malls surveyed are summarized and presented in Table 3.1. It can be seen that most of the shopping malls were constructed in the late 90's and were built to fit the best aesthetic value.

As discussed earlier the buildings were categorized based on their available Shopping Area. The largest, Al-Rashid mall, located in Al-Khobar, constructed in 1995 having Y-shape with its main entrance facing south. It is a three floor structure with eleven entrances on different orientations and approximately 140 stores on each floor. Of the total building area 73 % is conditioned and the rest unconditioned. Further the mall is designed for a maximum capacity of 25,000 persons, which may be reached during peak seasons.

The second largest mall Al-Waha Shopping Centre, located in Dammam was constructed two year prior to Al-Rashid mall. It is L-shaped facing Southeast, with three floors with approximately 80 stores on each floor. The first two floors are utilized for Shopping Area while the top floor is occupied by offices. 93% of the total area is conditioned and designed for a maximum capacity of 15,000 people which may be reached during the month of Ramadan.

Table 3.1 General Information Pertaining to Different Surveyed Malls

Categorization	Name Of Shopping mall	Gross Floor Area (m^2)	Maximum Capacity (Persons)	Year Of Construction	Shape	Geometry
Large	Al-Rashid Mall	1,15,000	25,000	1995	Y-Shape	
Medium	Al-Waha Shopping Centre	37,550	15,000	1993	L-Shape	
Small	Al-Khobar Mall	14,000	6,000	1995	Hexagon	
	Al-Khobar Plaza	11,200	4,500	1996	Rectangle	
	Al-Essa Souk	8000	3,000	1994	Rectangle	

The other three malls; Al-Khobar Mall, Al-Essa Souk, and Al-Khobar Plaza are located in Khobar; two of them are rectangular in shape while the other is irregular hexagon. Constructed almost during the same period each has approximate capacity ranging between 3,000 to 6,000 persons to accommodate during peak hours.

3.2.2 Building Envelope Characteristics

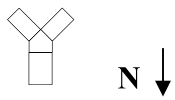
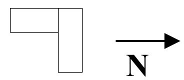
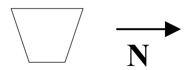
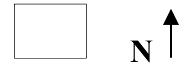
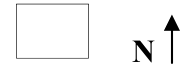
The first step towards data collection was to identify building the configuration and method of construction being practiced in Saudi Arabia. The survey of selected commercial buildings revealed envelope configuration which did not differ much from one another. Though the building's survey sample was small compared to the available commercial centers in the Eastern Province, from the analysis and review of data collected it was found to be supportive and justifiable to use them as a representative to the other facilities. The different building envelope parameters as obtained from the survey and data collection are summarized and presented in the Table 3.2. Using the above obtained information, one facility among the buildings surveyed will be selected to be modeled for energy analysis using Visual DOE simulation program.

From Table 3.2 it can be seen that the buildings surveyed have orientation either north or south dominated, which shows that these structures are safe from high heat gain through solar radiation when facing east as found from the literature. The exterior construction system differed pre-cast to CMU medium weight, while the roof is built in combination of concrete slab and glass wool insulation or reinforced concrete and polyurethane insulation. As the buildings surveyed are of different sizes and shapes the glazing area is varying. The color of exterior wall and roof selected, interior walls, flooring, glazing and openings type and operation of facility are much similar to one another.

3.2.3 Building Systems and Operation

In this section the different building system such as lighting, equipment and HVAC system being used in different shopping building will be discussed. Table 3.3 presents an overview of the building systems in practice in Eastern Province. Saudi Arabia. Among the buildings selected for survey it was found that only two facilities have centralized air-conditioning system while other remaining shopping malls have separate residential type split system installed. Centralized air-conditioning system was available in Al-Rashid mall and Al-Essa Souk. At Al-Rashid mall air-water system is being used to distribute chilled water from the air-cooled chillers located on the roof top and air through AHU to the terminal fan coil unit, where as Al-Essa souk has all-water system to circulate chilled water from water-cooled chiller to FCU.

Table 3.2 Summary of Building Envelope Characteristic

Envelope Parameters	Al-Rashid Mall	Al-Waha Shopping Centre	Al-Khobar Mall	Al-Khobar Plaza	Al-Essa Souk
Orientation					
Wall System	Precast (200 mm)	CMU Medium Weight 200 mm	CMU Medium Weight 200 mm	CMU Medium Weight 200 mm	CMU Medium Weight 200 mm
Roof System	200mm Concrete Slab, Glass wool insulation 50mm	Polyurethane expanded 100 mm, Heavy Weight un-dried 200 mm.	Reinforced Concrete 200 mm, Polystyrene Expanded 100 mm.	Reinforced Concrete 200 mm, Polystyrene Expanded 100 mm.	Concrete Slab 200 mm, Glass wool insulation 50mm
Interior Walls	Gypsum Board	Gypsum Board	Gypsum Board	Gypsum Board	Gypsum Board
Flooring Finish	Ceramic Tiles	Ceramic Tiles	Marble Floor	Ceramic Tiles	Ceramic Tiles
Window Glazing	Single Clear 10 mm	Single Pane Single Clear/ Tinted 8 mm	Single Clear 8 mm	Single Clear Tinted 8 mm	Single Clear Tinted 8 mm
Glazing Area	4486 m^2	1548 m^2	700 m^2	450 m^2	312 m^2
Skylight	3453 m^2	2396 m^2	1500 m^2	NA	75 m^2
Door Material	Single Clear	Single Pane Single Refractive	Single Clear	Single Clear Tinted	Single Clear Tinted
Operation of Facility	08:00-23:00 (Summer / Winter) 09:30-03:00 (Ramadan)	09:00-23:00 (Summer / Winter) 09:30-03:00 (Ramadan)	08:00-23:00 (Summer / Winter) 09:00-03:00 (Ramadan)	08:00-23:00 (Summer / Winter) 10:00-03:00 (Ramadan)	08:00-23:00 (Summer / Winter) 09:30-03:00 (Ramadan)

The HVAC systems are operated for 24 hours to achieve desired temperature indoor conditions. This results in uneven indoor temperature as found from the measurements conducted. The present prevailing temperature is much lower than that required in achieving thermal comfort. Improper location of thermostat such as inside cup-board or room corner was another reason for low indoor temperature.

It was noted that majority of the shops surveyed in different malls had lighting available through fluorescent lighting system and the lighting installed was more than what was actually needed. The lighting systems are operated throughout the day as the shops are enclosed and do not carry any openings for permitting daylight.

3.2.4 Energy Consumption

The electrical energy consumption for each shopping mall was obtained to get an insight of energy usage. This will help to identify the trend in consumption for commercial buildings based on their total floor area. Annual electrical consumption for different shopping malls was obtained from the utility bills provided by the management or SEC. From the above Table 3.4 it can be seen that electrical consumption for all the building studied had almost the same consumption per unit area.

Table 3.3 Summary of Different Building Systems Installed in Surveyed Malls

Type Of System	Al-Rashid Mall	Al-Waha Shopping Centre	Al-Khobar Mall	Al-Khobar Plaza	Al-Essa Souk
HVAC System	Each Shop provided with separate FCU, and common areas through AHU controlled by air-cooled chillers installed on roof top.	Each Shop provided with separate Split Unit, common areas are controlled by PSZ	Each Shop provided with separate Split Unit, common areas are controlled by AHU	Each Shop provided with separate Split Unit, common areas are controlled by PSZ	Each Shop provided with separate FCU, common areas with PSZ, controlled by water cooled chillers.
HVAC Operation	Operation same as the facility	Operation same as the facility	Operation same as the facility	Operation same as the facility	Operation same as the facility
Average Operative Temperature and Humidity	DBT: 23.5^{o} C RH: 66.4 %	DBT: 20^{o} C RH: 65 %	DBT: 22^{o} C RH: 60 %	DBT: 20^{o} C RH: 64.1 %	DBT: 20^{o} C RH: 62 %
Lighting System	Lighting Provided by fluorescent lamp and decorative lamps	Lighting Provided by fluorescent lamp and decorative lamps	Lighting Provided by fluorescent lamp and decorative lamps	Lighting Provided by fluorescent lamp and decorative lamps	Lighting Provided by fluorescent lamp and decorative lamps
Equipments	Either one Computer per shop or cash dispenser.	Either one Computer per shop or cash dispenser.	Either one Computer per shop or cash dispenser.	Either one Computer per shop or cash dispenser.	Either one Computer per shop or cash dispenser.

Table 3.4 Summary of Electrical Consumption in Surveyed Malls

	Al-Rashid Mall	Al-Waha Shopping Centre	Al-Khobar Mall	Al-Khobar Plaza	Al-Essa Souk
Gross Annual Consumption (kWh)	31,452,70	10,056,92	3857,49	2799,05	2107,93
Annual Consumption (kWh/m^2)	273.5	267.8	275.5	249.9	263.5

Annual electrical consumption for five different shopping malls was obtained from the utility bills provided by the management or SEC. From the above Table 3.4 it can be seen that electrical consumption for all the building studied had almost the same consumption per unit area. The highest was 275.5 kWh/m^2/year for Khobar Mall and the least 249.9 kWh/m^2/year for Khobar Plaza. As these shopping buildings surveyed were representative, based upon the above results an energy index can be derived. This can help to identify the building performance of the current surveyed and other available commercial building. The EUI can be calculated by taking the average of annual consumption per unit area (m^2) for all the five building.

$$EUI = \frac{273.5 + 267.8 + 275.5 + 249.9 + 263.5}{5}$$

$$\text{EUI} = 266$$

The EUI = 266 suggests that any shopping mall having an average annual consumption per square meter less than or equal to the above value is performing within the normal range of energy consumption. However this value could be optimized based on the implemented energy conservation measures. Further the present EUI developed for shopping malls in Eastern Province, Saudi Arabia, are compared with EUI for shopping malls in other countries with identical weather characteristics. Table 3.5 shows the EUI for other countries and the value for Saudi Arabia is found to be more than normal value.

Table 3.5 Energy Utilization Index for Other Countries

Location (Resources)	EUI (Kwh/m²/year) Mean Value	Number Of Samples
Indonesia [+]	147	4
Thailand [+]	237	7
Malaysia [+]	269	26
Philippines [+]	235	26
Singapore [+]	222	65
Hong Kong [++]	238	8
Australia *	213	1
Greece **	187	186
Japan [+++]	174	1
New Zealand ***	168	15
Sweden [1]	70	1
USA [2]	247	200

[+] Loewen (1992), [++] JRP (1991), * Hughes (1989), ** Santamouris, et al., (1994), [+++] Fawkes, (1993), *** Brickell Moss (1986), [1] Morse (1990), [2] EIA, (1992b)

3.3 Assessing the Thermal Comfort Conditions

ANSI/ASH RAE Standard 55-1992, Thermal Environmental Conditions for Human Occupancy Standard defines an acceptable thermal environment with conditions in which 80% or more of the occupants will find the environment thermally acceptable (ASHRAE Handbook). The purpose of this standard is to specify the combinations of an indoor space environment and personal factors that will produce thermal environmental conditions acceptable to 80% or more of the occupants within a certain space.

3.3.1 Factors Affecting Thermal Comfort

Controlling and maintaining comfort inside the building means taking care of those factors that lead to discomfort. In fact there are numerous factors that affect the comfort, however a few important of them are briefly described here. The environmental factors controlling thermal comfort are temperature, mean radiant temperature, operative temperature, relative humidity and air speed. The personal and physical factors controlling thermal comfort are clothing and the nature of human activity. These are discussed in detail in the next section.

A. Temperature:

Temperature is the measure of thermal activity in a body. The activity depends on the velocity of the molecules and other particles of which all the matter is composed (ANSI, 1992). Temperature is perhaps the most important environmental factor that determines the perception of comfort. Generally, humans are sharp to react to this parameter.

B. Mean Radiant Temperature

Another factor that affects comfort is the MRT. It is defined as the "*uniform temperature of an imaginary black enclosure which would result in the same heat loss by radiation from the person as the actual enclosure*" (Parker et al., 1982). To calculate this value temperature of different surfaces and angle factors between the person and surface is required. Measuring the temperature of all surfaces in the room is very time consuming, and even more time consuming is the calculation of corresponding angle factors. That is why the use of mean radiant temperature to evaluate indoor comfort conditions is not common in the literature (Parker et al., 1982).

C. Operative Temperature

Operative Temperature is the uniform temperature of a radiant black enclosure in which an occupant exchanges the same amount of heat by radiation plus convection as in the actual non-uniform environment. Numerically, operative temperature is the average weighted heat transfer coefficient of the air (Ronald et al., 1998). The acceptable range of operative temperature and humidity for winter and summer is defined on the psychometric chart. Figure 3.1 shows the thermal comfort zones defined for summer and winter for the building occupants of shopping malls.

- Winter: T_{Air} = 20.1 to 23.4^0 C (68.2^0 to 74.1^0 F) at 50% RH, or T_{Air} = 20.3^0 to 23.8^0 C (68.5^0 to 74.8^0 F) at 2.1^0 C dew point. The slanting side boundaries of the winter zone correspond to 20.1 and 23.4^0 C (68.2^0 to 74.1^0 F) effective temperature (ET^*) lines.

- Summer: T_{Air} = 23.0 to 25.9^0 C (73.6^0 to 78.6^0 F) at 50% RH, or T_{Air} = 23.3^0 to 26.3^0 C (73.9^0 to 79.3^0 F) at 2.1^0 C dew point. The slanting side boundaries of the winter zone correspond to 23.0 and 25.9^0 C (73.6^0 to 78.6^0 F) ET^* lines.

D. Relative Humidity

Relative Humidity is an important parameter that governs the percentage of comfort in humans. It is the percentage of moisture in air relative to the amount it could hold if saturated at the same temperature. In the zone occupied by people engaged in light, primarily sedentary activity (<1.2 met), the humidity shall conform to the limits shown in Figure 3.1. Note that the upper and lower limits of humidity are based on considerations at dry skin, eye irritation, respiratory health, and other moisture related phenomena (Pita, 1981).

E. Clothing

An individual can alter his or her comfort conditions through adding or subtracting clothing with regard to indoor situations. Based on research carried out at Kansas State University it has been proved that the most comfortable condition as with light clothing corresponding to an air velocity of 0.177 m/s and air temperature of 79 ^{0} C at 50 % relative humidity ranges between 0.4-0.6 clo. Clothing worn by people indoors is modified to a great extent following changes in seasons and outdoor weather conditions. During the summer months, typical clothing in commercial establishments consists of lightweight dresses, lightweight trousers, and short or longed sleeved shirts and blouses.

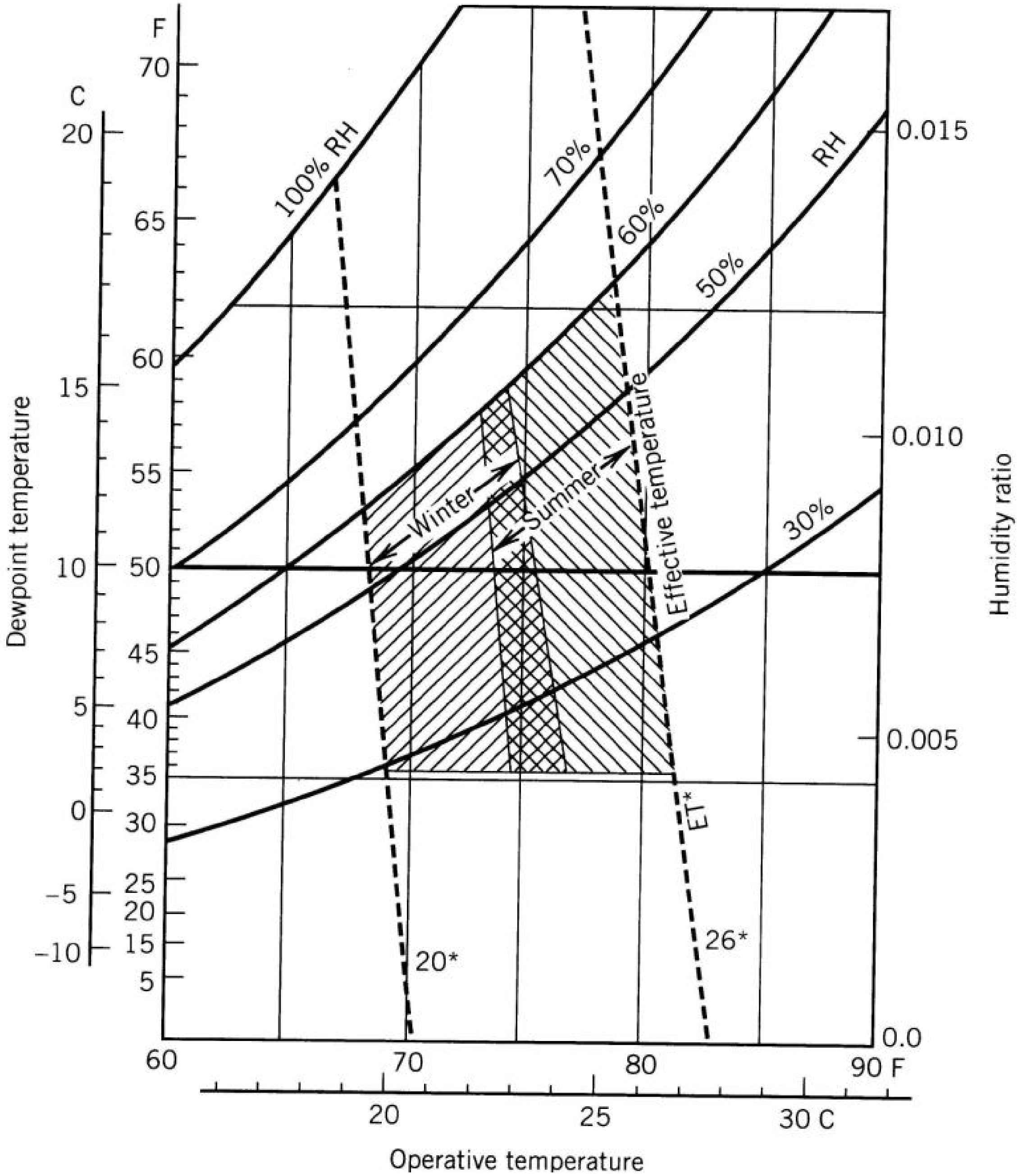


Figure 3.1Thermal Comfort Zones defined for Summer and Winter Conditions

These ensembles have clothing insulation values (I_{cl}) ranging from 0.35 to 0.6 clo. During winter season people wear garments constructed of thicker, heavier (i.e, warmer) fabrics and often add more garments layers to an ensemble (ASHRAE Handbook). A typical indoor winter ensemble will have an I_{cl} value ranging from 0.8 to 0.12 clo. Where the outside temperature range does not vary any great deal from season to season, people do not change the types of garments they wear year-round as much as people who experience extremely hot and cold climates.

F. Air speed

For thermally acceptable range of temperature as shown in Figure 3.1 air movement should be within the range of 0.127 to 0.229 m/s for thermal comfort. For sedentary persons, it is essential to avoid drafts. The temperature may be increased above the level allowed for comfort zone if a means is provided to increase the air speed. The benefits that can be gained by increasing the air speed depend on clothing, activity, and difference between the surface temperature of clothing/skin and the air temperature.

3.3.2 Thermal Comfort Models

Due to numerous methodologies in establishing thermal comfort zones in buildings, the need to have one standard reference is of interest to researchers. Two most important and widely used thermal comfort models are defined and explained in the following section.

A. The ASHRAE Model

The model is based on the condition defined in terms of the effective temperature, designed for the occupants wearing typical clothing. The model relates the effective temperature with the operative temperature which would influence the MRT. Although initially the model was designed for a specific value of clothing and activity level, but now alteration to operative temperature to suite different clothing and activity level can be accommodated. The model does not set minimum value for air movement but recommends values not exceeding 0.15 m/s and 0.25 m/s during winter and summer season respectively (Neil and Gustar, 1989).

B. The Fanger's Comfort Model

From a set of comfort equations Fanger developed comfort diagrams which include activity and clothing levels for all ranges for air temperature and relative air velocity for achieving optimal thermal comfort for person under steady state conditions (Neil and Gustar, 1989). The significance of Fanger's model is due to its comprehensiveness comprising of all the four environmental parameters via, air temperature, MRT, air velocity and relative humidity.

3.3.3 Comfort Assessment

To assess the prevailing thermal comfort conditions in commercial building under study, both quantitative and qualitative analysis were performed. These analyses are explained below.

A. Subjective Analysis

Subjective analysis comprising of a questionnaire survey was performed. In order to perform the survey a questionnaire was designed to assess the thermal comfort perception of the occupants for the environment. This questionnaire was administered with the aim of acquiring information on the following aspects:

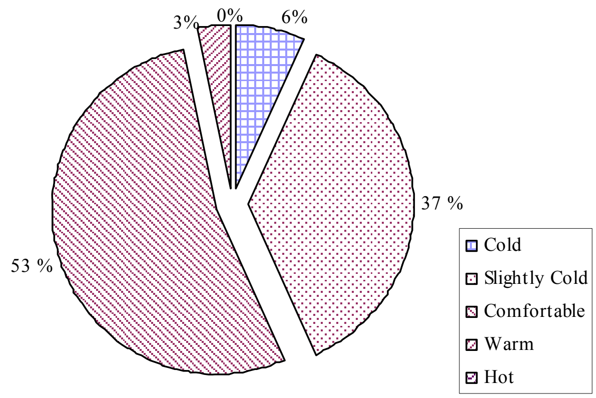
- To seek general information about the respondent age, responsibilities and duration of stay.
- To get information regarding occupants feeling on the indoor environmental parameters of temperature, humidity and air motion.
- To enquire about the affect of season and time of day on occupants thermal comfort conditions.

The information gathered through the questionnaire is considered to be representative for the building occupants in general. Therefore, in order to get a realistic response from the occupants, great care was taken in the designing and distribution of questionnaire. As all building surveyed consists majority of Shopping Area, the respondents were shop owners who spend most of their time in the building. The survey is conducted for four different days in months of October and November 2004.

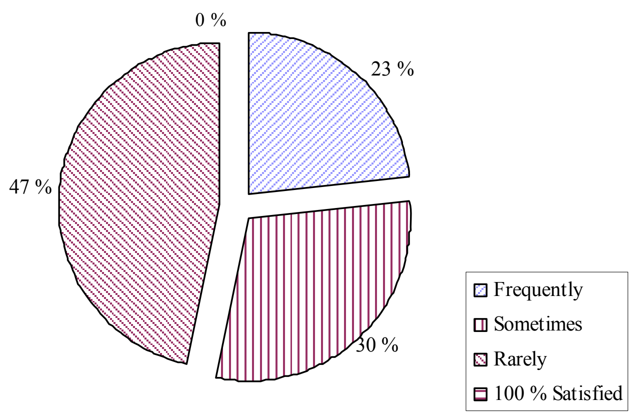
At Al-Waha Shopping Centre from the 30 respondent's interviews majority of them expressed a mixed feeling towards the indoor conditions. Most respondents performed medium activity level, while putting on light clothing. The thermal responses and the indoor prevailing conditions obtained for Al-Waha Shopping Centre served by individual systems are shown in Figure 3.2. It can be understood that due the presence of individual system serving each zones variations existed in the indoor conditions.

The occupants were asked to express their feeling towards the indoor conditions. The type of thermal responses obtained is shown in Figure 3.2 (a). Among the sample of 30 respondents surveyed 53 % felt comfortable, 36 % slightly cold, 3 % were experiencing warm and another 6 % felt the indoor conditions to be cold.

Of the 30 respondents, 70 % expressed that they did not experience much discomfort; the other 30 % respondents were experiencing some discomfort during different period of year. However review of above responses indicated that the respondents who gave a response as “COMFORTABLE” may or may not be fully satisfied. Their discomfort feeling might be relatively less when compared to the other people experiencing discomfort over some period or the other. This can be better understood from the Figure 3.2 (b) where the frequency of discomfort occurrence as reported by all the 30 respondents is shown. In relation to the thermal feeling experienced with regard to discomfort 47 % answered to rare occurrences, 30 % sometimes and 23 % frequently.



(a)



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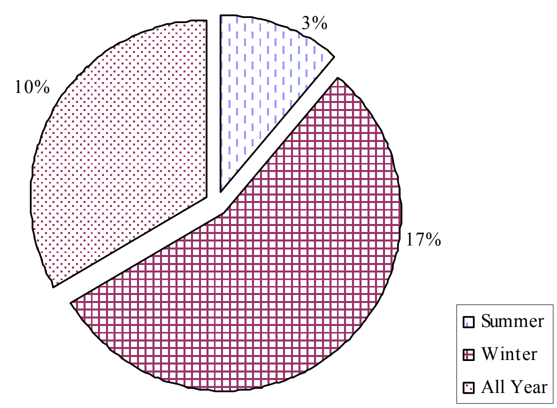


(c)

Figure 3.2 Thermal Comfort Assessment at Al-Waha Shopping Centre: (a) Thermal Response, (b) Frequency of Discomfort Occurrence, (c) Period of Discomfort

The occupants were also asked to specify the period of year for which they were experiencing discomfort during their stay at work. Figure 3.2 (c) reveals the different period of year of those occupants experiencing thermal discomfort. Of the 30 % respondents 17 % were experiencing severe discomfort during winter period, 3 % during summer and other 10 % throughout the year.

Further to the above evaluation of detailed thermal response and the frequency of discomfort occurrence experienced by the occupants depicted in the Figure 3.2 (b), an important point to note was none of the occupants surveyed were 100% satisfied. A step further towards the evaluation of thermal responses was to identify the clothing and activity levels being adopted in the facility as this would be of assistance to define the thermal comfort zone for Saudi Arabia. In this shopping complex, majority of the occupants were found to put on light clothing and performed light activities. A small portion of the building occupants was involved in sedentary activity due to the presence of offices.

Based on the analysis of the survey data, it can be concluded that 45% of people have rarely experienced discomfort and another 30% are not comfortable sometime. According to ASHRAE for a facility to be thermally acceptable at least 80% of its occupants should be satisfied. Since these two responses are near to comfort achievement, when added up the resultant percentage suggest this facility be close to thermal acceptance.

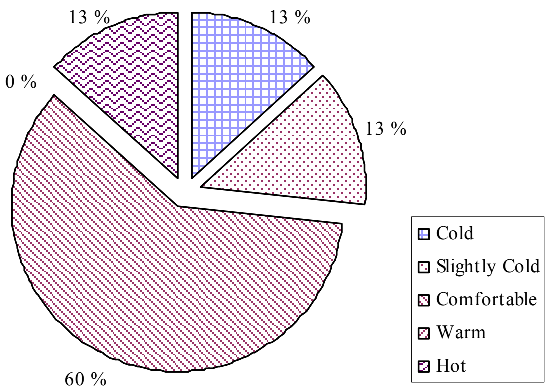
To have general and comparative view regarding thermal comfort response in shopping mall questionnaire survey and measurements were also performed in another building which was served by central air conditioning system. The questionnaire survey was performed at Al-Rashid during the month of November 2004. The main reason behind selecting specifically Al-Rashid and not the other two buildings surveyed was that it has centralized air conditioning system and the results would help in justifying which system of air conditioning the building produced better results. Samples of 30 questionnaires were distributed to the occupants and were asked to give their opinion regarding the current thermal indoor conditions. The thermal responses and the indoor conditions obtained for Al-Rashid shopping mall served by central air conditioning systems are presented in Figure 3.3. Among the 30 respondents, 73 % reported that the current conditions were acceptable to them except for some period and the other 27 % respondents were not comfortable with the current conditions. The thermal responses obtained from the 30 occupant are shown in Figure 3.3 (a). Among the sample of 30 respondents surveyed 60 % felt comfortable, 13 % slightly cold, 13% felt the conditions to be cold and last 14 % had hot perception.

Figure 3.3 (b) reveals the frequency of discomfort occurrence as reported by all the 30 respondents. The thermal feeling experienced by the occupants with regard to discomfort is as follows, 20 % respondents answered to rare occurrences, 23 % sometimes and another 20 % frequently. The remaining 37 % have expressed that they were fully satisfied by the existing conditions. Figure 3.3 (c) shows different period of the year for those 27 % occupants experiencing thermal discomfort. Among 8 respondents 25 % were experiencing severe discomfort during winter period, 25 % during summer and another 50 % all the year.

