IMPACT OF BUILDING REZONING AND CHANGE OF USE ON ENERGY CONSUMPTION AND OCCUPANTS THERMAL COMFORT

BY

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THESIS ABSTRACT

NAME OF STUDENT	:	**KHURSHID ALAM SIDDIQUI**
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This thesis presents a study on the impact of building rezoning and change of use on energy consumption and occupants' thermal comfort. Most buildings are subjected to a change in function as well as modifications in partitions layout, which normally impacts space thermal loads. The architectural and structural drawings and interior layouts are normally reviewed during modification planning but the suitability of the HVAC system to the required alterations is normally neglected. This usually causes numerous problems, such as poor air distribution and balancing, which results in thermal discomfort and unacceptable indoor air quality. Additionally, these modifications affect building energy consumption if proper HVAC design and thermal rezoning are not considered accordingly.

In this research, building – 19 at King Fahd University of Petroleum & Minerals (KFUPM) is taken as a case study. The original building layout was changed by partitioning the large design studios into classrooms and offices at various locations in the building. Quantitative and qualitative analyses were carried out to assess the impact of imposed modifications on occupants' thermal comfort, while the study of building energy consumption was performed through building energy analysis. The thermal comfort qualitative analysis was performed through occupants' responses obtained by distributing questionnaire, while the quantitative analysis was conducted by measuring the temperature and relative humidity at various places in the building. DOE – 2.1D energy analysis software was used for the calculations of building energy consumption. In this work, a systematic approach for building HVAC system retrofitting is proposed. This approach can be very useful in planning of building retrofit projects, to ensure proper HVAC system design that will maintain the required thermal comfort with minimum possible energy use.

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ملخص الرسالة

اسم الطالب : خورشيد علم صديقي
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تقدّم هذه الرسالة دراسة عن تأثير تغيير تصميم و استخدام المبنى على إستهلاك الطاقة والراحة الحرارية للمستخدمين. فمعظم المباني تخضع إلى تغيير في الوظيفة بالإضافة إلى تعديلات في تقسيماتها الداخلية ، الأمر الذي يؤثر طبيعياً على الحمل الحراري لها. وعادة ما تتم مراجعة الرسومات المعمارية والهيكلية والمخططات الداخلية أثناء مرحلة التخطيط لإجراء تعديلات في المبنى، و لكن تهمل اعتبارات ملاءمة نظام التكييف (HVAC) للتعديلات الجديدة، وهذا يسبّب مشاكل عديدة، مثل سوء توزيع الهواء، مما يؤدّي إلى تدني مستوى الراحة الحرارية للمستخدمين وكذلك رداءة نوعية الهواء الداخلي للمبنى. إضافةً إلى ذلك، فإن هذه التعديلات تؤثر على الطاقة المستهلكة لتشغيل المبنى إذا لم يؤخذ في الاعتبار إعادة تصميم نظام التكييف والتقسيمات الحرارية للمبنى في ضوء هذه التعديلات.

في هذا البحث، تم اختيار مبنى - 19 في جامعة الملك فهد للبترول والمعادن كحالة دراسية (Case study). حيث تعرّض المبنى إلى تغيير التقسيم الداخلي لمعامل الرسم الكبيرة الى فصول دراسية و مكاتب بواسطة فواصل في مواقع مختلفة من المبنى. وفي هذه الدراسة تم القيام بتحليلات كمّية ونوعية لتقييم تأثير تعديل المبنى على الراحة الحرارية للمستخدمين. حيث تمت دراسة التحليل النوعي من خلال إجابات المستخدمين على استفتاء لتقييم الراحة الحرارية، بينما أُجري التحليل الكمّي بقياس درجة الحرارة والرطوبة النسبية في مواقع مختلفة من المبنى. كما تم استخدام برنامج (DOE-2.1D) لتحليل الطاقة في حسابات استهلاك المبنى للطاقة حسب تصميمه الأصلي مقارنة بالتعديلات التي أجريت عليه. وقد أثبتت النتائج وجود تأثير سلبي لإجراء تعديلات على المبنى وذلك على الراحة الحرارية للمستخدمين وعلى مقدار استهلاكه للطاقة وذلك في غياب إجراء التعديلات اللازمة على نظام التكييف ليتوافق مع هذه التعديلات. كما خلص البحث إلى تطوير أداة سهلة ومبسطة يمكن الاستعانة بها من قبل المصممين لتتبع الخطوات اللازمة عند إعادة تأهيل أي مبنى لضمان جودة الراحة الحرارية فيه باستخدام أقل قدر ممكن من الطاقة لتشغيله.

درجة الماجستير في العلوم
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CHAPTER-1

INTRODUCTION

1.1 BACKGROUND

The function of a building is always an important consideration during the design process. There are many types of buildings like residential, commercial and academic facilities, which have their own special features. For example, in a typical school we have classrooms, faculty rooms and assembly areas, while residential and commercial buildings normally don't have these features. When there is a need to change the use of a building certain complications arise because of particular areas and spacing. Therefore, good engineering skills and efficient planning are needed to incorporate these changes.

The change in the usage of a building may require major alteration in its layout, physical zoning and its services. For maintaining similar indoor environmental quality, as per original design, these alterations must be planned and executed properly. Modifications in physical parameter of a building complicate the comfort issue due to the involvement of an array of interlinked elements. In order to support any modification in the usage of a building and/or its physical rezoning, a pre-analysis of the building's facilities and system is very essential.

The energy usage of a building varies according to its function and use. Power and air conditioning equipment are selected to meet the peak demand. Unexpected variations in peak demand may cause serious problems like poor air distribution and improper cooling. Therefore, it is always wise to take every possible change into consideration during the design stage. Moreover, as mentioned earlier, good engineering skills and efficient planning can minimize magnitude of the inner environmental problems.

1.2 STATEMENT OF THE PROBLEM

Most buildings are subjected to a change in function as well as modifications in partition layout, which normally impacts space thermal load. The architectural and structural drawings and interior layouts are normally reviewed during modification planning but the suitability of HVAC system to the required alterations is normally neglected. This usually causes numerous problems, such as poor air distribution and balancing, which results in thermal discomfort and unacceptable indoor air quality. Additionally, these modifications affect building energy consumption if proper HVAC design and thermal rezoning are not considered accordingly.

Change of space usage and an alteration in the building's partitioning system normally add more heat generating sources. To achieve a desired comfort condition, higher capacity cooling equipment might be required. The installation of higher capacity equipment may require updating of the ducting system, piping system and other architectural adjustments. Furthermore, installation of higher capacity equipment not only increases the cost of modification but also increases the monthly utility bills. Even if an increase in the building's internal cooling load does not demand additional equipment, this increase will at least raise the building energy use.

The aim of this research is to study the impact of change of use and physical rezoning of a building on its occupants' thermal comfort and on the associated building energy requirements. Possible remedies to problems linked with such changes are suggested. In this research, building – 19 at King Fahd University of Petroleum and Minerals (KFUPM), is taken as a case study. The original building layout was changed by partitioning the large design studios into classrooms and offices at various locations in the building. In this work, quantitative and qualitative analyses were carried out to assess the impact of building's modification on occupants' thermal comfort. While the study of building energy consumption was performed through building energy analysis.

1.3 RESEARCH OBJECTIVES

The objectives of this research are as follows:

I). To assess the impact of the building's physical rezoning and change of use on occupants thermal comfort,

II). To assess the impact of the building's change of use on energy consumption,

III). To develop design guidelines and recommendations for the building's physical rezoning and change of use to ensure thermal comfort at minimum energy requirements.

1.4 SCOPE AND LIMITATIONS

The aim of this research study is to evaluate the impact of building's physical rezoning and change of use on occupants' thermal comfort and energy consumption. Being subjected to major modification and change of use, and building 19 being an accessible building 19 at KFUPM which houses the college of Environmental Design is selected as a case study.

In assessing thermal comfort qualitative analysis was performed through occupants' responses, obtained by distributing questionnaire, while quantitative analysis was conducted by measuring the temperature, relative humidity and supply airflow. In assessing energy consumption and the impact of change of use DOE – 2.1D energy analysis software was used for calculations of the building energy consumptions. By using thermal zones of the building, energy simulations were performed both as per original and existing design and usage of the building

1.5 RESEARCH METHODOLOGY

In this section, different phases of this research are outlined. A flowchart of the research methodology is shown in Figure 1.1.

1.5.1 Phase I: Literature Review

Literature review is a process that not only sets the target of a research project or study but also helps to find out the state of the art and latest findings of the particular area. For this reason, literature in this subject and related fields was thoroughly reviewed. Experiences of various researchers in the subject were analyzed and utilized throughout the course of this research.

1.5.2 Phase II: Facility Energy Audit

In Phase II, energy audit of building – 19 at KFUPM was performed. The building was selected due to a number of modifications, which had been carried out in its original design, and also due to easy accessibility and familiarity. Since the partition layout of this building was not updated, hence existing partition layout was developed by site visits and physical measurements. Comparisons were made between the original design and existing partition layouts. To improve the quality of work, energy audit charts designed by ESD (Elite Software Development, interfaced designers of EZDOE software, which is used in the current study) were used; the audit charts are shown in Appendix C. All the data required for simulation were gathered as per thermal zones of the building under study. Thermal zones of the building are shown in Appendix Figures A5 and A6.

1.5.3 Phase III: Thermal Comfort Analyses

The objective of thermal comfort analyses was to evaluate the comfort conditions qualitatively and quantitatively. In this study, two types of comfort analyses were performed:

- Distribution of questionnaires to assess comfort status of the occupants
- Monitoring of environmental parameters (i.e., temperature, humidity) and supply airflow to correlate comfort status with occupants responses.

1.5.3.1 Questionnaire Analysis

To assess the feeling of the occupants regarding thermal conditions of the building, the survey was conducted twice. Once during August and second during October. Detailed description of the objectives and content of the questionnaire are mentioned in Section 5.5.

1.5.3.2 Data Monitoring Of Environmental Parameters

The objective of measuring environmental parameters, like temperature and humidity was to collect the data for quantitative analysis of thermal comfort in the building. This process was conducted twice: the first time during the month of August for a week and the second time during the month of October for a period of two weeks. Plots of the temperature and humidity profiles were drawn, and are discussed Section 5.3. Airflow measurements were also conducted using a hood type air flow meter. The measurements were conducted in every room where temperature and humidity measurements were logged.

1.5.4 Phase IV: Energy Simulations

The objectives of the energy simulations were as follows:

- To calculate building energy consumption both as per its original and existing design and usage.

- To estimate building peak cooling load and the required supply airflow to meet the existing demand of the building.

Energy analysis was performed by using DOE-2.1 D energy analysis software. All information required by the DOE-2.1D was collected in the facility energy audit phase.

1.5.5 Phase V: Data Analyses

In the final phase of this study, results of the building's energy and comfort analyses were compared were analyzed. Conclusions are derived and recommendations are suggested. Finally, on the basis of experience gained from this study, a systematic approach for a future retrofitting project is generated.

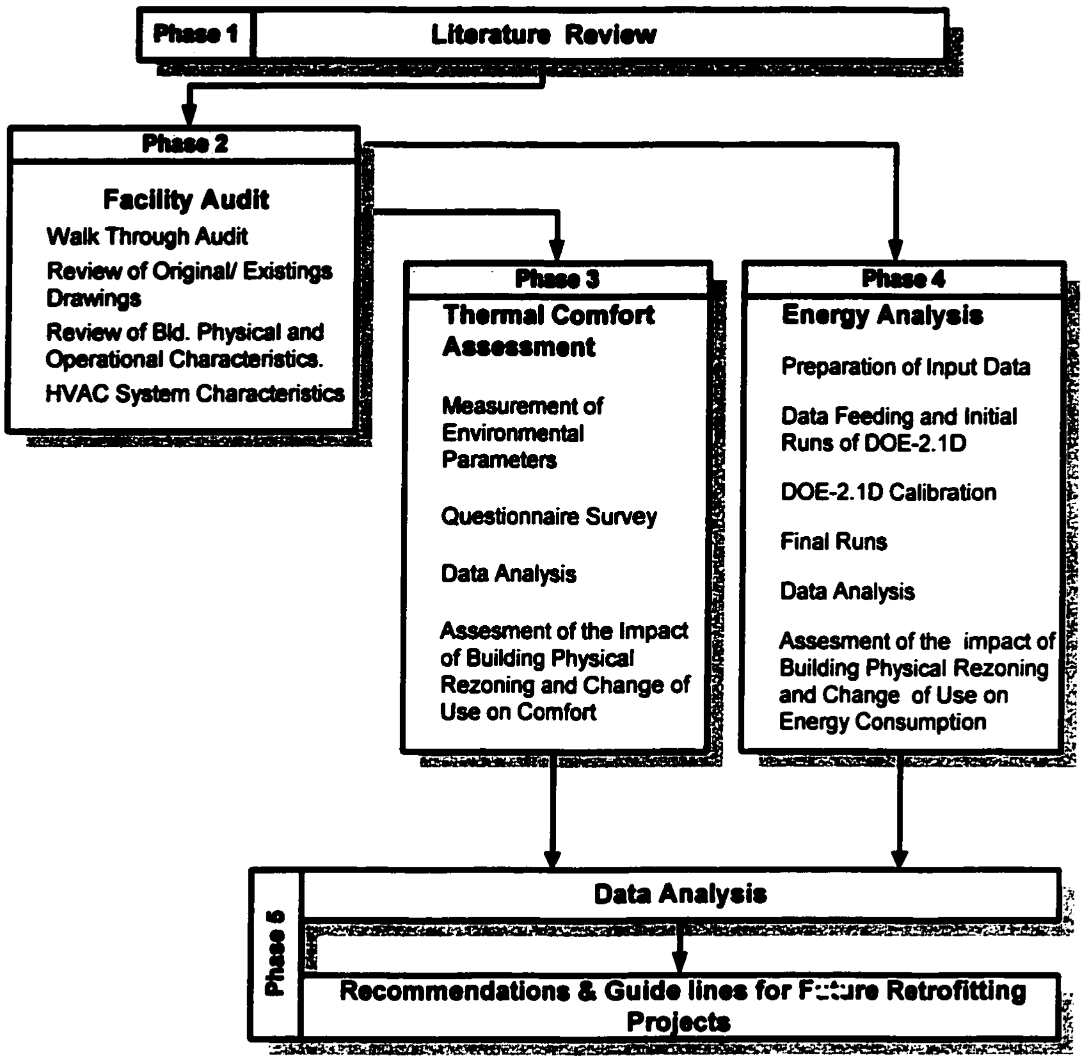


Figure 1.1 : Flow Chart of the Research Methodology

CHAPTER-2

LITERATURE REVIEW

2.1 GENERAL

The basic function of buildings has always been to shelter humans from the elements of nature while at the same time to provide thermally and visually comfortable indoor conditions. Comfort has been a main criterion in design of all types of buildings that house people.

Modern buildings are made more comfortable than earlier buildings by using various systems such as lighting, heating and air conditioning. However, these comfort conditions require more energy than earlier ones. Theoretically this should lead to better design and energy efficient buildings as compared to earlier designs.

There are always chances of improvement in building's systems (e.g., lighting, heating and air conditioning). Building evaluation is a continuous process; it should be carried out during pre and post occupancy conditions of a building. The results obtained through pre and post occupancy analyses can further be improved by using these results and changing some parameters.

Initially, manual methods were used to calculate the building energy consumption [1]. In the mid-1960s, the only acceptable methods for calculating a building's energy consumption were the degree-day and bin calculation methods, which were used for calculation of heating energy only. For cooling, equivalent full-load-hour (EQFL) method was the major energy calculation method used at that time. Efforts to improve the EQFL resulted in the development of the simplified building load analysis (SBLA), which shows the variation in space heating and cooling loads with changes in outside air temperature. Thus it became the basis for the earliest bin heating/cooling energy calculation procedure [2].

The invention of computers also brought a revolution in the field of design of air conditioning systems. Many building analysis softwares were developed to assist architects and engineers in estimating the energy consumption of different design alternatives, as defined by the user. Initially, the softwares were mainframe-based, and were very complicated; but due to recent development in computers technology (after 1980) building energy analysis programs for personal computers have been released [3]. The current energy related softwares tools are very helpful for the analysis of energy consumption, selection and sizing of HVAC equipment [4]. Most of these tools were developed for the purpose of design verification and to meet building regulation requirements.

Software tools are used to perform building energy analyses so that energy efficient buildings could be designed. By changing various design parameters (for example building envelope material, internal temperature etc.), building energy simulations are performed and their effects on total energy consumption are studied. Analysis of the energy performance of an air-conditioned building is a highly complex issue, which involves climate, building physical characteristics, building operation characteristics, and air-conditioning system characteristics.

Only a few of the available software tools are capable of simulating both buildings and systems. They can only perform hour-by-hour energy analysis using hourly weather data. DOE-2 (program produced by the US department of Energy) and BLAST (Building Load Analysis and System Thermodynamics) are two such comprehensive and widely used programs [5]. The DOE 2.1D has the ability to simulate a wide variety of potential energy conservation measure in buildings and it has been widely used because of its accuracy [6]. The code of DOE 2.1D interfaced by Elite Software Developments Inc. (ESD) with the commercial name EZDOE is used in the current research. The software was selected due to its wide recognition by the researchers and ASHRAE, and its availability.

Pre and post occupancy energy analyses are commonly performed using these software tools. There are various software tools available for investigation of indoor air quality, illumination and acoustic. For the case of thermal comfort it is very difficult to perform such analyses only with the help of software tools because human requirements vary with age, seasons, nature of responsibilities, feelings and other human variables. One of the basic objectives of this study, is to investigate the impact of alteration in building partition on thermal comfort. This is also a complex issue because alteration in building partitions (location and their height) causes changes in supply airflow and indoor temperature. This directly affects the thermal comfort. These issues are discussed in detail in the next section.

2.2 IMPACT OF ALTERATION OF BUILDING PARTITIONS AND CHANGE OF USE ON THERMAL COMFORT

One of the main objectives of this study, is to asses the impact of alterations in building partitions and its change of use on thermal comfort. It is a complex issue because it involves various parameters such as dimensions of the room, size and location of the partition, thermostat settings, the quantity of diffusers (supply air outlets) and their locations, nature of activity going on in the space, heat load density (w/m^2) etc. Interior designers usually design the partition layout after the building is handed over to the tenant. Therefore, in the case of centrally air-conditioned buildings, the air distribution device might be separated by low partitions and certain parts of the building may have poor air distribution [7]. The magnitude of the problem further increases if these alterations were performed without considering the thermal comfort.

Under certain conditions, these partitions divert the airflow between conventional ceiling - mounted supply diffusers and return registers so that the workstations (cubicles) themselves create problems of thermal discomfort [8]. The partitions are often reconfigured to accommodate any changes, which affect the HVAC system's ability to meet the loads for which they were designed. The increase in internal cooling load further complicates the problem.

There is a lack of research in the field of how energy consumption and occupants' thermal comfort is affected by an alteration in a building's partition layout. Researchers like F.S. Bauman, D. Faulker, E.A. Arens, W. J. Fisk, L.P. Johnstan, P.J.McNeel, D. Pih, H.Zhang, R.James and Randall S. Helm concluded that there is a lack of research in this field

[8,9]. According to James et al., [10] " a search of the literature found no publisher test data to guide the designer in determining how a different combination of partition height, orientation of workstation, heat load and location of supply and return diffuser / grills affect conditions within the workstation."

In an experimental study Chow [7] observed an interruption in air distribution pattern due to alteration in partitions. This causes a variation in space air temperature and supply airflow in various locations of workstations. Furthermore, a linear relationship was found between mean air speed and the standard deviation of air speed. Bauman et al. [8,9] conducted various investigations to evaluate the effect of office partition design on air movement and thermal comfort. They performed these experiments by varying the height of partition walls, putting an opening at the bottom of the partitions and using solid, full –sized or partial sized airflow gap partition wall. They concluded that an increase in solid partition height affects the overall thermal conditions, and an opening at the bottom of the partitions produces a slight increment in air velocities near the floor. No significant improvement was found by using airflow gap partition walls. In addition, the test parameters found to have a more substantial impact on comfort were heat load density, supply air temperature and supply air diffuser location. Hence, it was shown that an alteration in the partitions demand an adjustment of these parameters to achieve required comfort conditions.

In an experimental study in a modern office, filled with movable partition workstations, comfort conditions can vary widely based upon the type of diffuser, diffuser location, amount of air per diffuser, ceiling height, temperature of the supply air, location of the thermostat and the location of the return grilles [10]. In experiments, a temperature difference of 72.5 ^{o}F to 76.5 ^{o}F is observed at various places of same hall divided by the partitions, while variation of supply air velocity is observed in the range of 0 Ft/min to 40 Ft/min. These variations of temperature and air velocity affect the occupant thermal comfort.

F. Haghighat et al., [11] found that heat transfer rate and airflow pattern are very sensitive to changes in the door size and location on the partitions. In another research conducted by Bauman et al., [12] it was observed that an increase in the size of workstation, ceiling height, location of the supply air diffuser and alteration in air distribution patterns affect the comfort conditions. They further concluded that, " *heat load in partitioned workstations had a significant impact on air temperatures, mean radiant temperatures and overall comfort condition. As the heat load density increased or the workstation size decreased, thermal conditions became less comfortable*".

Hence, it is concluded that alteration in partition layout disturbs the supply airflow, space air velocity, air distribution pattern and heat transfer rate, which affects the occupants' comfort. It is further observed that these partitions are designed without a proper consideration of the HVAC system and air distribution pattern. Unfortunately, there is a lack of research in this area and there is no specific standard for the partition wall design. There is a serious need to develop a systematic approach for performing the modifications and alterations of these systems. These issues should be considered in the planning stages.

Following are two case studies of retrofitting projects. A review of these case studies shows the benefits of more extensive research.

An existing fragmented retail mall HVAC system was converted into a dual-use system serving a combination of computer data center and the retail mall [13]. Many extensions in the building were observed since its construction in 1984. It was required by the owner to use existing equipment as much as possible, shift all the individual equipment in two mechanical rooms, and provide a central building management system for HVAC and other systems. Additionally, it was desired by the owner to perform these operations in a minimum amount of time. The remaining life and efficiency of the equipment at its state of investigation were calculated. Compatibility of existing equipment with the new design was checked. In the new design, running cost was lowered and cooling efficiency rate of approximately 0.85 kW/ton was achieved versus the previous 1.3 kW/ton. This was only achieved as a result of careful design and consideration of the HVAC system with the new function of the building.

On the other hand when *Toys R Us* [14], the famous American toys firm, moved into its 50,000 ft^2 Douglaston, NY store, the company knew that many tenants had moved in and out since it was built in the 1960s and some renovation would be necessary. In the summer of the 1999, conditions became so unbearable that the entire chilled water system had to be replaced with high-efficiency rooftop units to heat and cool the space. This major modification resulted in huge costs as well as an increase in the monthly energy charges.