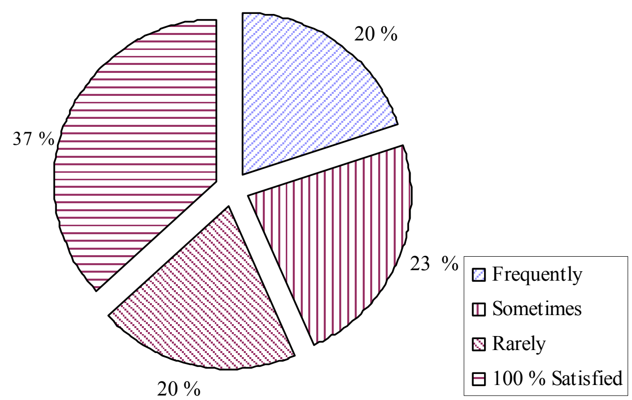
It can be seen, more number of persons have expressed satisfaction to the existing indoor conditions at Al-Rashid than at Al-Waha Shopping Centre. The three thermal responses, fully satisfied, rarely and sometime discomfort experienced suggest this shopping mall to be more thermally acceptable, as the percent of satisfied occupants comes to 80%.

B. Quantitative Analysis

Quantitative analysis involving measurement of indoor parameters was undertaken. This was attained by making measurement of the case study building temperature; relative humidity and air flow were measured in different cores of the building. These cores were identified based on their location, occupancy traffic, cooling load, etc.



(a)



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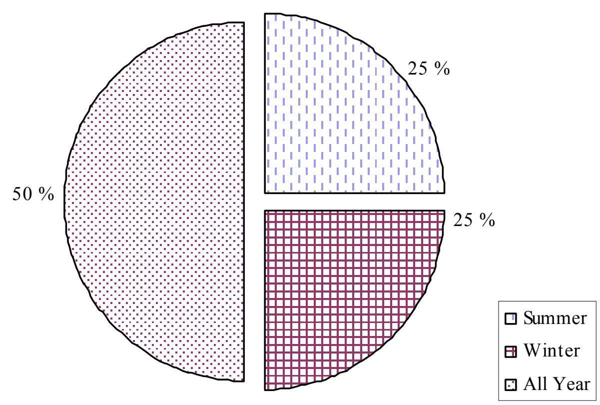


(c)

Figure 3.3 Thermal Comfort Assessment at Al-Rashid Mall: (a) Thermal Response, (b) Frequency of Discomfort Occurrence, (c) Period of Discomfort

B.1 Layouts and Equipments

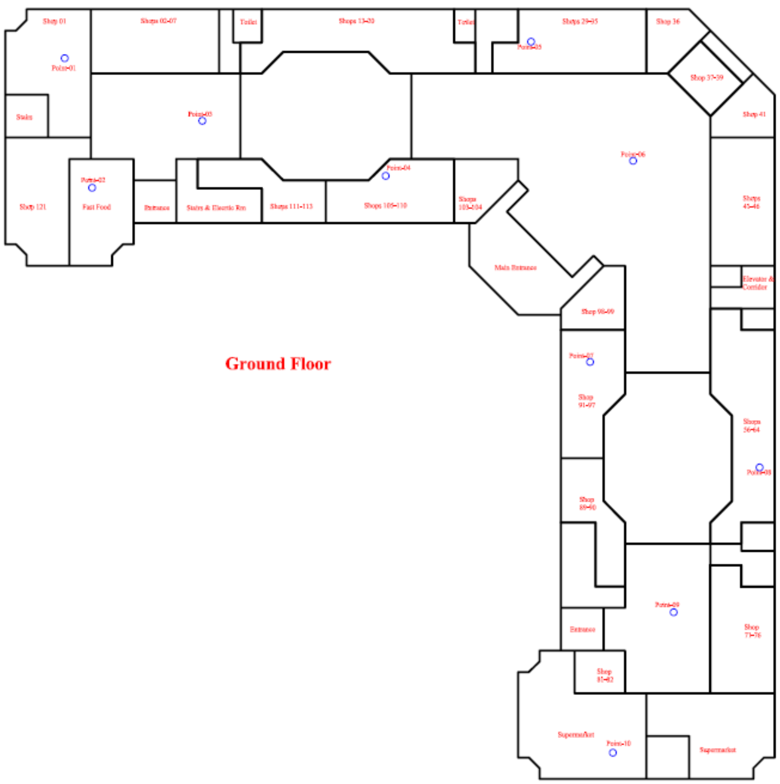
Solomat and Air flow meters were used the record the temperature, humidity and air velocity in different location of the building in order to identify the prevailing thermal comfort conditions. Figure 3.4 and 3.5 shows the different location inside the building for performing the measurements and Figure 3.6 shows the equipments required to conduct measurements.

B.2 Analysis of Measurements

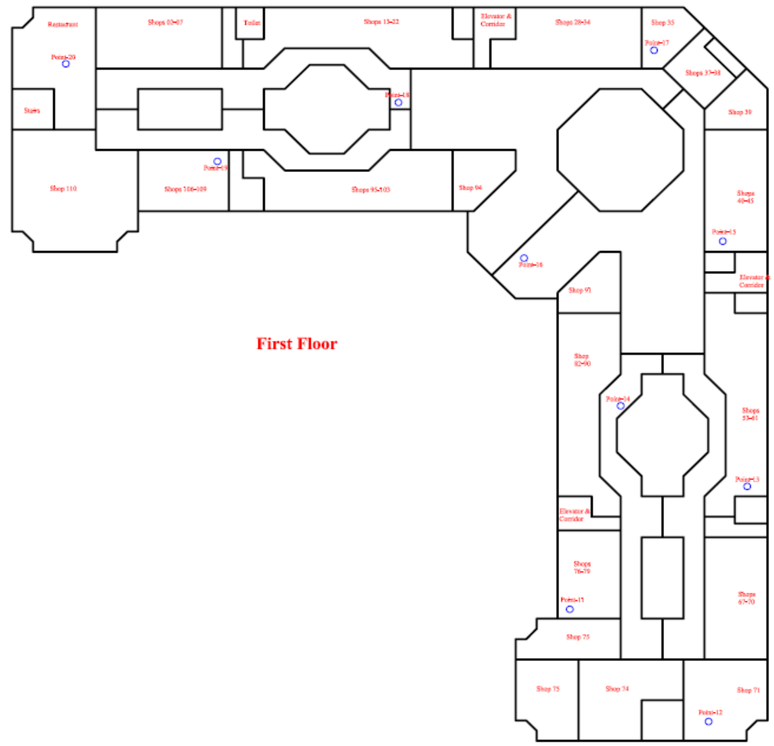
The indoor temperature ranged from 18^0 C - 24^0 C and average air temperature for the whole building based on the measurements was 20^0 C. Temperature profile for the measurement made at 30 different locations and the average building temperature represented by a horizontal line are shown in Figure 3.7 (a). The hatched region represents the thermal comfort range for summer season for moderate activity and normal clothing of 0.5 clo. Among the different location at which measurements were made $2/3^{rd}$ (66 %) were identified with temperature below the lower limit of comfort zone as seen from the Figure 3.7 (a). Thereby it can be concluded that the mall managements are maintaining relatively low temperature than that required in achieving thermal comfort.

Due to the presence of individual system installed separately for each shop, variation in indoor relative humidity was found. The minimum being 60% while maximum is 70%. The RH curve shown in Figure 3.7 (b) represents the measurements taken at different point inside the building. Average Relative humidity of the building as identified from the measurement taken is 65 % which is acceptable for indoor conditions. Fifty percent of the zones monitored were operating above the average RH, another 40 % below and last 10% on average value. However all the zones had relative humidity within the range defined by ASHRAE and ISO for summer as well as winter season.

Air velocity was also measured using air flow meter at different locations inside the building. The air velocity varied from 0.05– 0.091 m/s and Figure 3.7 (c) shows the varying pattern. The average air velocity for the building is 0.07 m/s. Majority of the zones in which measurements are taken were being operating at low air velocity. This can also be factor for degraded thermal comfort.



(a)



(b)

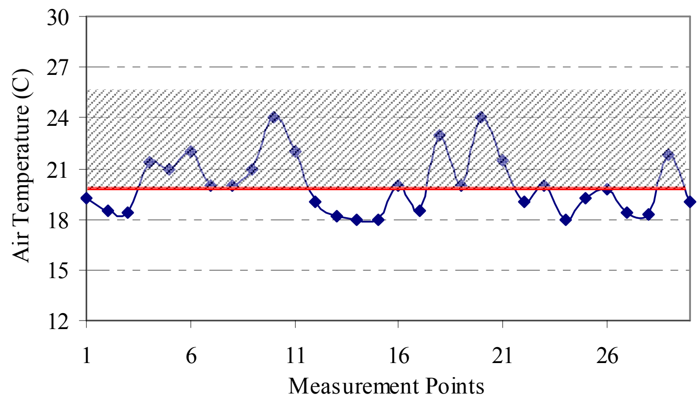
Figure 3.4 Measurement Location for Al-Waha Shopping Centre: (a) Ground Floor, (b) First Floor

Figure 3.5 Measurement Location for Al-Waha Shopping Centre: Second Floor

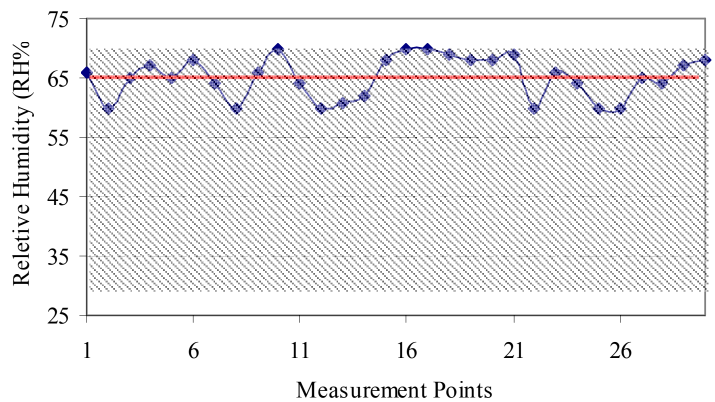
(a)

(b)

Figure 3.6 Equipments Used to Perform Measurements: (a) Solomat - Temperature, and Humidity and (b) Air Flow Meter- air Velocity



(a)



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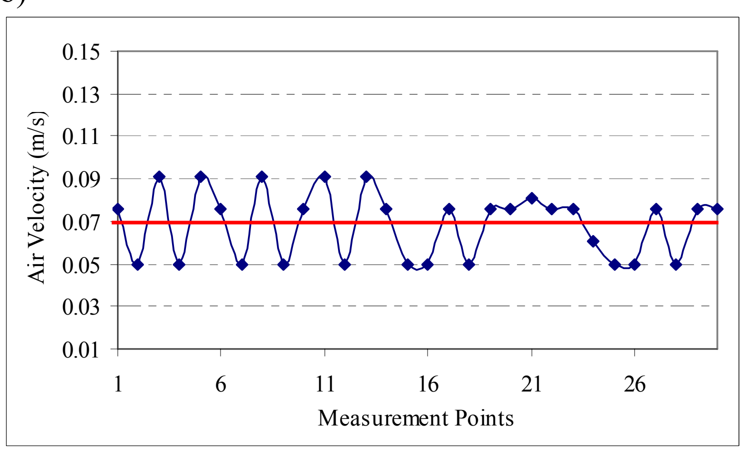


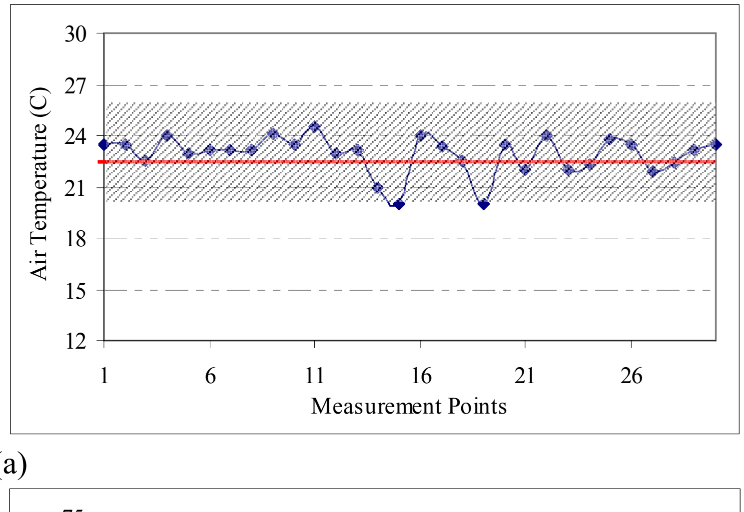
(c)

Figure 3.7 Thermal Comfort Parameters Measurements at Al-Waha Shopping Centre: (a) Temperature, (b) Relative Humidity, (c) Air Velocity

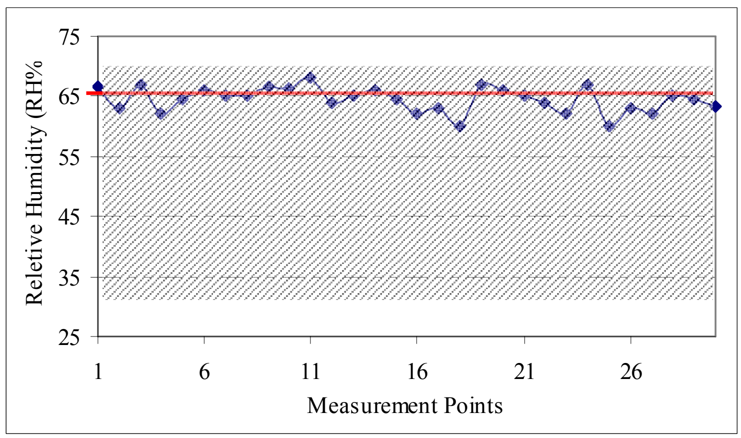
Measurements made at Al-Rashid were better than Al-Waha Shopping Centre, due to the fact that centralized air conditioning system was being used in this building. The indoor air temperature, relative humidity and air flow velocity measurement taken at 30 different cores are shown in Figure 3.8 (a) to 3.8 (c). The air temperature ranged from 20^0 C to 24^0 C, with an average of 23^0 C for the whole facility. The resulting average temperature falls in the range of thermal comfort. The majority of the zones in which measurements were performed lied within the temperature range defined by ASHRAE for summer season.

Relative humidity is another parameter which has an impact on thermal comfort. In case of Al-Rashid the indoor relative humidity ranged from 60 % - 68 %. The average RH for the building as identified from the measurements is 65 %. The relative humidity for all zones lied with acceptable range as shown in Figure 3.8 (b). The velocity of air entering the zone was measured at same points at which the other measurements were conducted. Large variations were found in the air flow velocity, with minimum at 0.025m/s and maximum value0.076 m/s. The variations in air flow velocity for different points are shown in Figure 3.8 (c).

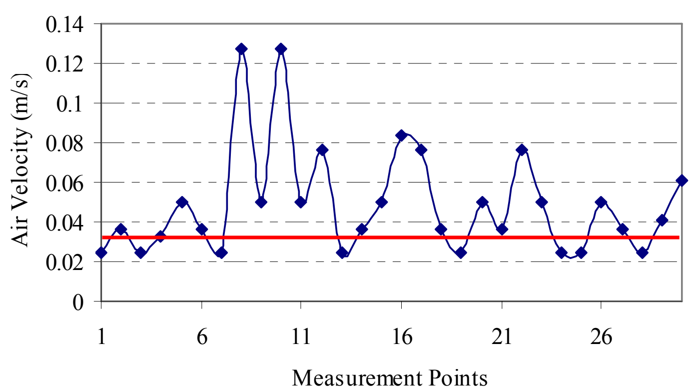
The above measurements in the mall can be used as a reference in the base case formulation. There are also helpful in evaluating the thermal performance of the selected building.



(a)



(b)



(c)

Figure 3.8 Thermal Comfort Parameters Measurements at Al-Rashid Mall: (a) Temperature, (b) Relative Humidity, (c) Air Velocity

CHAPTER FOUR

PREPRATION FOR ENERGY SUMULATION AND BASE CASE FORMULATION

4.1 Introduction

Modeling and simulation have been termed more as an art that can be achieved through human judgment, experience and computer programming skills (Neelamkavil, 1987). Building energy modeling and simulation are good means for the designer to achieve various attractive goals, such as: reducing energy cost, improving indoor thermal conditions, increasing equipment life, etc. at a much lower cost compared to field tests of actual implementation. Simulation studies require a reference building to serve as a benchmark for comparison and evaluation of the building performance. Based on the initial phases of literature review and data collected, a base model for shopping mall in the Eastern Province, Saudi Arabia was developed.

This chapter basically deals with modeling and simulation of the base model building to analyze its energy and thermal performance. Further, to achieve more accuracy and reliability of the final results, the base model was calibrated with actual energy consumption data obtained from SEC for the year 2002.

4.2 Building Selection

The base model represents a typical commercial building. Al-Waha Shopping Centre was selected as a base model for performing the necessary simulations, because of the following reasons.

1. It is a medium-size commercial building which includes different types of occupancies i.e. Shopping Area, restaurants, offices and common areas.
2. It has simple architectural design allowing easy geometric modeling for subsequent energy simulation.
3. Information and data was easily obtainable and the management showed interested in implementing different operation strategies if found economical.
4. The building is found to have more potential towards energy savings due to the presence of individual air conditioning systems which are operated 24hrs daily all the year round.
5. It has large air-conditioned floor area among the surveyed shopping malls.
6. It is located in hot-humid climatic conditions and the bulk of energy is consumed for maintaining indoor thermal condition as indicated by the utility bills

4.3 Description of the Base Case Model Building

Al-Waha shopping centre in Dammam was constructed in the year 1993. It is a three-storey building occupied by shopping area, supermarkets and restaurants in most of its ground and first floor area, while the offices are located mainly on the second floor. The mall has a maximum capacity 15,000 persons to be accommodated during peak seasons. Based on the review of the building drawing, it was found that minor modification work has been carried out on the exterior side of the building.

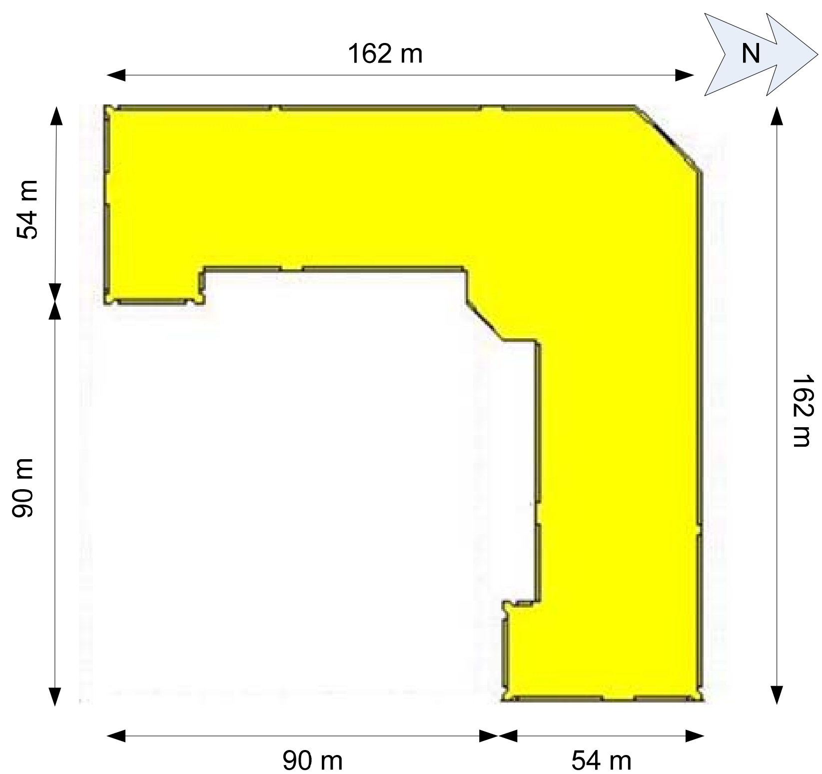


Figure 4.1 Base Case Model Layout

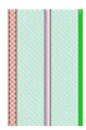
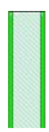
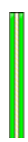
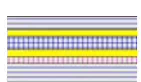
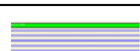
As shown in Figure 4.1, the building has L-shaped with its entrance facade facing southeast direction. The exterior walls are light-colored building, with doors having shatter proof single clear 8-mm glazing. Its windows are also fitted with shatter proof single reflective 8-mm and tinted 8-mm glazing. Almost all the building floor is made of ceramic tile finishing. The details of the building envelope characteristics are summarized in Table 4.1.

4.4 Building Operation and HVAC System

To calculate the space internal load for the building energy modeling, it is important to understand the building operation schedules and occupancy profile. The building has three types of occupants, i.e. retail shop owners, visitors/shoppers and the office staff. The representative occupancy profiles for the building users and schedules for different building system obtained from records maintained by the mall management are shown in Table 4.2.

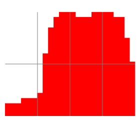
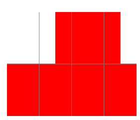
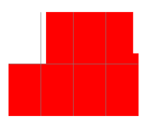
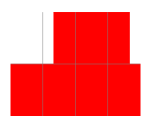
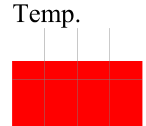
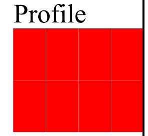
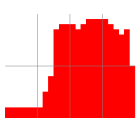
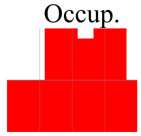
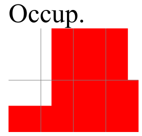
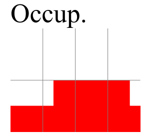
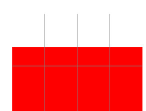
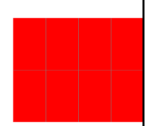
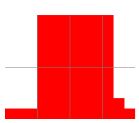
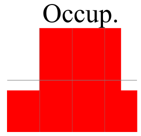
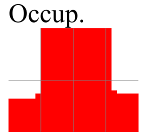
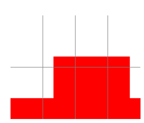
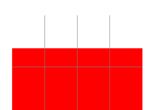
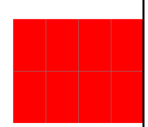
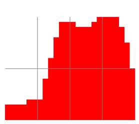
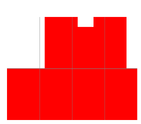
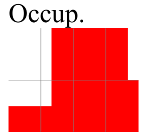
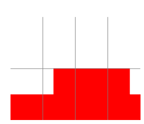
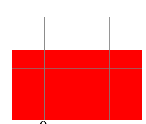
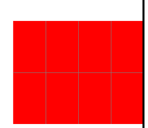
Most of the shops operate in shift from morning 9:00 and continue till 12:00 noon, followed by a break for four hours and reopen again at 16:00 and continue till 23:00 midnight with short break during prayer times.

Table 4.1 Characteristic of the Base Case Model

Characteristic	Description For Base Model	
Location	Dammam (Lat. 26° 25' 33N, Long. 50° 6' 51E Altitude 2m)	
Type of Building	Three stories, Commercial : Shopping and Office	
Plan Shape	L-Shape	
Total Height	13.5 m	
Floor Dimensions	54 m X 162 m X 162 m X 54 m X 90 m X 90 m	
Gross Floor Area	37,500 m^2	
Gross Wall Area	8262 m^2	
Window Area	1549.1 m^2	
WWR	0.19	
Window Set back	50 mm	
Type of Glazing	Single Pane, Single Clear / Tinted 8-mm, (U) = 5.6 W/m² K	
External Walls		Stucco 25-mm, CMU Medium Weight 200-mm, Wall Membrane, CMU Medium Weight 200-mm, Plaster 19-mm. (Light colored) (U) = 2.005 W/m² K
Internal core wall		19-mm plaster , 200-mm medium weight concrete and 19-mm plaster U-value = 1.930 W/m² K
Internal partitions		16-mm gypsum board, 25-mm airspace and 16-mm gypsum board. U-value = 1.680 W/m²·K
Roof		Gravel, Roof Wood Framing W/R-49, Polyurethane expanded 50-mm, Roof Wood Framing W/R-49, Roof Membrane, Heavy Weight un-dried aggregate 100-mm. (U) = 0.539 W/m² K
Internal Floors		50-mm screening, 150-mm light weight concrete, ceiling void and 19-mm ceiling panel U-value = 0.599 W/m² K
Floor	Ceramic Tiles	
People (maximum)	15000 Persons	
LPD (based on site survey)	Common Areas 13 W/m^2, Retail Shops 25 W/m^2, Office Areas 21 W/m^2, Restaurants 16 W/m^2	
EPD (based on site survey)	Restaurants 11 W/m^2, Retail Shops 2.7 W/m^2, Office Areas 8 W/m^2	
Operation Hours	Normal days during summer and winter : 09:00 – 23: 00 Ramadan months : 10:00 A.M. – 3:00 A.M. next day	

The summer and winter seasons follow the same pattern of occupancy, however in the holy month of Ramadan the occupancy starts at 13:00 hrs in afternoon continuing up to 00:00 hrs with breaks at prayer timings for first 20 days and for the rest of the month until Eid-day the mall is open up to 03:00 A.M. next day. However the offices located on the 2nd floor operate 10-12 hrs, with reduction in opening time to some extent in the month of Ramadan. The schedule of occupancy and operation of different systems in the shopping centre for different functions are presented in Table 4.2.

Table 4.2 Schedule of Occupancy and Operation

	Occupancy	Equipment	Lighting	Infiltration	Space Temp.	Fan Profile
Common Area	 Normal Operation.	 50% Unocc.100% Occup.	 50% Unocc. 100% Occup.	 50% Unocc. 100% Occup.	 20^0 C all time	 100 % ON all time
Shopping	 Normal Operation.	 50% Unocc. 100% Occup.	 25% Unocc. 100% Occup.	 25% Unocc. 50% Occup.	 20^0 C all time	 100 % ON all time
Office	 Normal Operation.	 40% Unocc. 100% Occup.	 20% Unocc. 100% Occup.	 20% Unocc. 60% Occup.	 20^0 C all time	 100 % ON all time
Restaurant	 Normal Operation.	 50% Unocc. 100% Occup.	 25% Unocc. 100% Occup.	 25% Unocc. 50% Occup.	 20^0 C all time	 100 % ON all time

The building is served by “residential type single-zone split units” for shops, “single-zone packaged units” are used for common areas like corridor, staircase, toilets, elevator lobbies etc, and offices. Each shop has its own unit installed having individual thermostat control. All units is operated 24 hrs in-orders to maintain the required indoor conditions. Description of the available HVAC system along with the setpoint adopted is presented in Table 4.3

Table 4.3 Characteristic of the HVAC Systems for the Base Case

Type Of System	Single-zone split system for shops, Single-zone packaged system for offices and common areas.
Thermostat Type	Proportional
Thermostat Settings	20^{0} CF – 23^{0} C
Relative Humidity	60 % – 70 %
Cooling Only	Available year round
Weather File	Dhahran, 2002

4.4.1 Building Energy Use Pattern

In-order to assess the energy performance and to evaluate the relative consumption of the selected building, energy use must be known. The energy audit provided a comprehensive record of all of the facility's electrical loads. The air- conditioning represents the largest single load (approx. 60%) in this shopping centre. Lighting consumes 15%, while refrigeration consumes 13%, followed by 5 % for hot water and kitchen equipment and 7 % is consumed by equipment. The energy consumption breakdown for the mentioned components is shown in Figure 4.2 and explained in the following section.