In the first case, retrofitting was performed as per owner requirement with efficient planning, good engineering and design skills, which resulted in owner satisfaction and reduction in energy consumption. While in the Toys R Us project, no optimization of these skills caused discomfort to users as well as the need for huge capital investment. One of the objectives of the current research is to study the impact of physical rezoning, i.e., alterations in a building, by using current literature and evaluating the comfort conditions of a selected building.

2.3 EVALUATION OF THERMAL COMFORT

A positive definition of comfort is a feeling of well-being. However, the more common experience of thermal comfort may be defined as a lack of discomfort [18]. A principle purpose of a heating, ventilation, and air conditioning system is to provide conditions for human thermal comfort. A widely accepted definition of thermal comfort is "that condition of mind which expresses satisfaction with the thermal environment" (ASHRAE Standard 5.5) [15].

A comfortable environment is created by simultaneously controlling temperature, humidity, air cleanliness and distribution within the occupant's vicinity. These factors include mean radiant temperature, as well as air temperature, odor control, and control of proper acoustic level within the occupant's vicinity. In addition, there are some behavioral actions that reduce feelings of discomfort. These are altering clothing, altering activity, changing posture or location, changing the thermostat setting, opening a window and by moving from one place to another [16]. Although regional climatic conditions, living conditions, and cultures differ widely throughout the world. The temperature that people choose for comfort under such conditions of clothing, activity, humidity and air movement has been found to be very similar [16].

According to Neil et al. " the human body has been considered as an inert object exchanging energy with its environment through radiation, convection, and conduction. It also experiences heat loss by evaporation and it is capable of adapting to conditions in order to regulate body temperature" [17]. The heat, which is produced due to metabolism either lost (in winter or at low ambient temperature) or stored (causes a rise in body temperature), affects the body. This may take place at the hot and cold extremes and might be unpleasant or even painful. Thermal comfort is associated with the conditions to which body can adjust readily [17].

Because of the thermal interaction among building structure, occupancy, climate and an HVAC system, pure steady state conditions are rarely encountered in practice. Madsen [18] found that indoor temperature fluctuations between 0.5 and 3.9°C (during 24 hours with a constant set point), depend upon the combination of heating and cooling. Thermal conditions vary from one point to another, creating non-uniformity of conditions. Recognizing this as a comfort-influencing factor, ASHRAE standard 62n has specified limits on non-uniformity of thermal conditions throughout the occupied zone.

Air motion always varies throughout the space. Drafts or a local feeling of coolness or warmth of any portion of the body is therefore, likely to occur. The impact of air movement and its flow patterns on thermal comfort has been the subject of many theoretical and experimental studies [19-21]. Results from those studies have emphasized the role of air velocity and air distribution patterns as a determinant factor of thermal comfort.

2.3.1 Environmental Indices

There are many parameters to describe the environment in terms of comfort. These indices are generally subdivided into three groups: direct, rationally derived and empirical[22]. Direct indices include dry bulb temperature, dew point temperature, wet bulb temperature, relative humidity and air velocity. Rationally derived indices include mean radiant temperature, operative temperature and humid operative temperature. Empirical indices include effective temperature, black globe temperature, corrected effective temperature, wet bulb globe temperature and wind chill index. The most important indices, which are normally used by most of the researchers in their experiments are dry bulb temperature, relative humidity, air velocity and mean radiant temperature [22].

Mean radiant temperature of an environment 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*". To calculate this value, temperature at different surfaces and angle factor between the person and surface is required. Measuring the temperature of all surfaces in the room is very time consuming. Even more time consuming is the calculation of the corresponding angle factors. That is why, to evaluate indoor comfort conditions the use of the Mean Radiant Temperature is not common in the literature [23].

Hence, on the basis of the above discussion it is concluded that the parameters of air temperature, mean radiant temperature, air velocity and humidity are the key factors behind thermal comfort conditions of a certain space. The influence of these parameters on thermal comfort is not equal, so it is not sufficient to measure only one of them. Finally, for the current study it was decided to measure dry bulb temperature and relative humidity. Since supply airflow is an important design parameter for the current study, it was measured in order to compare original and existing HVAC design.

CHAPTER-3

FACILITY AUDIT AND ENERGY ANALYSIS

Energy simulations are performed to assess the impact of retrofitting on building energy consumption. In the current study, the same technique of energy analysis using a simulation software tool was used to assess the impact of change of space usage and alteration of building partition layout on the building's energy consumption. The building's energy audit is a prerequisite to simulations because a performance of energy simulation information about the building's thermal and physical characteristics are required. Hence, the building's energy audit was conducted, so that the necessary information required by the DOE –2.1 D (energy analysis software used in the current study) could be collected. Hence, prior to discussing the energy modeling of the selected building, the building energy audit is discussed.

3.1 BUILDING ENERGY AUDIT

Energy audit provides a source for identifying the existing physical and operational conditions of buildings and their energy systems [24]. The simplest definition of an energy audit is " to identify where a building or plant uses energy and to identify energy conservation opportunities" [25]. The main objective of an energy audit is to balance the input energy (i.e. electricity) against known uses. Energy savings can then be easily achieved through the adjustments of these uses. The auditing process generally includes: site measurements and the analysis of energy consumption, implementation of energy management program, implementation of energy conservation techniques, and finally, to monitor the impact of these changes on the building's energy consumption.

Three levels of energy audits can be classified as follows: a walk – through audit, an energy survey and analysis, and a detailed analysis. The performance of these different levels depends on the use of energy characteristics of a building. These levels of energy audits, however, do not have distinct boundaries between them. These are general categories for identifying the types of information that can be expected and an indication of the level of effort and confidence in the results.

There are several different uses of energy in buildings. The major uses are for lighting; cooling, heating, power delivery to equipment and appliances, and domestic hot water. However, the best way to determine the energy use in a particular building is to analyze its utility bills over a period of time as part of an energy audit. In the current study, due to absence of utility bills, as well as power / electricity connections not are from a single supply line. These types of comparison were not possible. So, the building energy analysis was performed to assess the use of building energy before and after the alterations. As mentioned in the beginning of this chapter that, building energy audit was performed prior to modeling and energy simulation. Hence, a building energy audit of the case study building is discussed in detail in the next section. A flow chart of this audit process is shown in Figure 3.1.

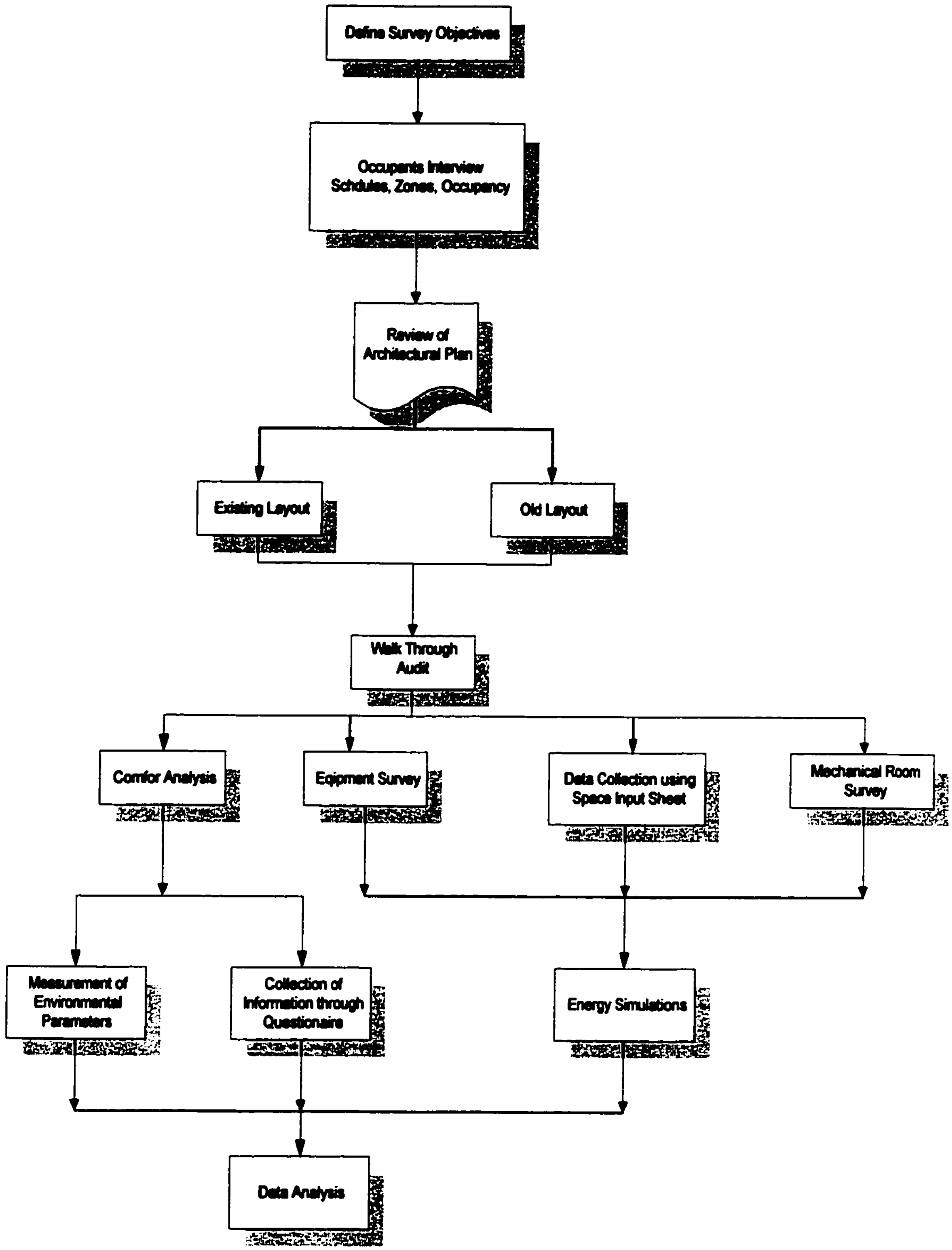


Figure 3.1: Energy Audit and Comfort Survey Flow Chart

3.1.1 Description Of The Case Study Building

Building – 19 at King Fahd University of Petroleum and Minerals (KFUPM) was constructed in the early 1980s. To fulfill the requirements of an increased number of classrooms, the original building layout was changed by partitioning the large studio area into classrooms and offices at various locations in the building. The building has four-stories, with most of the first and second floors are used as car parking. The remaining floors contain a few offices, a photocopy center, an audiovisual lab on the second floor, and three labs on first floor. Since major modifications in the building's partitioning layout were carried out on the third and fourth floors, these two floors were selected for energy analysis evaluation.

Building – 19, is a rectangular building, with its front facade facing in Northeast direction. Other buildings are located on its Northwest and Southeast sides, so it is not exposed to outside solar radiation from these directions. However, the front and back facades of the building are exposed to the outside solar radiations. Its color is light brown, with the doors and windows having a brown tinted glazing. The roof is constructed of pre-cast beams. Besides the normal concrete construction, there is a layer of rigid thermal insulation under the layer of screed. The construction details are mentioned in Table 3.1.

Almost all of the building is carpeted except two long corridors, which are mosaic. Most of the carpets were dark brown in color, except in few classes where old carpets are replaced with new ones. The center of the third floor has a praying area, where Duhr and Asr prayers are offered. The prayer area and its surroundings are of double height. There is a spacious exhibition area on the third floor, where models prepared by the students are displayed; glass walls are used in the exhibition area. There is a studio along the Southwest wall on the third floor, which is occupied till late night. The remaining part of the third floor has faculty offices, stores, classrooms and secretarial rooms. As per design layout of the building, there was no exhibition area and there was only one classroom instead of three. The Audio Visual lab on the third floor in the Northwest side of the building was also converted to the classroom.

Table 3.1: Physical characteristics of the building

Plan shape	Rectangular
Number of stories	Four stories, major part of level 1 & 2 are car parking, analysis are done for level 3 & 4.
Total floor area	6490 m^2.
Ceiling height	3 m.
Gross wall area	21967 m^2.
Glass area	309 m^2.
Type of glass	Single 12mm thick tinted glass.
Partitioning wall material	Partitioning wall with gypsum plaster.
Roof materials	35mm screed, 40mm rigid insulation, 80mm screed with asphalt topping, 175mm concrete slab
Lighting System	Florescent and Incandescent lamps.
Floor Finishing	All rooms have carpeted floors, while corridors have mosaic tile finishing.

The fourth floor of the building has classrooms, faculty offices, secretary offices and labs. Major modifications were carried out on the fourth floor. Four rooms of the Chairman's office were converted to classrooms. One studio at the southeast side is divided into four rooms for chairman office and a hall for secretaries. In the center of the building another design studio was converted to GIS computer lab. The old computer lab was also divided into five rooms and now every department has its own lab, instead of one combined big lab. The details of the spaces as per existing and original designed partition layout are shown in Table 3.2.

A glass area covers a big portion of the building envelope. Venetian blinds are used to reduce solar heat gain. Doors are fitted with weather stripping in order to decrease the infiltration rate, and although there are many doors, only two of them are frequently used.

3.1.2 Building Operation And HVAC System

To calculate the space internal cooling load for building energy modeling, it is important to understand the building's operating schedules and occupancy profiles. The building has three types of occupants, i.e., faculty members, students and administrators. The representative occupancy profiles for such users are shown in Appendices B1 to B7. These profiles were used in the building energy analysis. Most of the spaces were used as classrooms, faculty offices, secretarial offices, labs and design studios. Classes and other related activities start around 7:30 in the morning and continue up to 4:00 in the afternoon, with a small brake for lunch and prayer. However, design studios and computer labs are normally occupied up to 10:00 or 12:00 at night. The building physical and operational characteristics are summarized in Tables 3.2.

Table 3.2: Comparison of building space functions as per the original and existing layouts.

	Existing Partitioning layout	Original Designed Partitioning layout
3rd Floor		
Total rooms	39	35
Faculty rooms	20	20
Class rooms	3	2
Computer labs	2	1
AHU rooms	2	2
Offices	3	3
Electrical rooms	2	2
Toilet	2	2
Store	3	3
Faculty lounge	2	0
4th Floor		
Total rooms	32	20
Faculty rooms	12	6
Class rooms	7	0
Studios	6	7
AHU rooms	4	4
Electrical rooms	2	2
Toilet	1	1

The type of HVAC system serving the building is a multi zone all air system. Chilled water is distributed from the two chillers on the ground floor. Six multi zone modular air handlers are supplying the air to the 3rd and 4th floors of the building. Existing fresh airflow rate were measured by visiting the mechanical rooms of these two floors. The remaining data was obtained from the information written on the tags of these units and from the mechanical drawings of the building.

3.1.3 Review Of Architectural Plans

Review of the plans is an important aspect of an energy audit program. Architectural and mechanical drawings of the building were obtained from the Projects and Maintenance Department. Due to recent modifications of partitioning layout, available drawings were not up to date. Therefore by taking site measurements, existing partitioning layouts of the building's drawings were developed. From the mechanical drawings of the building, important information like capacity of various installed equipment, ducting routes, supply of airflow to various zones and spaces, lighting loads etc. were obtained.

3.1.4 Building Thermal Zoning

A thermal zone is defined as any distinct area in a building that has its own thermostat. For example, a computer room with a separately controlled air conditioning system would be treated as a separate zone [25]. Dividing the building into the proper thermal zones is important for analyzing the HVAC system loads and other operational profiles. For the current research in the modeling of energy analysis, the same thermal zones have been used which were specified in the building's HVAC layouts. Layouts of the thermal zones are shown in Appendices A5 and A6.

3.1.5 Space Input Sheet

A space input sheet developed by Elite Software Development [6] was used so that all the information required for simulation could be collected. Details were gathered from all zones, including the building areas, lighting systems, various equipment, exterior wall sections, materials, roof and glazing. A sample input sheet is shown in Appendix D.

3.1.6 Building Exterior Factors

After the building interior had been thoroughly inspected, a survey was conducted to inspect the building under study from the outside. The building's external parameters affecting energy consumption were inspected. These parameters include glazing shades, dimensions of overhangs and fins, surrounding surface colors, wall finish colors and other related parameters. These external factors contributed an important role in the building's comfort condition. For example, a fin or an overhang of a window glazing on the south wall prevented a lot of direct solar radiation entering the building. Hence, these external features were carefully noted.

3.1.7 Inventory Of HVAC Plant Rooms

The next major step in the energy audit process was a careful inventory of the HVAC mechanical rooms. This includes obtaining data of the air handling units, chillers, motors, cooling towers, fans, dampers, thermostats and their settings. Part of this phase of equipment survey includes collection of equipment data from the HVAC layouts obtained from the Projects and Maintenance Department.

After accomplishing the building's energy audit phase, the collected data was finally reviewed in order to avoid any error. By reviewing and cross checking the collected data, chances of incorrect data could be minimized. As this data is going to be used in the energy simulation phase, it will be very difficult to trace the source of errors. This led the study to enter in the phase of the building's energy analysis.

3.2 BUILDING ENERGY MODELING

A model is a representation of reality. An assumed real system is modeled in terms of its dominant factors using reasonable assumptions. Simulation models are flexible performance tools that can be used effectively for analyzing the behavior of real systems [26,27]. In the building's design, simulation models are used to evaluate the performance of various building systems using a predetermined set of design variables.

3.2.1 Simulation Technique

Two modeling strategies are commonly used in a building's energy simulation programs. These are the sequential (referred to as Load, System, Plant, and Economics (LSPE) sequence) and the simultaneous solution approaches [27-28].

In the sequential approach shown in Figure 3.2, the heating and cooling loads are first calculated for each space of the building for the whole year. This is followed by the secondary system simulation. First the energy required for the air handling units or other equipment supplied by the central plant are calculated. Then the energy required for the central plant is calculated to determine the source energy requirements. The sequential approach lacks interaction between loads, system and plant, which could produce doubtful results. Especially when the equipment capacity cannot meet the required load [28-29]. To overcome the problems of the sequential approach, the simultaneous modeling approach was introduced [27-28]. Their models are solved simultaneously at each time step as shown in Figure 3.3.

The major step of a building's energy modeling is the building's load estimation. Therefore, it is discussed in detail next. In a building's load modeling, basically the input load to the building is calculated. The calculated "load" should be the summation of the building's internal load (equipment and occupants etc.) and external load (building envelope heat gain or loss). The most commonly used approaches of load modeling are

- Weighting factors method and
- Heat balance method

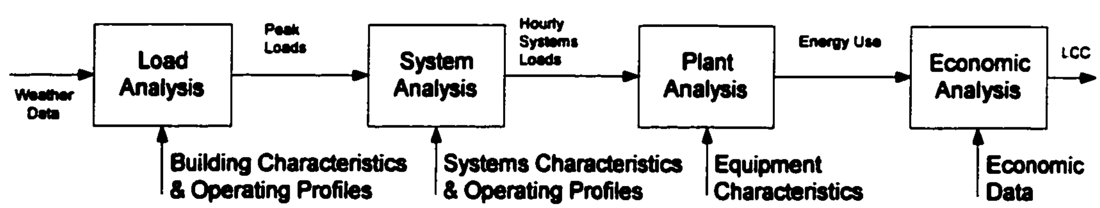


Figure 3.2: Sequential simulation approach [28]

3.2.1.1 Weighting Factors Method

The heat gain weighting factors are a set of parameters that quantitatively determine the storage of energy entering the space and then how rapidly this stored energy is released during later hours. This method represents a compromise between simpler methods that ignore the building's mass effects such as steady-state methods, and the more complex methods, such as complete heat balance calculations [28].

The best known example of the above method is the DOE-2 program produced by the US Department of Energy which is a public domain program that can be used for analyzing the energy behavior of buildings and their associated heating, ventilation and air-conditioning (HVAC) systems. DOE-2 utilizes hourly weather data to calculate the hour-by-hour performance and response of a building with a known description. It can also provide users with an economical analysis of the energy use with the costs and benefits of varying the design [28].

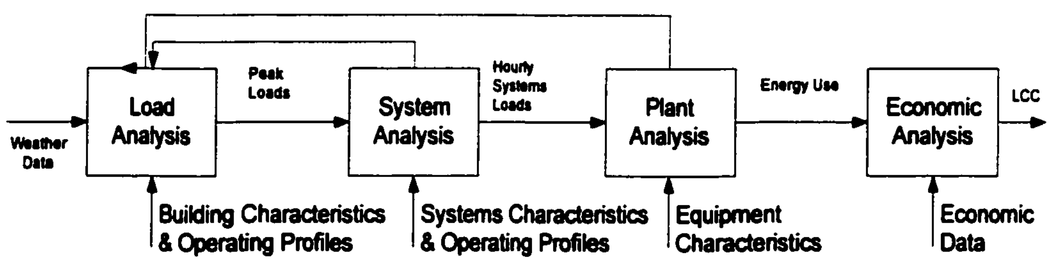


Figure 3.3: Simultaneous simulation approach [28]

3.2.1.2 Heat Balance Method

In the heat balance method, a detailed heat model of the thermal transfer processes in the rooms is used to calculate loads due to heat gains. The net instantaneous heating and cooling loads are calculated on the space air mass. The sets of equations for each enclosing surface and room air are solved for the unknown surface and air temperatures. Based on these temperatures, the convective heat flow to or from the space air mass is calculated. This method requires fewer assumptions than the weighting factors method [28].

The best-known example of this method is the Building Load Analysis and System Thermodynamics (BLAST) simulation program, which was first developed by the US Army Construction Engineers Research Laboratory in 1977 [28]. BLAST was developed for predicting energy consumption and system performance and costs of new or retrofit building designs of different types and sizes.

In this research, DOE energy analysis software was used, because of its accuracy, abundant use and recognition by most researchers. Hence, it is necessary to discuss it in detail at this stage. Basically, DOE - 2 has one subprogram for giving the input (i.e. BDL Processor) and four subprograms LOADS, SYSTEMS, PLANT and ECON. These subprograms are executed in a sequence, that is, the output of LOADS is the input of SYSTEMS and the output of SYSTEMS is the input of PLANT and the output of PLANT is the input of ECON. Each of the simulation subprograms also produces printed reports of its results. The elements of DOE-2 program [29] are shown in Figure 3.4.

3.2.1.3 BDL PROCESSOR

The Building Description Language (BDL) processor reads the input data supply and converts it into computer recognizable form. It also calculates response factors for the transient heat flow in walls and weighting factors for the thermal response of building spaces.

3.2.1.4 LOADS

The LOADS simulation subprogram calculates the sensible and latent components of the load for hourly heating or cooling for each user-designated space in the building (assuming that each space is kept at a constant user-specified temperature). LOADS takes into account various factors such as weather and solar conditions, schedules of people, lighting and equipment, infiltration, heat transfer through walls, roofs, windows, and the effect of building shades on solar radiation.

3.2.1.5 SYSTEMS

The SYSTEMS subprogram handles secondary systems. This subprogram calculates the performance of airside equipment (fans, coils, and ducts). It corrects the constant-temperature loads (calculated by the LOADS subprogram) by taking into account outside air requirements, hours of equipment operations, equipment control strategies, and thermostat set points. The output of SYSTEMS is airflow and coil loads.

3.2.1.6 PLANT

The PLANT subprogram handles primary systems. It calculates the behavior of boilers, chillers, cooling towers, storage tanks, etc. to fulfill the requirement of secondary systems heating and cooling loads. It takes into account the partial load characteristic of the primary equipment in order to calculate the fuel and electrical demands of the building.