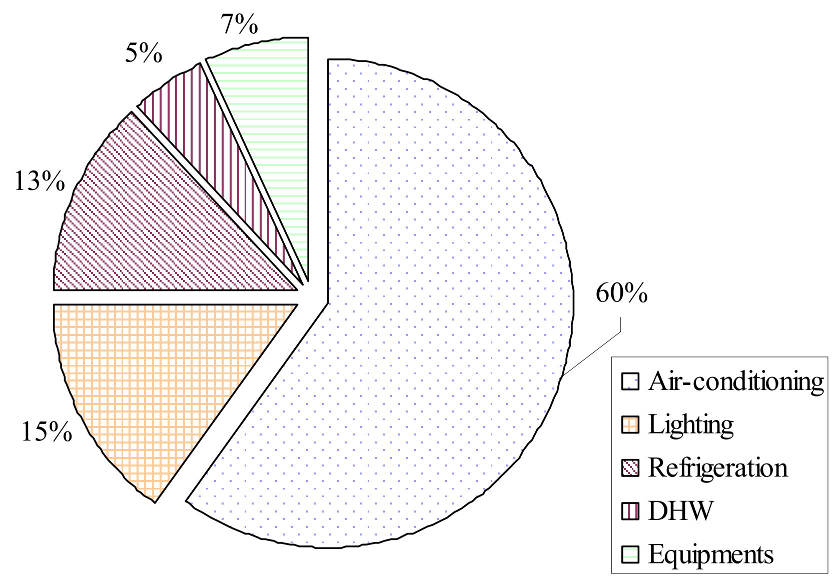
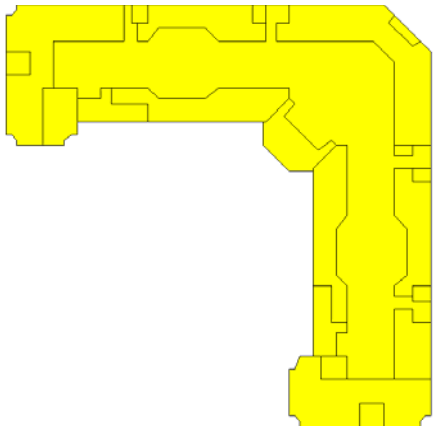


Figure 4.2 Breakdown of Building Actual Annual Electrical Energy Consumption

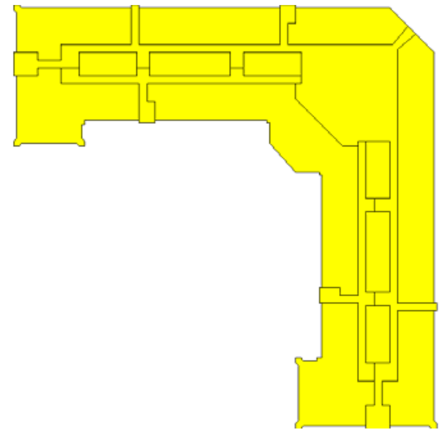
4.5 Building Thermal Zoning

A thermal zone is defined as any enclosed polygon in a building meant to have the same thermal conditions and having its own thermostat control. Dividing the building into proper thermal zones is important for analyzing the HVAC system loads and their operation profiles. With this respect, modeling for energy simulation, the thermal zones have been modified from those specified in the HVAC layout in-order to reduce the actual zoning complexity of the case study. Layout of the actual floor plan and modified thermal zones is shown Figure 4.3 and 4.4

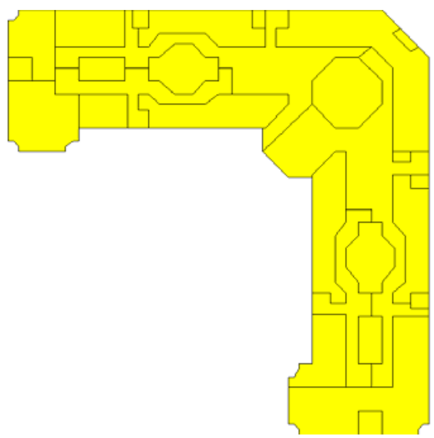
Figure 4.3 Actual Ground Floor Plan for Al-Waha Shopping Centre



(a)



(c)



(b)

Figure 4.4 Thermal Zones for Al-Waha Shopping Centre; (a) Ground Floor, (b) First Floor, (C) Second Floor

4.6 Base Case Formulation

Base case formulation process requires developing a simulation model that would result in similar energy consumption pattern and magnitude. Input parameters influencing energy consumption can be changed within reasonable ranges through the calibration process to achieve good match between the simulated and measured values.

In principle, materials' properties and constructions can be presented with consistency since the existing data sets for investigated buildings are found to be similar. Ideally, the base model is developed from data accumulated through actual, detailed survey and audits conducted locally. However, detailed building surveys are usually very limited, and the available data are often inconsistent or incomplete for simulation needs. Therefore, certain assumptions are made to select and determine the necessary inputs for the reference building.

4.6.1 Base Case Modeling

Accurate building modeling using any computer simulation tool consists of three steps. The first is to accurately survey the building thermal characteristics and defined representative thermal zoning scheme and carefully enter these parameters into the simulation tool. Available architectural drawings are used in combination with an interview with the client and a walk through survey. The second step involves calibrating the model using at least one year of utility data and finally, potential ECM's can be evaluated using the calibrated model.

In order to investigate the impact of HVAC operation strategies on energy consumption and thermal comfort, the selected shopping centre was modeled and simulated using Visual DOE 4.0 energy simulation program. The simulation was performed using Dhahran weather data file for the year 2002. The initial base case model was developed considering the following assumptions:

1. The partition walls were assumed as adiabatic layers with no heat energy transfer between the different separated zones.
2. In order to minimize deviation, reduce complexity and to adhere to program limitation total number of zones per floor were reduced. Shops with identical operation and characteristic were grouped to form a single zone.
3. Since each entrance had a lobby before joining into the main zone, the infiltration rate through the entrance was assumed to be minimal.
4. The cooling season was assumed to fall between March 1st and 15th September while the heating season starts from November and ends in February.

5. The areas exposed to skylight have double floor height, in such case, an imaginary horizontal layer of air between floors was assumed to separate different floors in their particular location.
6. The building was assumed to be an air tight envelope with a constant infiltration rate of 0.5 ACH.
7. The air-conditioning system is continuously operating for 24 hrs a day.
8. Exterior lighting was not being considered to be part of energy consumption as it cannot be modeled.
9. All retail shops are served by residential type split system, while the office and common areas are served by single-zone packaged unit
10. Since periodic variations in thermostat are not performed, the thermostat setting was assumed to be the same at all times of the year.

4.6.2 Extraction of Utility Data

The monthly energy consumption for the year 2002 for the selected building was obtained from SEC, but since the data was present in Hijri format it had to be converted into Gregorian form before being used for comparison. Figure 4.5 shows an illustrative example for an occurring period.

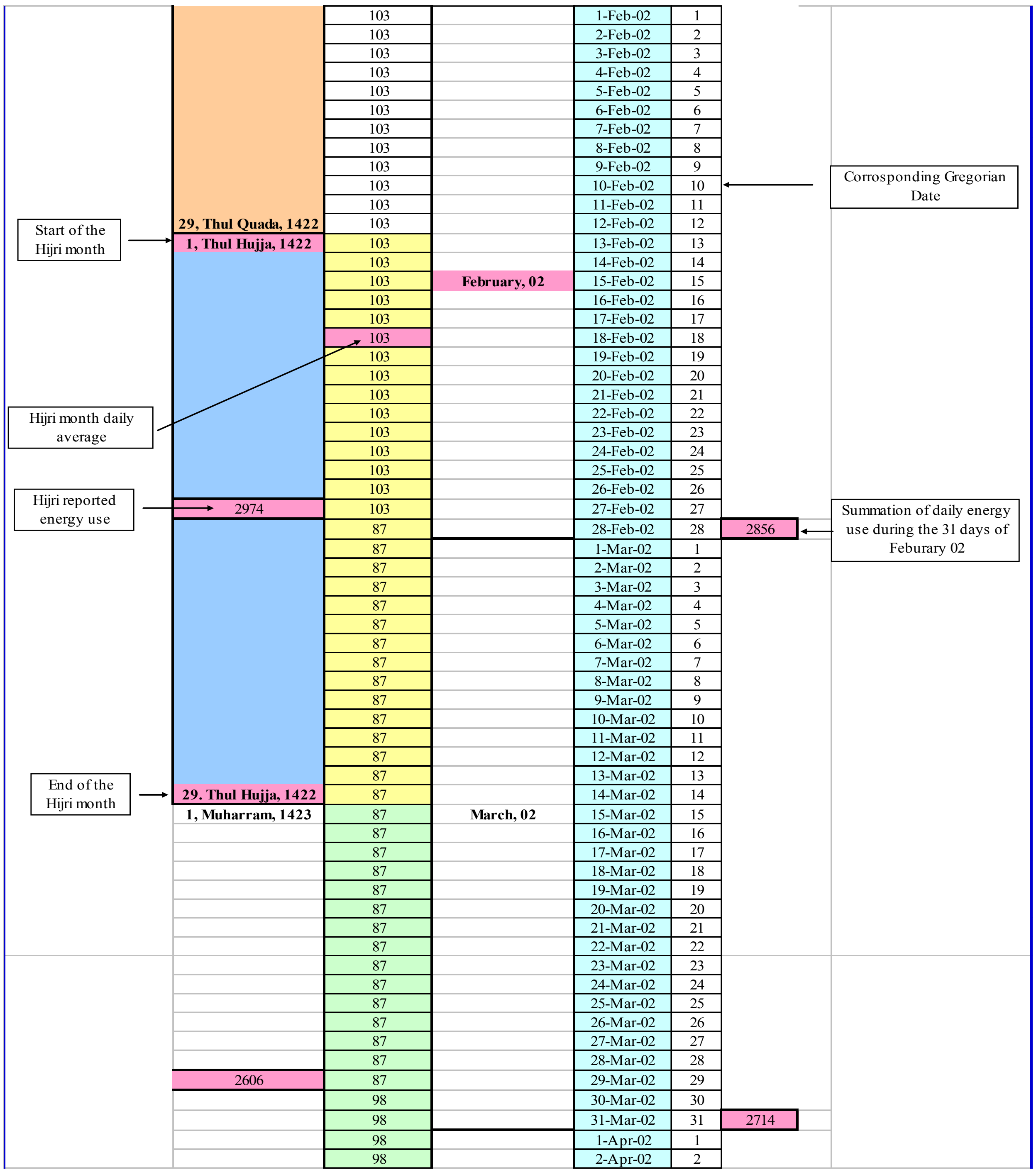


Figure 4.5 An Illustrative Example for the Procedure of Hijri – Gregorian Electric Energy Bills Data Conversion

4.6.3 Results of Initial Base Model Simulation

Analysis of the simulation results of the base model is essential for understanding the important components and elements of the model. The annual electricity consumption is compared with actual consumption so as to develop a match of the characteristics of building energy performance. The results obtained after the initial simulation of the base case are presented in Table 4.4.

Table 4.4 Initial Base Case: Simulation vs. Actual Consumption

	Actual	Simulated
Annual Energy Consumption (kWh)	10,056,000	8,104,868
Peak Cooling Load (kW)	Unavailable	1697.804 reached on July 19th
Annual Energy Cost (SR)	5,028,000	4,052,434

The energy consumption of the simulated base model was 8,104,868 kWh compared to utility billing of 10,056,000 kWh yielding a deviation close to 20 %. After the initial base case run, the model has to be calibrated to reflect the existing utility data and subsequently to determine the effectiveness of the energy conservation measures.

4.7 Calibration of the Base Case Model

Calibration procedure has been recognized as a key element to apply many ECM when using computer model to evaluate energy performance and their impacts for existing buildings. Commonly the calibration of computer model compares the simulated results with the actual collected data and proves the validity of the model for further applications of the possible ECM's. The recent research trends to develop a calibration process focus on comparing most hourly data measured with simulated data because the hourly simulations represent the building dynamic energy characteristics in more accurate and reliable way (Bou-Saada and Haberl, 1995). However, additional expensive data loggers are required to measure the hourly energy consumption.

Thus, the difficulties from measurement cost and extra data availability often make it very difficult to implement the hourly data to calibrate the building energy computer model. In general, monthly invoiced bills for electricity and gas could be easily collected and just statistically compared. However, no standard methods of calibrating the computer model for building energy performance based on the monthly data are available.

In order to properly model thermal and energy behavior of the building, the existing loads and schedules need to be accurately calibrated to determine the effectiveness of the

Energy Conservation Measures (ECM's). To get any informative output from VisualDOE, we need to ensure that our model's energy consumption is relatively accurate compared to the utility bills. The goal of this step was to calibrate the base model within 10% of the annual utility consumption. After establishing the initial building envelope, the calibration process was attained using the utility data obtained from the SEC.

The calibration of electrical consumption was a hard task because of numerous variables contributing to the electrical load. In order to calibrate the model to the electric data the lighting and the equipment schedule were varied to adjust the electrical base load to meet the utility data. Figure 4.6 shows the trail process of calibration of base case model.

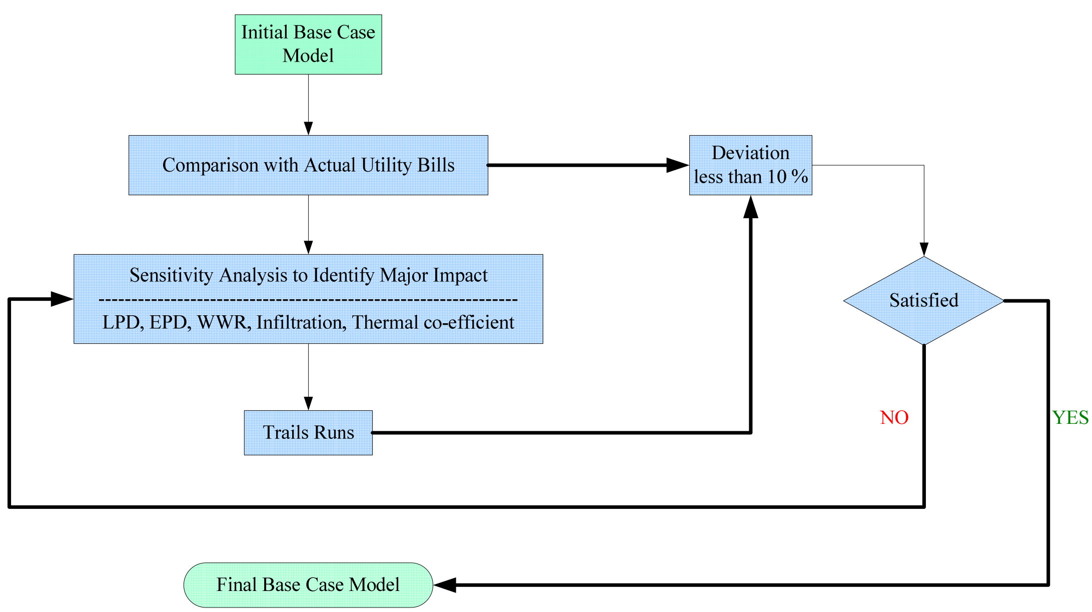
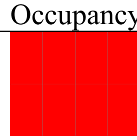
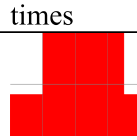
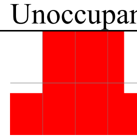
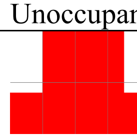


Figure 4.6 Flowchart for Trial and Error Method of Calibration Base Case Model

4.7.1 Implemented Changes for Calibration of the Base Case

After establishing the initial building envelope and running the program, we had to calibrate the model to mirror the existing utility data. These actual steps employed to calibrate the base model are explained and summarized in the table 4.6.

Table 4.5 Calibration of Base Case Model and Respective Deviation

Occupancy Type	Action taken or Changes made		Resultant Consumption (kWh)	Deviation
Initial Base Model	-NIL-		8,104,868	$\simeq$ 20 %
Common Areas	Lighting Schedule	 50 % Unoccupancy 100 % Occupancy	8,235,864	$\simeq$ 18 %
	Equipment Schedule	 100% all times	8,547,600	$\simeq$ 15 %
Offices	Lighting Schedule	 40 % Unoccupancy	8,617,992	$\simeq$ 14 %
	Equipment Schedule	 40 % Unoccupancy	8,879,448	$\simeq$ 12 %
Restaurants	Equipment Schedule	 40 % Unoccupancy	8,949,840	$\simeq$ 11 %
	EPD Changed to 11 W/m^2		9,050,400	$\simeq$ 10 %
Supermarket	EPD Changed to 27 W/m^2		9,066,206	$\simeq$ 9 %

The lighting schedule for the common areas was modified since the onsite investigation revealed setup of new shops in the corridor areas which requires additional lighting for their operation. This increased lighting operation time will impact the energy consumption and thereby will help to develop the initial base model consumption close to the actual value. Additional shops in the common area affect the EPD, since actual density is difficult to establish this load can be compensated with increased operation time for the common area. It was also assumed that the atleast 40 % of the lighting and equipments are to be in operation even after the closure of offices. This modification will compensate for some offices that have more operation time than the normal as specified by the management.

Further atleast 40 % of the equipments in the restaurant are required to operate during unoccupied period for preserving edibles. Lastly it was found that the EPD provided by the mall management for restaurants and supermarket was very less, therefore a higher vale as specified by the ASHRAE standards was used and this step brought the deviation for simulation results within 10 % proximity of utility bills.

Figure 4.7 shows comparison of the electrical data from the base case simulation and the corresponding utility bills. The actual annual electrical consumption from the utility bills was 10,056.961 kWh, while the calibrated model annual electrical consumption was found to be 9,066,331 kWh. The calibration brought the electric use in the Visual DOE simulation very close, thus the model was accurately calibrated with 9.85% deviation of the actual utility bill data. After performing whole building calibration, the energy consumption for the three floors obtained from simulations and utility bills were compared separately. It was found that energy consumption differences were 6 %, 9.6 %, 16 % for ground, first and second floor respectively.

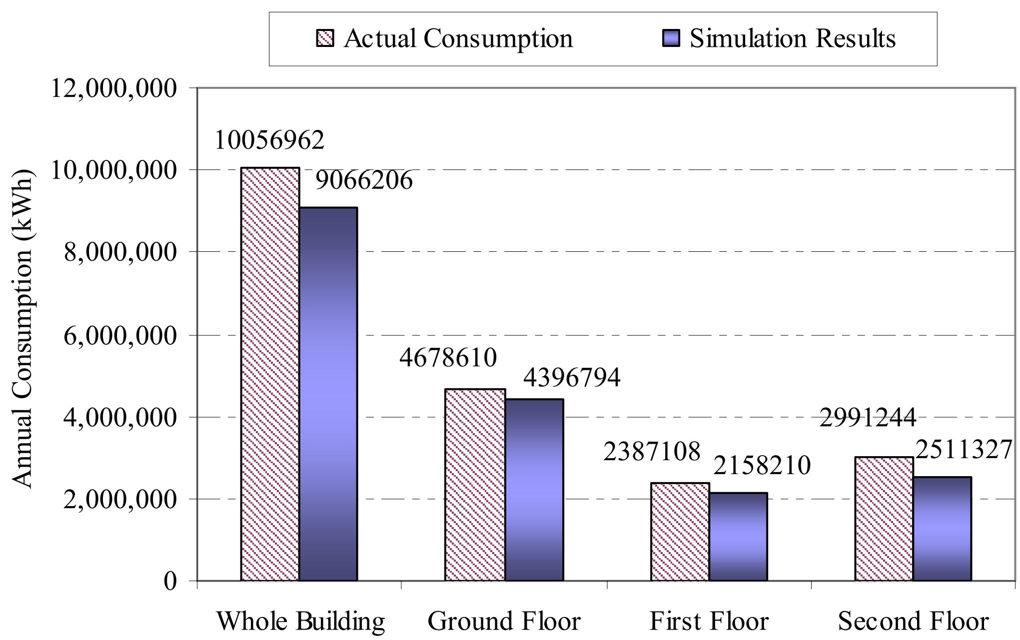


Figure 4.7 Al-Waha Shopping Centre Annual Electrical Consumption Simulated Results and Actual

Further, to have a comprehensive view regarding energy consumption pattern by each zone at different levels, monthly consumption obtained from simulation results for individual zones were compared with billing history. Since majority of Shopping Area have been designed for same occupancy and operation only minimal difference in the electrical energy consumption was observed and this occurred due to variations in their floor area. Also at the second level all offices were observed to have similar pattern of occupancy and operation. Therefore only a selected number of these comparisons are graphically represented in Figures 4.8 through 4.10 while the comparisons of the remaining zones are included in Appendix – B.

Figure 4.8 (a) reveals the comparison between the actual and simulated results for ground floor Common area. Both the curves follow the same trend with peak consumption occurring in the month of August and the least in February. This zone has maximum deviation during all the heating months; however the average for the whole year is just 12 %, which can be considered to be within the acceptable range.

Electrical Energy consumption comparison for ground floor zone – III is shown in Figure 4.8 (b). Both the curves overlap each other thereby restricting the average deviation between them to 3 % only. But the peak consumption is attained in July and August respectively by the base model and billing history. Figure 4.8 (c) shows the energy comparison for ground floor zone – VII, where as Figure 4.8 (d) represents the zones for which calibration plots are shown Trend in the monthly energy consumption varies in the same pattern for both the simulated and actual results. However the second peak during the month of October involving Ramadan is more evident in actual history than in simulated.

Comparison between the actual billing and the results obtained for the restaurant located on the first floor are shown in Figure 4.9 (a). The energy consumption trend in both the case is almost the same with peak consumption occurring in the month of August. The average difference between the two values is found to be only 2% which indicates that this zone was modeled near to reality. Figure 4.9 (b) represents the variation in electrical energy consumption for the simulated base model and actual billing history. Peak consumptions were attained during the month of August for both the cases corresponding to the year 2002. The difference in the energy consumption on an average did not exceed 13 % with maximum difference during the winter season.

First floor zone – IV energy consumption for simulated base model and actual billing history is graphically represented in Figure 4.9 (c). The profile shows gradual increase in consumption from the start of cooling season, until it attains its peak in month of August, thereafter it starts decreasing while remaining constant between October and November encompassing Ramadan period. The average deviation between the two values attained is 12% which can be acceptable, thereby concluding that the current modeled zone is functioning in close to reality. Figure 4.9 (d) shows the zones for which calibration plots are presented here.

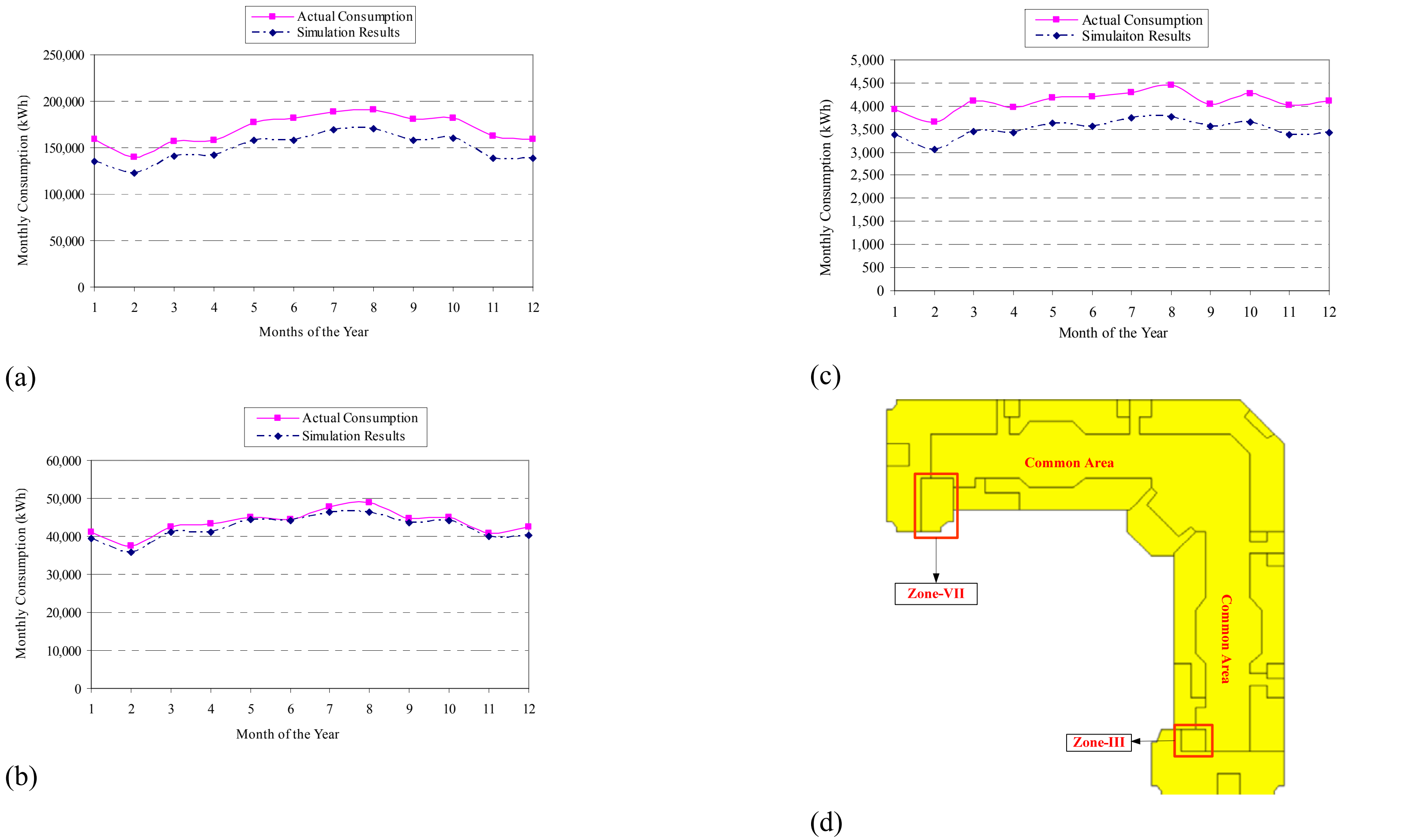


Figure 4.8 Comparison of Ground Floor Zones Monthly Consumption Simulated Vs. Actual; (a) Common Area, (b) Zone-III, (c) Zone-VII, (d) Layout Indicating Zones.

Figure 4.10 (a) reveals the energy consumption attained by the base model and billing history for second floor zone-III. The trend for the base model is similar to actual consumption, the deviation between the two cases on average did not exceed 11%, and therefore the modeled zone is functioning close to reality.

The annual energy consumption of two more zone namely corridor-1 and zone – VII are represented in Figure 4.10 (b) and 4.10 (c) respectively. Figure 4.10 (d) shows the zones highlighted by colored border to indicate their identity with respect to the calibration results.