3.2.1.7 ECON

The ECON subprogram calculates the cost of energy. It can also be used to compare the cost-benefits of different buildings or to calculate savings of retrofits to an existing building.

3.2.1.8 Weather Data

The weather data for the location consists of hourly values of outside dry-bulb temperature, wet-bulb temperature, atmospheric pressure, wind speed and direction, cloud cover, and solar radiation. Weather data suitable for use in DOE-2 is produced by running the DOE-2 weather processor on raw weather files.

3.2.1.9 Library

DOE-2 includes a library of building input elements, including wall materials, layered wall constructions, roof material, layered roof construction, different internal walls, glazing and their shades etc. By using these library elements, effective modeling can be done.

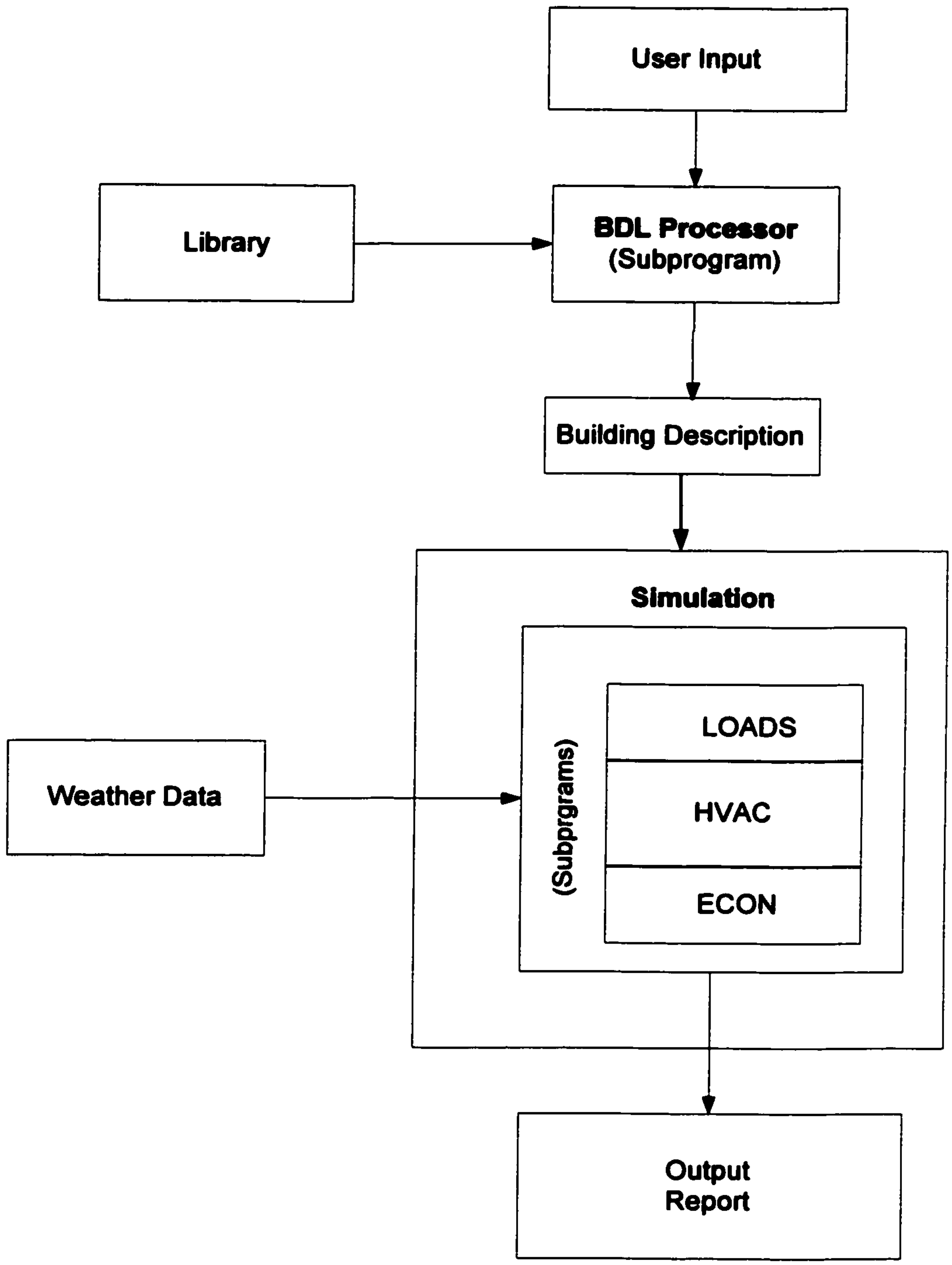


Figure 3.4: DOE – 2.1D Flow Chart [29]

3.3 MODELING OF THE CASE STUDY BUILDING

To perform energy analysis of the case study (Building-19), the building was simulated in order to study the impact of rezoning and change of use on its HVAC system requirement and energy consumption. As mentioned earlier, DOE – 2.1.D was used for this research. All the information required by DOE – 2.1.D was gathered during the energy audit phase of the current research. The 3rd and 4th floors of the building were selected for this study, as major modifications and rezoning were performed on these two floors.

3.3.1 Planning

Modeling of the building was performed according to its thermal zones. The term "zone" means a provision for separate thermostatic control, whereas the term "room" implies a partitioned area that may or may not require separate control. After reviewing the building HVAC drawings, it was found that the third floor had two air-handling units both having a 26 ton capacity. Through a ducting system, the third floor is divided into 30 zones. The fourth floor contains four air-handling units which are of 21, 18, 18 and 21 ton capacity and through the ducting system the fourth floor is divided into 30 zones. Air handling units of both floors are of the multi-zone type. Hence, by using a space input sheet developed by Elite Software Development (user interface designers of DOE – 2.1.D) the necessary information for auditing was gathered.

3.3.2 Data Feeding

All project data including weekly and monthly schedule of occupants, lighting, air conditioning, and equipment were collected. Through space input sheets, information of each room, building internal load, envelope load etc. were fed. Building materials characteristics such as U- Value of walls, roofs, partitioning walls and glasses were also given as input into the software. From the DOE – 2.1D element library air handling units and chillers were selected. The information related to the HVAC system (i.e., AHU supply, return and fresh air design values, etc.) was fed as input to the program. The simulation was performed using Dhahran weather data for the existing and the original building design partitioning layout and usage.

3.3.3 Debugging Of The Model

Chances of errors cannot be ruled out especially during initial runs. Careful debugging is necessary to ensure a smooth execution of the program. This was achieved by reviewing the BDL output and log files to check for errors. During the initial runs, input files generated by the BDL processor were compared to the actual input that was used during the data feeding, in order to avoid the typing mistakes. After correcting any errors, final runs were started.

3.3.4 Assumptions

To model the building, a number of assumptions were made. These assumptions are as follows:

- There is an imaginary horizontal layer of air over the third floor prayer hall that separates the third floor from the fourth floor.
- The building was assumed to be a "tight envelope", because doors were fitted with weather strips.
- Since external doors of the fourth floor are normally not in use, half of the calculated airflow is used for infiltration for these doors.
- Blinds are "open" during the daytime to allow more light in the room.
- The air conditioning system is on for 24 hours.
- Schedule of classes as well as the number of students remain the same every year.
- Fifty percent of the computers are assumed to be in the use in labs at one time.
- Task lights are "ON" during working hours only.
- Since all the ducts are running in a conditioned area. Hence, heat gain of ducts is taken less than 0.5°F.
- Since periodic variation in thermostats are not performed, the summer and winter thermostats settings are assumed to be same.

CHAPTER-4
THERMAL COMFORT ANALYSIS

4.1 INTRODUCTION

Ever since humans have inhabited this planet, they have tried to protect themselves from exposure to harsh weather conditions. Early man found refuge in naturally occurring shelters such as caves and thick bushes in forests. With the passage of time he began to develop his habitat to achieve greater security and comfort. The advancement in science and technology led to more sophisticate housing units that are more comfortable and secure than before.

Before the 19th century there was no mechanical refrigeration. In order to artificially cool the air, the use of ice, snow, cold water or evaporative cooling was required [30]. Air conditioning, which provides thermal comfort by mechanical methods, first appeared in buildings about a hundred years ago [31].

Willis H. Carrier (1876-1950) has often been referred to as the "Father of Air Conditioning." His analytical and practical accomplishments contributed greatly to the development of the refrigeration industry [32]. Among his many important contributions two are mentioned here. In 1911 in an ASME meeting, Carrier presented his paper, " Rational Psychometric Formulae," which related dry-bulb, wet-bulb, and dew-point temperatures of air, along with its sensible, latent, and total heat load. The formulae and psychometrics chart presented in his paper became the basis of all fundamental calculations used by the air-conditioning industry. By 1922, Carrier's centrifugal refrigeration machine made water chilling for large and medium-size commercial and industrial applications both economical and practical [32]. Various researchers extended the work of Carrier. A lot of research is still going on to achieve more comfort with less energy requirements. One of the main aim of various researchers is to achieve human comfort, which is explained next.

4.2 HUMAN COMFORT

The purpose of air conditioning systems is to provide a comfortable and healthy environment. It is therefore, necessary to know what factors affect comfort. First, it will be useful to explain how the human body reacts to its surroundings. The human body continuously produces heat by the oxidation of food: a process called metabolism. The heat must continuously be rejected by the body to its surroundings at a certain rate to keep the body at a constant temperature. There are four ways through which the body automatically exchanges heat with the surroundings:

- Convection
- Conduction
- Radiation
- Evaporation

In convection, the air surrounding the body, at a lower temperature, receives the heat from the body and carries it away. The air surrounding the body is thereby continuously being replaced with cool air. In conduction, the body exchanges heat with those objects with which it has a direct contact like clothing. In radiation the body radiates heat directly to the surrounding objects at a lower temperature, such as a nearby wall. If the surroundings are at a higher temperature, the reverse heat flow occurs, e.g., heat flowing to a body from a fire. The fourth method of losing heat is by evaporation (perspiration). Water from the body evaporates into the surrounding air, thus producing a cooling effect.

When the rate of heat rejected from the body is within certain limits, a physical and mental condition of comfort is felt [15]. If the rate of heat loss is too great, the body will try to maintain it by generating more heat, but in doing so it feels uncomfortably cold. If the rate of heat loss is too slow, the person feels uncomfortably hot. The surrounding condition of the air therefore controls the rate of heat loss form the body.

4.3 DEFINITION OF THERMAL COMFORT

As per ASHRAE [34] the definition of thermal comfort is "The condition of mind that expresses satisfaction with the thermal environment" whereas the thermal environment is the characteristics of the environment that affect heat loss from the human body [15].

ANSI/ ASH RAE Standard 55-1992, Thermal Environmental Conditions for Human Occupancy Standard define an acceptable thermal environment as environment with conditions in which 80% or more of the occupants will find the environment thermally acceptable [34]. 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. 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.

4.3.1 Temperature

Temperature is a measure of the thermal activity in a body. This activity depends on the velocity of the molecules and other particles of which all matter is composed [35]. Temperature is perhaps the most important environmental factor that determines the perception of comfort. Generally, humans are sharp to react to this parameter.

4.3.2 Mean Radiant Temperature (Mrt)

Mean radiant temperature of an environment 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*" [36]. 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 the corresponding angle factors. That is why the use of the Mean Radiant Temperature to evaluate indoor comfort conditions is not common in the literature [36]

4.3.3 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 and mean radiant temperature [15]. The acceptable range of operative temperature and humidity for the winter and summer is defined on the psychometric chart in Figure 4.1. The coordinates of the comfort zone are

(a) Winter: t = 20 to 23.5°C (68° to 74°F) at 60% RH, t = 20.5° to 24.5°C (69 to 76°F) at 2°C (36°F) dew point. The slanting side boundaries of the winter zone correspond to 20° and 23.5°C (68 ° and 74 ° F) effective temperature (ET*) lines and are loci of constant comfort or thermal sensations

(b) Summer: t = 22.5 to 26°C (73 to 79°F) at 60%RH and t = 23.5 to 27°C(74 to 81°F) at 2°C (36°F) dew point. The slanting side boundaries of the summer zone correspond to 23° and 26°C (73 and 79°F) ET* lines [34].

4.3.4 Relative Humidity

Relative humidity is an important parameter that governs the percentage of comfort in humans. It is the percentage of moisture in the 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 with the limits shown in Figure 4.1. Note that the upper and lower limits of humidity are based on considerations of dry skin, eye irritation, respiratory health, microbial growth, and other moisture related phenomena. It should be noted that temperatures of building surfaces and material (e.g. windows and ductwork) must be controlled to avoid condensation [33].

4.3.5 Clothing

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, light weight trousers, short or long sleeved shirts and blouses. These ensembles have clothing insulation values (I_{cl}) ranging form 0.35 to 0.6 clo (1 clo = 0.88 ^oF. .ft^2.h/Btu). During the winter season people wear garments constructed of thicker, heavier (i.e., warmer) fabrics and often add more garment layers to an ensemble [34]. A typical indoor winter ensemble would have an I_{cl} value ranging from 0.8 to 1.2 clo. Where the outside temperature range does not vary a 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.

4.3.6 Air Speed

Air movement should be within the range of 0.127 to 0.229 m/s (25 to 45 fpm) for thermal comfort, within the thermally acceptable ranges as shown in Figure 4.1. For sedentary persons, it is essential to avoid drafts. The temperature may be increased above the level allowed for the comfort zone if a means is provided to elevate the air speed. The benefits

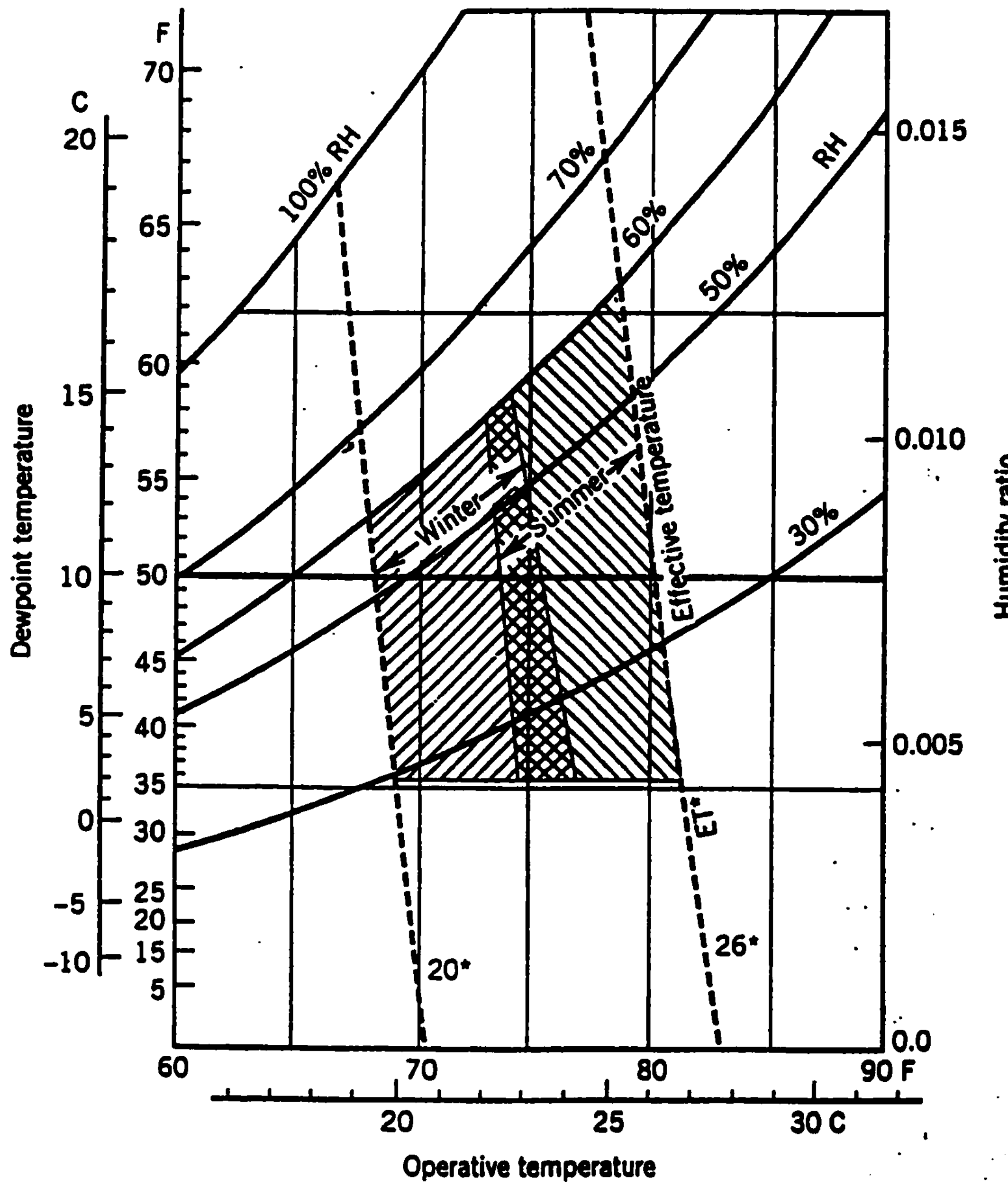


Figure 4.1: ASHRAE Psychometric Chart [34]

that can be gained by increasing air speed depend on clothing, activity, and the difference between the surface temperature of clothing/ skin and the air temperature [15].

4.4 COMFORT ASSESSMENT OF THE CASE STUDY BUILDING

To assess the comfort conditions of the case study building i.e., building – 19 of KFUPM, both qualitative and quantitative analyses were performed. These analyses are

- A questionnaire survey (qualitative analysis)
- Measurement of temperature, relative humidity and supply air flow (quantitative analysis).

In section 4.4.1 the qualitative analysis will be discussed, while quantitative analysis will be enlighten in section 4.4.2.

4.4.1 Qualitative Analysis

To perform the qualitative analysis of the case study building a questionnaire was designed to assess occupants' thermal perception for their environment. This questionnaire was administered with the aim of acquiring information on the following aspects:

a) To seek general information about the respondents like age, responsibilities, and duration of stay in the building.

b) To get the information about the occupants feelings for indoor environmental parameters of temperature, humidity and air motion

c) To enquire the affect of seasons and time of day on occupants thermal comfort conditions.

d) To assess the impact of building's rezoning and space change of use on occupants' perception about indoor thermal comfort conditions.

The information gathered through the questionnaire is considered to be a representative of the feelings of the building occupants in general. Therefore, in order to get realistic responses from occupants, (e.g., faculty, students, secretaries and lab technicians), great care was taken in the development of the questionnaire. Neither during the distribution of the questionnaire nor after its analysis, a single complaint was observed regarding confusion in any part of the questionnaire. Since Building 19 at KFUPM is an academic building, most of the responses were from students. Many of these students were not frequent users of this building; they belonged to other departments, locating at different buildings. They used to come only for two or three hours per week while the rest of respondents were from the same building who usually spent more time in it. Faculty members and other staff normally stay in the building more than students, so their responses were also collected.

4.4.2 Quantitative Analysis

To perform the quantitative analysis of the case study building, temperature relative humidity profiles were recorded and supply airflow of the selected rooms were measured. Air temperature, relative humidity and supply airflow were recorded in 12 different places in the building. These data measuring points are shown in Appendix Figures A7 and A8.

These data measuring points were selected on the basis of the nature of modification carried out in these spaces. Spaces were categorized in three types,

I). **Spaces with major modifications:** In this type, the space usages as well as its partition layout were changed, the thermal conditions were affected more due to these alterations and numbers of complaints from occupants were also high.

II). **Spaces with minor modifications:** In this type, the space usages as well as its partition layout were changed, with relatively less complaints from the building's occupants in comparison with major modified spaces.

III). **Space with no modifications:** Implies that neither the space usage nor its partition layout was changed.

The data were collected in two phases, i.e., in summer and in winter. During both periods data were measured at 12 different places.

To measure the supply airflow from the diffusers, a hood type electronic airflow meter was used, which was manufactured by Alnor Instrument Co. The picture of Electronic Balo-meter (trade name of the hood type airflow meter) is shown in figure 4.2. To measure the airflow inside the ducts, a digital anemometer was used, which was manufactured by Dwyer Co. The picture of the Thermo Anemometer is shown in Figure 4.3. To capture the 24 hours air temperature (dry bulb) and relative humidity patterns, data loggers were used. These data loggers were manufactured by M-Tech. The picture of Smart loggers (trade name of the data loggers) is shown in Figure 4.4.

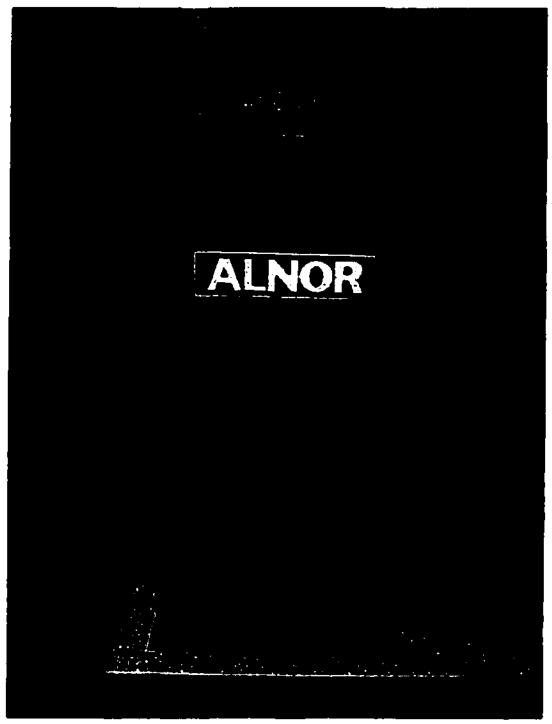


Figure 4.2: Hood type electronic supply airflow meter

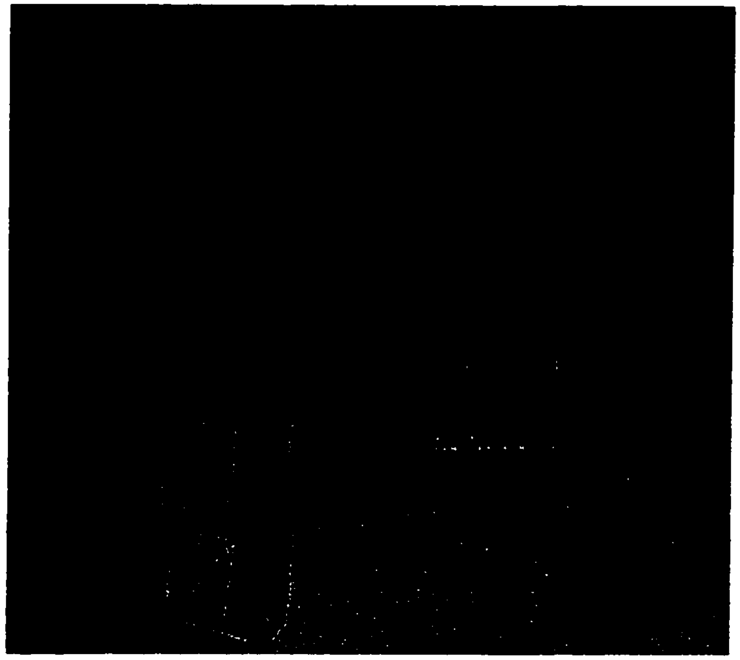


Figure 4.3: Digital anemometer

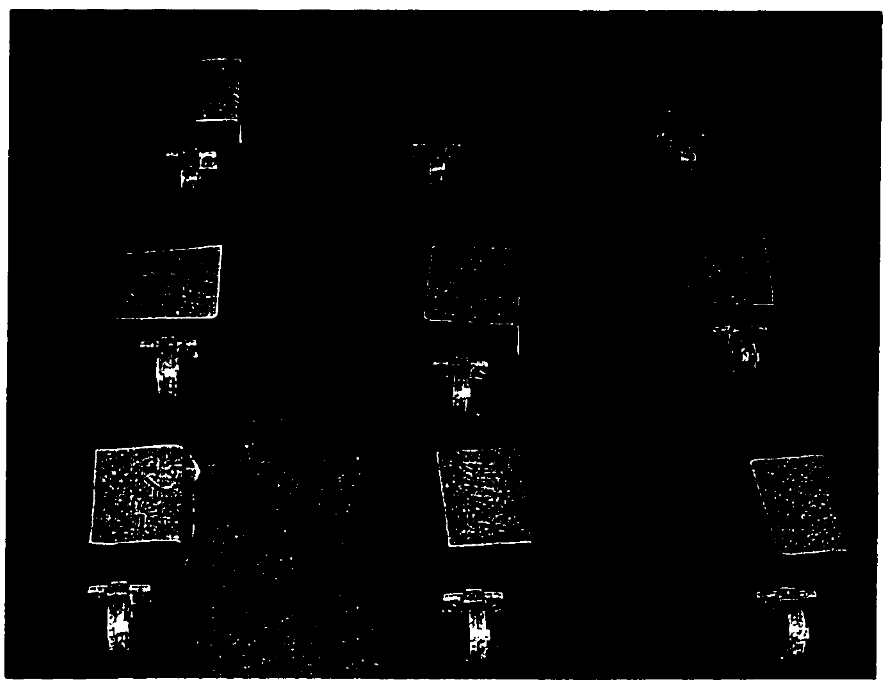


Figure 4.4: Temperature and relative humidity data loggers.