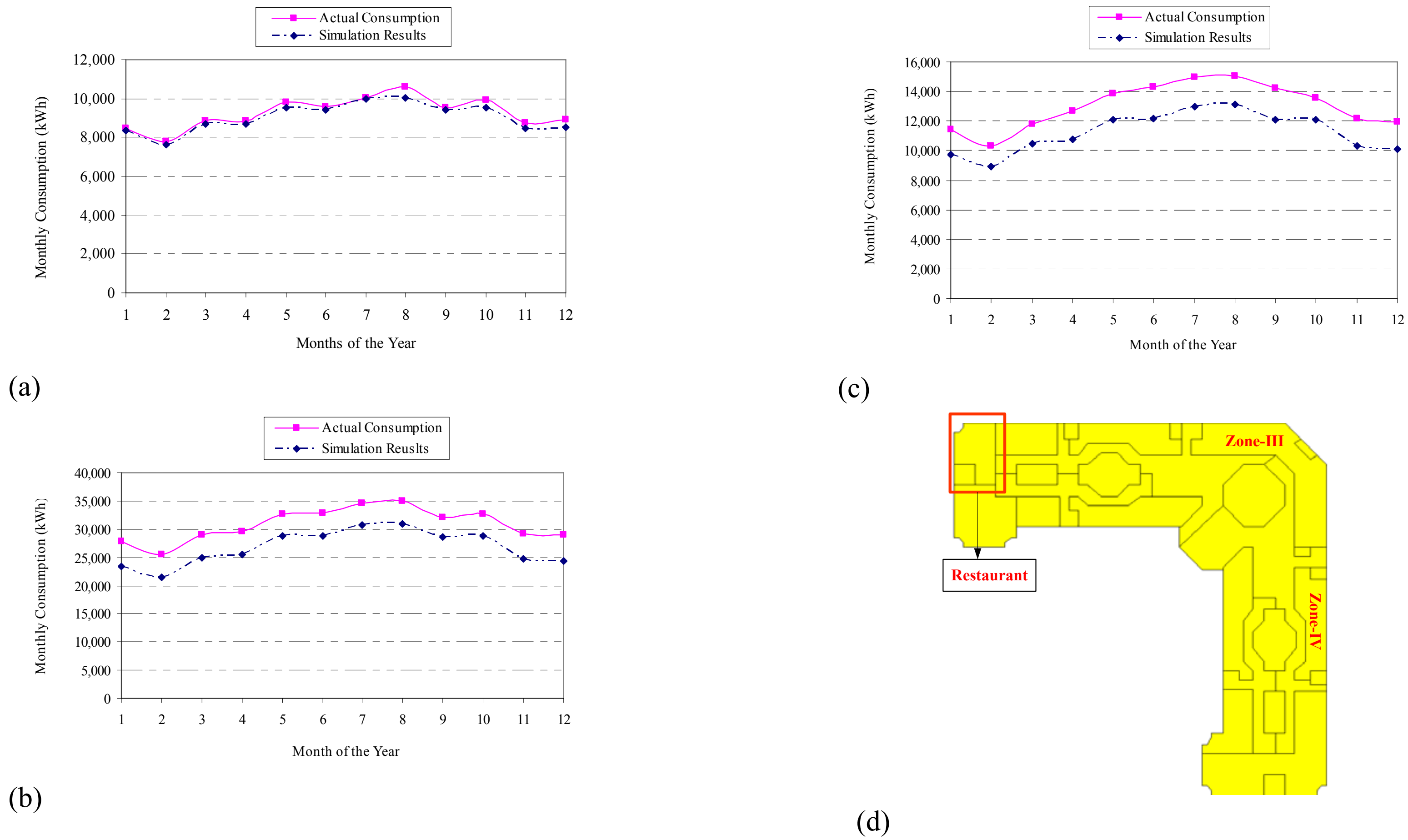


Figure 4.9 Comparison of First Floor Zones Monthly Consumption Simulated Vs. Actual; (a) Restaurant, (b) Zone-III, (c) Zone-IV, (d) Layout Indicating Zones

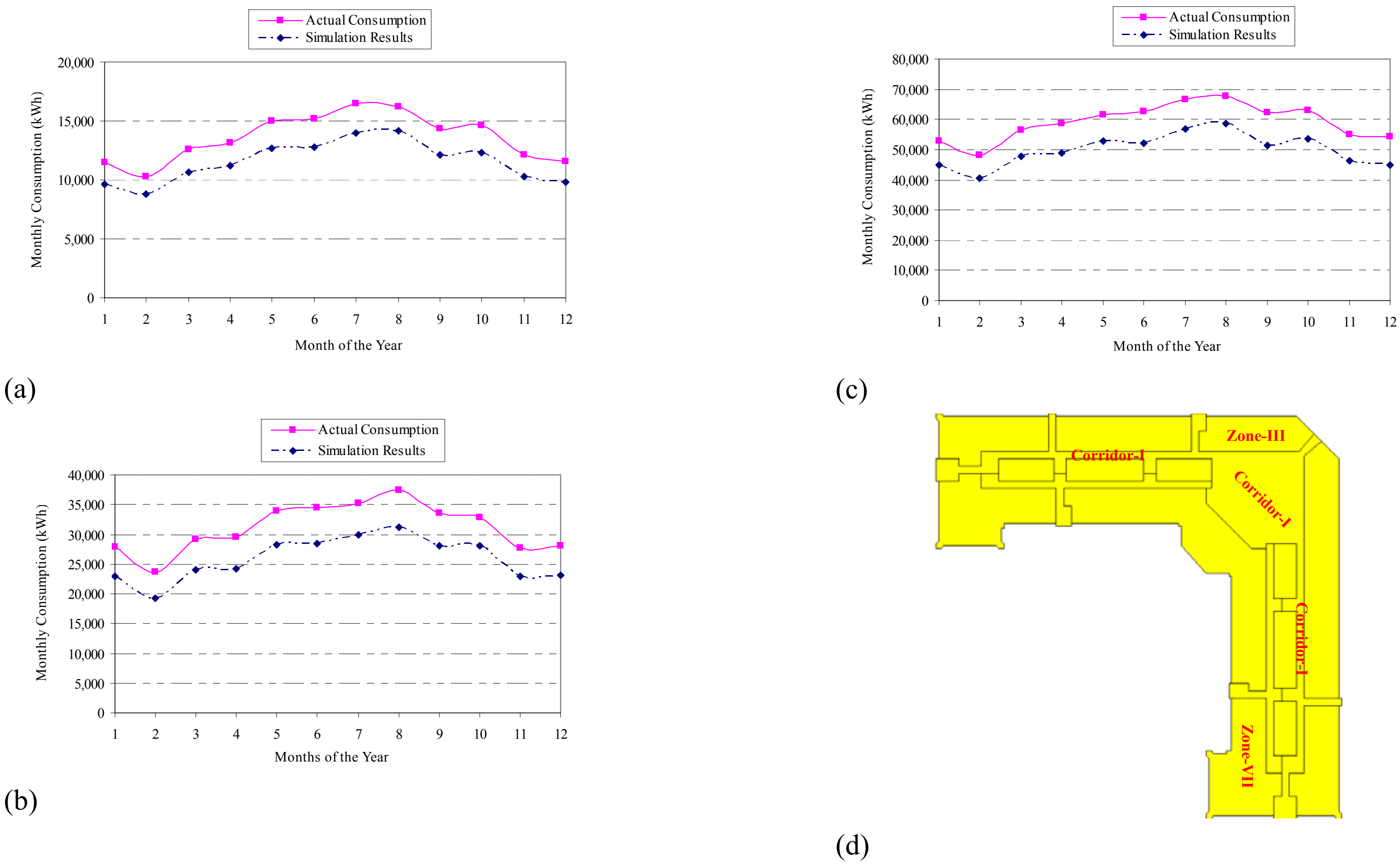


Figure 4.10 Comparison of Second Floor Zones Monthly Consumption Simulated Vs. Actual; (a) Zone-III, (b), Corridor-I, (c) Zone-VII, (d) Layout Indicating Zones

4.8 Model Performance

When compared to actual data, the model's predicted annual electricity consumption differs from the utility bills by 9.85%. The electricity plot illustrates that actual consumption is more variable than model predictions, but over the course of a year they are very similar. This is most likely due to the fact that the utility data is measured at the end of each Lunar (Arabic) month as per the calendar while the model estimates usage throughout the month as a whole. In other words, the "March" data from the utility bill is actually the last half of February and the first half of March. Thus the model is reliable for evaluating the effects energy conservation measures in a year.

CHAPTER FIVE

INVESTIGATION OF IMPACT OF HVAC OPERATION ON ENERGY USE AND THERMAL COMFORT IN COMMERCIAL BUILDINGS

5.1 Introduction

There is a clear relationship between the economic growth and energy consumption in a country. For example, in United States energy consumption in buildings accounts for over 60 percent from electric energy and almost 40 percent from the natural gas. Commercial buildings, however, account for approximately one-sixth of this energy consumption and out of which almost one-third comes from electricity (E-Star Colorado, 2001). In UK, the rate of growth in final energy demand in the commercial sector from 1973-1996 was approximately three times greater than in the domestic sector and the consumption is expected to grow faster than any other sectors except transportation (Scrase , 2001).

In Asia, the situation is not different. In Hong Kong, for example, Commercial sector consumed 44% of the total electricity consumption in 1991(Lam and Hui. 1993). Therefore, it is believed that there is a significant potential to improve the energy performance of commercial buildings. Based on experience in US, well-established, cost-effective measures can reduce energy use in commercial buildings by 20-30 percent. Such techniques include building envelope, energy-efficient lighting, high efficiency heating and cooling systems, better building controls and operation (E-Star Colorado, 2001).

HVAC operation plays an equal role as much as designing of the system. The objective of HVAC operation is to control the indoor environment. At the same time it should be operated so that at least 80% of the building occupant feel comfortable, based on which the whole facility can be classified to have thermally acceptable indoor environment. In this chapter various HVAC operation are investigated as conserving energy measures with subsequently maintained thermal comfort in the facility.

5.2 Evaluation of Energy Conservation Measures

Detailed study about the energy use pattern of the building has generated options for classifying various energy conservation measures for HVAC system. The ECM's based on the economic interest can be grouped into three categories as follows: Zero Investment, Minor Investment and Major Investment. The detail grouping can be depicted in the Table 5.1.

Table 5.1 Classification of ECM's based on Economic Interest

Economic Interest	Energy Conservation Measures	Remarks	Resultant Savings (kWh)
Zero Investment	Change in Thermostat Set Point	From 20^0 C to 23^0 C for all days of the year.	586,311
	Night Purge-Phase One	Temperature is set at 28^0 C during unoccupied hours for summer from 11:00 PM to 6:00 AM next day for normal days and 3:00 AM to 9:00 AM during Ramadan	524,400
	Night Purge-Phase Two	Temperature is set at 30^0 C during unoccupied hours for summer from 11:00 PM to 6:00 AM next day for normal days.	647,086
	Time Schedule of Operation- Phase One	Turn OFF Fan during unoccupied hours. (12:00 P.M to 6:00 A.M).	686,220
	Time Schedule of Operation-Phase Two	Turn OFF Fan during unoccupied hours. (11:00 PM Midnight and to 7:00 AM).	882,714
Minor Investment	Thermostat Type	Utilizing Two position and Reverse action thermostat	11,868
Major Investment	Central Air Conditioning	Employing different air conditioning system.	
	Enthalpy Economizer	Economizer was tested with VAV and CAV System	

The above ECM's are to be implemented on the base case model developed while maintaining all the parameters same. The energy consumption and temperature behavior for selected zone will be presented in this chapter as a representative of the zones behavior. The selection of the zone for presentation as a representative to others is based on the floor area and occupancy density and operation characteristic and the strategy to be implemented.

5.2.1 Zero Investment Energy Conservation Measures

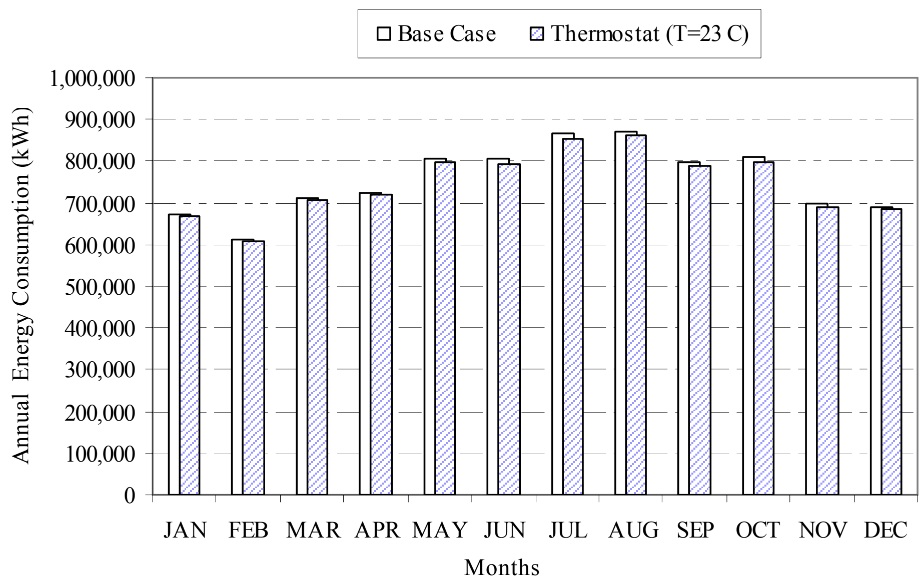
This set of energy conservation measures do not require any investment or modification to be done in the existing system or the facility. It simply requires detailed study of operation of building and HVAC system so as to optimize the operation of HVAC system.

5.2.1.1 Change of Thermostat Setting

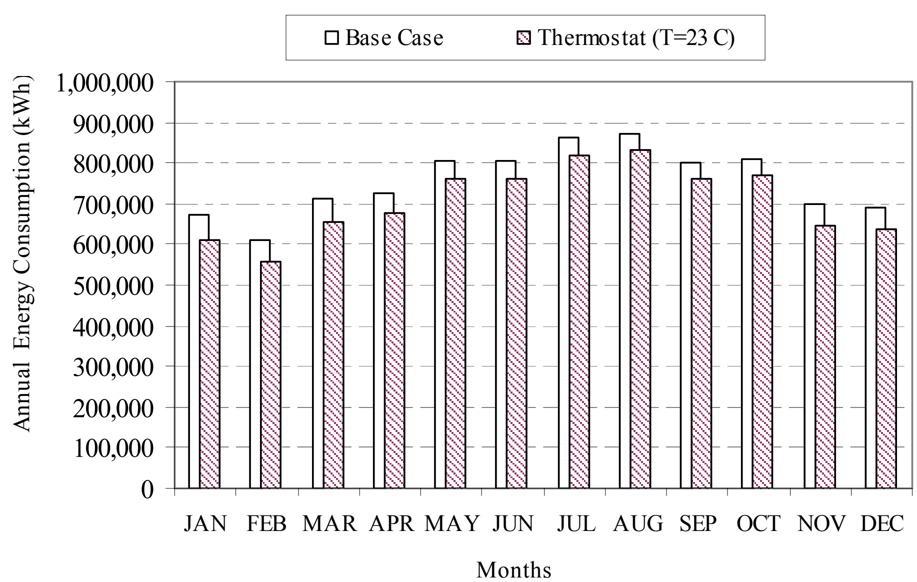
In this section a new optimized setpoint for the selected building is to be recommended therefore different temperature setpoint are tested. Since constant temperature is being maintained for the whole year, the new selected value should be able to satisfy building occupants in all the seasons. Initially the setpoint temperature is changed from 20^0 C to 25^0 C, but because of the presence of 2^0 C throttling range it is difficult to achieve desired temperature during daytime and more ever the indoor temperature is exceeding the defined comfort limits. Therefore temperature setpoint is reduced to 23^0 C taking into consideration the comfort of people performing moderate activity (2 met); thereby it also achieves the thermal requirement for other people performing activity < 2 met. Further since the selected temperature setpoint lies within the comfort zones of the two different seasons, it is hoped that it would satisfy occupants for the whole year.

Figure 5.1 (a) illustrates the energy consumption comparison as achieved by the base case and the current ECM after implementation to the common areas. It has been observed that implementation of new thermostat setpoint produces small monthly savings which accumulates to 1.4 % annually for common areas only. Further to investigate the energy savings in other zones with different occupancies ECM # 1 is implemented for shopping area, restaurants and office. Use of higher setpoint has resulted in approximate energy savings of 2.7 %, 0.2 % and 4.8 % respectively for other three occupancies. Separately 23^0 C setpoint is implemented for the whole building to be maintained for the whole year. This has generated cumulative energy saving for the whole building is 586311 kWh, corresponding to 6.5 % savings annually, with the new thermostat setting which is shown in Figure 5.1 (b)

The thermal comfort conditions are evaluated for a year with the new thermostat settings of 23^0 C. However only peak months are shown as it is assumed that thermal comfort attained during these months will be representative for other months. For summer, comfortable range varies from 23.0^0 C – 25.9^0 C, relative humidity of 50%, air flow velocity 0.1 m/s, moderate activity of 2 met, light clothing of 0.5 clo. For winter same operating conditions of 50% RH, air velocity of 0.1 m/s and 2 met activity level is used. The clothing level is increased to 0.9 clo and the comfort conditions lies between 20.1^0 C and 23.4^0 C.



(a)

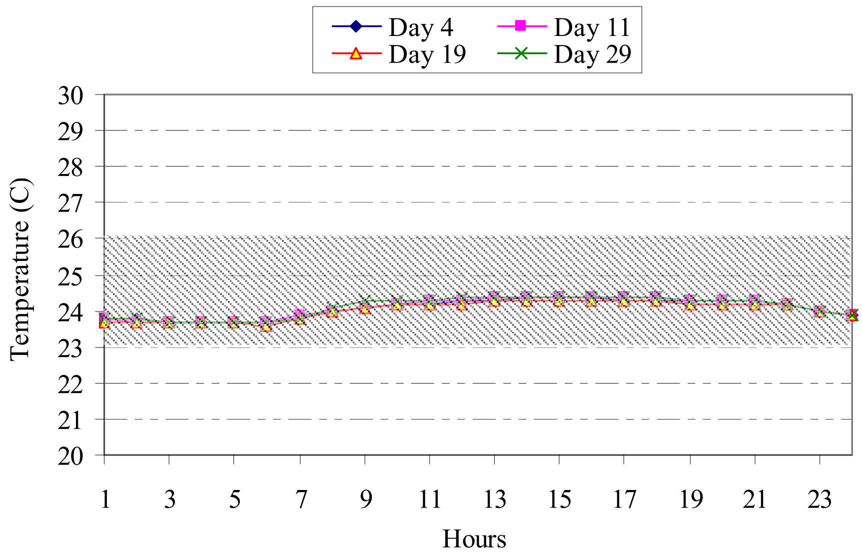


(b)

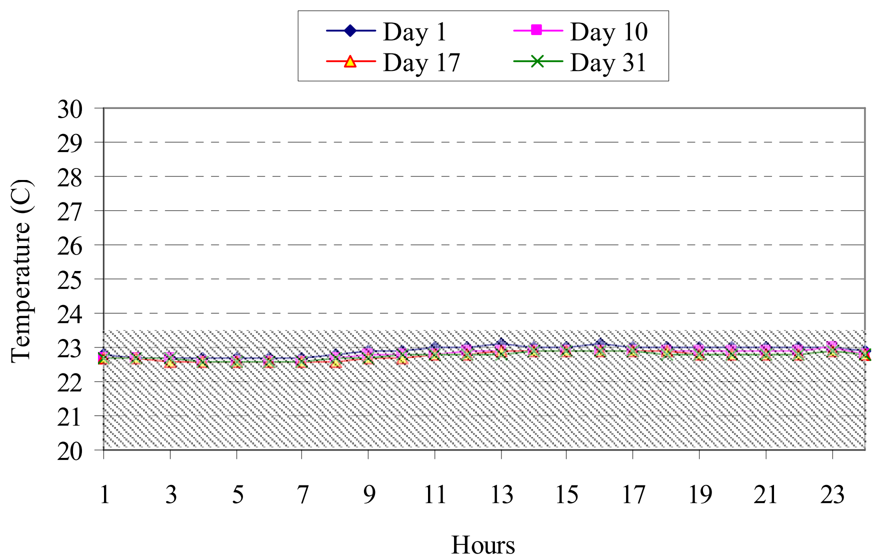
Figure 5.1 Monthly Energy Consumption Comparisons between Base Case and ECM # 1: (a) Common Areas and (b) Whole Building

Figure 5.2 (a) and 5.2 (b) shows the indoor hourly temperature curves of common areas for four different days in the month of July and January which corresponds to peak summer and peak winter months. The temperature profiles indicate that reasonable reduction in the operative temperature have facilitated energy saving along with achieving occupant's thermal comfort in the whole building. The figures shows hatched area representing thermal comfort ranges for summer and winter seasons previously discussed in chapter three.

Figure 5.2 (a) shows the temperature profile for the month of July. Increasing the setpoint temperature by 3^0 C, produces an output which is 1^0 C higher than the desired setpoint to be maintained during daytime. Due to presence of less internal loads the resulting temperature during unoccupied periods is less than the value achieved for occupied periods. The profile can be further explained as to drop in temperature with closure of shopping centre and remains the same until 6 A.M. next morning, thereafter it begins to increase with start of occupancy. Hence it can be concluded that the resulting temperature arising from change in thermostat setpoint is acceptable as per ASHRAE and International Standards Organization (ISO). Similarly temperature patters are found for other zones with different occupancies during the summer season.



(a)



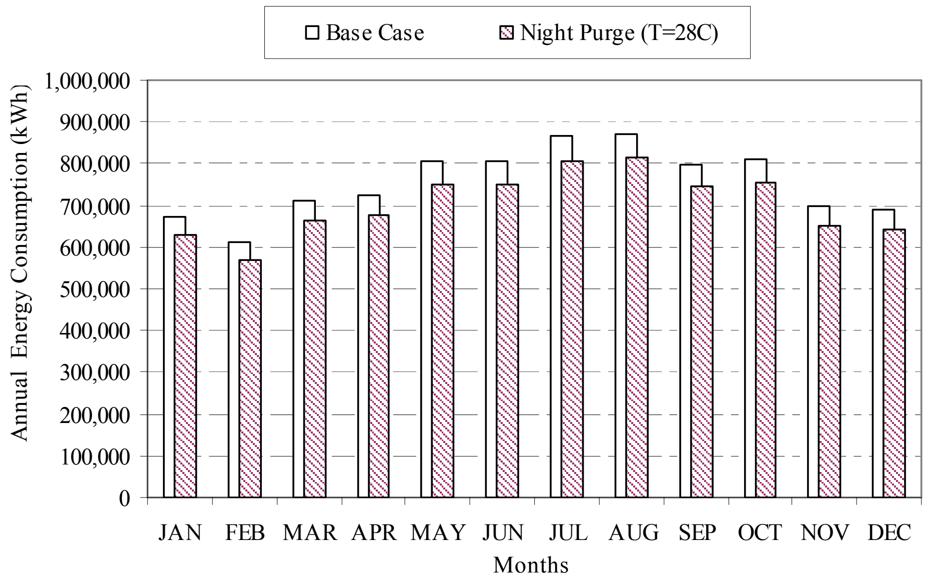
(b)

Figure 5.2 Daily Profile of Operative Temperature for Common Area with ECM # 1: (a) July Representing Summer and (b) January Representing Winter

From Figure 5.2 (b) it can be seen that during unoccupied period when minimum load is experienced and with system operating continuously, the zone temperature has fallen below the setpoint. The new temperature attained during occupancy with the change in setpoint is well within the defined comfort zone. Similar variation in temperature is found in other zones during the winter season.

5.2.1.2 Night Purge Phase One

For the selected facility, low occupancy always occurs in the early morning hours and late night time (i.e. 11.00 P.M to 6.00 A.M next day) compared to the total capacity of the mall. Therefore it is not required to maintain temperature within comfort limits; hence the temperature setpoint can be increased above comfort zone during such period which would help in reducing the energy consumption required for maintaining comfort. For this ECM, the indoor temperature for summer during the unoccupied hours is raised from 20^0 C to 28^0 C, while maintaining 20^0 during occupied periods. Energy consumption for the whole shopping centre was reduced by 5.8 % annually. Since the present thermal conditions were found to be relatively low than recommended by ASHRAE, therefore current strategy was modified to maintain 23^0 C during occupied hours rather then 20^0 C, while maintaining 28^0 C during unoccupied hours. Figure 5.3 (a) shows the energy results obtained after the implementation of this strategy for the office area which has yielded on an average of 6.8 % energy saving annually.



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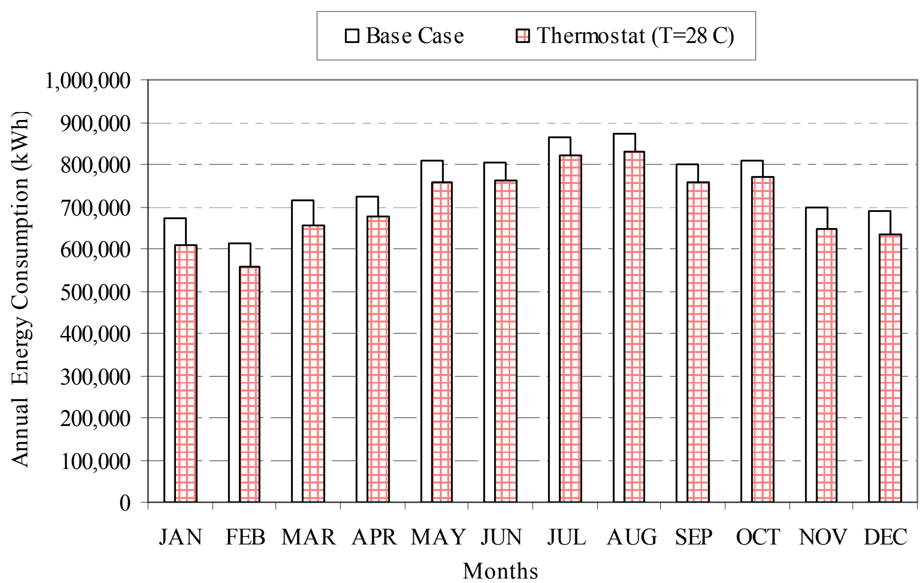


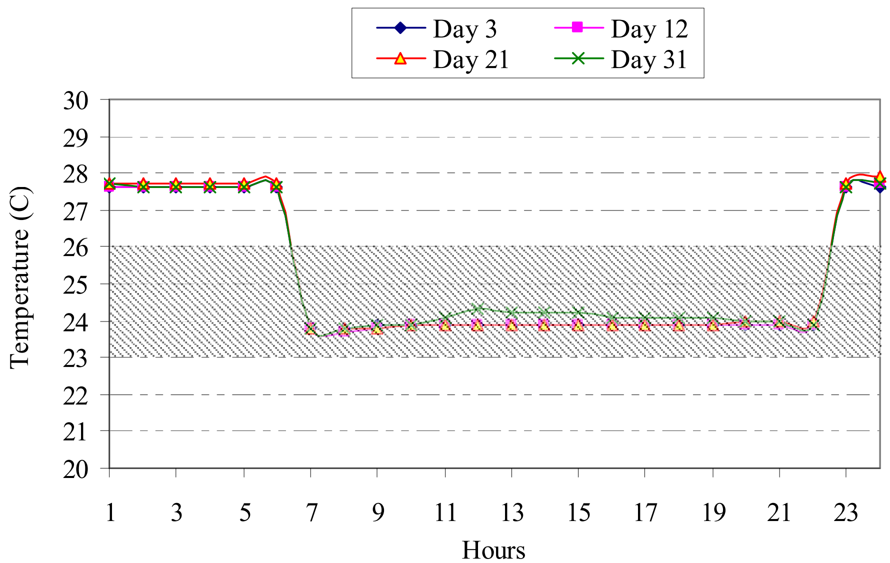
(b)

Figure 5.3 Monthly Energy Consumption Comparisons between Base Case and ECM # 1 and ECM # 2: (a) Offices and (b) Whole Building

After having reviewed the results attained for office area, similar operation strategy is applied to other zones with different occupancies and the energy consumption is monitored. The cumulative energy saving when this strategy is applied in sequence to the whole building accounts to 1096418 kWh, corresponding to 12 %. The comparison of monthly energy consumption between the base case and when the ECM (i.e. 23^0 C during occupied hours and 28^0 C for unoccupied hours) is implemented for the whole building is shown graphically in Figure 5.3 (b).

Figure 5.4 (a) and 5.4 (b) shows the graphical representation of the hourly indoor temperature for shopping area after the implementation of strategy. The temperature profiles are similar for all the cooling seasons, therefore only one month profile is presented here, while the remaining are attached in the Appendix-C.

In this strategy the fan is continuously operating but the indoor temperature is raised to 28^0 C from evening 11:00 P.M. when most the occupants begin to leave the building, until 06:00 A.M. next day, two hours early before the actual occupancy starts. It can be seen from Figure 5.4 (a) increasing temperature during unoccupied periods causes the temperature to reach close to setpoint (28^0 C) and thereafter remains constant until next morning. However the temperature is maintained within the defined comfort zone and throttling range for occupied periods.



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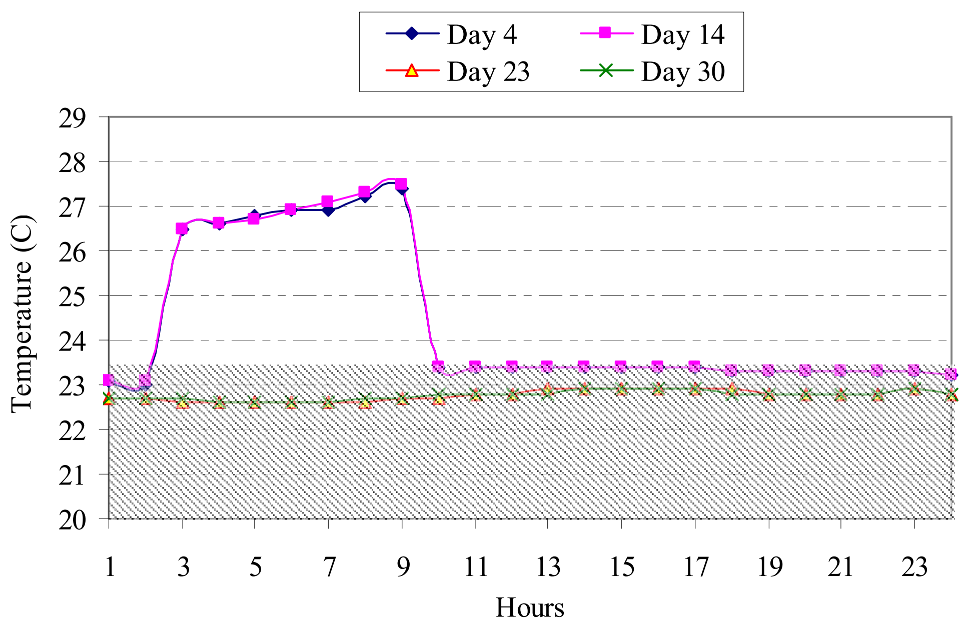


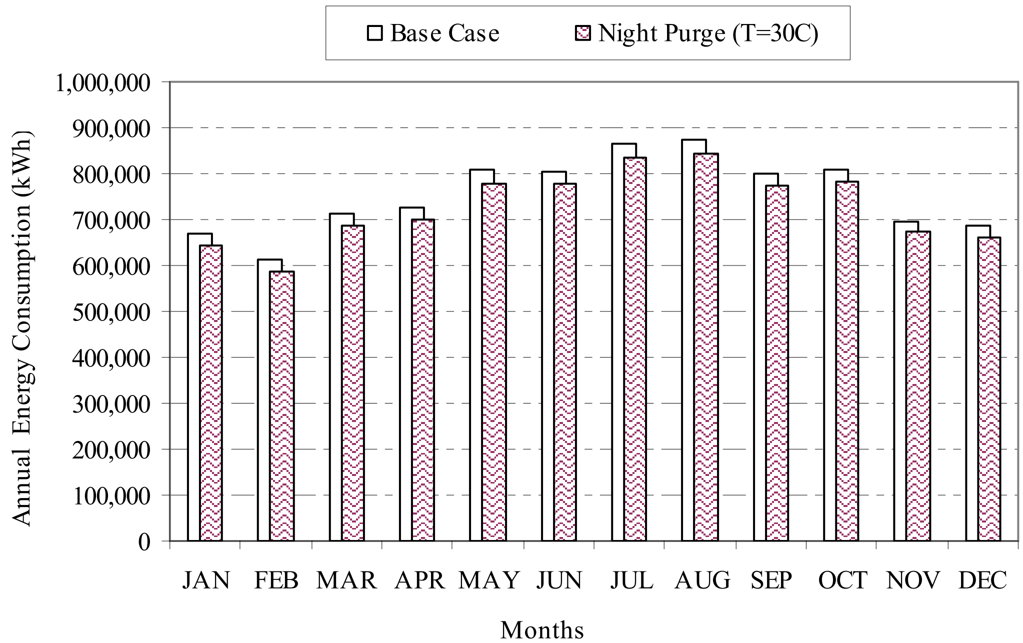
(b)

Figure 5.4 Daily Profile of Operative Temperature for Shopping Area with ECM # 1 and ECM # 2: (a) July Representing Summer and (b) November Representing Ramadan

Figure 5.4 (b) represents temperature variation for two different periods, namely winter and Ramadan which overlaps with first fifteen days of November wherein the facility is operated from 10:00 A.M to 2:00 A.M next day. The indoor temperature returns within the comfort zone almost immediately after the start of occupancy in both the two periods. It can be seen that with system operating continuously and thermostat setting increased by reasonable amount have resulted in acceptable thermal environment along with substantial energy savings.

5.2.1.3 Night Purge Phase Two

After reviewing the energy saving and corresponding temperature profiles obtained with the increase in temperature during unoccupied hours, an interest is enlightened to investigate ECM # 2 with further increase in temperature during unoccupied periods. Optimization of temperature setpoint for unoccupied periods is undertaken keeping in view the time taken by the system to reach desired conditions in occupied periods. For this strategy indoor temperature during unoccupied period is increased from 28^0 C to 30^0 C, while maintaining 20^0 C during occupied period. Increasing the temperature by 2^0 C during unoccupied periods which represents a short period of day has resulted in energy savings for the whole building by 7 %. This was followed by studying the cumulative affect of ECM # 1 and ECM # 3.



(a)

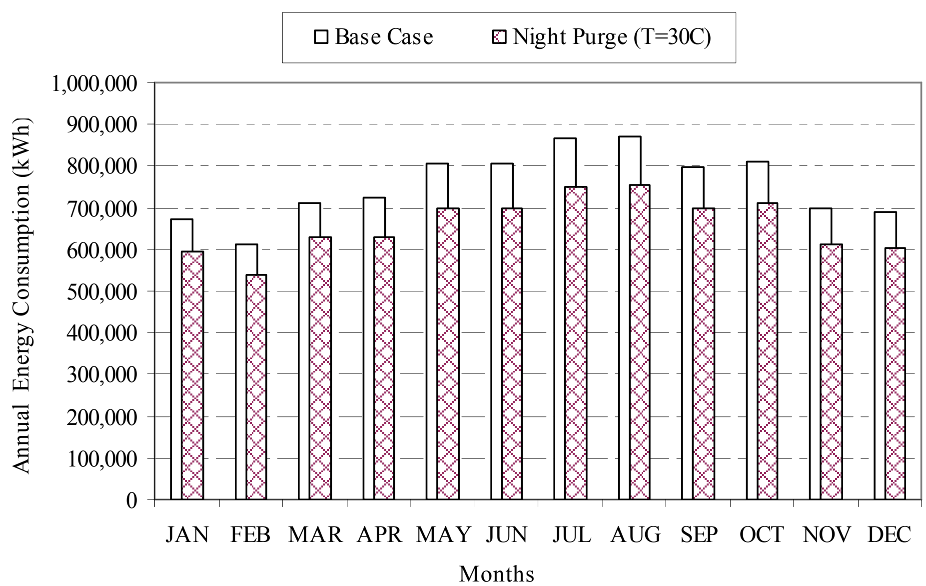


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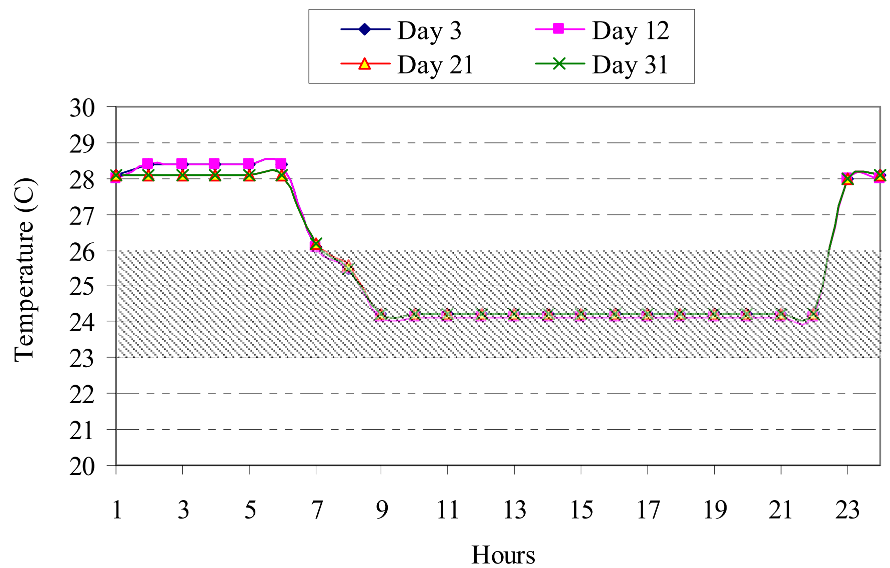
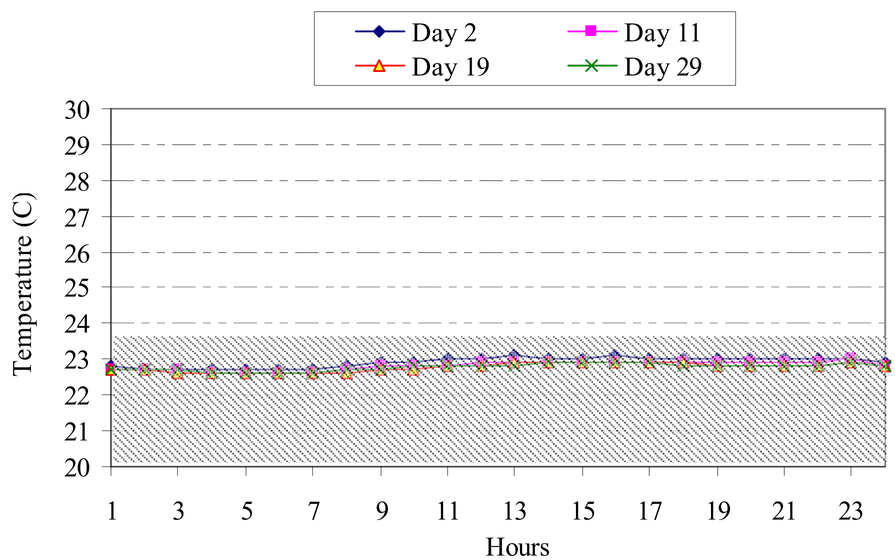
Figure 5.5 Monthly Energy Consumption Comparisons between Base Case and ECM # 1 and ECM # 3: (a) Shopping Area and (b) Whole Building



(a)



(b)

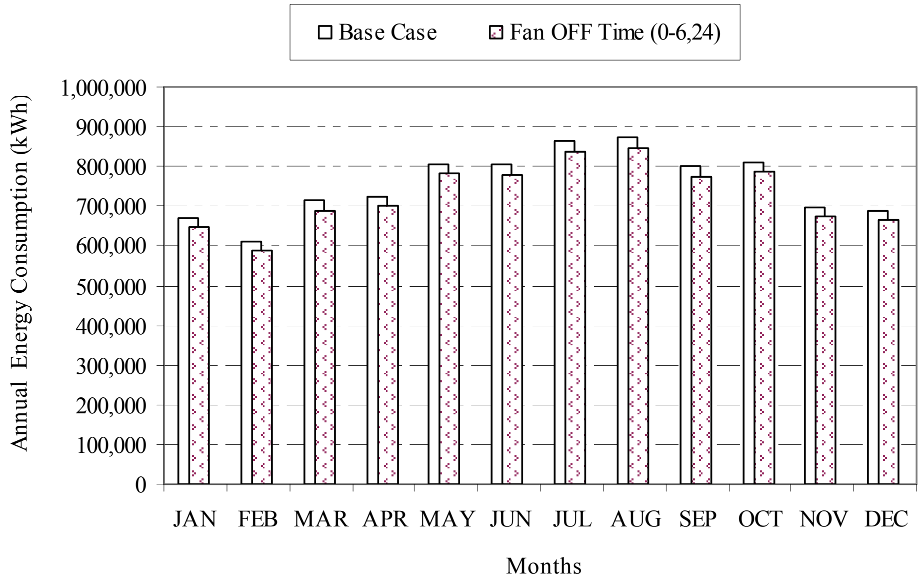
Figure 5.6 Daily Profile Operative Temperature for Shopping Area with ECM # 1 and ECM # 3: (a) July and (b) January

The cumulative affect of temperature change during both occupied and unoccupied periods is initiated by increasing the indoor temperature to 23^0 C for occupied periods while maintaining 30^0 C during unoccupied periods. Figure 5.5 (a) shows the obtained energy results after the implementation newly formulated operation strategy for the shopping area alone. It can be depicted that saving of 3.6 % equivalent to 324,079 kWh of energy is achieved. Figure 5.5 (b) shows the energy consumption comparisons between the base case and newly implemented operation strategy for the whole building. The current strategy when applied for the whole building has resulted in energy saving of 1,142,357 kWh which is equivalent to 12.6 %. Therefore it can be concluded that rise of temperature during unoccupied periods by additional 2^0 C compared to ECM # 2 have not much facilitated in energy reduction.

The hourly temperature profiles are generated to observe the impact of ECM # 3 on indoor thermal comfort for different seasons. Figure 5.6 (a) shows the variation in indoor temperature for month of July. The temperature reaches it thermostat set point (30^0 C) during unoccupied hours. However with the presence of normal internal loads and additional increase in temperature during unoccupied period the system is unable to meet the cooling requirements. As a result with start of occupancy the temperature just reached the upper limit of defined comfort zone and it takes the system additional two hours before it comes within the allowed throttling range and thereafter it remains constant. Therefore there is a probability that the occupants might initially feel slightly uncomfortable at the present achieved temperature after the implementation of this strategy at the start of occupancy time. Figure 5.6 (b) illustrates the variation in indoor temperature occurring as a result of implementation of new thermostat set point during unoccupied periods in winter. Since the system is designed for cooling only no changes are made in the setpoint for winter during night times. With loss of heat to the ambient atmosphere the indoor temperature fall below the setpoint (i.e. 23^0 C), but with the start of occupancy period the temperature returns within acceptable range without any delay.

5.2.1.4 Time Schedule of Operation Phase One

As discussed in chapter two, time schedule operation is the simplest of all the strategies and requires no new installation. On other hand, it can provide greatest potential of energy savings when the system is operated only during unoccupied period. In this strategy, the air-conditioning systems are Turned-OFF at 12 A.M midnight until 6 A.M. the next day for summer and winter season. This strategy is initially developed based on the base case model which has helped to achieve energy saving of 686,220 kWh equivalent to 7.6 % annually for the whole building. Later this strategy is implemented in combination with ECM # 1 for shopping area and has generated energy savings of 290,332 kWh corresponding to 3.2 % as compared to the base case. Figure 5.7 (a) illustrates the energy consumption comparison between the base case and when this strategy is implemented for shopping area.



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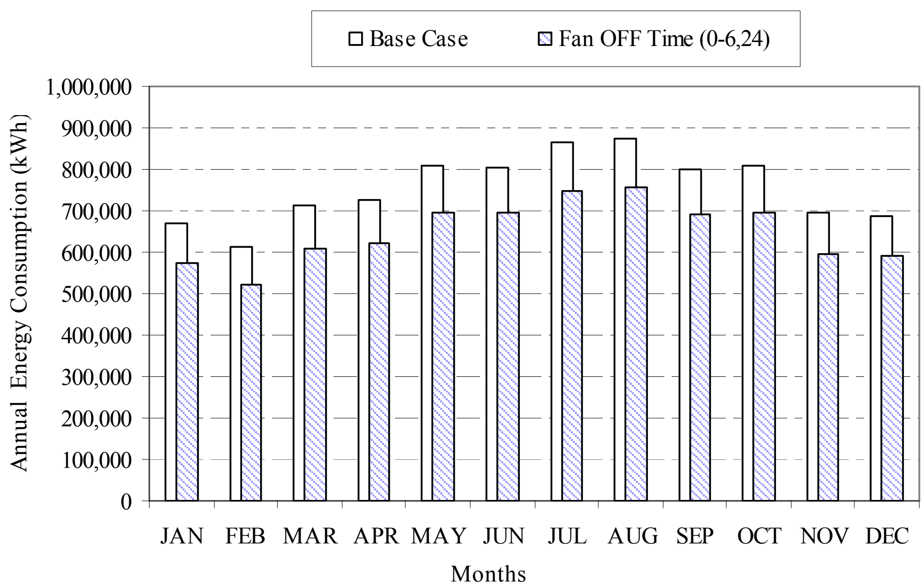
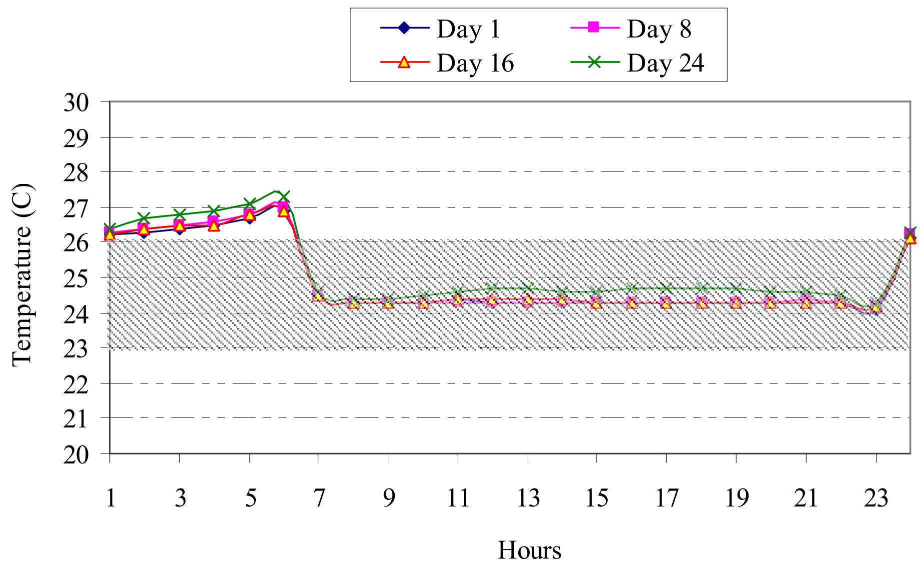


(b)

Figure 5.7 Monthly Energy Consumption Comparisons between Base Case and ECM # 1 and ECM # 4: (a) Shopping Area, (b) Whole Building

Based on the savings obtained for shopping areas, the same ECM is applied to common areas, restaurants and offices, resulting in reduction in consumption by 4.6 %, 0.3 % and 9 % respectively. Therefore upon the implementation of modified ECM # 4 for the whole building, has yielded energy saving of 1,259,554 kWh, corresponding to 14 % reduction. This strategy can also be used as duty cycling in which the system is Shut-Off for a predetermined short period of time during normal operating hours. Figure 5.7 (b) shows the difference in energy consumed by the base case and newly developed strategy for the whole building.

Figure 5.8 (a) shows the graphical representation for the temperature profiles generated as a result of implementation of new strategy for summer season. It can be noted that as the system is not in operation from midnight 12:00 A.M to next day 6:00 A.M the indoor temperature rises above the comfort zone. With the start of system two hours early to the actual occupancy helps to bring back the temperature within comfort zone limit. The temperature from morning 7:00 A.M to 11:00 P.M. is almost constant in both the seasons. Figure 5.8 (b) shows the variation in temperature in the month of January, for four different days. With negligible load, the night temperature decreases from midnight 12:00 A.M till 6:00 A.M. Since the system is also not operating the indoor temperature rises above comfort zone. However with the start of air-conditioning two hours before actual occupancy the temperature drops within the limits of comfort and remains so during the occupancy hours with only small fluctuation in temperature.



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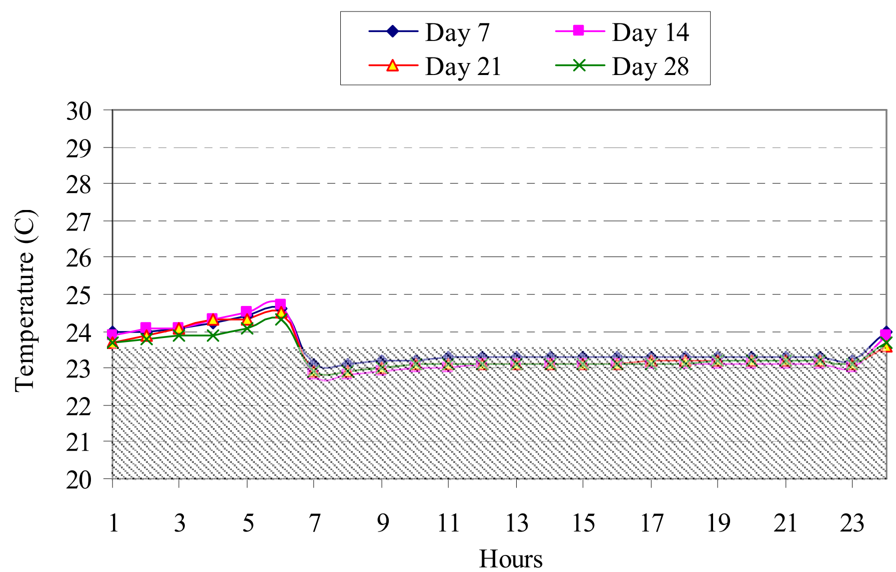


(b)

Figure 5.8 Daily Profile Operative Temperature for Shopping Area with ECM # 1 and ECM # 4: (a) July and (b) January

5.2.1.5 Time Schedule of Operation Phase Two

Considering the previous results obtained from ECM # 4, another strategy is evaluated to identify the optimal stop/start time for the system. For this strategy the system is turned OFF one hour before to closure of the facility and is started one hour before occupancy (i.e. the system remains turned OFF from 11:00 P.M. to 7:00 A.M next day. This strategy has produce savings of 882,714 kWh for the whole building corresponding to 9 %. In order to investigate the cumulative affect of this strategy with ECM # 1, the current setpoint is altered from constant 20^0 C to 23^0 C for occupied periods. The modified ECM increased the energy saving by 16.7 % compared to the base case which is equivalent to 1,514,585 kWh as illustrated in Figure 5.9

The resulting hourly temperature profiles after the implementation of the developed strategy to the shopping area are plotted in Figure 5.10 (a) and (b). The system takes additional 2-3 hours to reach the within the throttling range. Even after the time delay the reduction in temperature is only by small amount which continues to remain constant rest of the day. Therefore this has resulted in higher temperature during occupied times which to some extent can create sense of discomfort to the occupants with subsequent increase in internal building loads

Figure 5.10 (b) shows the operative temperature daily profile generated for four different days in month of January for shopping area. Indoor temperature gradually increases during the night time until next day 7:00 A.M; however there is not immediate drop in temperature with start of occupancy. The system has a delay of more than two hours and thereafter it remains constant at the upper limit of thermal comfort zone. With occupants wearing heavy winter clothing and performing higher metabolic activities, there is a possibility of discomfort among them.

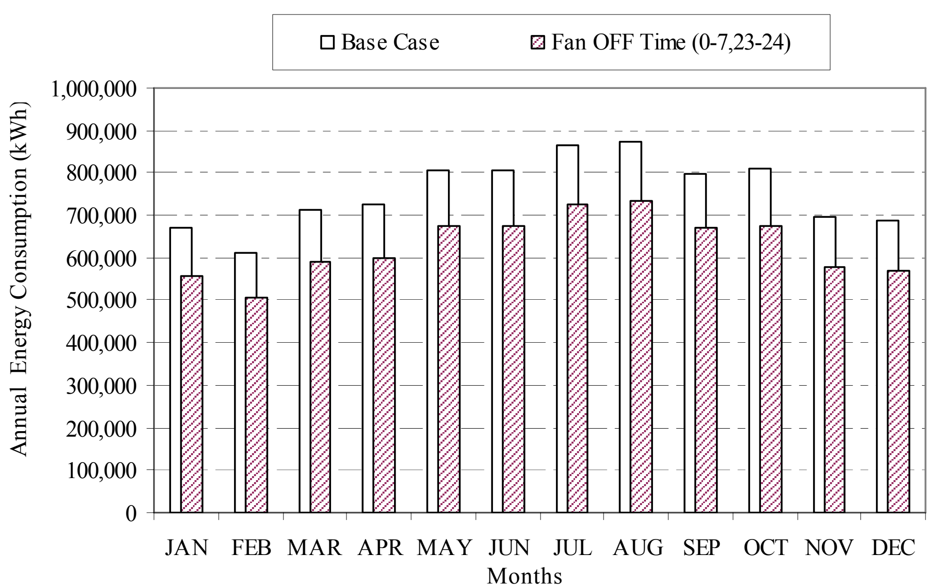
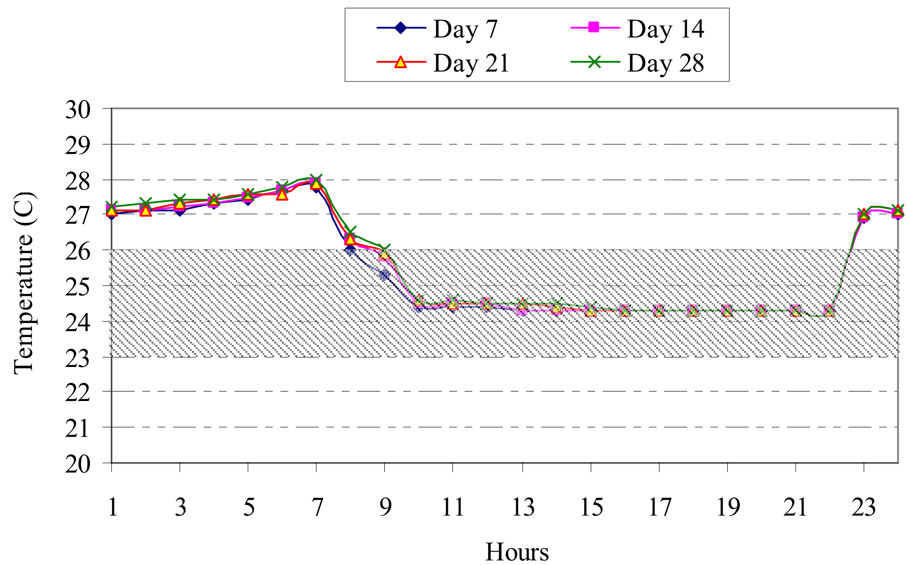


Figure 5.9 Monthly Energy Consumption Comparisons between Base Case and ECM # 1 and ECM # 5 for Whole Building



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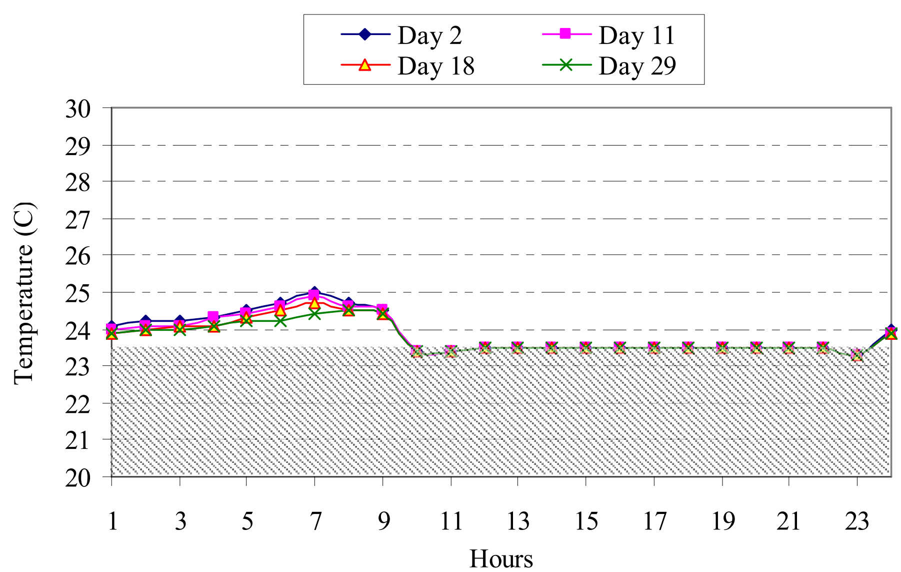
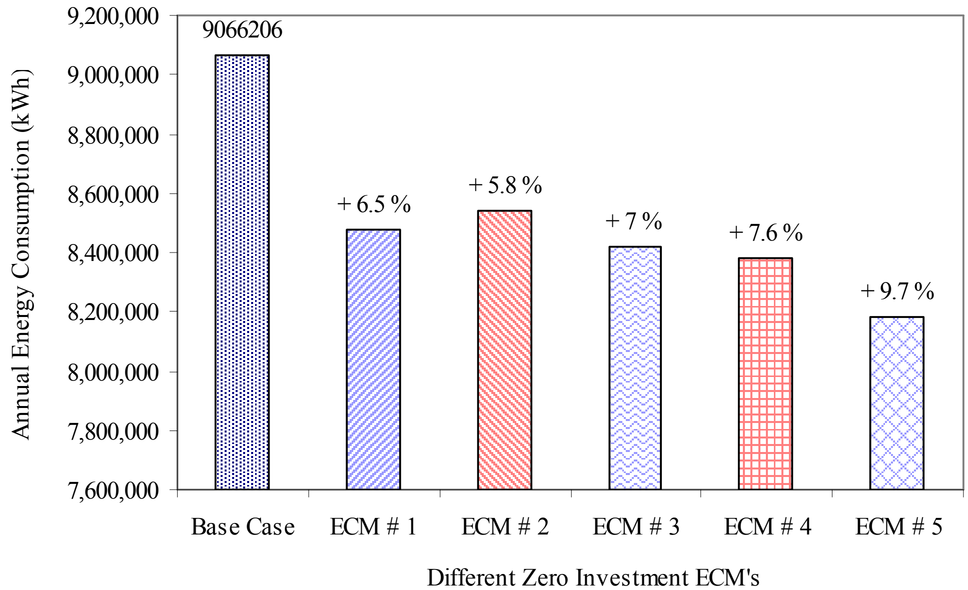


(b)

Figure 5.10 Daily Profile Operative Temperature for Shopping Area with ECM # 1 and ECM # 5: (a) July Representing Summer, (b) January Representing Winter

Annual energy consumption comparisons for the five different operation strategies implemented on the base case are shown in Figure 5.11. It can be seen that initial change in thermostat setpoint from 20^0 C to 23^0 C is able to reduce consumption by 6.5 %, while night temperature setback strategies i.e. ECM # 2 and 3, were able to achieve energy saving of 5.8 % and 7 % respectively. Reduction in the operation time of the system through unoccupied periods as discussed in ECM # 4 and 5 has generated savings of 7.6% and 9.7% respectively.