CHAPTER 5
RESULTS AND DISCUSSIONS

5.1 GENERAL

The current study was performed to assess the impact of Building-19's physical rezoning and the change of the building's use on occupants' thermal comfort and building energy consumption. Energy and comfort analyses of the building under study were performed both quantitatively and qualitatively. Results of these investigations are presented below in Section 5.2 and 5.3.

5.2 ENERGY ANALYSIS

Energy simulations were performed to assess building energy consumption. Simulation runs were conducted according to the existing conditions of the building under study as well as its original design. The simulation results describing the usage of monthly building cooling energy, electric energy and total energy are given in table 5.1. in Table 5.2 the results of the peak cooling load components are presented Electrical energy consumption is the sum of the building's lighting and equipment energy used. The comparative analysis shows that the total annual energy consumption for original designed conditions was equal to 2190198.4 kWh (337.43 kWh/m^2) in comparison to 2488787.4 kWh (383.44 kWh/m^2) for existing partitioning ,thus showing an increase of 13.6 %.

The total capacity of the installed cooling equipment in the building under study is 1565 kW (130 Refrigeration Tons). From the simulation studies, the maximum peak-cooling load for original design conditions 1665.5 kW (138 Refrigeration Tons), which is very near to the capacity of the installed equipment. But, the maximum peak-cooling load as per building's existing design is 1914.7 kW (159 Refrigeration Tons). Thus an increment of 15.6%,

Table 5.1: Building Monthly Energy Use From The Simulation Results

	Cooling Energy Consumption		Electric Energy Consumption		Total Energy consumption	
	Original Design	Existing Design	Original Design	Existing Design	Original Design	Existing Design
	kWh	kWh	kWh	kWh	kWh	kWh
January	33056.4	39586.5	58926.0	72064.0	91982.4	111650.5
February	8322.2	12556.8	53633.0	65360.0	61955.2	77916.8
March	56750.2	60329.5	59996.0	73131.0	116746.2	133460.5
April	114877.8	123437.7	56972.0	69281.0	171849.8	192718.7
May	173758.8	187728.9	59461.0	72597.0	233219.8	260325.9
June	159576.4	174924.7	57875.0	70540.0	217451.4	245464.7
July	180606.6	196455.9	58558.0	71338.0	239164.6	267793.9
August	230955.8	258387.2	59996.0	73131.0	290951.8	331518.2
September	191304.1	213001.9	57507.0	69814.0	248811.1	282815.9
October	152887.6	166562.3	58926.0	72064.0	211813.6	238626.3
November	141919.8	150216.8	57875.0	70540.0	199794.8	220756.8
December	47364.7	53868.3	59093.0	71871.0	106457.7	125739.3
Total (kWh)	1491380.4	1637056.4	698818.0	851731.0	2190198.4	2488787.4
kWh/m^2	229.7	252.2	107.6	131.2	337.4	383.4

equivalent to 259.5, kW (21 Refrigeration Tons) is observed, which is due to the change of use and modification in the building's partitions. The building's peak cooling load components are shown in Table 5.2. It is observed that the only increase in the building's peak load for existing conditions is due to the increase of two things: equipments and occupants' load, which are due newly introduced class rooms and labs in the building. It was found that each lab is contributed a considerable amount in annual energy consumption, because of large number of computers, printers, plotters, scanners, servers, power devices and overhead projectors.

This increase in the number of occupant and equipments load not only result in higher annual electricity consumption, but also affects the building peak load. Thus, additional cooling or energy is required to remove the heat generated in the space which ultimately raise the total energy consumption.

Table 5.2: Building Peak Cooling Load Components (kW) From The Simulation Results

	Original Design Load	Existing Design Load	Increment
	(kW)	(kW)	%
WALLS	57.274	57.274	0
ROOFS	87.245	87.245	0
GLASS CONDUCTION	59.194	59.194	0
GLASS SOLAR	46.952	46.952	0
INTERNAL SURFACE	0.287	0.287	0
OCCUPANTS	28.263	31.724	12.2
LIGHT	55.191	55.238	0.1
EQUIPMENT	8.478	24.996	194.8
INFILTRATION	3.992	3.992	0

Simulations are carried out to calculate the peak cooling load for both original and existing design and space usage. These calculations are required during the phase of equipment selection, because HVAC equipment are selected to meet the building peak cooling demand. Post modifications of peak electric and cooling load requirements of the building are presented in Table 5.3, which shows the major increment of 20.9 % electric usage, and 15.7 % in peak cooling load. This increase in peak load not only consumes more energy but also requires higher capacity equipment. These design issues should be considered during the planning stage of building retrofitting.

Table 5.3: Building Peak Load From The Simulation

	Peak Electric Energy Load (kW)	Peak Cooling Load (kW)
Original Design	131.5	485.1
Existing Design	159.0	561.2
Increment (%)	20.9	15.7

The building monthly energy usages are shown in Figure 5.1. Building total energy consumption is found maximum in the month of August, and the minimum in the month of February. The building monthly cooling energy usages are presented in Figure 5.2. From above two figures it is clearly observed that both follow a similar trend. Hence, it is proved that cooling contributed a significant part in the building total energy consumption, i.e., 65.7% of the building's annual energy consumption.

Figure 5.3 illustrated the monthly building electric energy usage. Electric energy consumption is the sum of the building's lighting and equipment energy. Since the electric energy consumed by lighting and equipment remains constant throughout the year, it is normally taken as a base load.

Increase in internal heat generating sources cause an increase in the building's peak cooling load. In Figures 5.4 and 5.5 the peak cooling load requirement for the zones of the third and fourth floor are shown. It is observed from these figures that peak cooling demand of

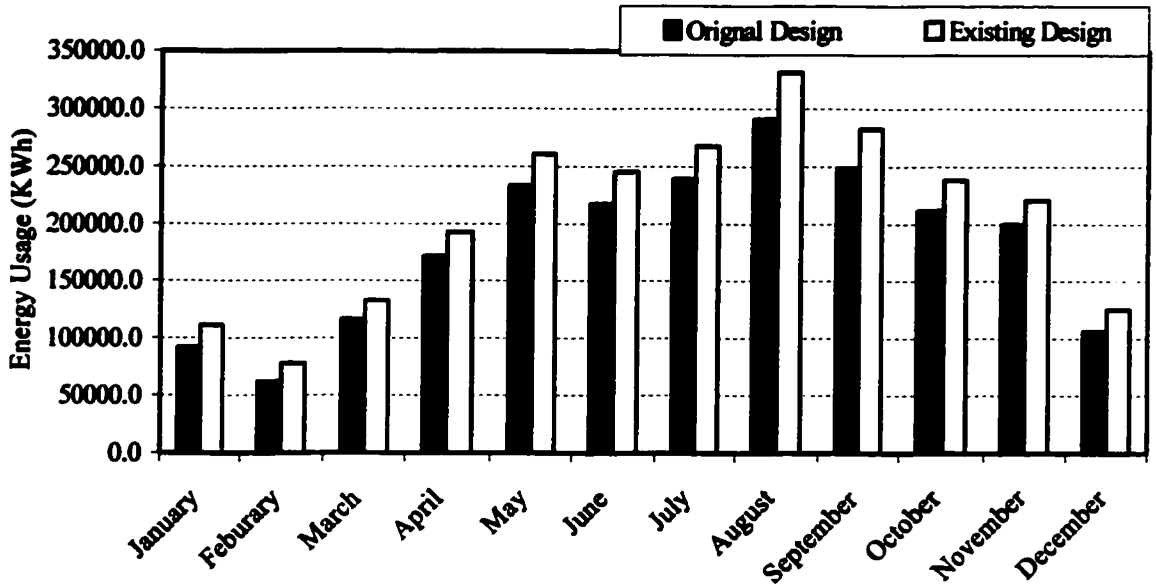


Figure 5.1: Building monthly total energy consumption.

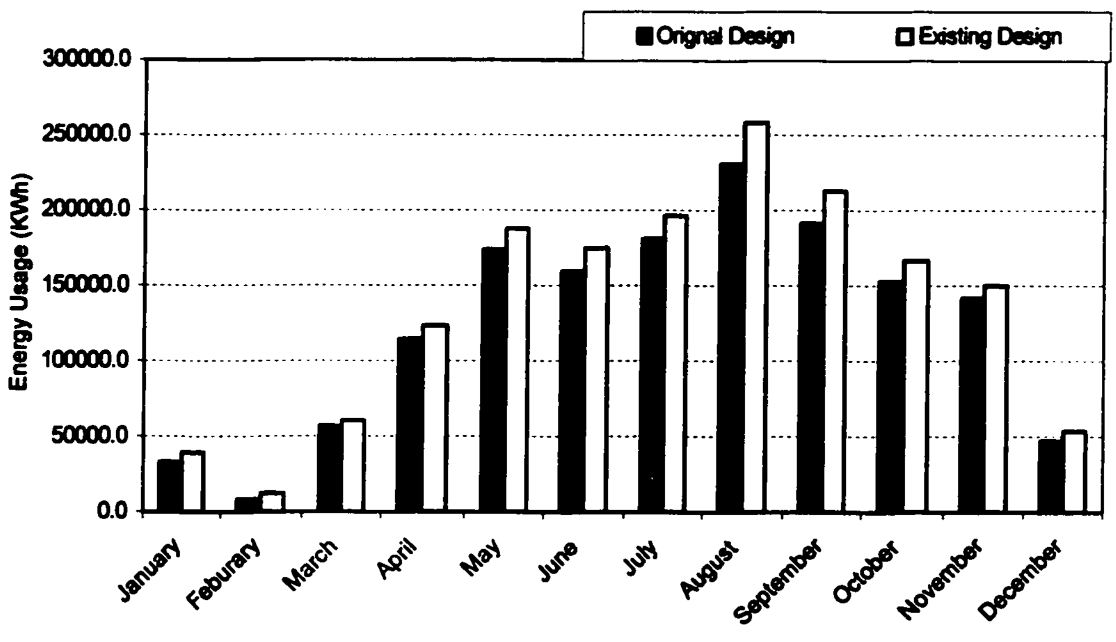


Figure 5.2: Building monthly Cooling energy consumption.

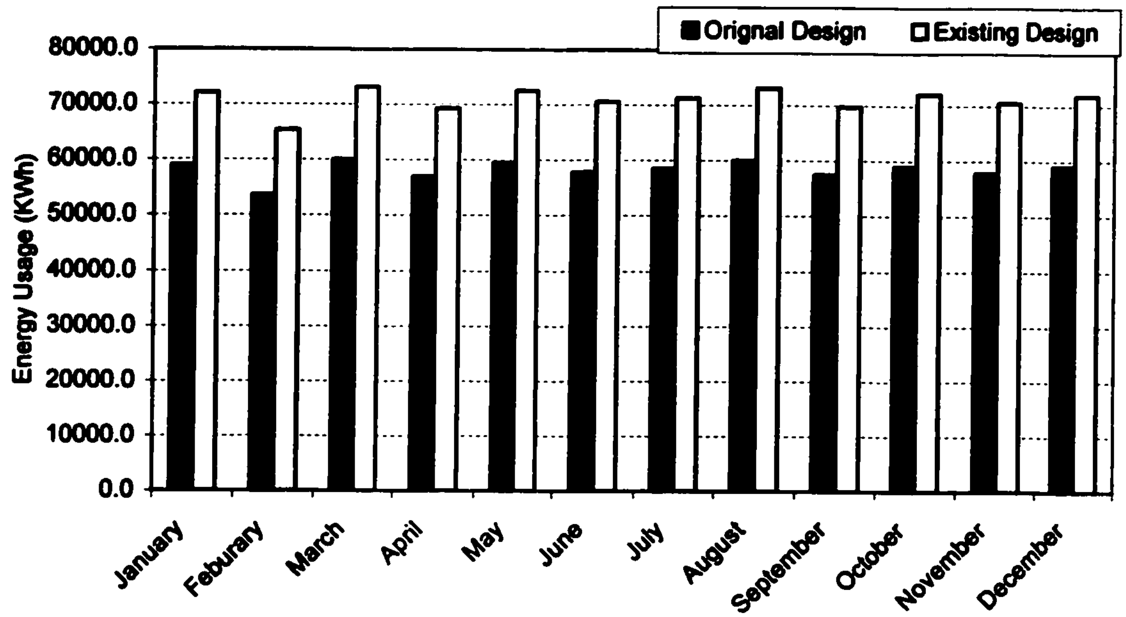


Figure 5.3: Building monthly electric energy consumption.

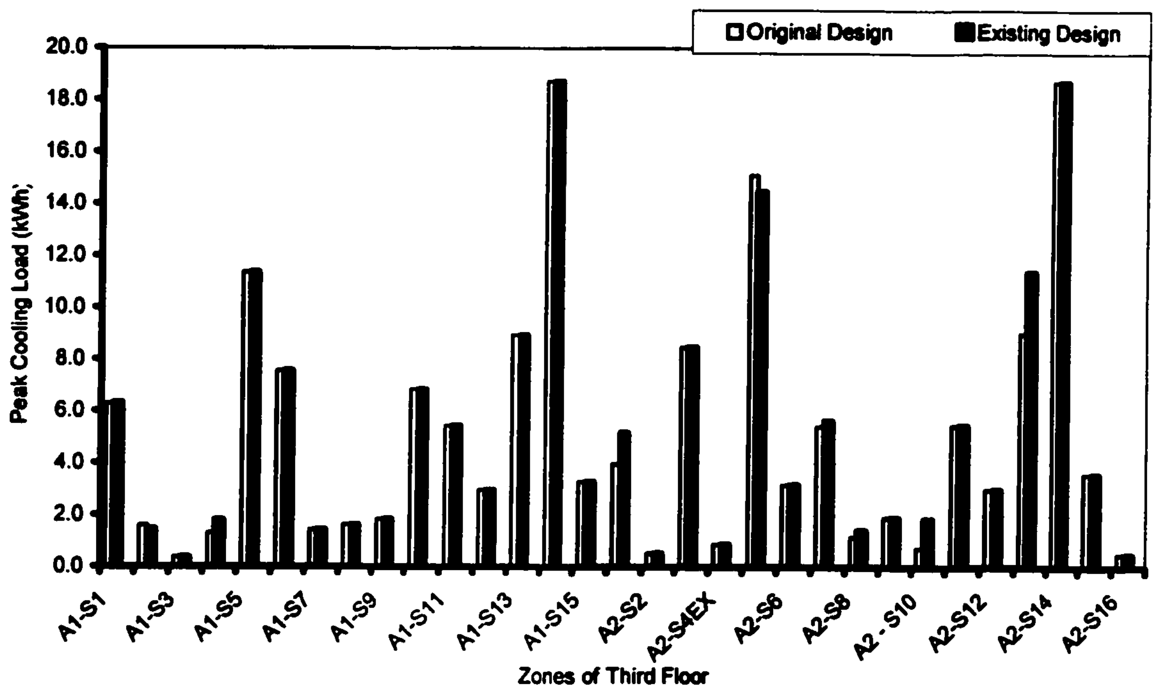


Figure 5.4: Third floor peak cooling demand.

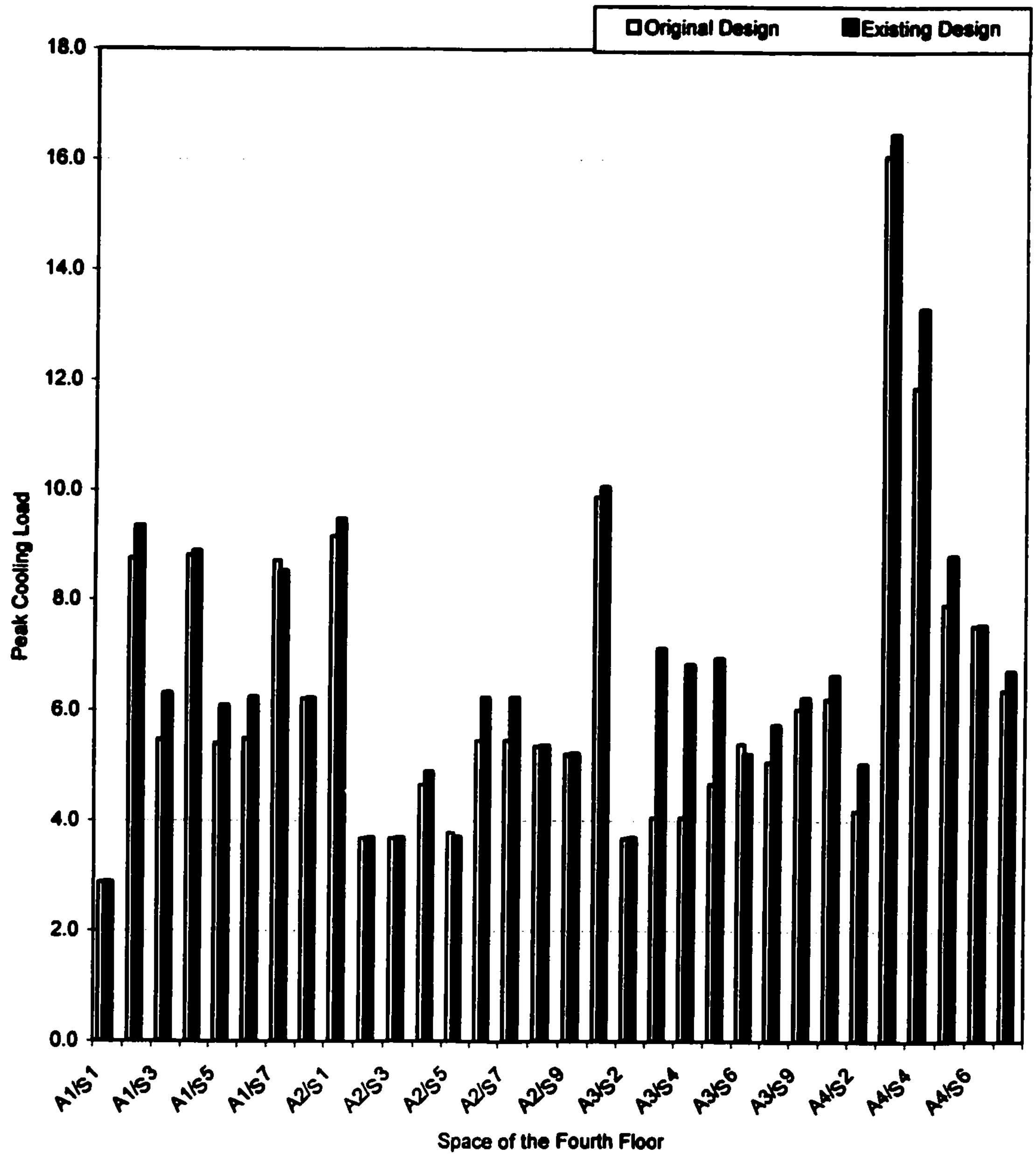


Figure 5.5: Fourth floor peak cooling demands.

few of the zones remain the same in comparison with the original design. For the remaining zones' peak cooling load is increased. The magnitude of the increase in peak cooling load depends on the nature of alterations performed in respective zones. This increase in internal cooling load needs more electric energy to maintain the required comfort conditions. For detailed studies, five thermal zones are selected which represented the minor and major modified zones. These zones are 3FA2S1, 4FA3S5, 4FA3S6, 4FA2S7, and 4FA3S3. Thermal zones 4FA3S5, 4FA3S6, 4FA3S3 and 4FA2S7 represented the major modified zones whereas 3FA2S7 represented the minor modified thermal zones.

Major Modified Zone 3FA2S1

Monthly cooling energy consumption of minor modified zone 3FA2S1 is shown in Figure 5.6. This zone was designed to be used as an audiovisual lab and its HVAC system was designed accordingly. Now after modifications the same zone is being used as a classroom. The existing peak load of the zone is slightly less than the original designed load and therefore resulting in a condition of overcooling as illustrated in Figure 5.6.

Major Modified Zone 4FA3S5

The monthly cooling energy consumption of major modified zone 4FA3S5 is shown in Figure 5.7. As per original design, thermal zone 4FA3S5 was a graduate studio, but now it is being used as a computer lab. Due to this change of usage, this zone is consuming more energy to cool this specific zone, as compared to its earlier usage.