In order to investigate and compare the energy saving achieved with the implementation of ECM's on base case with use of higher setpoint during occupied period, ECM # 1 is studied in combination with all other ECM's. It can be seen that increasing the indoor temperature to 23^0 C during occupied periods and use of night setback strategy has helped to achieve double the energy saving (12 %) as compared to that achieved with use of 20^0 C. However there is no prominent difference in the energy savings produced from ECM # 2 and 3, rather the latter has disrupted much of the thermal comfort conditions. Further the reduction in operation time of system along with high setpoint during occupied periods has given a substantial increase in energy savings by approximately 7 % for ECM # 4 and 5 each, as compared to these strategies being implemented individually.



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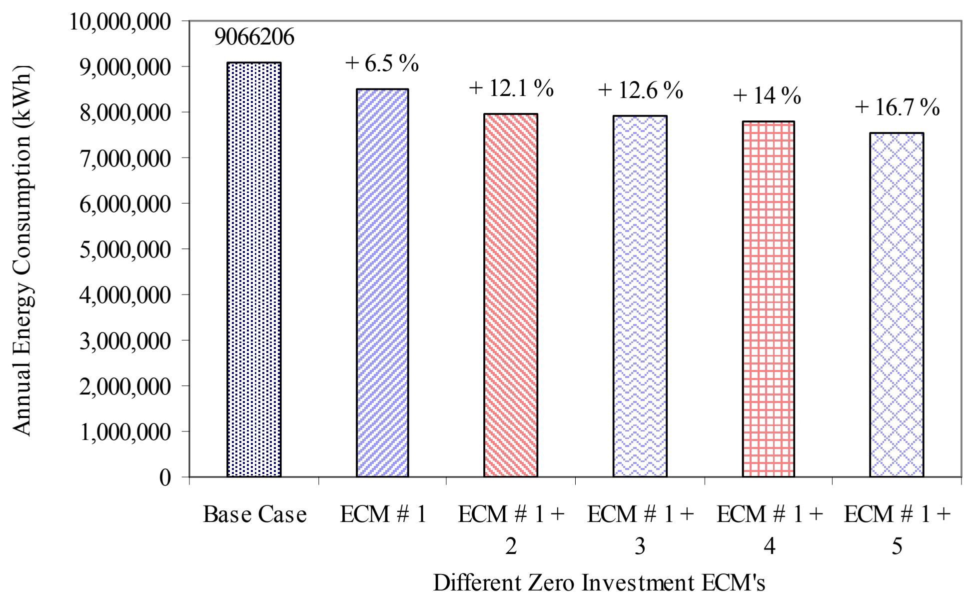


(b)

Figure 5.11 Annual Energy Savings for the Whole Shopping Centre achieved after Implementation of Energy Conservation Strategies: (a) Individual and (b) Cumulative with ECM # 1

5.2.2 Minor Investment Energy Conservation Measure

These measures can be implemented for the modification of system control or its other small peripherals.

5.2.2.1 Thermostat Type

Thermostats control nearly all types of heating and cooling equipment, keeping room temperatures within a set range to ensure comfort, cut energy waste, and offer considerable convenience. There are basically three different types of thermostat compatible with Visual DOE and each of them will be discussed in brief here.

A. Two Position Control

Two-position control compares the value of an analog or variable input with definition of an upper and lower limit and generates a digital (two-position) output. The output changes it values as the input crosses these limit values, however there are no standard for defining these limits. The most common terminology is setpoint and differential, where setpoint indicates point at which output plug-in

B. Proportional Control

A proportional control response produces an analog or variable output change in proportion to a varying input. In this control response, there is a linear relationship between the input and the output. A setpoint, throttling range and action typically define this relationship. In a proportional control response, there is a unique value of the measured variable that corresponds to full travel of the controlled device and a unique value that corresponds to zero travel on the controlled device. The change in the measured variable that causes the controlled device to move from fully closed to fully open is called the throttling range. It is within this range that the control loop will control, assuming that the system has the capacity to meet the requirements.

The affect of thermostat type on energy consumption for the base case is investigated. The variation in energy consumption for three different thermostats can be seen in Figure 5.12. Use of “Two Position” type of thermostat instead of proportional as used in base model, has reduced energy consumption by 0.13 %. However using “Reverse Action” has increased the consumption value beyond that attained in base case. This is because reverser action thermostat increases the zone air flow as the cooling load increases thereby energy consumption increases.

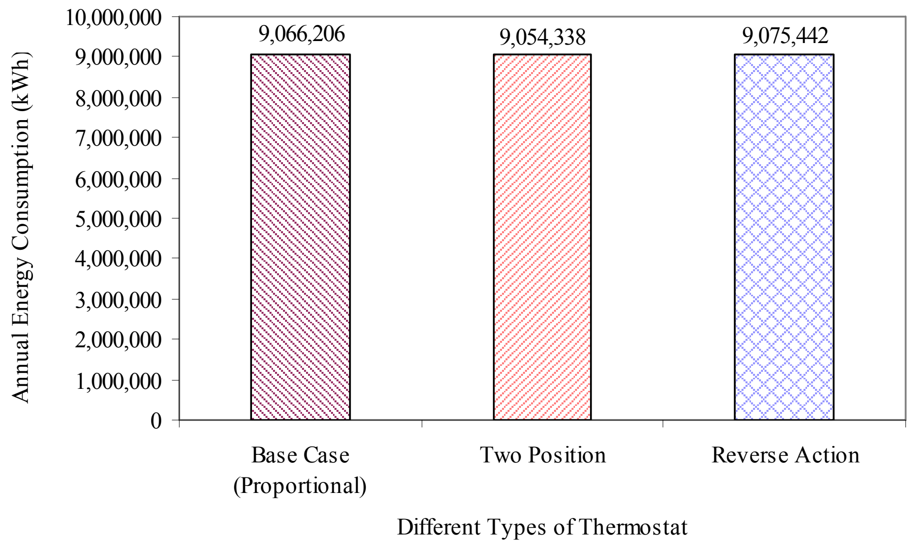
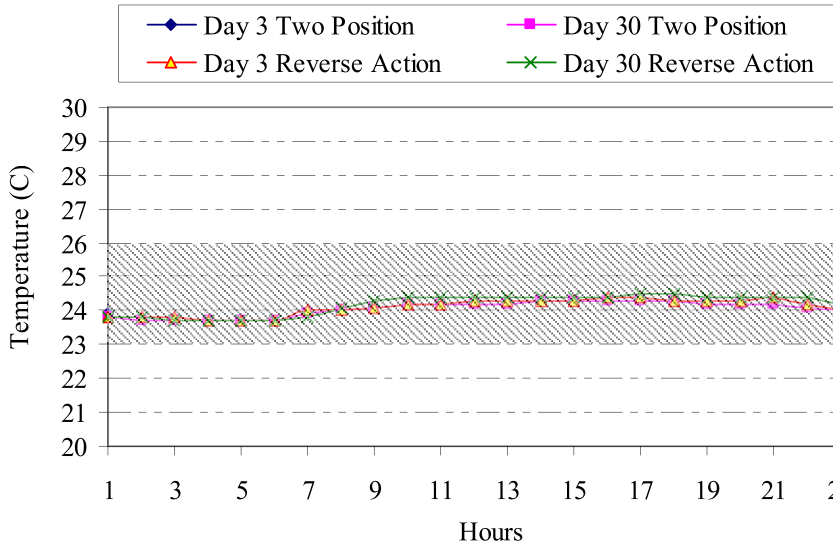


Figure 5.12 Effect of Thermostat Type on Energy Consumption

The temperature variations with the implementation of new thermostat are shown in Figures 5.13 (a) and (b) respectively corresponding to July and January representing summer and winter months. It can be seen in both figures that variation in temperature as a result of different thermostat being employed are not much and more ever two position generates savings than compared to proportional and reverse action type.



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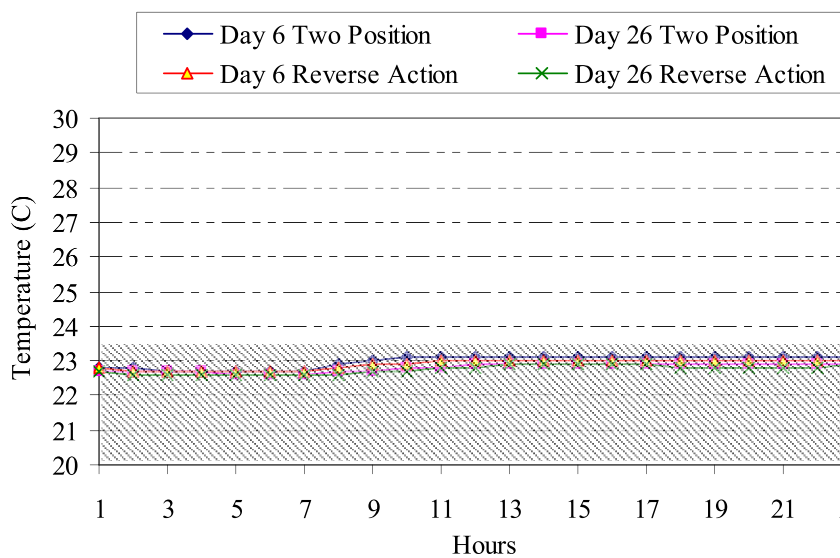


(b)

Figure 5.13 Daily Profile Operative Temperature for Common Areas with different Thermostats: (a) July and (b) January

5.2.3 Major Investment ECM’s

These energy conservation measures require considerable amount of investment to be made for the implementation of new strategies. This phase also requires wise judgments and comparison between the investment input, the saving being attained and the pay back period.

5.2.3.1 HVAC System Type

Five different systems, namely packaged multi zone system (PMZS), variable air volume (VAV), constant air volume with reheat (CAV-Rh), multi zone system (MZS) and two pipe fan coil (TPFC) unit are evaluated. Further savings from CAV-Rh for the core zones is investigated in combination with VAV and TPFC for the peripheral zones in two different cases. Annual energy consumption by each system in compared to the base case is shown in Figure 5.14. It can be seen that switching over to centralized air-conditioning system rather is using individual system as in the base case model is beneficial in most of the alternatives except PMZS.

Among the system evaluated for energy conservation it is found that PMZS gave the worst thermal and energy performance. CAV-Rh is not much energy efficient though it is able to satisfy the indoor comfort requirements at reduced energy consumption. VAV gave best thermal and energy performance followed by TPFC. Further more CAV-Rh when evaluated with VAV and TPFC did not show much improvement in energy savings, it was found to consume more energy than compared to latter system when evaluated individually. This shows that CAV-Rh system is not suitable as it is deteriorating the performance of VAV and TPFC.

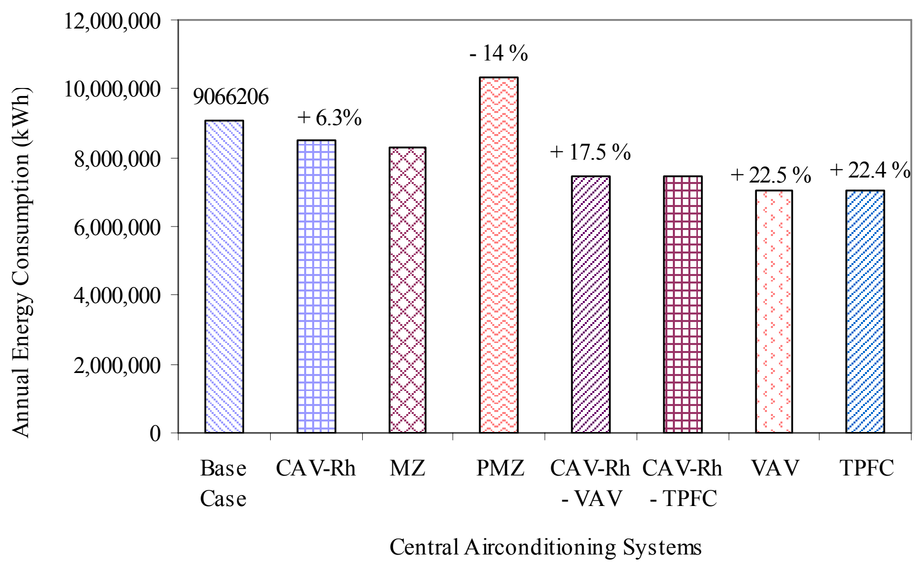


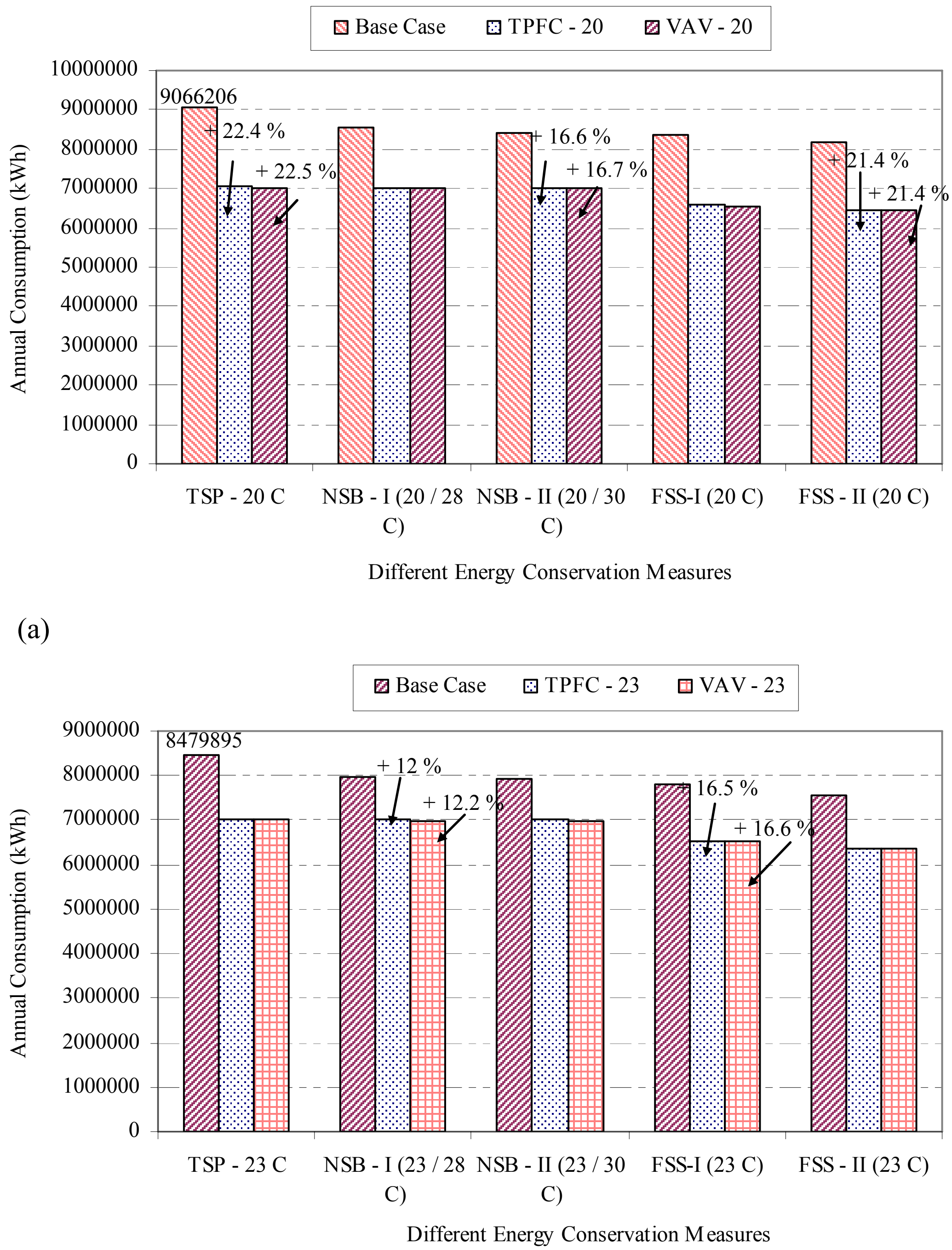
Figure 5.14 Effect of Different HVAC System on Annual Energy Consumption

Energy conservative measure implemented for the base case system can be evaluated to have a broader view of energy saving that can be achieved upon replacement of individual system with centralized. For this purpose best performing system identified as a result of initial simulation as shown in Figure 5.14. With use of base case original setpoint (20^0 C), energy savings from VAV and TPFC are investigated. Figure 5.15 (a) shows a comparison between base case and newly employed systems. It can be seen that also similar saving are achieved for VAV and TPFC after implementation of ECM # 1 through ECM # 5 and the maximum (21.4 %) is achieved for ECM # 5.

Energy savings achieved from the central systems (namely VAV and TPFC) after implementation of ECM # 1 through ECM # 5 with modified occupied period setpoint in comparison with base is illustrated in Figure 5.15 (b). Energy savings are almost similar to those achieved when the thermostat setpoint is maintained at 20^0 C. Maximum energy saving (17 %) is obtained for setpoint change during occupied period to 23^0 C.

5.2.3.2 Enthalpy Economizer

Enthalpy economizer is used in conjunction with the two different types of HVAC centralized air conditioning systems. It can be seen that with the use of economizer the annual saving are further increased by 3% approximately for each system compared to system with no economizer. Figure 5.16 shows energy the comparison between the base case and newly implemented strategies for constant air volume reheat system and variable air volume system.



(b)

Figure 5.15 Annual Energy Consumption Comparisons between Split System, TPFC and VAV: (a) Occupancy Setpoint 20^0 C and (b) Occupancy Setpoint 23^0 C

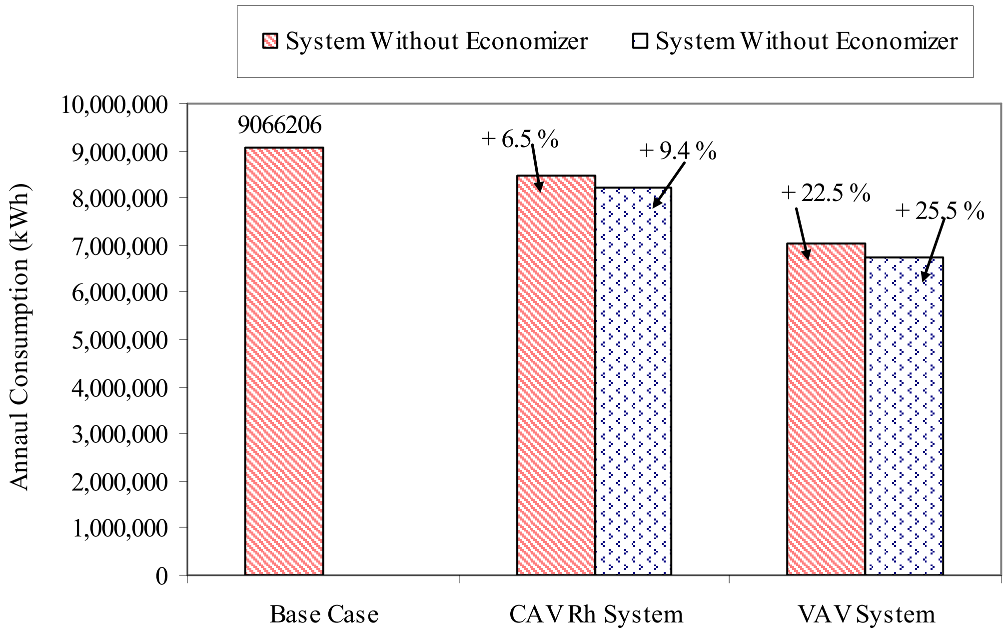


Figure 5.16 Effect of Enthalpy Economizer on Annual Energy Consumption

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 Summary and Conclusions

This study has been carried out in different phases to achieve its objective. In the initial stage, extensive literature was reviewed for HVAC operation, energy conservation and thermal comfort. It is evident from previous studies that energy and thermal comfort problems were mainly associated with HVAC System design and operation. In many cases, concern about conserving energy, has lead designers to pay less attention towards occupants' comfort or visa versa. Therefore, a proper and careful balance must be attained in order to achieve the desired thermal environment with the least energy consumption.

In order to investigate the energy performance of commercial building in Saudi Arabia and gather the required data to perform energy simulation, information regarding building characteristics and systems were collected from a sample of five different malls, based on their size. The data acquired from different shopping malls was analyzed and discussed to identify existing similarity in construction and functioning. Simultaneously the building comfort analyses for the building occupants was performed through survey by collecting responses from building users and measurement of temperature and humidity data to have perception about present indoor conditions.

It is found that neither the owners nor the designers were energy conscious and aware of the air-conditioning system to be used. Among the five facilities surveyed it was found that only two buildings had centralized air conditioning system. Further from the thermal comfort analysis it was found that in one of the shopping malls more number of occupants were dissatisfied with the prevailing conditions, while the rest of the few showed satisfaction to the prevailing thermal conditions. Also an important point worth noting is that the shopping malls were operating their HVAC system with low temperature set points through out the year, thereby resulting in unnecessary utilizing of cooling energy.

Among the five buildings surveyed, one was selected for modeling and simulation, for energy performance and thermal comfort. This building was selected based on its typical characteristics to other facilities. The Building was modeled and simulated using Visual DOE 4.0 to investigate the building energy performance and explore potential energy savings with implementation of ECM's. The annual energy consumption obtained for the base model is compared with energy consumption obtained from SEC to find deviations. Initial results of the base case model presented a deviation close to 20 %; therefore it was required to calibrate the model to have realistic results. Further this would help to have more reliability of the final results with the implementation of new strategies. For this purpose known parameters and variations identified from the onsite inspection were changed to develop the base case model close to 10 % of the actual case.

Three different types of HVAC operation strategies based on economic value were tested to investigate their impact on energy consumption and thermal comfort. For the ECM # 1 with no investment, effect on energy and thermal comfort is investigated. Initially the indoor temperature set-point is increased to 25^0 C from original value of 20^0 C, though this modification produced substantial energy savings but was not able to achieve desired thermal comfort. This resulted because of the use of 2^0 C throttling range, therefore thermostat setting were changed to 23^0 C and have generated annual energy savings of 6.5 %. Without making any changes to the indoor temperature during occupied periods for the base case model, the temperature during unoccupancy (i.e. 12:00 A.M to 6:00 A.M) was increased to 28^0 C. This has resulted in producing annual saving of 5.8 %, while maintaining occupants comfort. However further to investigate the cumulative effect of temperature change during both occupied and unoccupied periods, ECM # 2 was modified to maintain 23^0 C during occupied periods. The cumulative strategy was more effective in reducing the energy consumption by almost double (12 %) the amount.

For ECM # 3 the night time temperature from 12:00 A.M to 6:00 A.M for the base case model was increased to 30^0 C and subsequently cumulative effect of ECM # 3 in combination with ECM # 1 were investigated. Each of these modifications in the base case model has helped to reduce the energy consumption by 7 % and 12.6 % respectively. However in the latter case the temperature attained after the implementation of cumulative strategy reaches just the upper limit of comfort zone requiring another two hours to drop within throttling range. Hence there could be a possibility of slight uncomfortable conditions at the start of occupancy hours.

Switching OFF the system when occupants start to leave the building (one hour before the complete closure) and switching it ON two hours before the actual occupancy, has resulted in acceptable indoor condition and 7.6 % of energy savings. ECM # 4 was also evaluated in combination with ECM # 1 thereby resulting in acceptable indoor conditions and energy saving amounting to 14 %. In order to optimize the stop/start time, the system was turned OFF from 11:00 P.M to 7:00 A.M, resulting in slightly uncomfortable conditions, though the saving were accounted to 9.7 %. Use of 23^0 C set-point during occupied period and turning OFF system at night times, was able to produce substantial energy savings equivalent to 16.7 %. However, it was found that this strategy could not achieve the desired temperature or even reach within the range of comfort zone.

Different types of available thermostats are investigated for their impact on energy consumption and thermal comfort. It was found that using reverse action type increased the energy consumption to attain the desired indoor temperature. This is because; it increases the zone air flow ratio with slight variation in indoor load. Though the use of two position type of thermostat resulted in energy saving but it was found to be negligible (0.2 %).

In order to identify energy saving from the use of centralized air-conditioning system and compare it with individual system performance, five different systems were evaluated. VAV, CAV-Rh, TPFC, multi-zone system were some of the central air-conditions investigated. It was found that packaged multi-zone system gave worst performance with increase in energy consumption by 14 %. This was followed by constant air volume reheat with relative less reduction amounting to 6.3 % compared to other central system. Variable air volume was highly energy efficient producing saving of 22.5 % followed by TPFC unit (22.4 %). Two different system combinations namely CAVRH with variable air volume system and CAVRH with two pipe fan coil unit were investigated and an energy savings of 17.6 % was achieved for each.

Based on the results achieved from the change of HVAC system for the base case, the best performing system was investigated for energy saving through implementation of ECM's formulated for the base case. Energy savings up to 17 % are achieved in both the case with individual systems replaced with central system (VAV and TPFC) and occupancy period set-point maintained at 20^0 C. These savings are further increased up to approximately 22 % when these systems are operated with indoor temperature maintained at 23^0 C during occupied period.

Enthalpy economizer is also evaluated in conjunction with two different systems, namely VAV and CAV-Rh system. It is found that the performance of the economizer with respect to energy consumption is more or less similar in both the cases and each produced saving up to 3 %. However VAV showed higher performance towards temperature control.

From the above discussion can be concluded that major energy savings up to 23 % can be achieved in commercial buildings provided proper system is selected and operated in proper and efficient manner based on the occupancy type. Table 6.1 presents a concise version of impact of various applicable ECM's studied on energy savings. Only few of the strategies found from the literature review have been implemented here due to time constraints.

Table 6.1 Concise Version of Applicable Operation Strategies and their Corresponding Energy Consumption Change

Operation Strategies / System	Variations / Modifications	System Under Study							
		Unitary System	Multi zone Split System	Multi zone Packaged Unit	CAV-Rh	VAV	TPFC	CAV-Rh - VAV	CAV-Rh - TPFC
Temperature Setpoint	$T = 20^0$ C	Base Case	+ 8.3 %	- 14 %	+ 6.4 %	+ 22.5 %	+ 22.4 %	+ 17.6 %	+ 17.6 %
	$T = 23^0$ C	+ 6.5 %	NI**	NI**	NI**	+ 17.4 %	+ 17.1 %	NI**	NI**
Night Setback	$T_{Occ} = 20^0$ C $T_{Unocc} = 28^0$ C	+ 5.8 %	NI**	NI**	NI**	+ 17.9 %	+ 17.8 %	NI**	NI**
	$T_{Occ} = 23^0$ C $T_{Unocc} = 28^0$ C	+ 12 %	NI**	NI**	NI**	+ 12.2 %	+ 12 %	NI**	NI**
Start Stop Optimization	System Off : 12 – 6 A.M & $T_{Occ} = 20^0$ C	+ 7.6 %	NI**	NI**	NI**	+ 21.7 %	+ 21.6 %	NI**	NI**
	System Off : 12 – 6 A.M & $T_{Occ} = 23^0$ C	+ 14 %	NI**	NI**	NI**	+ 16.6 %	+ 16.5 %	NI**	NI**
Thermostat Type	Reverse	- 0.1 %	NI**	NI**	NI**	NI**	NI**	NI**	NI**
	Two Way	+ 0.1 %	NI**	NI**	NI**	NI**	NI**	NI**	NI**
Economizer	Enthalpy	NI**	NI**	NI**	+ 9.5 %	+ 25.5 %	NI**	NI**	NI**

NI:** Need to Investigate; **T_{Occ}:** Temperature Occupied Period; **T_{Unocc}:** Temperature Unoccupied Period

6.2 Recommendations

Based on the analysis of the results, the following recommendations are summarized in order to achieve energy conservation without sacrificing occupant's thermal comfort.

1. Adopting higher thermostat setpoint (i.e. 23^0 C) rather than 20^0 C as it has been proved to be energy efficient by providing energy savings of 6.5 % annually.
2. Use of higher setpoint (28^0 C) during night times is helpful in providing energy savings of 5.8 % without affecting the thermal comfort during occupancy. Further this strategy when implemented along with higher setpoint (23^0 C) during occupied periods can generate saving of 12.1 % annually.
3. Reducing the operation time of fan by turning it OFF especially during unoccupied periods (i.e. from 12 A.M. to 6 A.M. next day) has not effect on indoor conditions during occupied periods. Additionally this strategy can save energy required to maintain acceptable indoor conditions by 7.6 %. When implemented in combination with ECM # 1 this strategy can double the energy savings (14 %).
4. Buildings equipped with individual split system to serve different zones can be replaced by centralized system. Employing VAV system or TPFC, in these centralized systems provides substantial energy savings (21.4 %) and subsequent thermal comfort is also attained.

5. Employing VAV or TPFC for central air-conditioning with higher set-point temperatures during occupied periods has resulted in acceptable comfort conditions being achieved at much lower energy consumption.
6. When employing central systems, the core zones of the building with constant load can be installed with CAV-Rh system and peripheral zone with VAV or TPFC for energy saving and thermal comfort. Each of this combination (CAV-Rh – VAV and CAV-Rh – TPFC) has produced similar energy saving of 17.5 %
7. Two-pipe fan coil unit is seldom available with manufacturers in Saudi Arabia. When properly designed for harsh humid climatic conditions, it can perform better than VAV system, with regard to energy and thermal performance.
8. Enthalpy economizer in combination with VAV system can be helpful to produce additional 3 % saving than compared to VAV system being employed alone.

6.3 Design and Operation Guidelines for HVAC System in Commercial Buildings

Some guidelines based on the conclusion and recommendation of current research and in conjunction with ASHRAE Standards have been formulated for HVAC System operation in commercial buildings, Eastern Province Saudi Arabia. Table 6.2 through 6.4 summarizes the formulated guidelines based on literature review, current research finding and International Building energy code. These guidelines can be implemented in commercial buildings for achieving energy savings and thermal comfort generally for hot humid climate universally and particularly for Saudi Arabian climate.

Table 6.2 Guidelines formulated for HVAC System Design and Installation

System Design and Installation	Guidelines
Centralized System	Centralized systems are more energy efficient than individual systems for large commercial building. Therefore only central air conditioned systems should be employed in such buildings with different zones monitored by their own thermostats.
	High chilled water temperature and low condensing temperature should be preferred as this result in satisfactory space conditions at minimum energy consumption.
	Pumps and fans should have high operation point.
	Multiple systems should be used so that at part load some equipment can be shut down and the equipment operating will be close to full load at which it is more efficient.
Duct System	Design the ducting system for lowest friction loss by avoiding obstructions; make gradual transition in ducts and use wide turning radius with vanes if required.
	Provide airtight duct, test for leakage and ample insulation.
	Installing ducts and piping with shortest length of run and very few bends.
	Dampers with tight closing features shall be helpful in reducing energy wastage.
Thermostat	Avoiding thermostats that are prone to sense an abnormal condition.
	Use of two position type of thermostat shall be stressed as this has shown to consume least energy compared to other types.
	Central computerized control can be another possibility to provide most efficient operation all the times.

Table 6.3 Guidelines formulated for different Operations Strategy and Maintenance

System Operations and Maintenance	Guidelines
System Controls	Each cooling system shall be equipped with at least one temperature control device.
Zone Controls	The cooling requirement to each zone shall be controlled by individual thermostatic controls to respond to the temperature within a particular zone.
	When maintaining cooling comfort conditions, the thermostatic control should be capable of being set locally by adjusting the sensor up to 30^0 C.
	Use of humidistats to monitor comfort shall be capable to preventing unnecessary use of energy to reduce humidity below 60 % in summer.
Temperature Reset for Air System	Air system supplying cooling energy to multiple zones should be capable of resetting the supply air temperature depending on the building internal loads or outside air temperature.
	Reset shall be at least 25 % of design supply air temperature to room air temperature difference.
	Zones with constant loads shall be designed for maximum reset.
Unoccupied Hours Control	HVAC System shall be capable of reducing energy through the use of control setback or equipment shutdown during unoccupied hours.
	Outside air supply for improving indoor air quality or partially controlling indoor conditions shall be provided with dampers to shutoff or reduce depending on outside conditions.
	The system shall be Turned OFF with the users beginning to leave the building and restarted two hours before actual occupancy starts.
Economizer Control	System shall include enthalpy economizer capable of modulating outside air and return air dampers to provide 85 % of design supply air quantity.
Temperature Reset for Water System	Water system supplying chilled water to comfort conditioning system shall be capable to rest supply water temperature with respect to building load or outside air temperature.

	Reset shall be at least 25 % of design supply-to-return water temperature difference.
Maintenance	Regular check and replace or clean air filters to avoid reduction to air flow.
	Check all heat transfer surfaces regularly to facilitate proper convection of heat.
	Check the duct work regularly for any leaks that may have developed.
	Check for objects that may be obstructing air flow through room terminal units.
	Check for air distribution outlets that may have been tampered or thermostats and humidistats that have been readjusted by unauthorized personnel.

In addition to designing, installation and operation of HVAC there are other building components that affect the energy consumption pattern in a building. These components have indirect impact on occupants' thermal comfort and energy. Therefore a few guidelines are formulated for the envelope design that will help reduction in energy.

Table 6.4 Guidelines formulated for Envelope Design

Envelope Design	Guidelines
Insulation	Use high R-Value insulation throughout the building.
Fenestration	Consider use of heat absorbing glass.
	Provide effective interior shading devices.
	Minimize use of glass in the building, unless used on the south side for receiving solar heat in winter.
	Consider outside construction features that provide shading for glass.
	Use window sash that has tight seal at the frame or non operable windows, though this might prevent use of natural ventilation

Orientation	Orient the building so that solar radiation in summer is minimal on side with large glass areas.
Lighting and Equipment	Avoid unnecessarily use of excessive lighting and equipment levels.
	Use types of lighting fixtures with more efficiently convert electrical energy in light without generating much heat.

6.4 Further Research

Research is never ending; a finding today is a stepping stone for tomorrow. Likewise this particular research, though has achieved its proposed objectives, but can still be carried on taken further. HVAC operation strategies over the central plant side have not been considered due to time constraints. Building components such as lighting system, equipments have indirect impact of HVAC load; this could also be investigated in further.

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Appendix – A: Data Collection and Thermal Comfort Assessment

SUBJECT: Data Collection for M.S. Thesis Research

Mr. Mohammed Fasiuddin is a Research Assistant in the Architectural Engineering Department, King Fahd University of Petroleum and Minerals. As part of his Master program, he is currently conducting a research project titled **"HVAC System Operation Strategies for Energy Conservation and Thermal Comfort in Commercial Buildings in Saudi Arabia"** to be submitted to the university. An important step towards achieving this research objective is to collect information (like design/maintenance documents, specifications, working drawings, utility bills, photos, etc.), about commercial centers like yours and seek opinion of the people managing the facility. The outcome of the research will be useful for identifying HVAC operation strategies for energy conservation while maintaining thermal comfort. Your co-operation is highly appreciated in this regard.

Thank you.

Dr. Ismail M. Budaiwi
Chairman
Architectural Engineering Department

Detail Data Collection Form

Section 1: General Information Date ……………………

Organization Name: ………………………………………….…………………………………... Location:.…………………………………………………………………………………………	
Year of Construction …………………………….	Dimensions ……………………………………m
Gross Floor Area ……………..……………. m^2	Maximum Capacity ……………………..Persons
Conditioned Areas …………………………. m^2	Unconditioned Areas ………………………. m^2
Number of Floors ……………………………….	Number of stores/ floor …………………………..
Respondent Name: ……………………………… Job Title …………………………………….........	Phone No: …………..……..……………………. Fax No: …………..………..…………………….

Section 2: Building and its Components

A. Walls and Roof

1. **Components of Wall System Assembly. (Specify Below)**				
Component Name		Thickness mm	Component Name	Thickness mm
2. Exterior Color	☐ Light		☐ Medium	☐ Dark
3. **Components of Roof System Used. (Specify Below)**				
Component Name		Thickness mm	Component Name	Thickness mm
4. Exterior Color	☐ Light		☐ Medium	☐ Dark
5. Material of Flooring Used		☐ Marble		☐ Ceramic Tiles
☐ Floor with Carpet		☐ Others ………………………………………………………		

B. Fenestration

	Glass Material S-D-T-RC	Interior Shading C-B-N-O	Exterior Overhang		Exterior Fins		Total Glazing Area (m^2)	
			Depth	Width	Depth	Height	Side	Top
Orientation-1								
Orientation-2								
Orientation-3								
Orientation-4								
Orientation-5								
Skylight								

S-D-T-RC	S-Single Pane	D-Double Pane	T-Tinted	RC-Reinforced
C-B-N-O	C-Curtain	B-Blinds	N-No Shading	O-Others

C. Exterior Doors

	No. of Doors on each Face	Door Material	Type of Door R-D-S-SP-O	Dimensions of each Door (m)
Orientation-1				
Orientation-2				
Orientation-3				
Orientation-4				
Orientation-5				

R-D-S-SP-O	R-Revolving	D-Dual Panel	S-Sliding	SP-Single Panel
	O-Other Types			

D. Operation of the Facility

Day Time/Seasons	Summer	Winter	Ramadhan
Morning - Start Time			
End Time			
Evening - Start Time			
End Time			

E. Infiltration Rate

1. Infiltration rate predicted during design …………………………………………….ACH

Section 3: Building Systems

A. Lighting and Electrical System

1. Average Power Density (lighting load) used in the Building in different zones during occupancy ……………………………W/m^2				
2. Schedule of Lighting all round the year (Summer/Winter/Ramadhan)				
Morning (% of Total Density)	Evening (% of Total Density)	Unoccupied Periods		
…………………………………	…………………………………	…………………………………		
3. Average Equipment (Computer-Photocopy Machine-Printer) Load Density used in the Building in different zones during occupancy ..…………………W/m^2				
4. Schedule of Equipment all round the year. (Summer/Winter/Ramadhan)				
Morning (% of Total Density)	Evening (% of Total Density)	Unoccupied Periods		
…………………………………	…………………………………	…………………………………		
5. Is there a mechanism for reducing lighting energy consumption in the presence of daylight? If yes specify the mechanism below			☐ Yes	☐ No
☐ Dimming	☐ ON/OFF	☐ OFFand ON 50%		
☐ Other specify ………………………………………………………………………………………..				
6. Percentage of floor area lit by daylight ....%				

B. HVAC System

1. Type of HVAC System……………………………………………………………………………			
2. Operation of the HVAC System			
Day Time/Seasons	Summer	Winter	Ramadhan
Morning - Start Time			
Evening - End Time			
3. Thermostat Management for all year round			
Morning (Set point Temperature ^oC)	Evening (Set Point Temp. ^oC)	Unoccupied Periods (Temp. ^oC)	
4. Supply Fan Type			
☐ Const. High Efficiency 2 in.	☐ Vane 4 in. Med Efficiency	☐ Vane 6 in. Med Efficiency	
☐ VSD 6 in. High Efficiency	☐ Others Specify ……..……………………………………………		

5. Rated Fan Flow ………………..cfm.		
6. Fan Control during Operation	☐ Constant Volume	☐ Inlet vanes
☐ Cycle with Load	☐ Variable Speed	☐ Other ……………………..
7. Cooling Coil Types		
☐ DX Low Efficiency	☐ DX Medium Efficiency	☐ DX High Efficiency
☐ Water Coils	☐ Others ………………………………………………………..	
8. Supply Temperature …………………...….^{o}C	Sensible Capacity ……………………..………KW	
Total Coil Capacity …………………………KW	Coil Bypass Factor ……………………………..	
9. Maximum allowed RH of supply air …………………………………..%		
10. Heating Coil Types		
☐ Furnace Low	☐ Furnace High	☐ Heat Pump Low
☐ Heat Pump High	☐ Coils	☐ Others Specify……………………………….
11. Supply Temperature …………………………….		
12. Sources of heating	☐ Electric Resistance	☐ Hot water from Plant
☐ Electric Heat Pump	Others Specify…………………………………	
If heating is supplied from heat pump the answer the queries below………………………………		

13. Heat Pump Types	☐ Electric	☐ Medium Efficiency	☐ High Efficiency
☐ Electric Pumper	☐ Other Specify ……………………………………………………………		
14. Shut-Off Temperature for Heat Pump ………………….			
15. Control of HP	☐ On-Demand	☐ Timed	Others ………………………………

C. Central Plant

1. Type of Chillers used	☐ Electric Chillers		☐ Absorption Chillers	
2. Number of Electrical Chillers				
☐ None	☐ One	☐ Two	☐ Three	☐ Four
3. Size of Each Chiller …………………………..				
4. Chilled Water Supply Temp………………. ^{o}C		Entering Condenser Water Temp …… ^{o}C		
5. Designed Outdoor Dry Bulb Temperature for Air Cooled Chillers ………………………………. ^{o}C				
6. Full Load Efficiency at Reference conditions ……………………………………………KW/ton				
7. Part Load Efficiency at Reference conditions ……………………………………………KW/ton				
8. Absorption Chiller Types	☐ Single Stage		☐ Two Stage	
9. Number of Absorption Chillers				

☐ None	☐ One	☐ Two	☐ Three	☐ Four
10. Size of Each Chiller …………………………..				
11. Eclectic Energy Usage ………………………..KW/ton				
12. Water Cooled Condenser Cooling Tower Types				
☐ High Efficiency Air Cooled	☐ Open Low Efficiency		☐ Open High Efficiency	
☐ Closed Medium Efficiency	☐ Closed High Efficiency		Others ……………………….	
13. Cells in Cooling Tower	☐ Yes	☐ No	Number of Cells……………	
14. Control of Cooling Tower	☐ Minimum Cell Needed		☐ Maximum Cells Available	
15. Sizing of Cooling Tower				
Design WBT ……………… ^oC	Approach Temp …..……... ^oC		Design Range ….….…… ^oC	
16. Temperature Control in CT	☐ Fixed Temperature		☐ Wet Bulb Reset	
17. Capacity Control of CT	☐ One-Speed Fan		☐ Two Speed Fan	
☐ Variable Speed Fan	☐ Fluid Bypass		☐ Other ……………………	

Section 4: Operation

A. Occupancy

1. Maximum Number of People…………………					Occupancy Density………………… Persons /m^2						
2. Percentage of Occupancy during Weekdays											
Morning (% of Total Occupancy)					Evening (% of Total Occupancy)						
1st (Hour)	2nd	3rd	4th	5th	1st	2nd	3rd	4th	5th	6th	7th
3. Percentage of Occupancy during Weekends											
Morning (% of Total Occupancy)					Evening (% of Total Occupancy)						
1st	2nd	3rd	4th	5th	1st	2nd	3rd	4th	5th	6th	7th
4. Percentage of Occupancy during Ramadhan											
Morning (% of Total Occupancy)					Evening (% of Total Occupancy)						
1st	2nd	3rd	4th	5th	1st	2nd	3rd	4th	5th	6th	7th
5. Unoccupied Number of Days per year…………………………………….………….…days											

B. Ventilation

1. Ventilation Rate…………………………..………………….……………………………L/s/person		
2. Ventilation Schedule Management for all year round		
Morning (% of Total Outdoor Air)	Evening (% of Total Outdoor Air)	Unoccupied Periods (% of Total Outdoor Air)

C. Energy Consumption- Peak Load

1. Annual Energy Consumption……………………………………………………………..KW	
2. Peak Cooling Load………………….KW	Peak Heating Load………………………KW
3. Peak Cooling Demand………………KW	Peak Heating Demand…………………...KW

D. Actual Space Conditions (Measurements)

Parameters / Day Time	Morning	Evening
Temperature (^oC)		
Air Velocity (m/s)		
Relative Humidity (%)		

For any additional comments……………………………………………………………….............

………………………………………………………………………………………….……………..........

………………………………………………………………………………………….………………...

………………………………………

Thermal Comfort Analysis

The main objective of this survey is to gain insight of the existing thermal comfort conditions as experienced by the building users in shopping malls

Section 1: General Information (معلومات عـــامة)

Name: …………………………………….. الإسم: ....
Location ……………………………….. المكان: ....

Job Title ………………………………….. الوظيفة: ....
Age …………… Date ……………… العمر: .... التاريخ: ....
Working Since ……………………………………… تاريخ الإلتحاق بالعمل: ....

Section 2: Thermal Comfort (الراحة الحرارية)

1. How do you feel during working hours? 1. كيف تشعر خلال العمل؟

☐ Cold ☐ Hot ☐ Warm ☐ بارد ☐ حار ☐ دافيء
☐ Comfortable ☐Slightly Cool ☐ مرتاح ☐ بارد قليلاً

2. What period of year is most thermally uncomfortable? 2. متى تكون الحرارة غير مقبولة؟

☐ Summer ☐ Winter ☐ All Year ☐الصيف ☐ الشتاء ☐ كل العام

3. Thermally uncomfortable during summer relates to and at what time 3. خلال الصيف، في أي وقت تكون فيه الحرارة غير مقبولة؟

☐ Every day ☐ Most time ☐ Few days ☐كل يوم ☐كل يوم ☐بعض الأيام

☐ All day ☐ Early morning ☐ Late afternoon ☐كل اليوم ☐الصباح الباكر ☐بعد الظهر

4. Do you think relative humidity (moisture) to be acceptable within your workplace 4. هل تظن أن نسبة الرطوبة في مكان العمل مقبولة؟

☐ Strongly Disagree ☐ Disagree ☐ أعارض بقوة ☐ أعارض
☐ Strongly Agree ☐ Agree ☐ أوافق بقوة ☐ أوافق

5. Is the flow and air sufficient with comfortable velocity and direction? 5. هل كمية وإتجاه تدفق الهواء مناسبة ؟

☐ Strongly Agree ☐ Agree ☐ أوافق بقوة ☐ أوافق
☐ Disagree ☐ Strongly Disagree ☐ أعارض ☐ أعارض بقوة

6. In what range does your metabolic rate (activity level) fall? 6. ما هو تقييمك لنشاطك الحركي ؟

☐ Low ☐ Medium ☐ Heavy ☐ قليل ☐ وسط ☐ كثير

7. What type of clothing do you normally prefer? 7. ما نوع الملابس التي ترتديها في معظم الأحيان؟

☐ Typical Saudi dress	☐ Heavy (Woolen)	☐ سعودي تقليدي	☐ سعودي تقليدي
☐ Medium	☐ Light weight	☐ وسط	☐ وسط

8. Is there any opening into your workplace from outside? (window or skylight)

8. هل هناك فتحة تطل على الخارج في مكان العمل (نافذة أو فتحة سقف)؟

☐ Yes ☐ No ☐ لا ☐ نـــــعـــــم

9. Do you make use of fan whenever you feel uncomfortable?

9. هل تستخدم المروحة في حالة عدم الراحة (من الناحية الحرارية)؟

☐ No ☐ Occasionally ☐ Always ☐ دائماً ☐ أحيانا ☐ لا

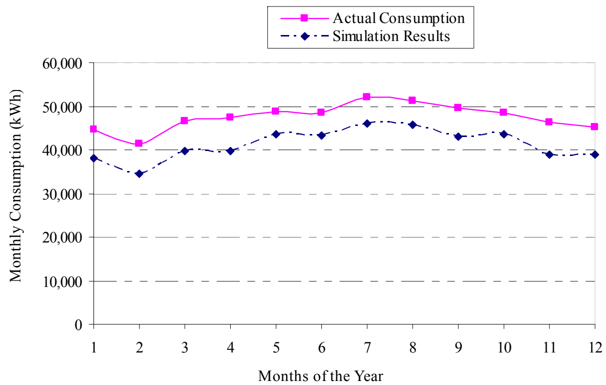
10. How do you feel upon use of fan for attaining thermal comfort?

10. كيف تشعر عندما تستخدم المروحة من أجل تلطيف الحرارة ؟

☐ Comfortable ☐ Partially Satisfied ☐ مرتاح قليلاً ☐ مرتاح

Appendix – B: Monthly Energy Consumption Comparison

Simulated Vs. Actual of Al-Waha Shopping Centre



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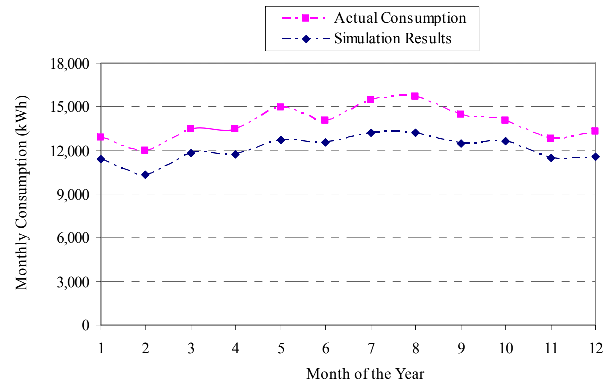

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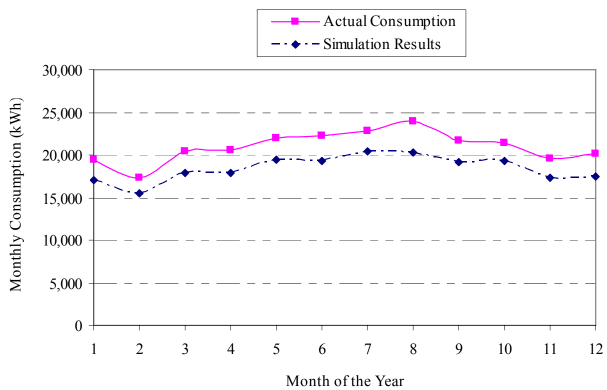

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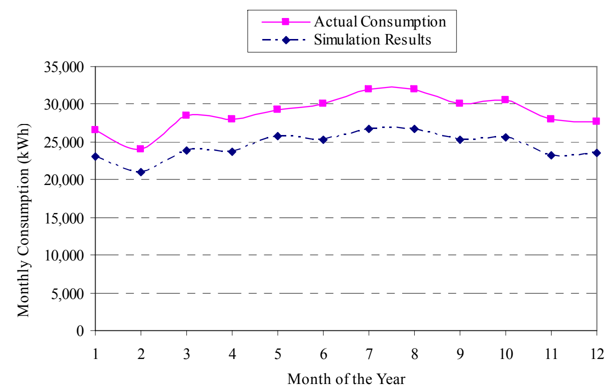


(d)

Figure B.1 Comparison of Ground Floor Zones Monthly Consumption Simulated Vs. Actual; (a) Zone-I, (b) Zone-IV, (c) Zone-V, (d) Zone-VIII

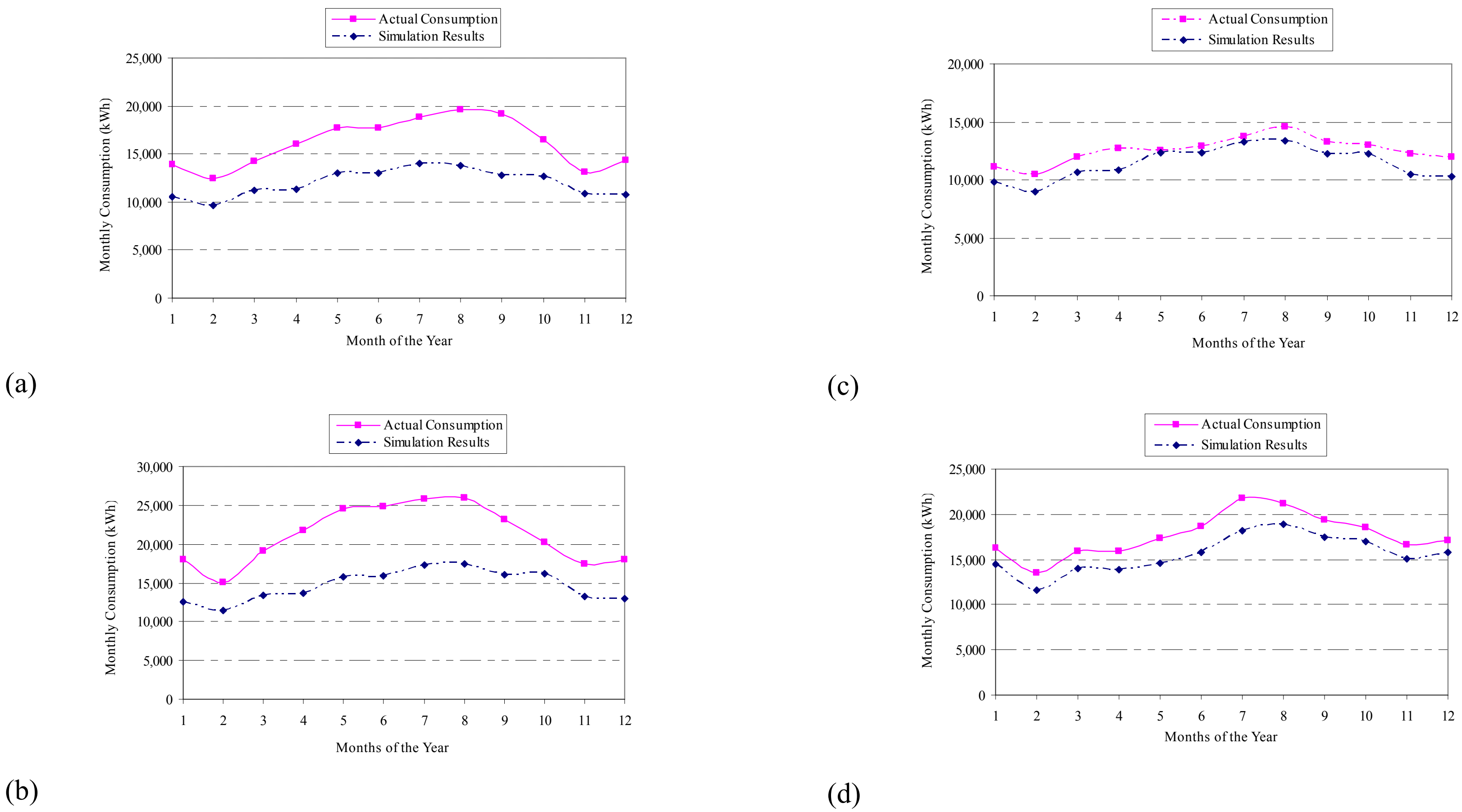
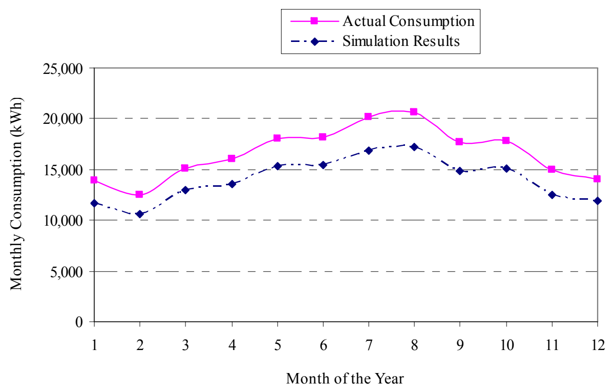
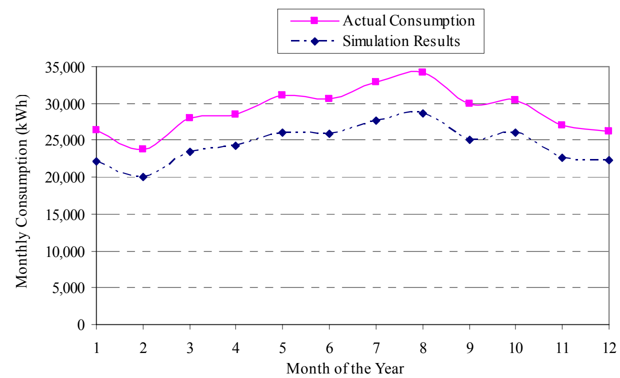