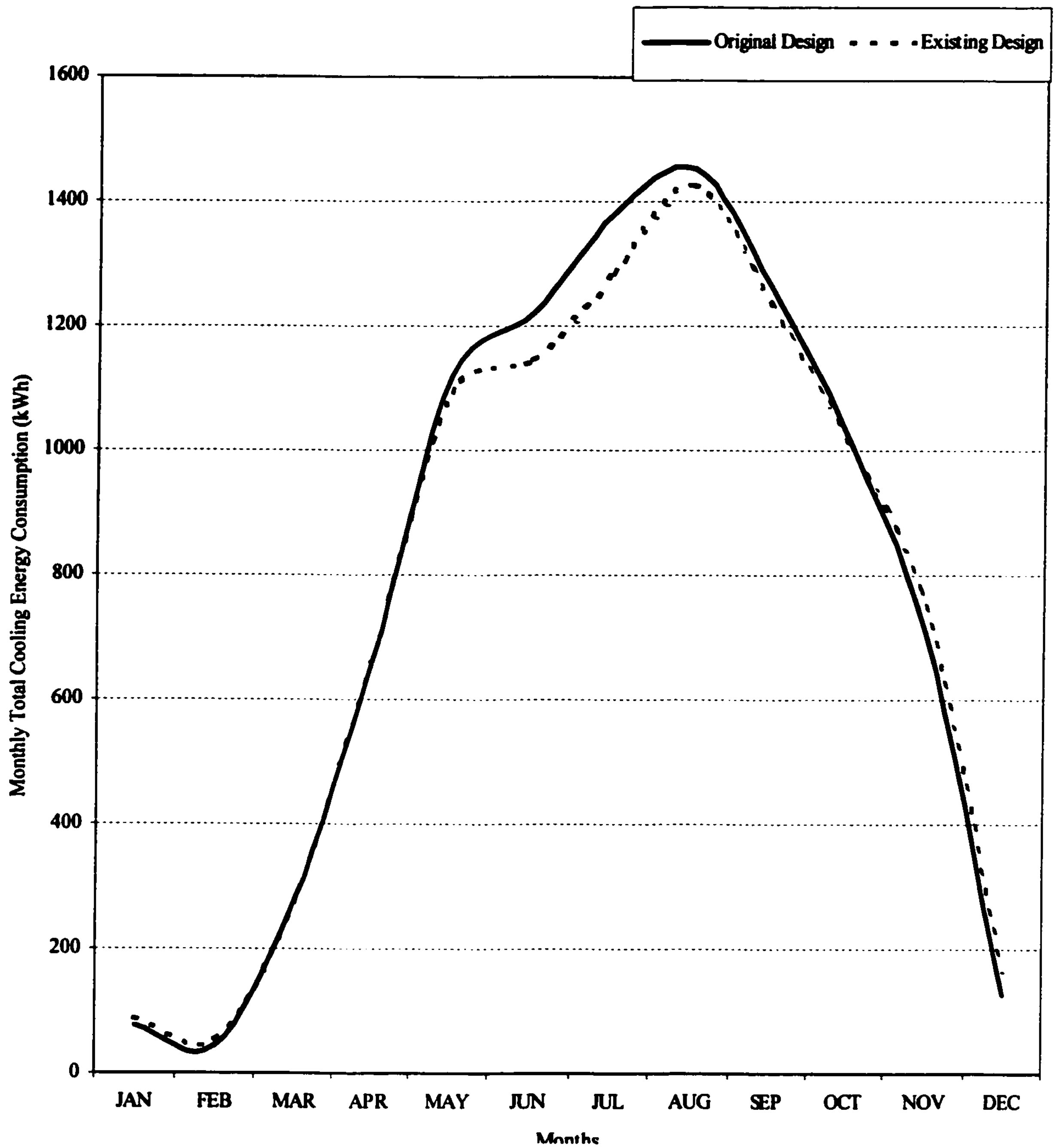


Figure 5.6: Monthly total cooling energy consumption of minor modified zone 3FA2S1

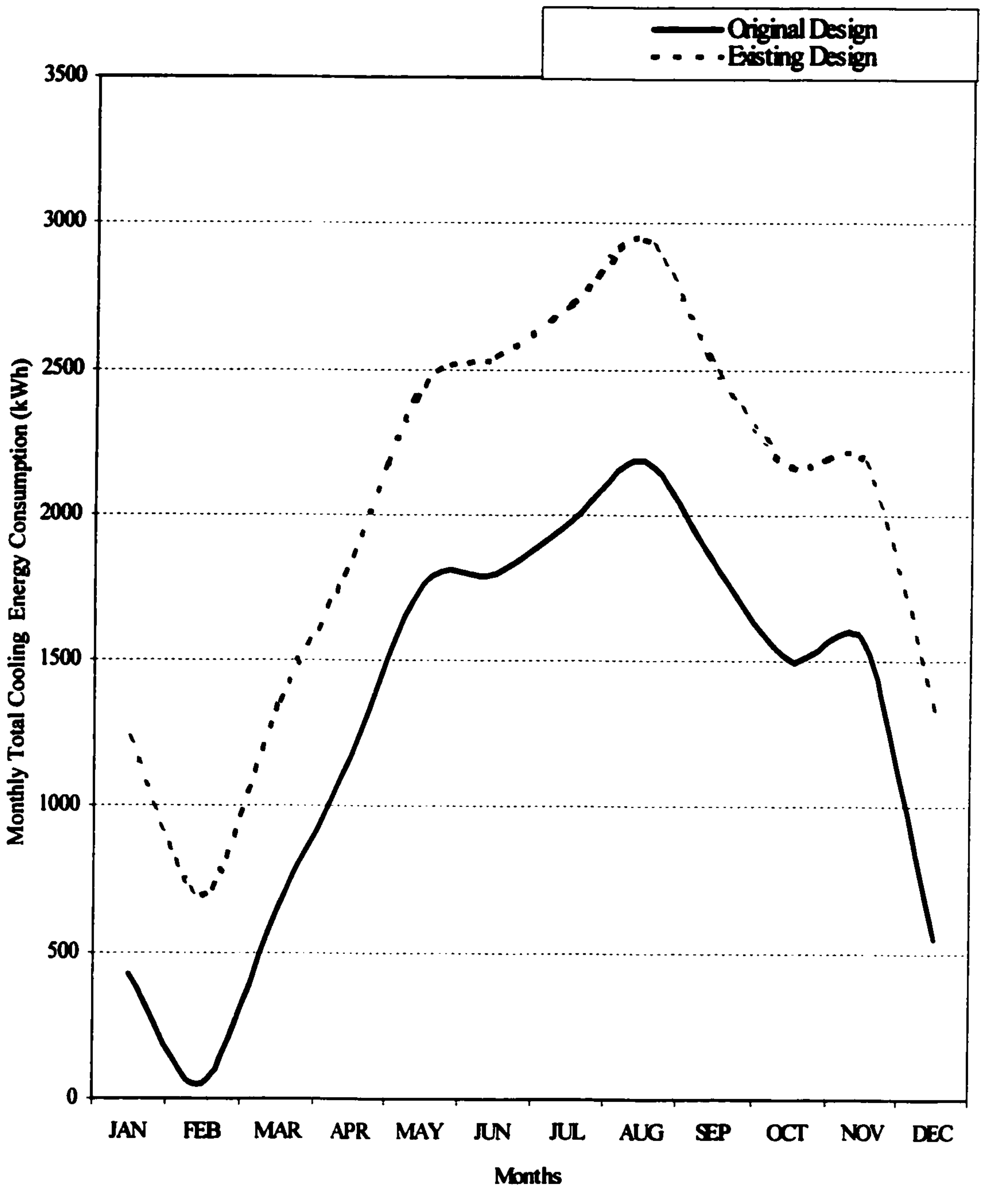


Figure 5.7: Monthly total cooling energy consumption of major modified zone 4FA3S5

Major Modified Zone 4FA3S5

The monthly cooling energy consumption for major modified zone 4FA3S6 is shown in Figure 5.8. This thermal zone was a graduate studio as per building original design, and now it is converted to chairman's office and secretaries' hall. Due to presence of computers and printers, additional cooling load was occurred that ultimately raise the monthly cooling energy requirements, for detail see Figure 5.8.

Major Modified Zone 4FA2S7

Originally the thermal zone 4FA2S7 was a big graduate studio. By using a partition wall, the graduate studio was converted to a faculty office and a wide corridor. Due to a change in space usage, (the building peak cooling load is increased and now more energy is required. The increase in cooling energy consumption is shown in Figure 5.9.

Major Modified Zone 4FA3S3

The monthly cooling energy consumption of major modified thermal zone 4FA3S3 is shown in Figure 5.10. According to original design the thermal zone 4FA3S3 was a design studio. As per existing design this zone is being used as a city and regional planning computer lab. The heat generated by computers, plotters and overhead projectors need to be compensated by more cooling.

The increment of 13% in building annual energy consumption is contributed by the above-mentioned cases shown in Figures 5.6 to 5.10. In

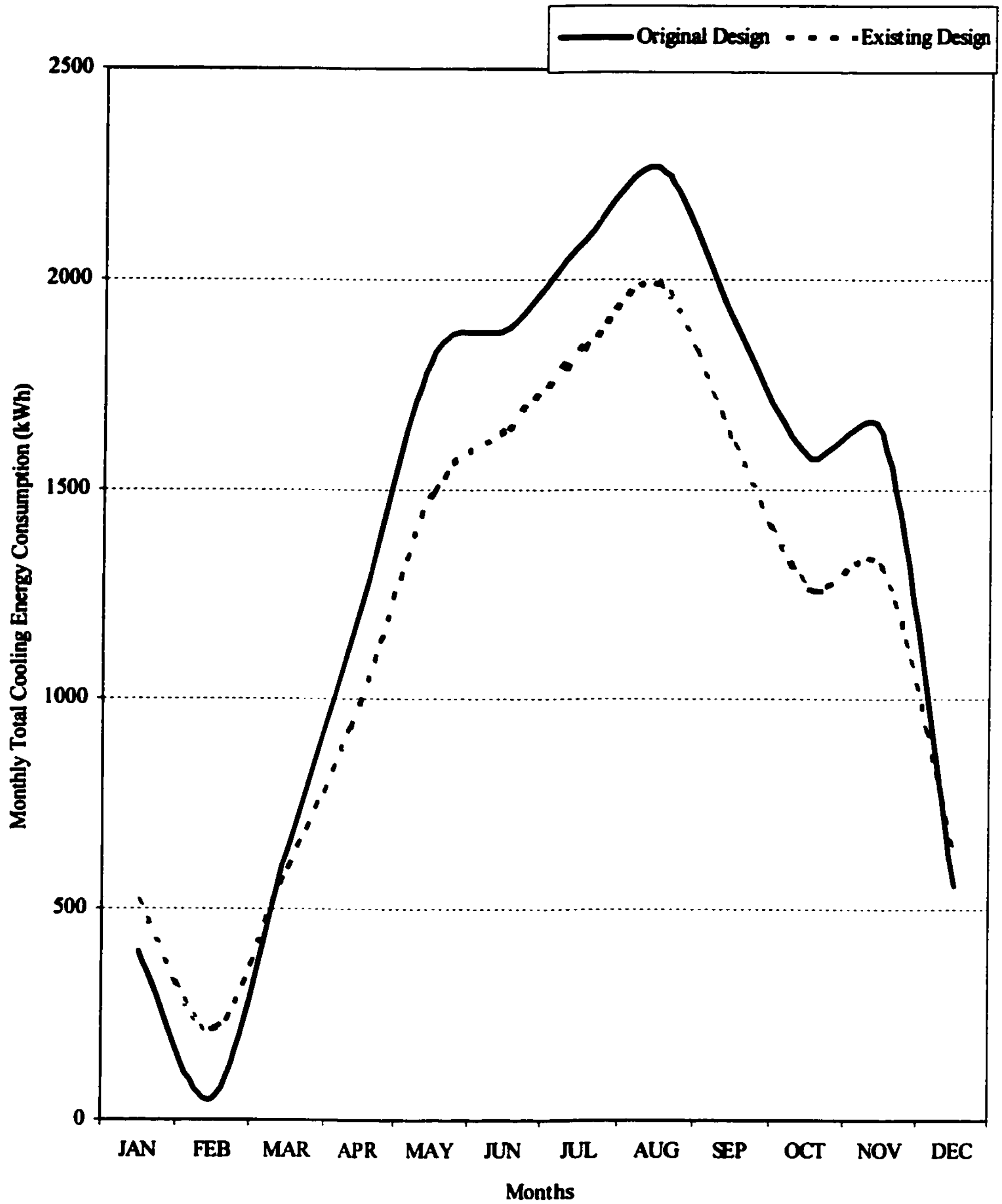


Figure 5.8: Monthly total cooling energy consumption of major modified zone 4FA3S6

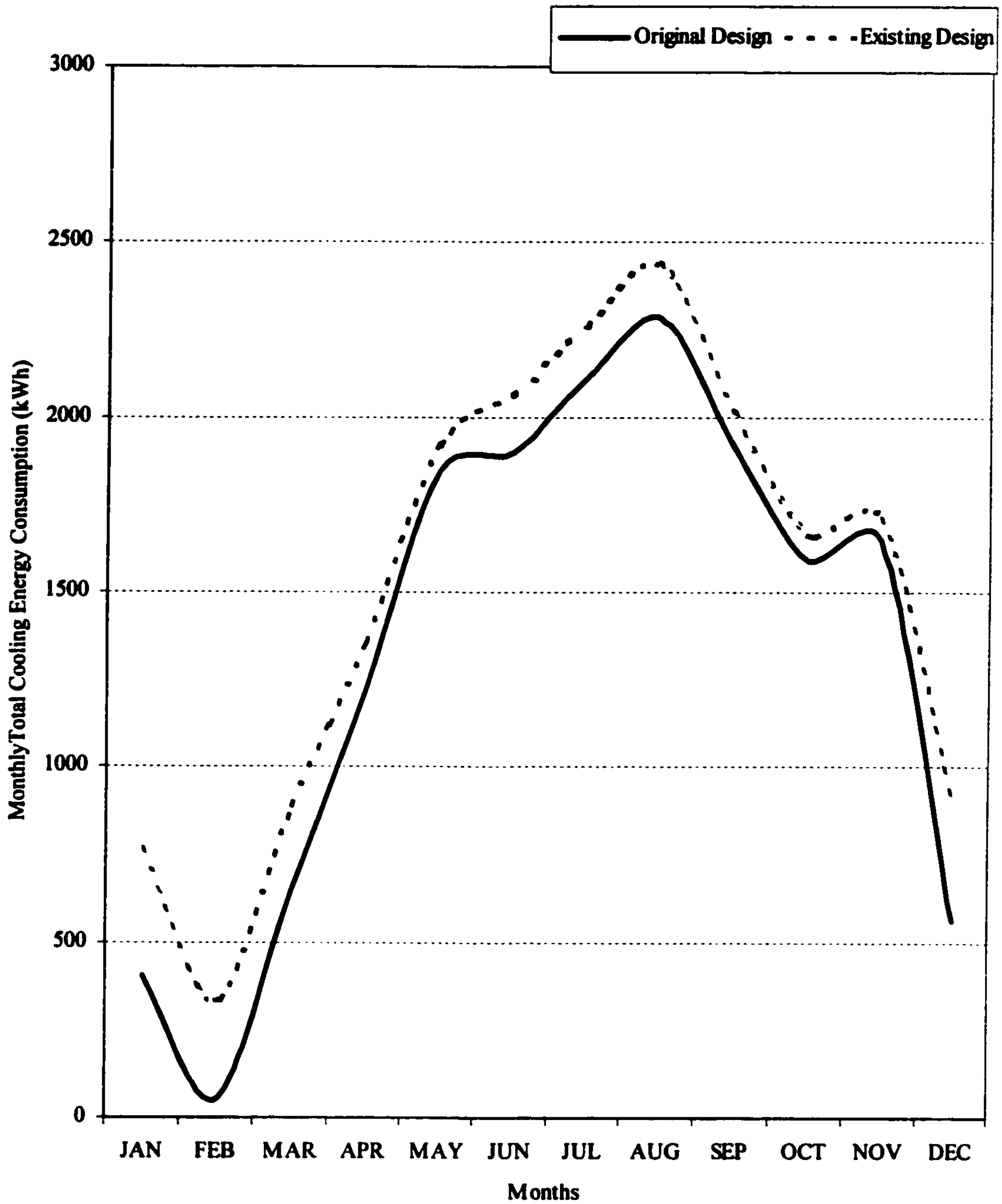


Figure 5.9: Monthly total cooling energy consumption of major modified zone 4FA2S7

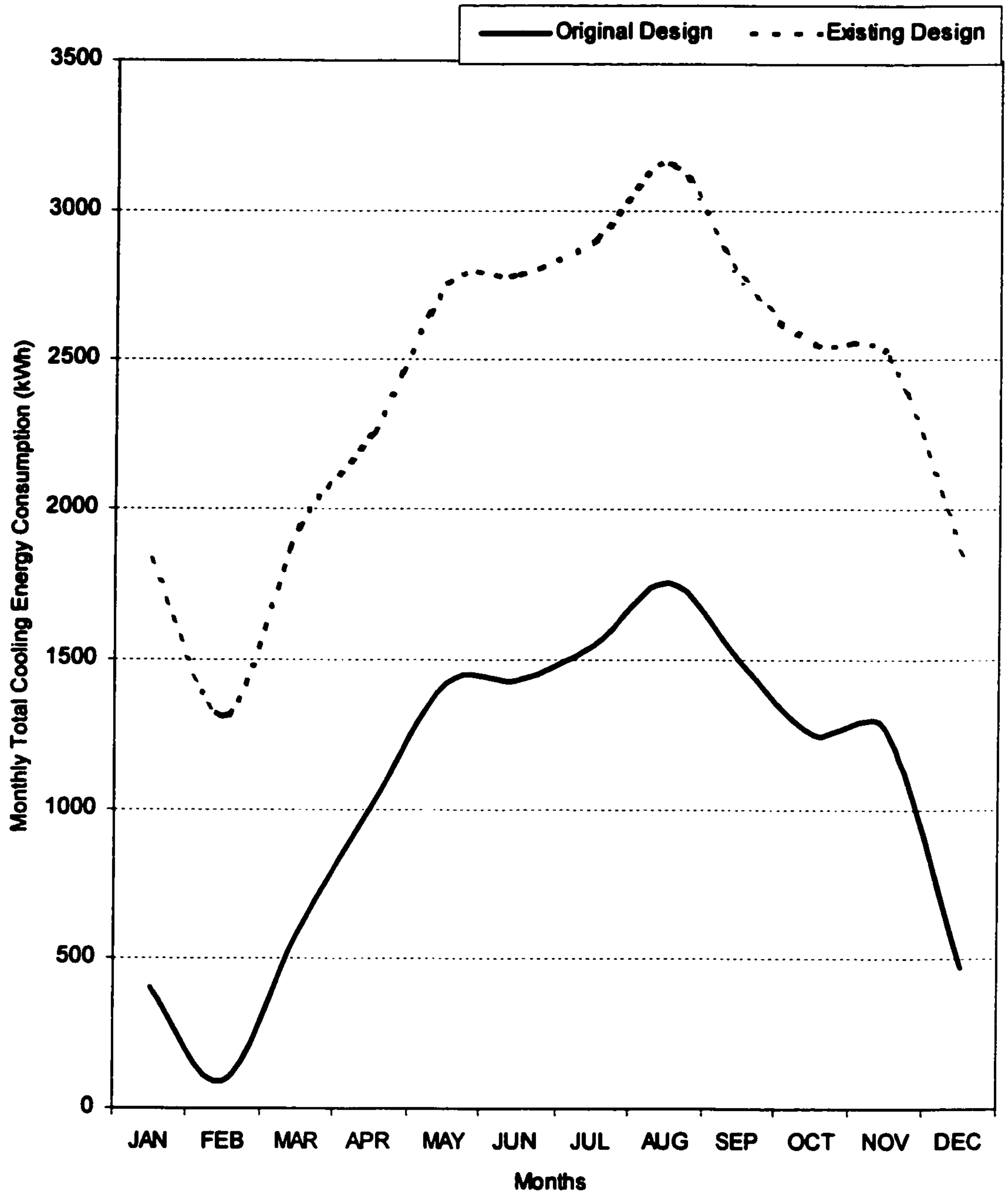


Figure 5.10: Monthly total cooling energy consumption of major modified zone 4FA3S3

addition to annual energy consumption, higher capacity equipments are also required to meet the excess cooling load.

5.2.1 Variation In Supply Airflow Demand Due To Alterations

The supply airflow of any zone or space is calculated according to its internal and envelope heat gain and it should be designed to meet the peak-cooling load of the space. Space of same dimensions with different internal cooling loads, may not have the same supply airflow. Hence, adjustment of the supply airflow is required for the case of variation in internal cooling load to achieve comfort conditions.

By using DOE - 2.1D simulations, building simulations were performed to calculate the required supply airflow of the various zones of the building. The comparison of the original designed airflow obtained from building HVAC drawings to different zones, existing supply air flow and required supply airflow as per existing design (obtained through simulations) are shown in Figures 5.11 and 5.12. Due to the change in the space usage and modifications through partition , requirements at various space supply airflow are changed. It was found that a few of the zones demand more supply air while most of them need less in comparison with their original design supply airflow. Those spaces, which are converted to labs and classrooms, need more supply airflow, because of over cooling and over heating is going on in these spaces. These spaces require adjustment in the supply airflow to achieve thermal comfort conditions for existing demand.

Supply airflow is an important building design parameter, which affects space comfort conditions. To compare existing supply airflow with the original design supply airflow for the selected spaces, a comparative

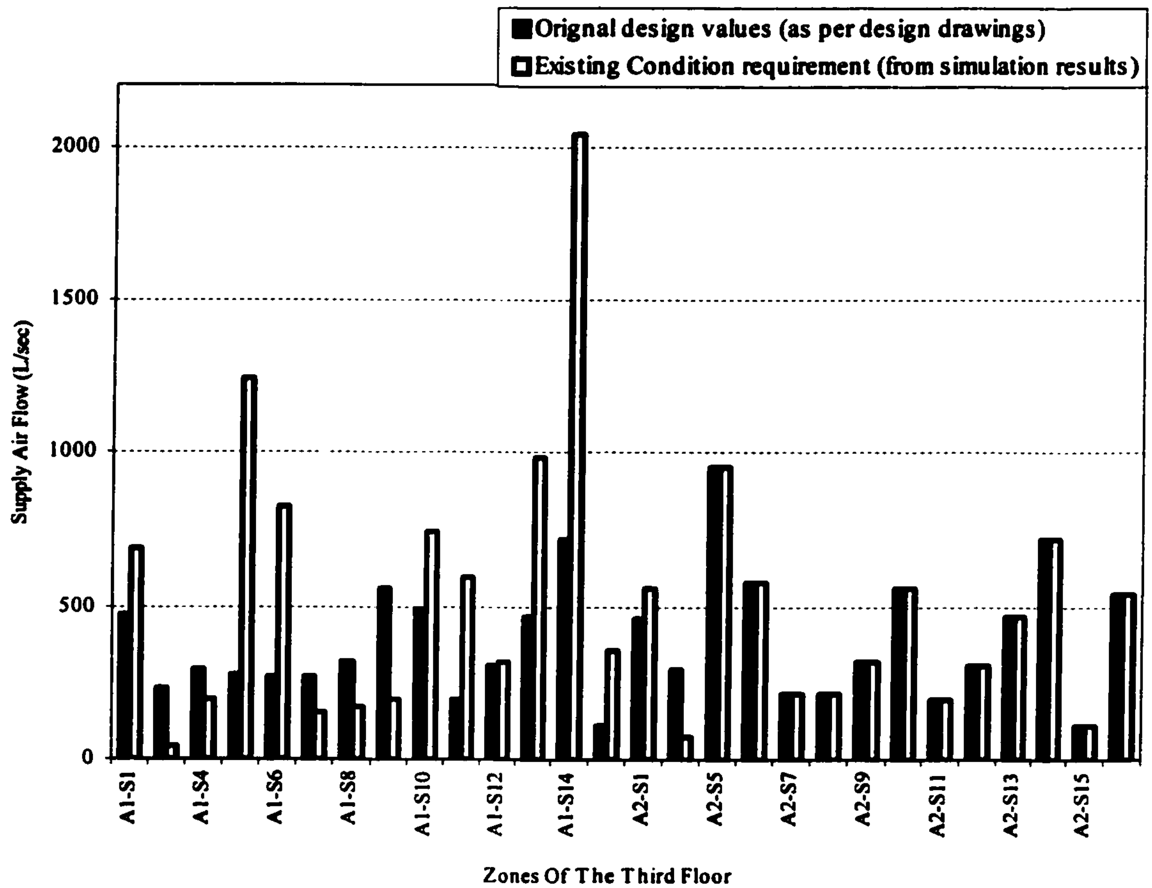


Figure 5.11: Comparison of the supply airflow for the third floor building 19.

bar chart is drawn, shown in Figure 5.13. The required supply airflow is calculated through simulations. It is observed from the Figure 5.13 and Table 5.4 that supply airflow at few zones are adjusted after the alteration in the building's partitions but in the case of room 445, 417 and 401 there

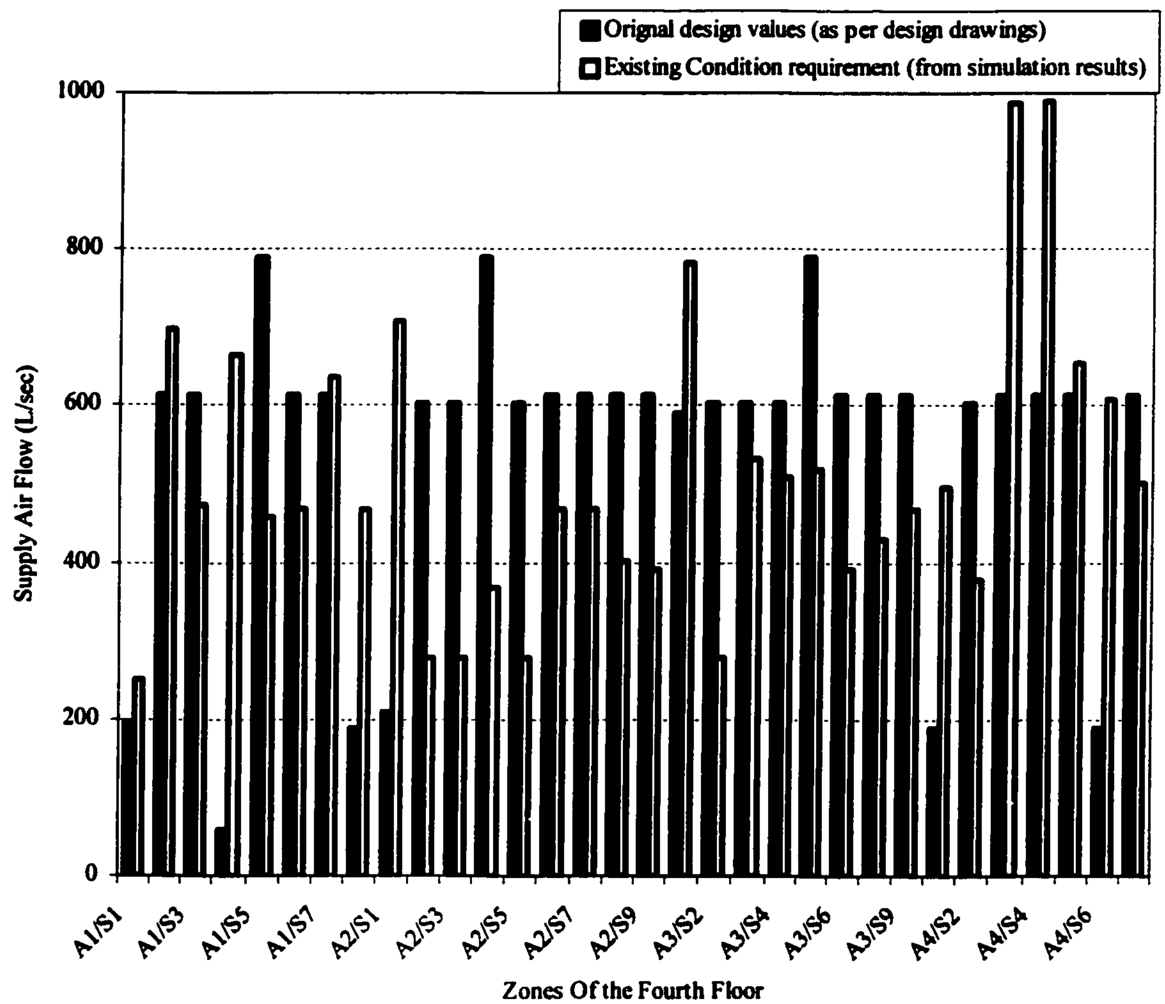


Figure 5.12: Comparison of the supply airflow for the fourth floor building 19.

are big differences between the measured value and original design value. In rooms like 447, 449 and 452, minimum difference between the design and existing measured supply airflow rates. Also, there are rooms where the supply airflow is unchanged like rooms 319, 330, 333 and 336. Hence, it is found that adjustments were performed in a few of the rooms but after collecting the response from the building's occupants (discussed in section 5.3), it is recommended to have a complete air balancing of the building.

By comparing the required supply airflow (required supply airflow values are not representing the specific rooms, these values are average zone supply airflow, because modeling was performed on the bases of the building's thermal zone not on the basis of the rooms) with the existing measured airflow, it is observed that adjustments in supply airflow are not done by performing cooling load calculations, because in a few of the rooms the required flow is found less but the measured value is quite high, specially in the cases of room 445 and 401. In the few rooms the supply airflow requirements are quite high but the post-adjusted flow is not meeting the demand. Rooms 452, 333 and 336 can be taken as a reference, for detail see Figure 5.13. Hence, the complaints of the occupants are justified by reviewing the comparison of these supply airflow rates to selected spaces.

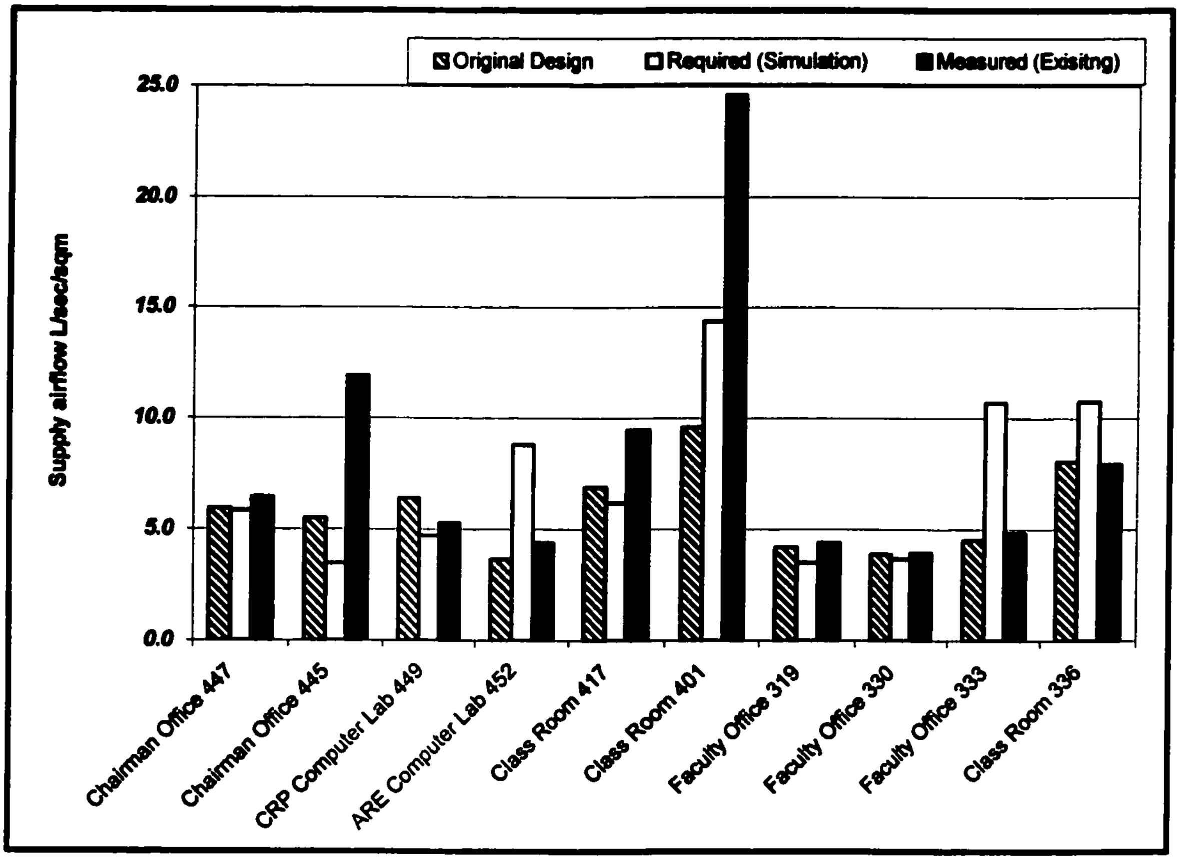


Figure 5.13: Supply airflow according to original design, measured value and required airflow obtained through simulaiton

Table 5.4: A Comparison Between The Original Design and Measure Supply Air Flow

	Supply Airflow (L/sec/m²)		Difference
	Original Design	Measured	
Chairman Office 447	5.93	6.45	8.70
Chairman Office 445	5.51	11.90	115.97
CRP Computer Lab 449	6.41	5.30	17.28
ARE Computer Lab 452	3.64	4.40	20.88
Class Room 417	6.89	9.48	37.65
Class Room 401	9.60	24.60	156.18
Faculty Office 319	4.20	4.40	4.72
Faculty Office 330	3.88	3.94	1.58
Faculty Office 333	4.53	4.84	6.96
Class Room 336	8.05	7.95	1.27

The simulation results show the increment of 13.6 % in the annual energy consumption and 15.6 % increase in peak cooling load. This shows that there is a need to install higher capacity cooling equipment. However, the system is currently running and the seriousness of this issue is not judged so critically that it would compel the concerned departments to install the higher capacity equipment. Furthermore, if there is a need to increase the capacity of HVAC equipment due to an increase in occupancy and equipment load, it is also not well reflected from the space temperature profiles (shown in section 5.3). The reason behind this observation is that, by decreasing the amount of fresh air supply to the HVAC equipment, additional load is encountered. Although this is a very simple and easy solution to deal with, additional cooling load without additional equipment, to maintain comfort for the cost of poor air quality is not wise. The current amount of fresh air supply is 2.4% of the total supply air and as per original design it should be 10%, for details see Table 5.5. Hence, it is recommended to recalculate the building's cooling load according to its existing partition system and usage, so that proper air quality and quantity would be supplied to each room in order to achieve a required comfort level as per ASHRAE standard 55-92.

Table 5.5: Fresh Air Supply to Air Handling Units

	Original Design	Existing Design
	L/sec	L/sec
Supply Air	16676	16676
Fresh Air	1770	400
Fresh Air as a Percentage of Supply Air	10.3%	2.40%

5.3 THERMAL COMFORT ANALYSES

To assess the thermal comfort conditions of the case study building qualitative and quantitative analyses were performed. The details of these investigations are mentioned in chapter 4. The results are presented and discussed on the basis of categories in which these spaces were categorized, i.e., major, minor and unmodified spaces. Before discussing them initially the general response of the occupants are mentioned regarding their age, nature of responsibilities and duration of stay in the building.

During the August survey, 164 occupants responded to the questionnaire, while in the October survey, 246 occupants responded, to the questionnaire. During the August survey, fewer occupants were visited due to summer vocation the occupants were found to be fewer than average occupancy of the building. During the August survey, around 70-80% of the respondents were those who were using the space for less than a semester, as shown in Table 5.6. While during October this percentage was lowered to 38.7 % as shown Table 5.7. Most of the visited occupants were using the building for about a year.

Table 5.6: Respondent Nature of Work

	Nature of Changes in Space		
	Major	Minor	Unmodified
	August Survey		
Faculty	1.6	1.4	0.0
Student	97.6	94.3	93.6
Other	0.8	4.3	6.4
	October Survey		
Faculty	6.7	28.3	0.0
Student	89.3	89.1	100.0
Other	4.0	4.3	0.0

Table 5.7: Respondent's Duration of Stay in Space

	Nature of Changes in Space		
	Major	Minor	Unmodified
	August Survey		
Less than a Semester	70.6	80.0	71.1
A year	13.5	4.3	8.9
More than a year	15.9	15.7	20.0
	October Survey		
Less than a Semester	38.7	23.9	6.7
A year	30.7	73.9	80.0
More than a year	30.7	23.9	13.3

The hourly occupancy variation is shown in Table 5.8. During August most of the surveyed occupants were students. Around 60 to 70% of them stayed for less than an hour in all three categories of spaces. The October survey was conducted among the building's regular occupants, especially in the categories of major and minor modified areas. Around 20 to 30 % of occupants surveyed stayed one hour in the building, while 8 to 22 % of the occupants stayed for 4 to 6 hours per day in the building.

Table 5.8: Respondent's Duration of Stay Per Day in Space

	Nature of Changes in Space		
	Major	Minor	Unmodified
	August Survey		
Less than a Semester	74.6	60.0	67.4
1 - 4 hrs	13.5	28.6	13.0
4 - 6 hrs	3.2	1.4	2.2
6 - 8 hrs	4.0	2.9	4.3
More than 8 hrs	4.8	7.1	13.0
	October Survey		
Less than a Semester	49.3	60.9	93.3
1 - 4 hrs	20.0	39.1	6.7
4 - 6 hrs	22.7	8.7	0.0
6 - 8 hrs	8.0	10.9	0.0
More than 8 hrs	0.0	2.2	0.0

In the next section, the analysis of the survey is according to the nature of changes performed in the spaces.

5.3.1 Major Modified Spaces

Air temperature is the most important environmental parameter for the assessment of human comfort conditions. For this purpose, the question of sensation of temperature was included in the questionnaire. Occupants' response for the space air temperature in major modified spaces is shown in Figure 5.14. It is observed from the figure that these spaces are overcooled because supply airflow is not well adjusted according to the internal partitions and heat generating sources. Although the local weather conditions are very hot and humid still there are complaints of overcooling inside the building. The occupants' complaints of overcooling occur more during October in comparison to the August survey . For details see figure 5.14.

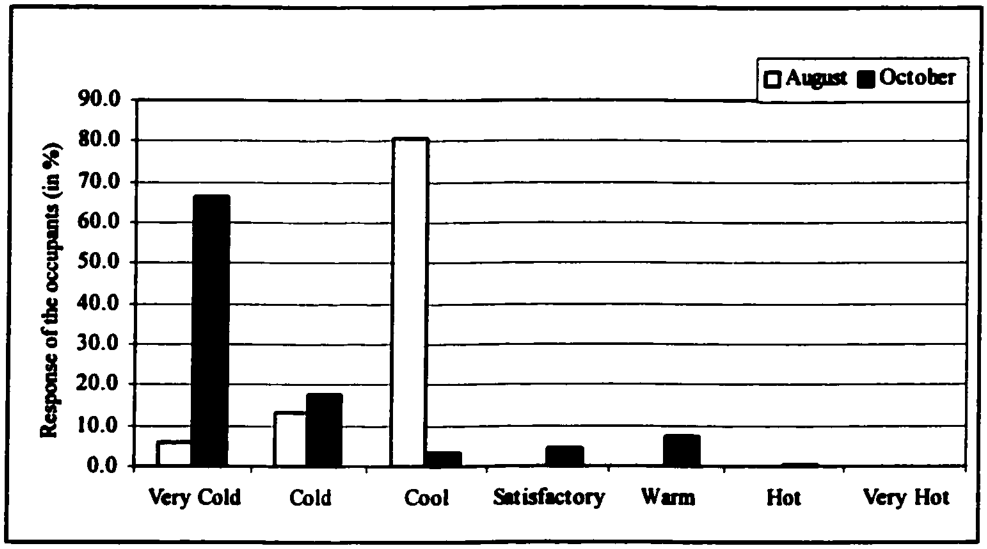


Figure 5.14: Response of the occupants for space temperature in major modified spaces.

Space relative humidity is an important environmental parameter, which directly affects comfort. In the current study it was included in the questionnaire due to its importance. The survey results, for the occupant response for relative humidity of major modified spaces are shown in Figure 5.15. The survey results conducted in August revealed that the most of the complaints were about humid environment; while in the October survey the most of the complaints were about dry indoor conditions.

In addition to space temperature and relative humidity, space air velocity is also an important environmental parameter to determine the occupants' thermal comfort. Occupants' response for space air motion is shown in Figure 5.16. It is observed in the August survey, that most of the

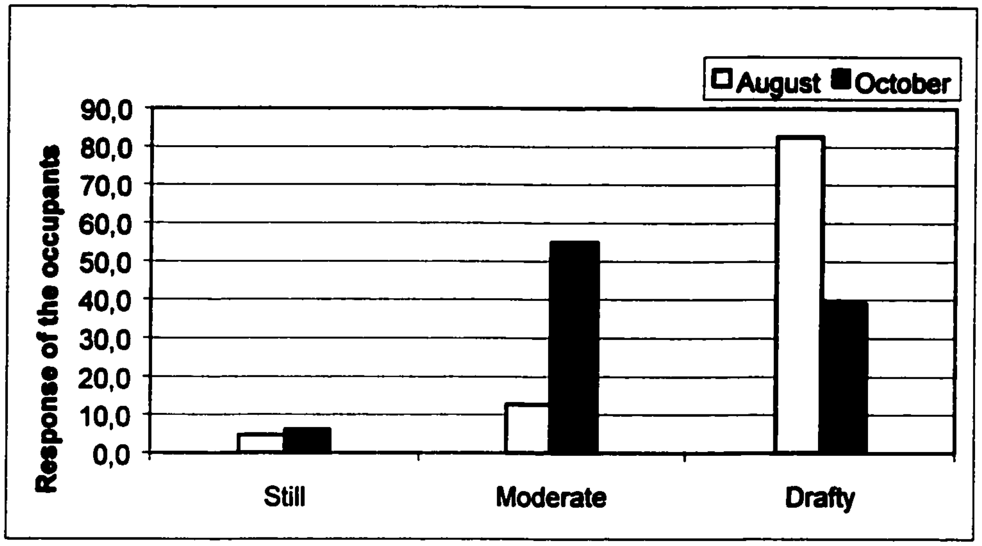


Figure 5.15: Response of the occupants for space relative Humidity in major modified spaces

occupants complained for an air draft. This complaint is further justified by reviewing the response of the occupants for low space temperature in the major modified spaces as shown in Figure 5.14. While in the October survey there were a few complaints of air draft (39 %) but the majority of the occupants reported moderate air motion. There were a few complaints of still air in both the survey results. The main reason behind these complaints of air draft and still air is the lack of air balancing and addition or removal of partitions. Due to these alterations, supply airflow is either more or less than the requirement, causing problems of thermal comfort. Response of the occupants for the overall comfort conditions was collected, so that the occupants' comfort could be evaluated. Figure 5.17 shows the response of overall conditions from the occupants of the major modified spaces. During the August survey, a majority of the occupants reported moderately comfortable conditions. While a few of

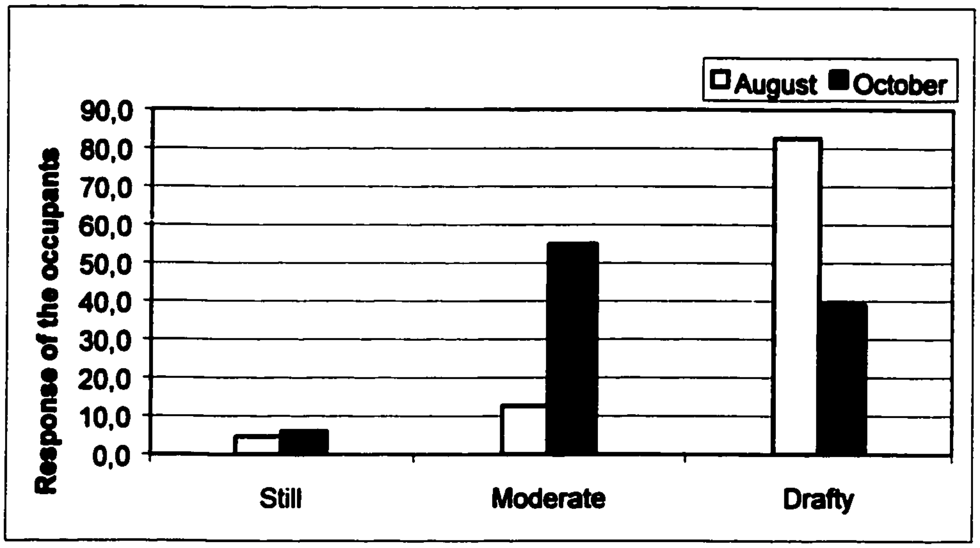


Figure 5.16: Response of the occupants for space air motion in major modified spaces

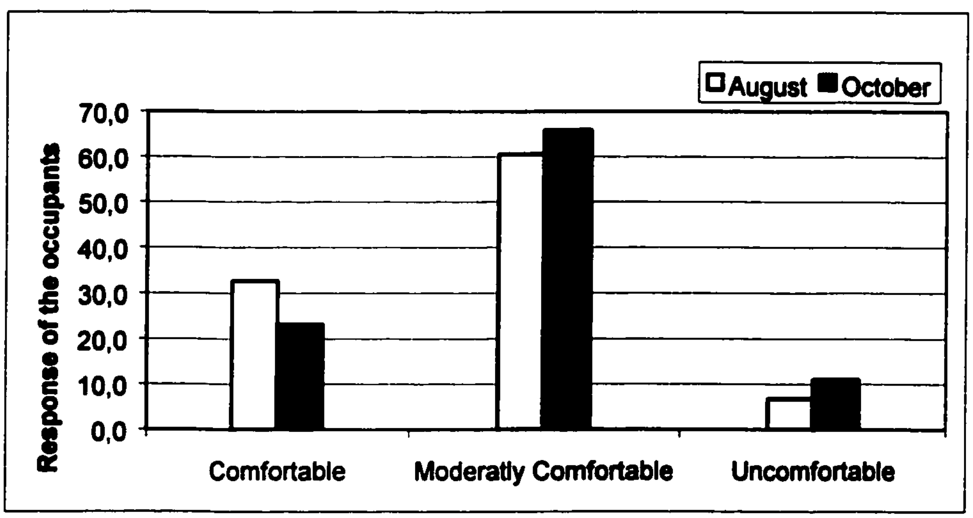


Figure 5.17: Response of the occupants for space overall conditions in major modified spaces.

respondents (32 %) satisfied with the indoor conditions. For the October survey, the majority of the occupants (65%) reported moderately comfortable conditions, while a response for feeling comfortable is only found to be 23%, which is less than the response for the August survey. While a response of uncomfortable condition is observed during both surveys, for the case of the October survey it is more. Hence, it could be concluded that the overall comfortable conditions of summer are better than winter in major modified spaces. The main reason of getting complaints of uncomfortable conditions in October's survey is due to the overcooling in these spaces, malfunction of the control devices and poor location of thermostats.