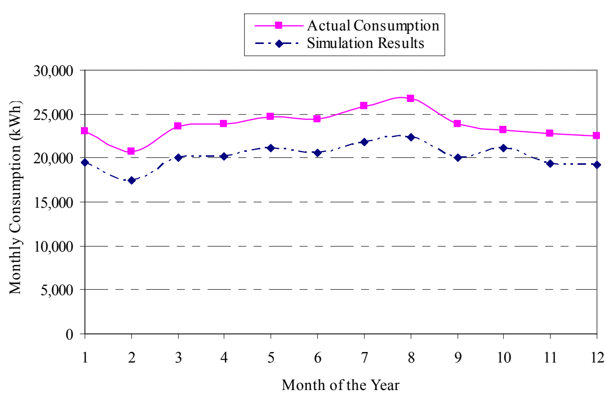
Figure B.2 Comparison of First Floor Zones Monthly Consumption Simulated Vs. Actual; (a) Corridor-I, (b) Corridor-III, (c) Zone-II, (d) Zone-V



(a) Zone-I



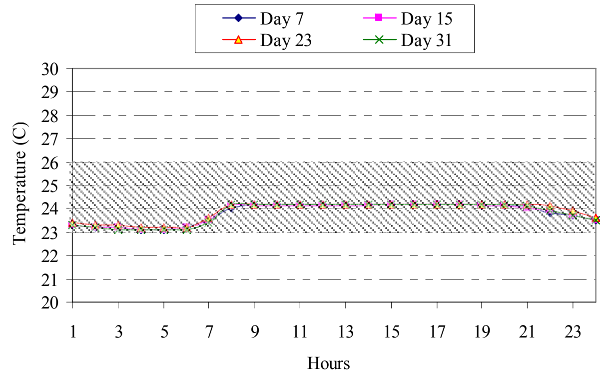
(c) Zone-VI



(b) Zone-IV

Figure B.3 Comparison of Second Floor Zones Monthly Consumption Simulated Vs. Actual; (a) Zone-I, (b) Zone-IV, (c) Zone-VI

Appendix – C: Daily Profile Operative Temperature for Various Zones and different Months



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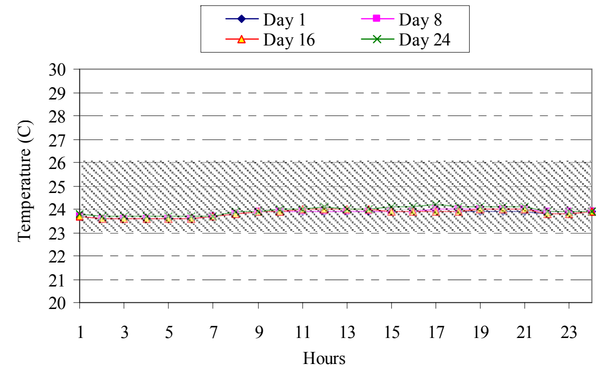
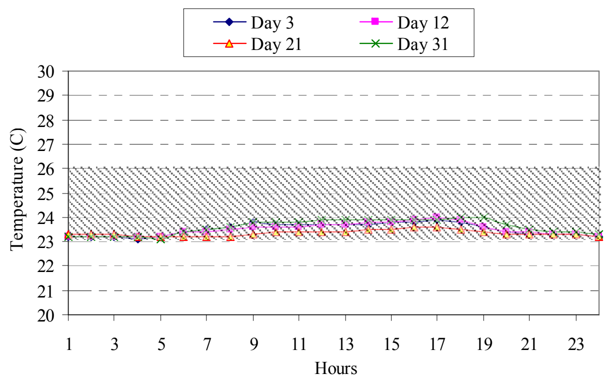
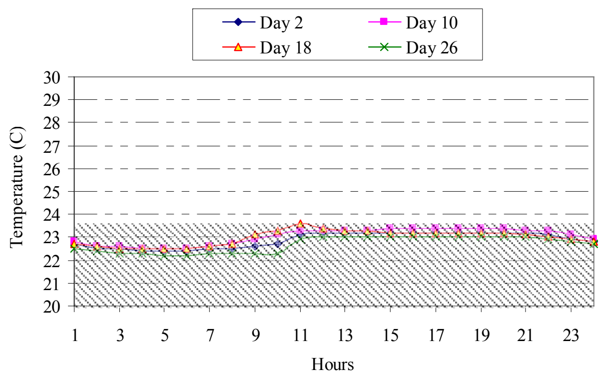


(c)

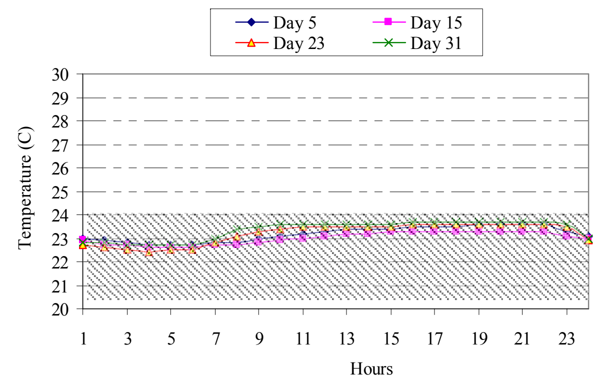


(b)

Figure C.1 Daily Profile of Operative Temperature in July after Implementation of ECM # 1: (a) Restaurants, (b) Office Area and (c) Shopping Area



(a)



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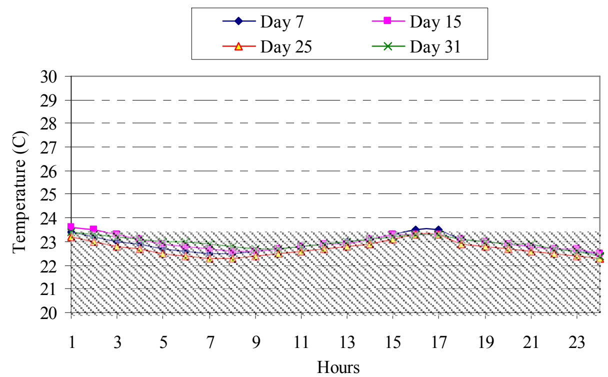
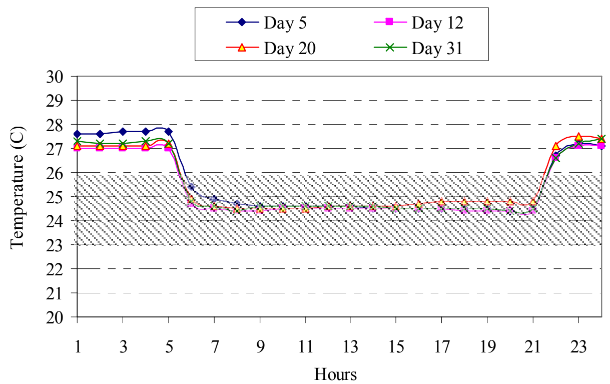


(b)

Figure C.2 Daily Profile of Operative Temperature in December after Implementation of ECM # 1: (a) Restaurants, (b) Office Area and (c) Shopping Area



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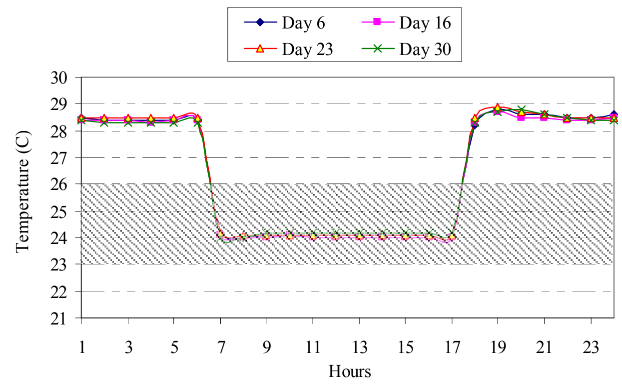

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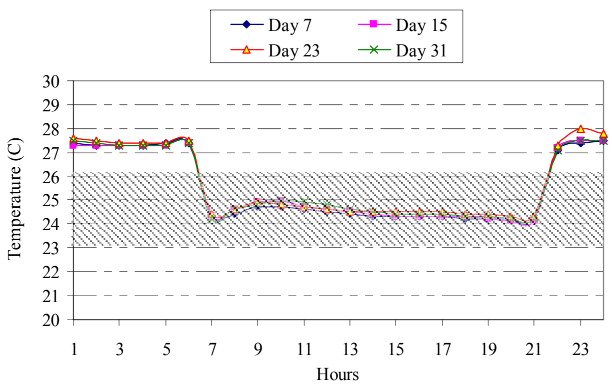
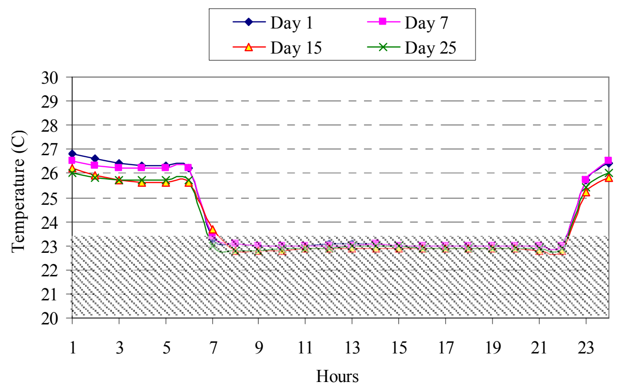


(b)

Figure C.3 Daily Profile of Operative Temperature in July after Implementation of ECM # 1 and ECM # 2: (a) Common Areas, (b) Restaurants and (c) Office Area



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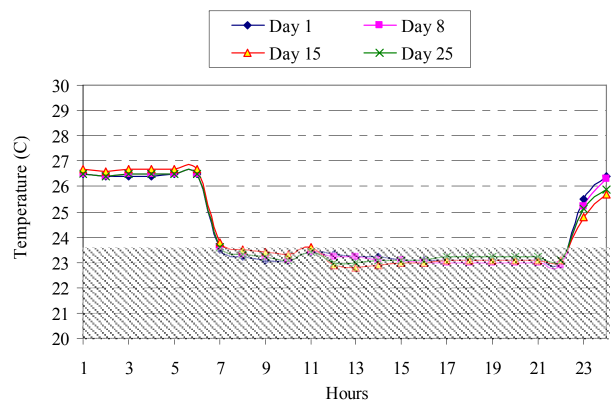

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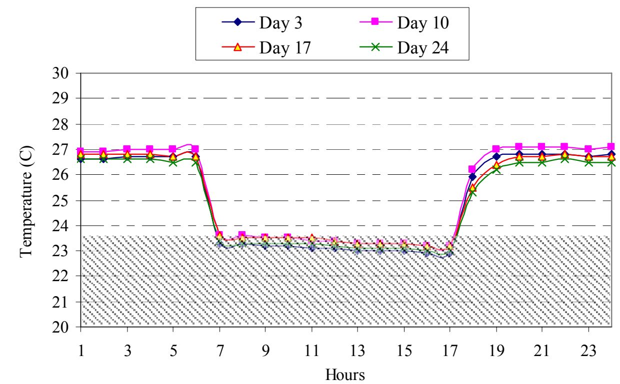
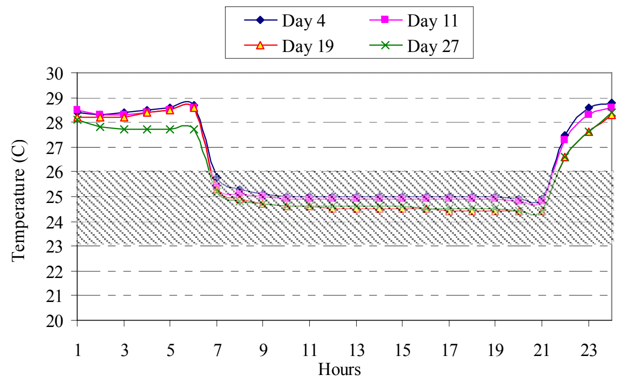


(c)

Figure C.4 Daily Profile of Operative Temperature in January after Implementation of ECM # 1 and ECM # 2: (a) Common Areas, (b) Restaurants and (c) Office Area



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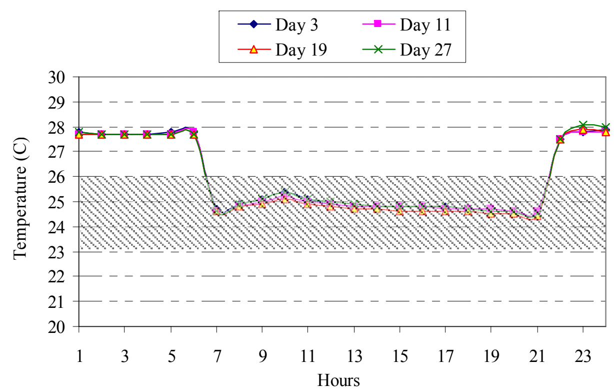

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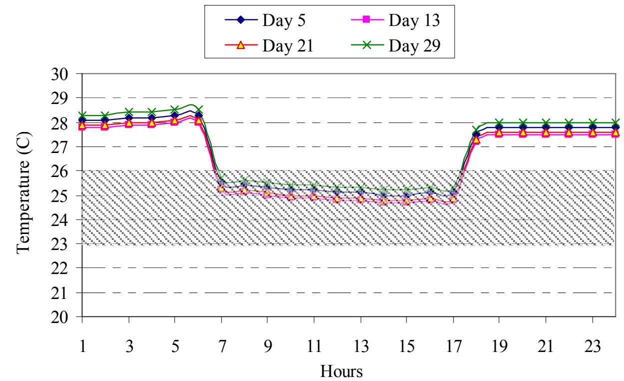


(c)

Figure C.5 Daily Profile of Operative Temperature in July after Implementation of ECM # 1 and ECM # 3: (a) Common Areas, (b) Restaurants and (c) Office Area

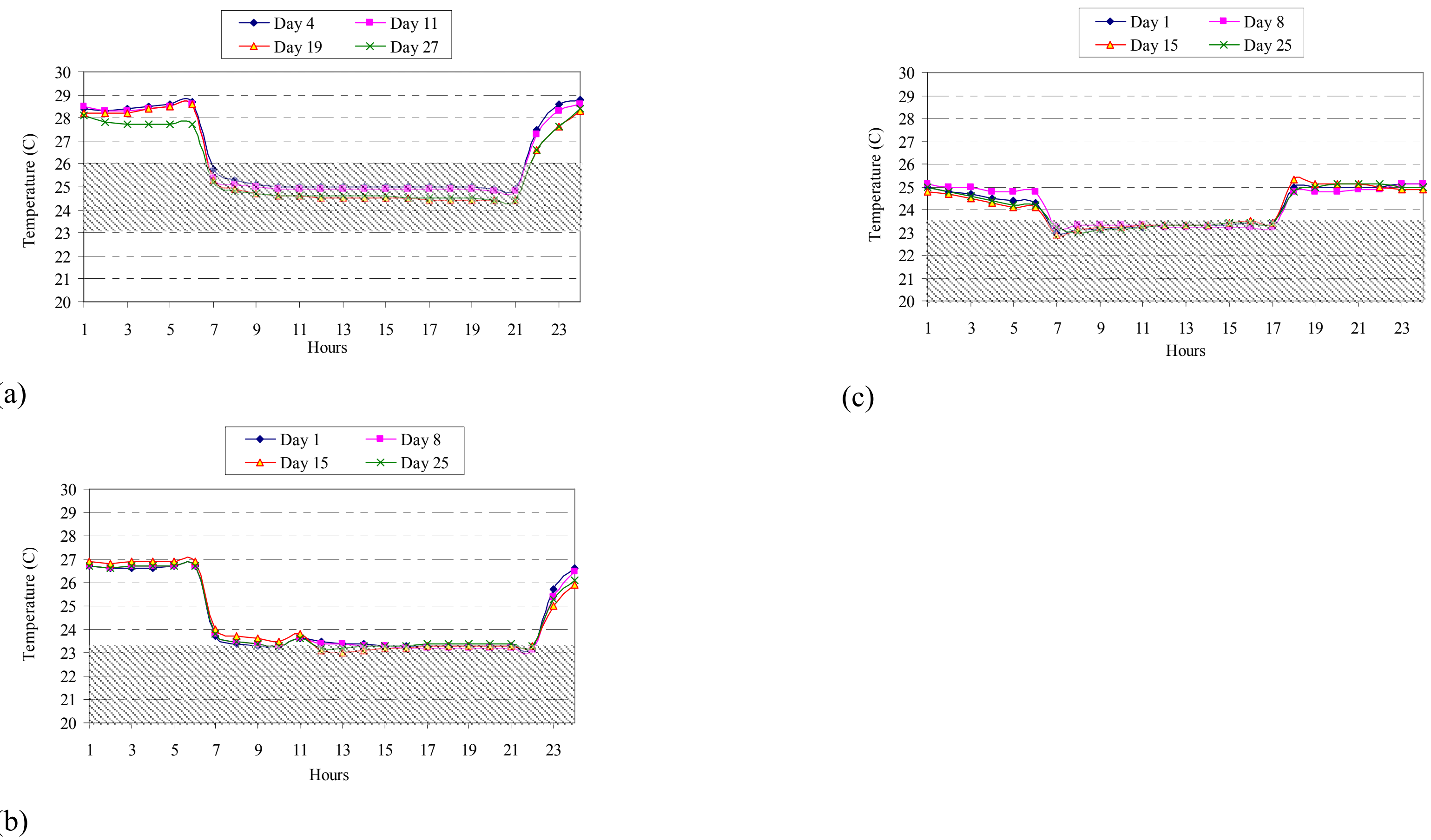
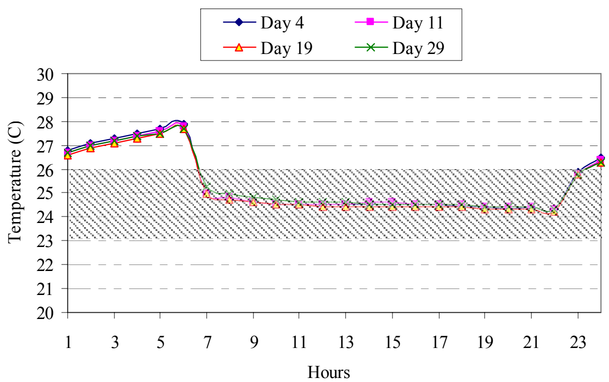


Figure C.6 Daily Profile of Operative Temperature in December after Implementation of ECM # 1 and ECM # 3: (a) Common Areas, (b) Restaurants and (c) Office Area



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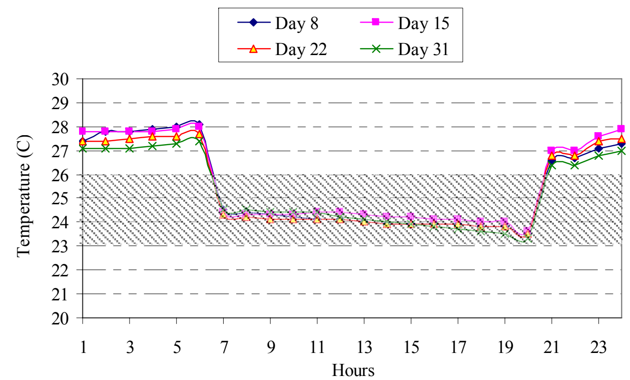

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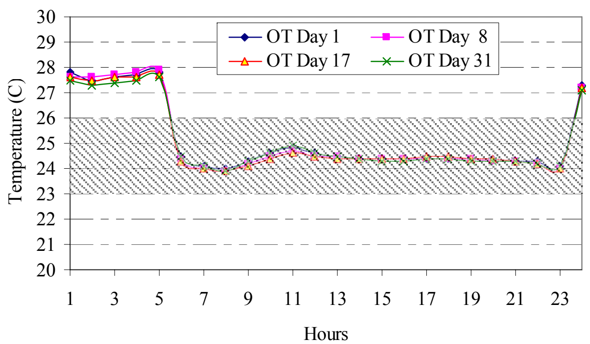
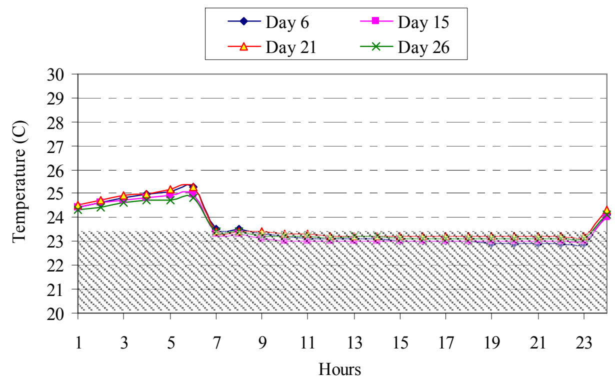
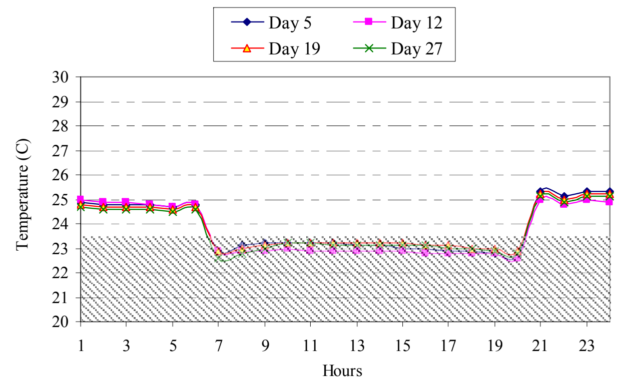


(b)

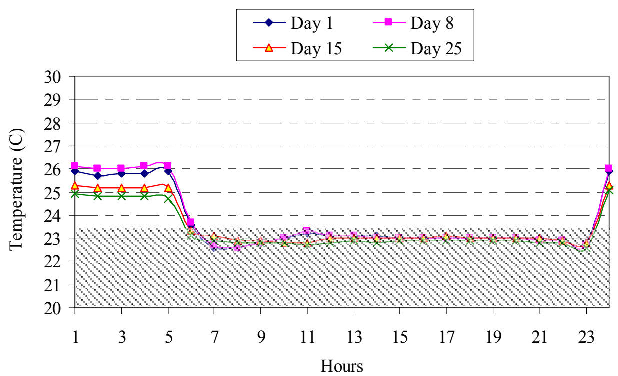
Figure C.7 Daily Profile of Operative Temperature in July after Implementation of ECM # 1 and ECM # 4: (a) Common Areas, (b) Restaurants and (c) Office Area



(a)

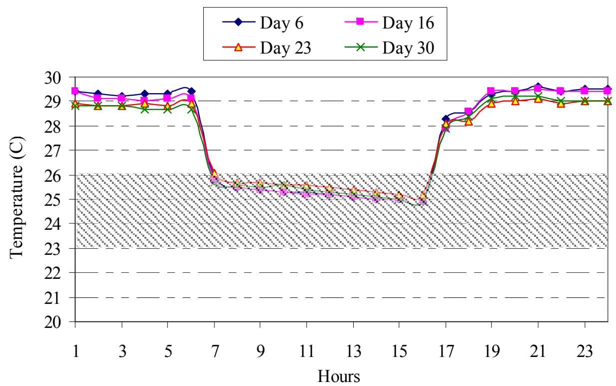


(c)

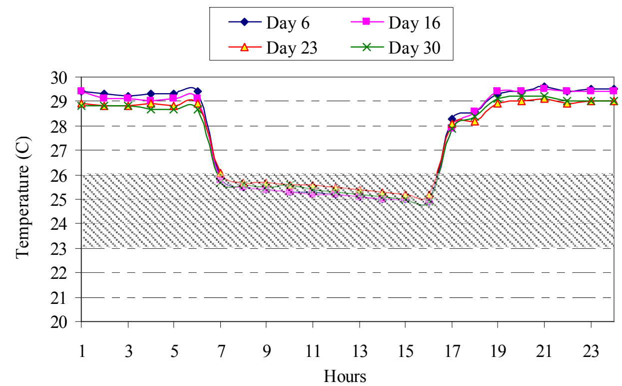


(b)

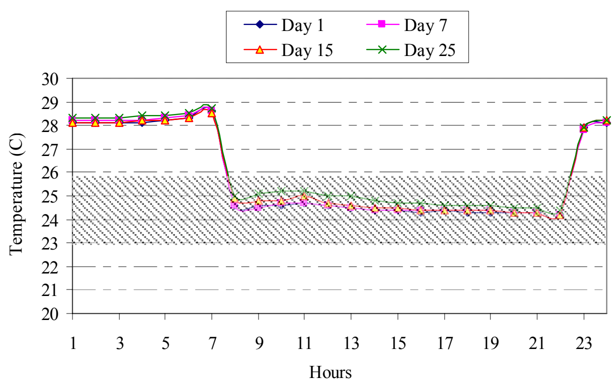
Figure C.8 Daily Profile of Operative Temperature in December after Implementation of ECM # 1 and ECM # 4: (a) Common Areas, (b) Restaurants and (c) Office Area



(a)

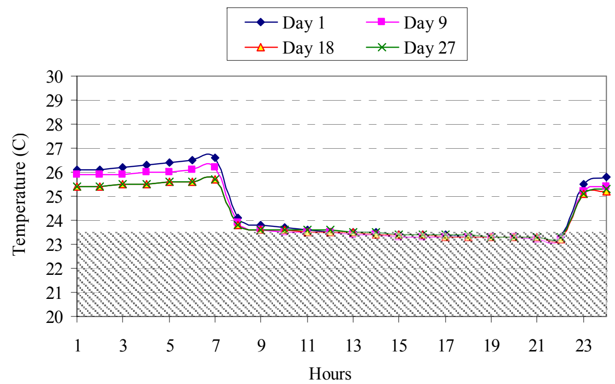


(c)

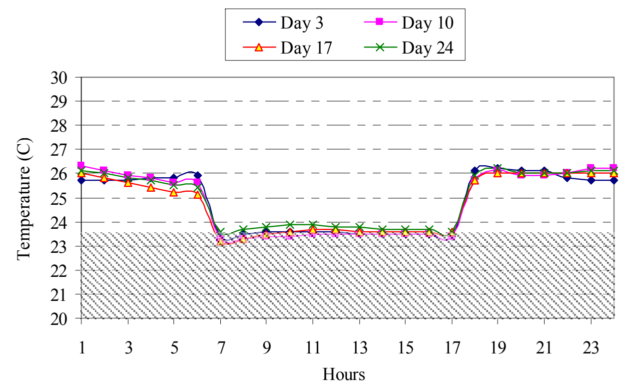


(b)

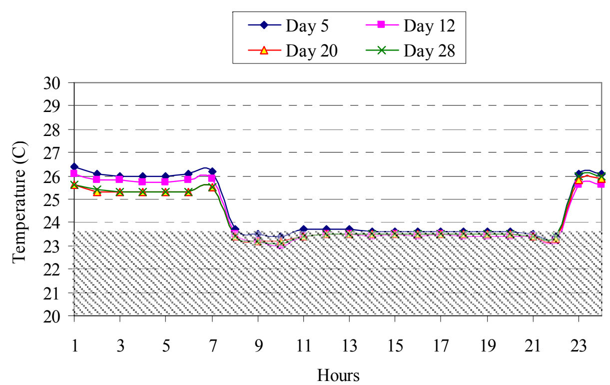
Figure C.9 Daily Profile of Operative Temperature in July after Implementation of ECM # 1 and ECM # 5: (a) Common Areas, (b) Restaurants and (c) Office Area



(a)



(c)



(b)

Figure C.10 Daily Profile of Operative Temperature in January after Implementation of ECM # 1 and ECM # 5: (a) Common Areas, (b) Restaurants and (c) Office Area

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