Impact of seasonal variation on the thermal comfort of the occupants was also enquired through the questionnaire. It was observed the in the October survey, which was a heating season, there were complaints about summer being an unpleasant season but still a few of the building's occupants reported winter as an uncomfortable season during the summer survey. While in the October survey, most of the complaints (75 %) were reported uncomfortable during winter. Hence, it is observed that the winter is the most uncomfortable season for the occupants of major modified spaces. For details see Figure 5.18.

The response of the occupants for which time of the day they feel most uncomfortable is shown in Figure 5.19. It is observed that for the case of summer, a majority of responses were for noon as the most uncomfortable time. While in winter the most uncomfortable time was reported for the evening. For details see figure 5.19. The reasons behind these complaints are due to the poor location of thermostats, poor air distribution and improper cooling.

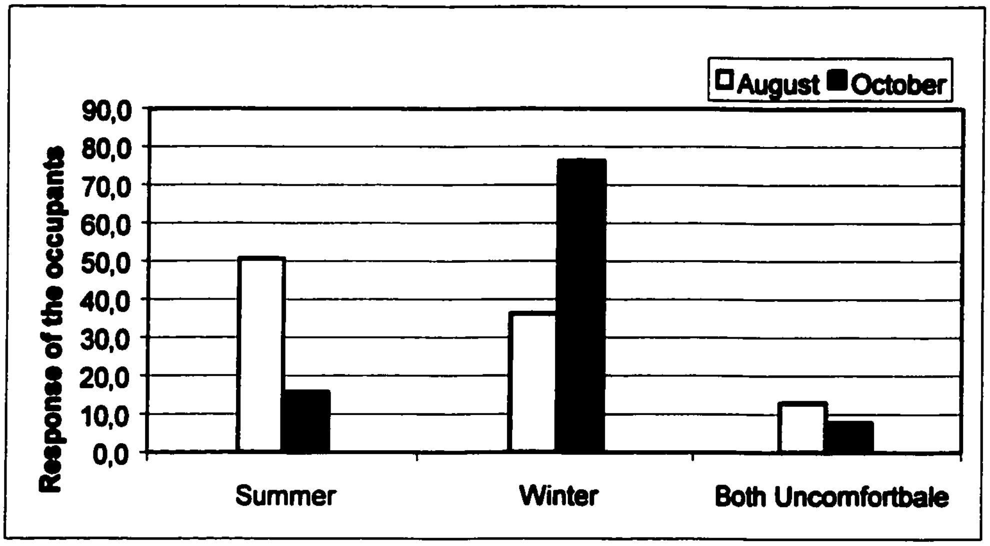


Figure 5.18: Response of the occupants for which season they feel most uncomfortable

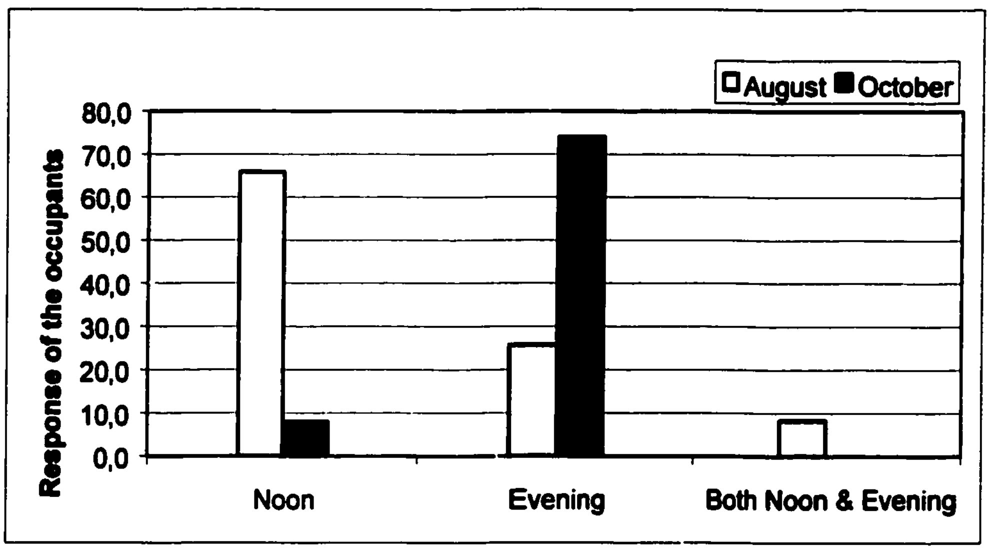


Figure 5.19: Response of the occupants for which time of the day they feel most uncomfortable

Quantitative analysis was performed in major modified spaces for the detailed evaluation of space thermal conditions. Four of the rooms were selected to represent major modified spaces. These spaces were selected due to the reasons these reasons: complaints of improper cooling, space change of functions, alteration in partitions and absence of thermostats. Classroom 401 and 417, faculty office 445 and computer lab 449 were selected to measure temperature and relative humidity readings.

Room 401 was originally designed to be used as a faculty office but later on it was converted to classroom. The electrical and HVAC systems of the spaces were designed accordingly. Being getting complained room building occupants, the supply airflow was raised to 24.60 $l/sec/m^2$ from 9.60 $l/sec/m^2$. The HVAC system was incompatible to handle this amount of supply air. In addition to overcooling, there were other problems which were observed during the survey for e.g., whistling noise of air and feelings of air draft near diffusers. The thermostat of the room was also not functioning. Due to absence of control devices, the overcooling problem could not be rectified, which was further proved from the temperature and relative humidity profile of the room. This is shown in Figure 5.20. In October readings of temperature are between 22 ^{o}C to 23 ^{o}C, causing an overcooling problem. Relative humidity readings are well inside the comfort limits; hence, the major problem in overcooling is due to an excess supply of air and faulty thermostat. It is strictly recommended to recalculate the cooling load of the spaces so that proper air balancing could be carried out along with replacement of malfunctioning thermostats.

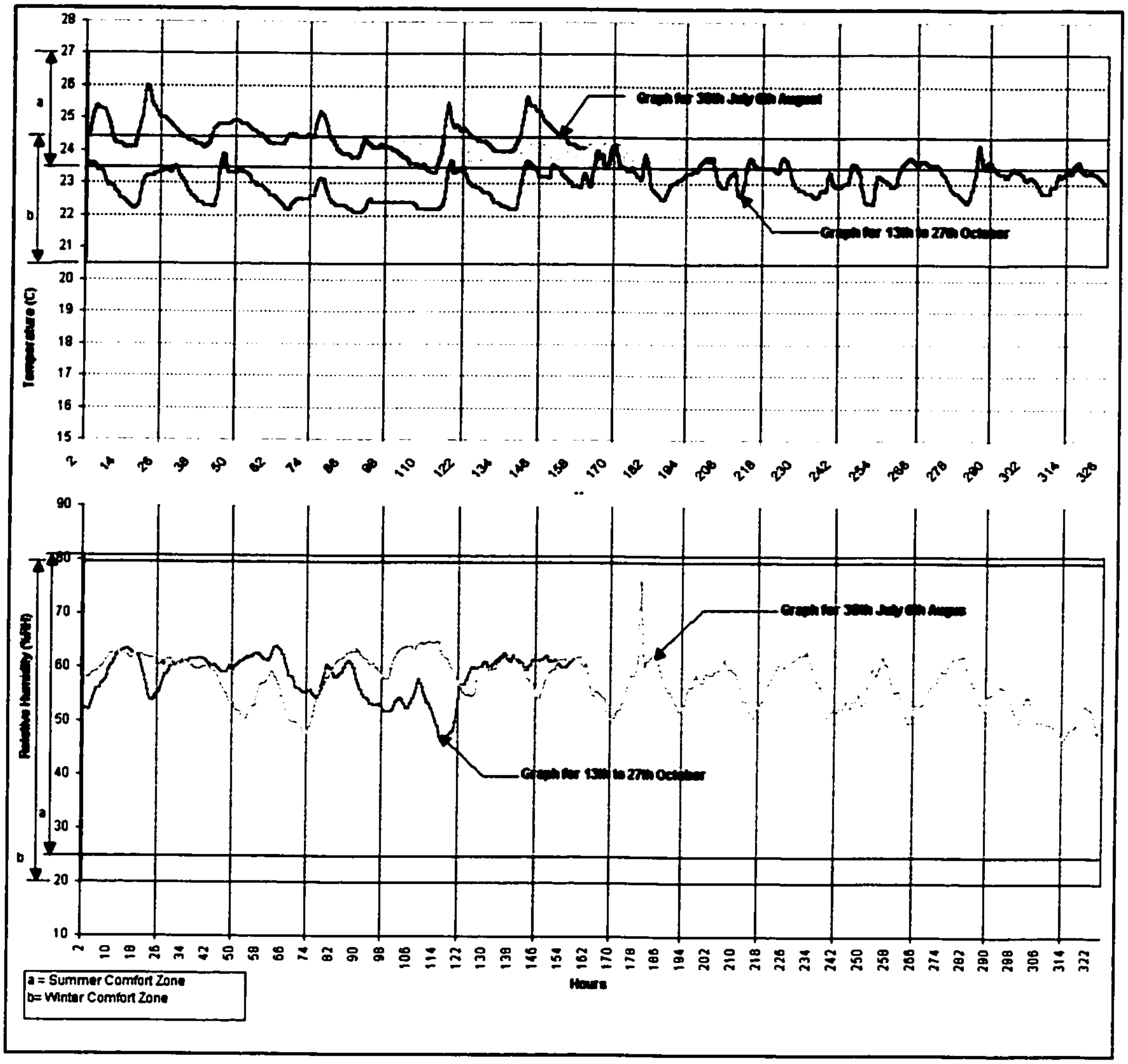


Figure 5.20: Temperature and Relative Humidity Profiles of Room 401

A similar problem of overcooling is also witnessed for the case of room 417, which was a Graduate Assistant (GA) lab, the room was converted to a classroom by partitioning the room in two parts. Due to this partitioning, the temperature of room 417 is now controlled by a thermostat which is located outside the room. Since, the room was originally designed to be used as GA lab, to satisfy the increase in occupancy the supply airflow was raised from 6.89 l/sec/m^2 to 9.48 l/sec/m^2. Since the adjustments of the supply airflow was not performed through proper calculation, airflow is found more than what is required. Temperature profiles of room 417 are shown in Figure 5.21, showing mostly low temperature. Hence, the complaints of the occupants for the overcooling are justified. The main reason behind the problem of thermal discomfort is the poor location of a thermostat and an improper air mixing due to partitions causing blockage of proper air mixing.

Another selected space representing a major modified space is room 445, which was a part of the GA lab before alteration of partition. The space was not originally designed to take the load of computers, printers and other heat generating equipment. Hence, to meet the cooling requirements, supply airflow was raised from 5.51 l/sec-m^2 to 11.90 l/sec-m^2. The existing airflow is more than the requirement, thus overcooling has occurred. Temperature profiles of room 445 are shown in Figure 5.22. The main reason behind this overcooling is the excess supply airflow, absence of a thermostat and poor air mixing. It is recommend that to recaluate the cooling load as per existing design and usage, so that proper air balancing could be performed.

Computer lab 449 is selected to represent a major modified space. It was established by dividing a graduate studio, using low height partition

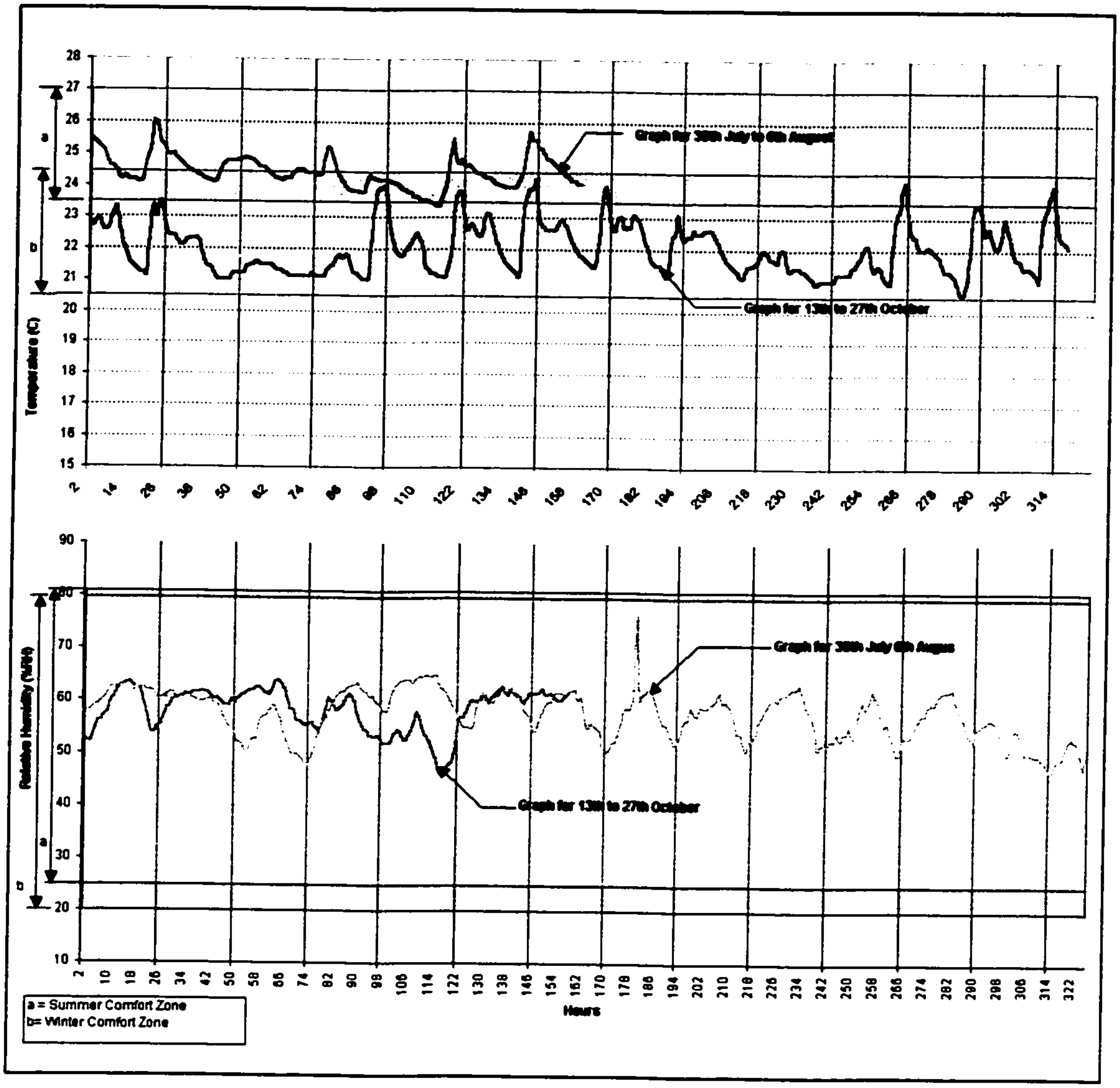


Figure 5.21: Temperature and Relative Humidity Profiles of Room 417

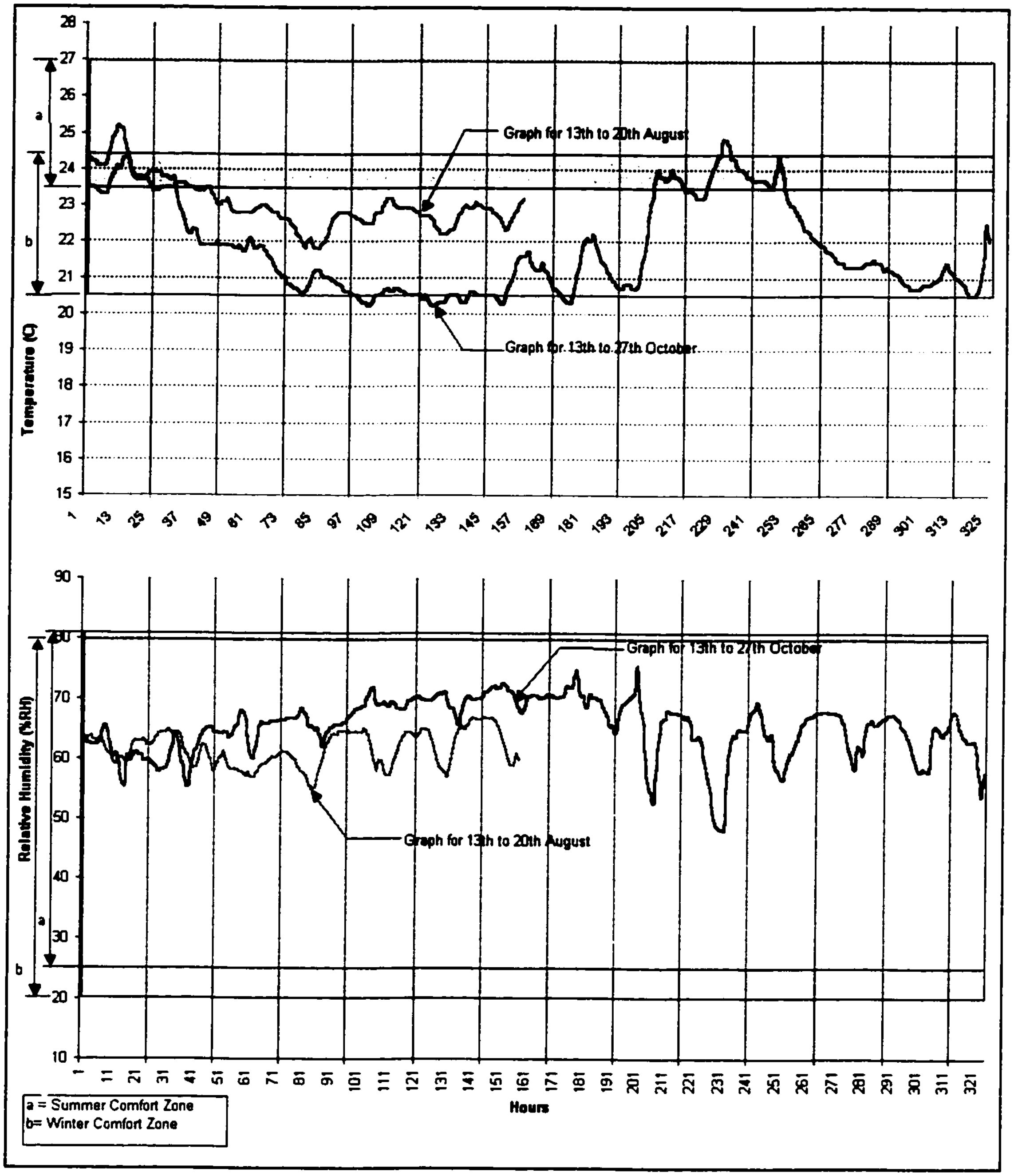


Figure 5.22: Temperature and Relative Humidity Profiles of Room 445

walls. Thermostat of the room is located in the corridor due to partitions; space internal cooling load is badly affected due to increase in the number of occupants, computers, and other devices. The temperature profiles of the room are shown in Figure 5.23. Low temperatures especially in evenings are depicted from the figure. The main reason behind this is over cooling due to low height partition walls and poor location of thermostats. Since, the thermostat is not located inside the room, it is not sensing the room temperature. Furthermore, half partitioned walls are unable to block the excess air coming from the nearby vertical diffusers. Hence, it is recommended to adjust the supply airflow and properly locate the thermostat.

On the basis of quantitative and qualitative results and analyses of the major modified spaces; overcooling is found to be the major problem. Temperature readings keep on changing even out of the comfort limits causing problems of thermal comfort. Post modification adjustments are found to be ineffective and revised load calculations are needed for effective distribution of airflow for the existing setup. Moreover, it is observed that the thermostats are not located properly or malfunctioned in some cases in the modified spaces, so their installation, inspection and relocation is recommended.

5.3.2 Minor Modified Spaces

Qualitative and quantitative thermal comfort analysis of the minor modified spaces of Building-19 was performed. Information was gathered through a survey about temperature relative humidity, and supply airflow at various minor modified spaces.

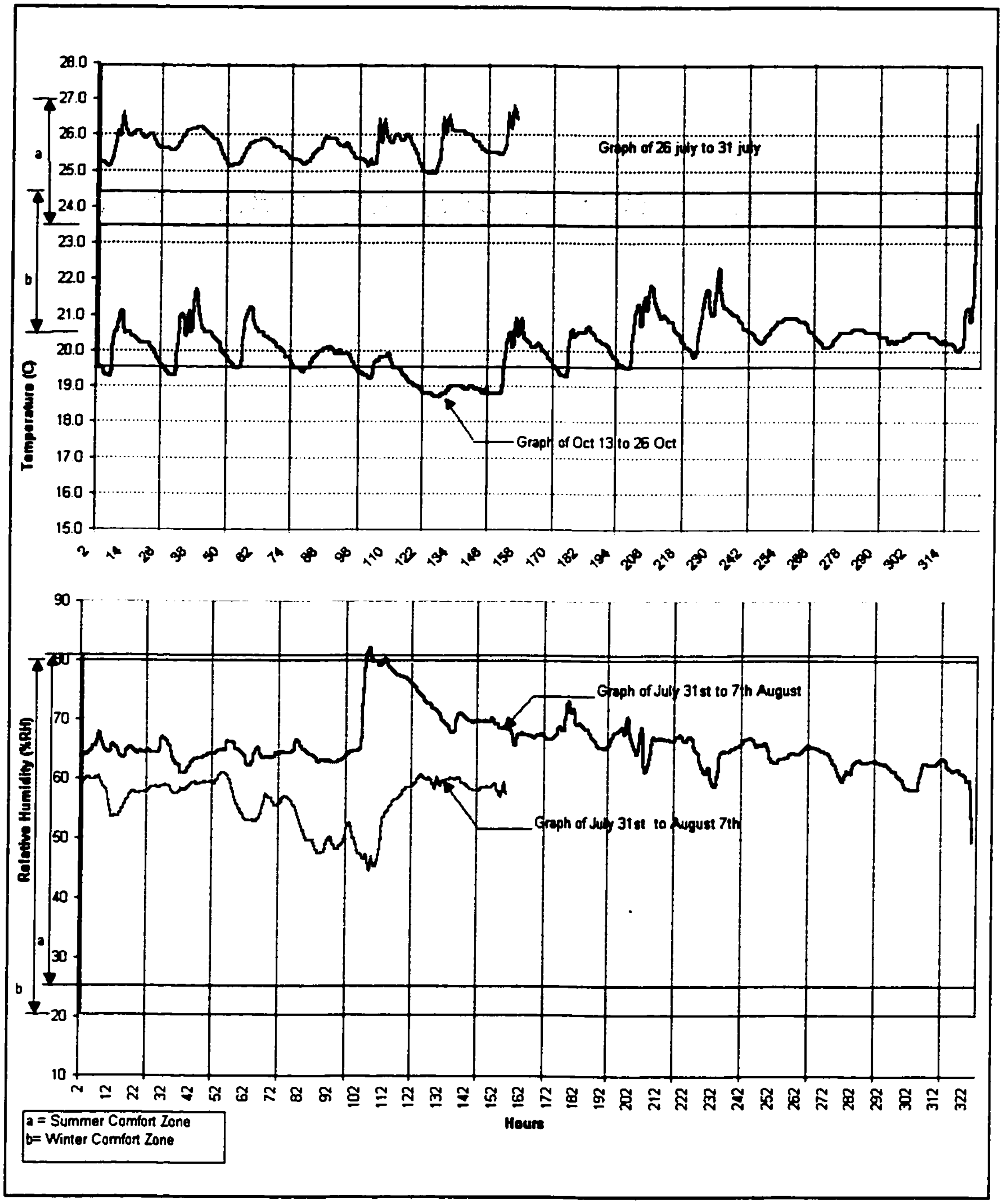


Figure 5.23: Temperature and Relative Humidity Profiles of Room 449

Figure 5.24 illustrates the response of the occupants for space temperature. It is observed from the survey conducted in the month of August, that majority of occupants complained about cooling, while in the October survey a majority of the occupants complained about very cold room temperature. Hence, in minor modified spaces, over cooling is observed. Although there are few complaints of hot temperature but they are less than 10% while complaints of over cooling is quite high as shown in figure 5.24.

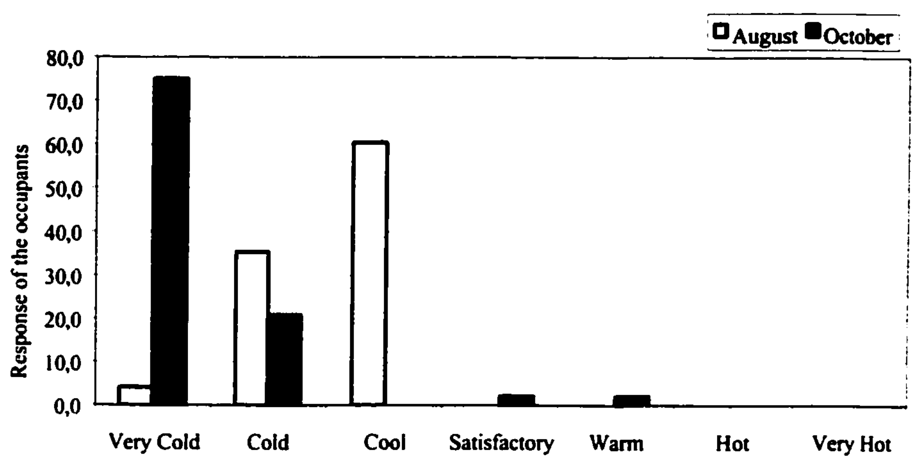


Figure 5.24: Response of the occupants for space temperature in minor modified spaces

Response of the occupants for space relative humidity for minor-modified spaces is shown in figure 5.25. It is observed from the survey results of August that a few occupants reported dry indoor conditions. Some of them reported feeling comfortable but a majority of them complained about a humid environment. While in the October survey, 92% of occupants reported dry indoor conditions and were not satisfied with space relative humidity. Response of the occupants for space air motion is shown in figure 5.26. It is observed from the August survey results that a majority of the occupants are satisfied with space air motion, but there were a few complaints of still air. While in October most of the occupants complained of drafty air.

Figure 5.27 shows the response of the occupant's minor modified spaces for over all space condition. It is observed from the survey results of August that a majority of the occupants are either comfortable or moderately comfortable. In the October survey although 60% of occupants reported feeling moderately comfortable, 35% of the occupants complained of discomfort. Hence, it is found that occupants of minor modified spaces are not very comfortable during the winter season. The main reason behind these complaints is the over cooling in the evenings, which is further proved from the survey results about the seasons. It is observed that the greater numbers of occupants are uncomfortable in winter in comparison to the summer season. For details see figure 5.27 and 5.28.

The response of the occupants for which time of the day they feel most uncomfortable are shown in figure 5.29. It is observed that during summer, the majority of the occupants complained at noon, while during the winter, the most uncomfortable time occurred during the evenings

Thermal comfort quantitative analysis of the minor modified spaces are performed by measuring the temperature, relative humidity and

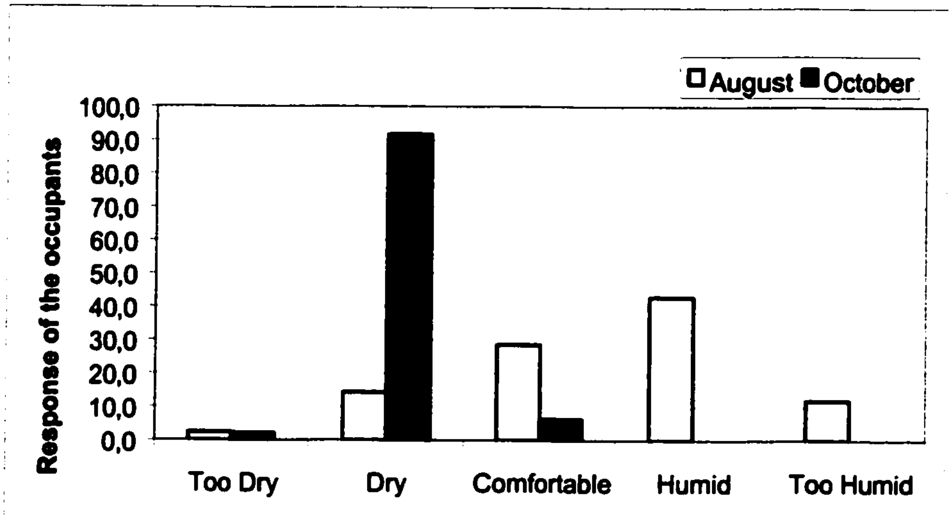


Figure 5.25: Response of the occupants for space relative humidity in minor modified spaces

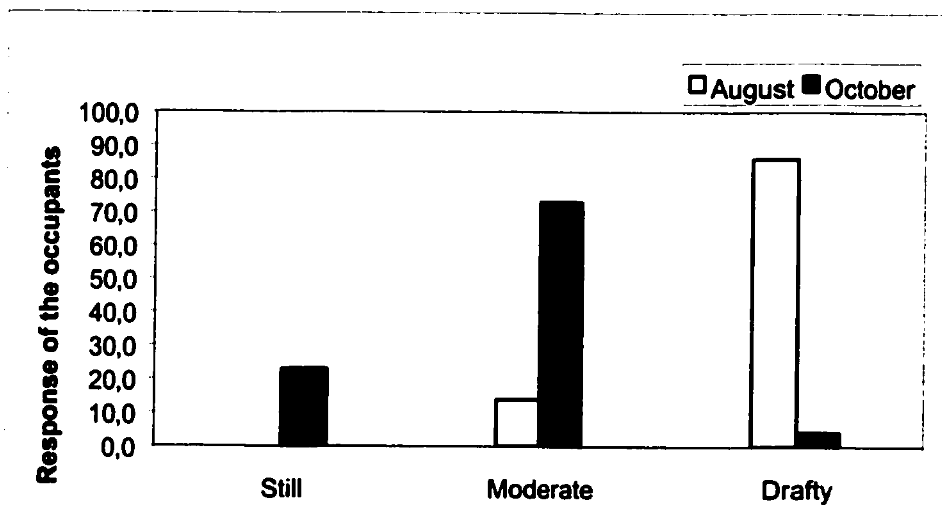


Figure 5.26: Response of the occupants for space air motion in minor modified spaces

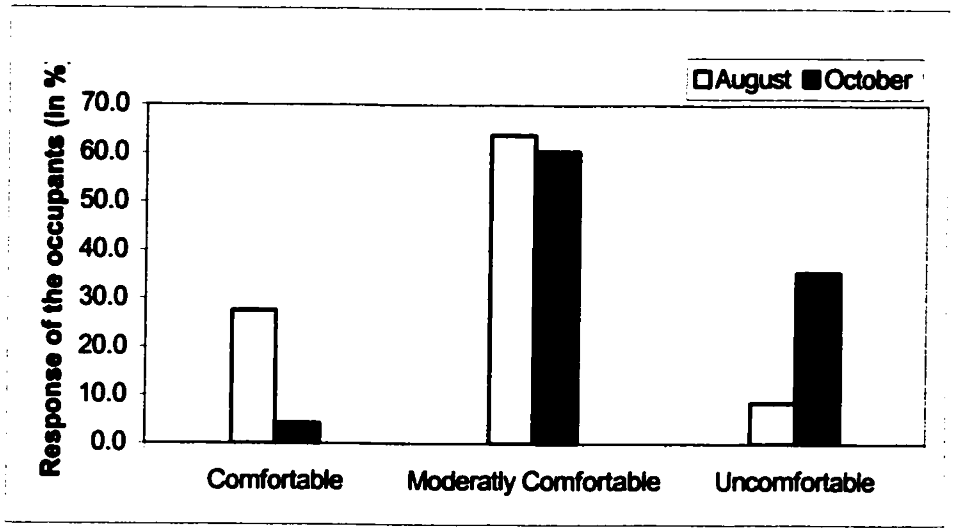


Figure 5.27: Response of the occupants for over all space Conditions in minor modified spaces.

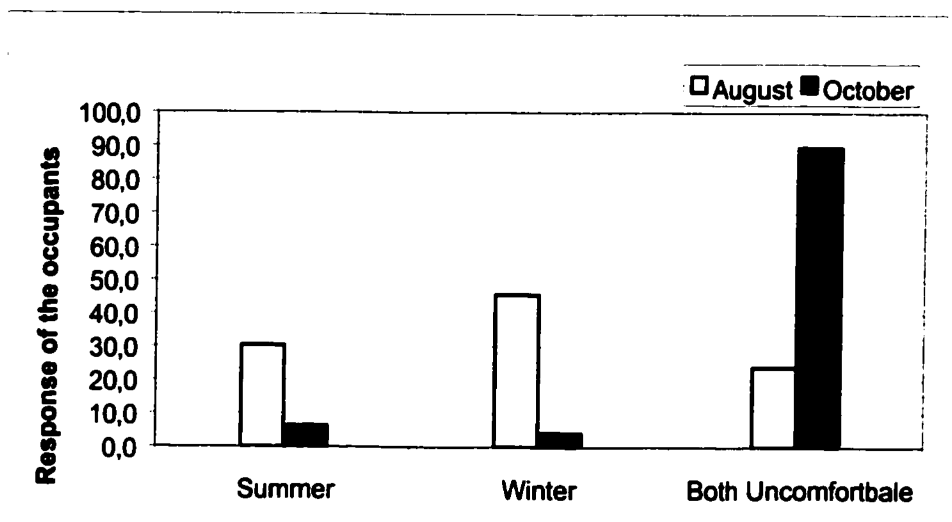


Figure 5.28: Response of the occupants for which season they feel most uncomfortable in minor modified spaces

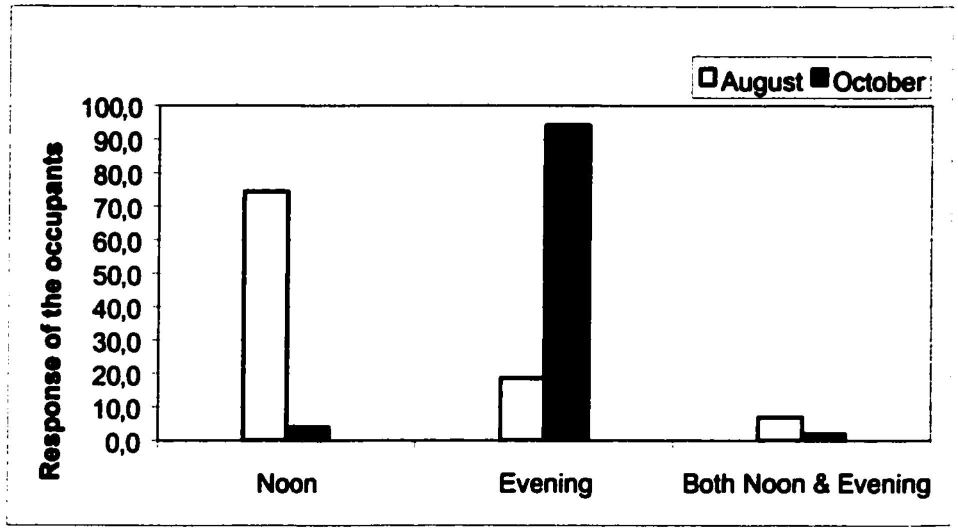


Figure 5.29: Response of the occupants for which time of the day they feel most uncomfortable in minor modified spaces

supply airflow at four spaces. These four spaces are include third floor down area, faculty office 447 and computer lab 452.

Third floor down area (student studios) was selected to represent minor modified spaces. This studio occupies a large open area, which is divided into small cubicles for the students, the location of measuring points are shown in Appendix A7. Temperature was measured at two ends of the studio, referred to as third floor down area A and B. The large studio area has three exposed walls and a large glass area on the Southwest wall. Earlier there was no partition wall, but now there is a low partition wall on the Southeastern side. Because the addition of computers and printers to this area the internal load of the space was increased. There are six thermal zones in this large studio, while four thermostats were installed to control the temperature. The temperature profiles of these two data stations are shown in figure 5.30. Since these two data points represent the two ends of the same studio, it was expected to have the same thermal conditions. By comparing the temperature profiles it was found that down area A was quite cooler than down area B (data points are shown in Appendices A7 and A8). The temperature readings of down area A are at the bottom of the thermal comfort zone, which implies low temperature in the space, during both the periods. Low temperature at down area A is observed in the figure 5.30 especially during the evening timings. While the temperature readings of down area B was at quite a higher side of the summer comfort limits and for few days temperature readings were even above the summer comfort limit. This increase in temperature readings occurred over a couple of days, and the same pattern was revised after a gap of five days. Hence, complaints of feeling uncomfortable are justified.

The summer and winter profiles of relative humidity for both the locations (i.e., down area A and down area B) are quite inside the respective comfort limits. Although summers of Dhahran are quite humid, the graph doesn't reflect the high indoor humidity. One reason behind this is that, this area doesn't have any door that opens to the outside (for detail see figure 5.30 and 5.31).

Faculty office 447 is formed by partitioning the graduate lab. The HVAC system of room 447 was not updated after the modifications. The temperature measurement in room 447 is shown in Figure 5.32. It is observed from the figure that temperature readings are at a higher side of the comfort zone. The reason behind this uncomfortable condition is an increase in space internal load due to computer, printers etc. A space airflow pattern is disturbed due to partitions. To meet the space cooling requirement, supply airflow is raised to 6.45 $l/s/m^2$. Initially it was 5.93 $l/s/m^2$. Since these changes were not performed on the basis of re-calculation of

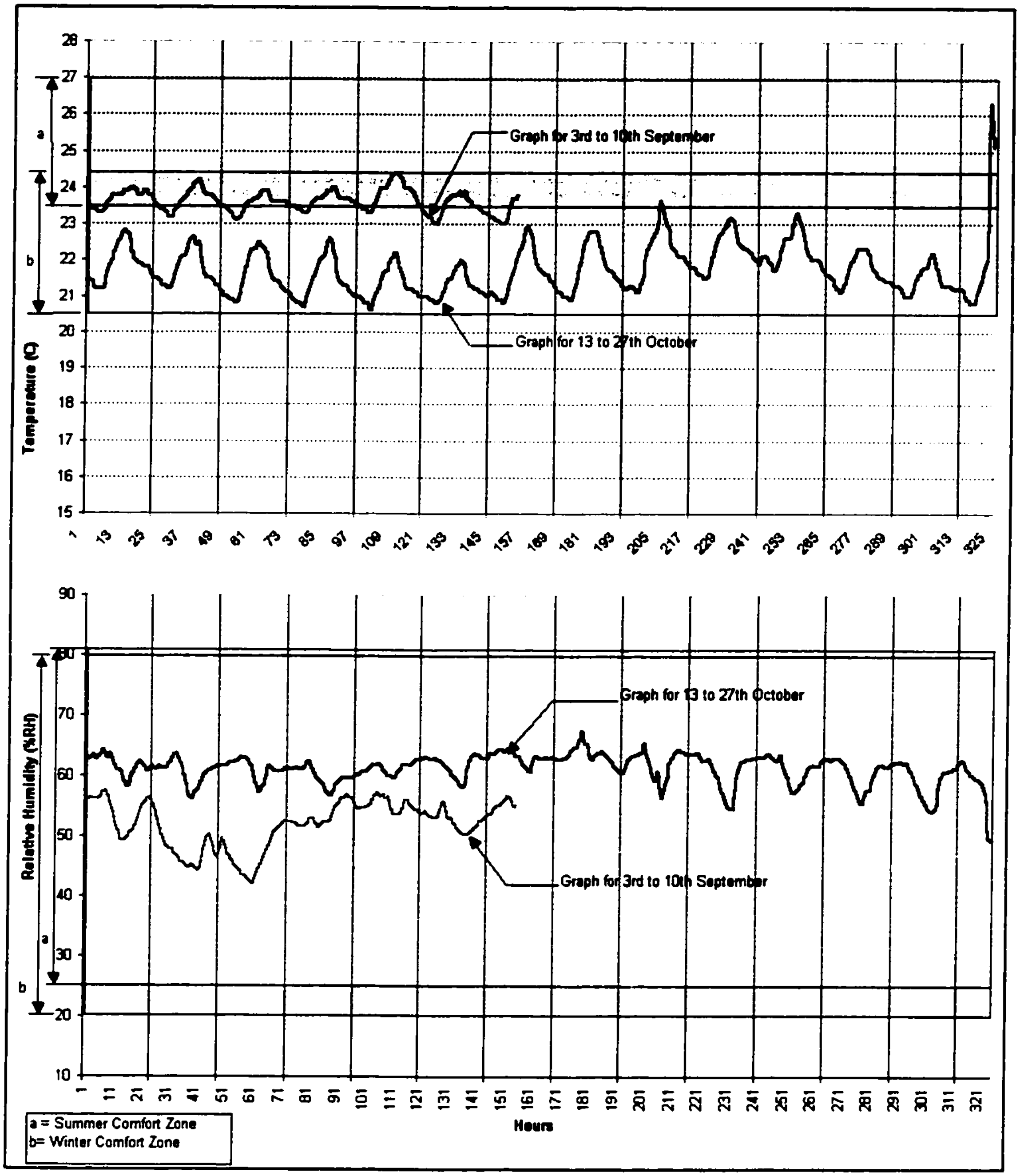


Figure 5.30: Temperature and Relative Humidity Profiles of
Third Floor Down Area -A

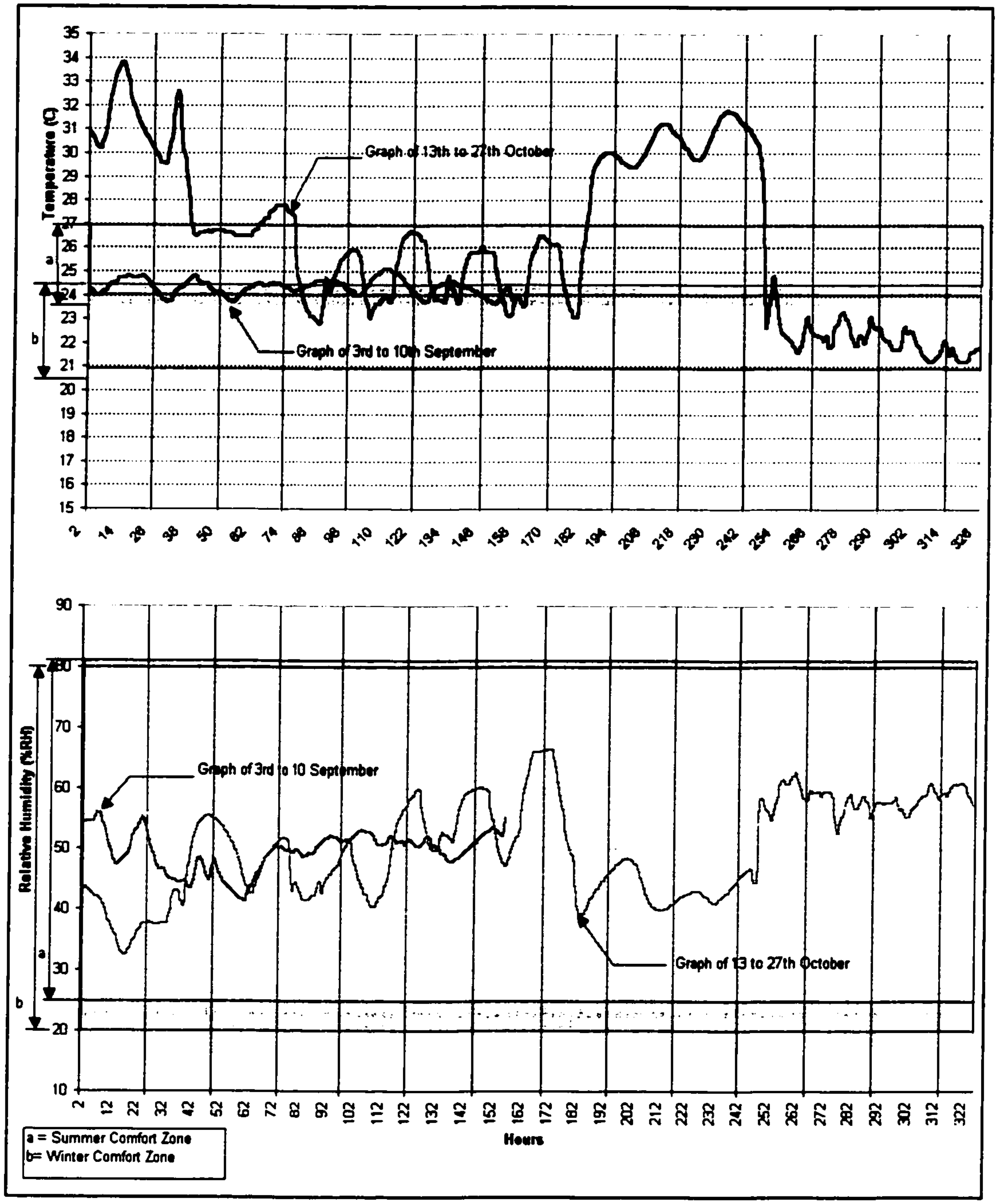


Figure 5.31: Temperature and Relative Humidity Profiles of Third Floor Down Area -B

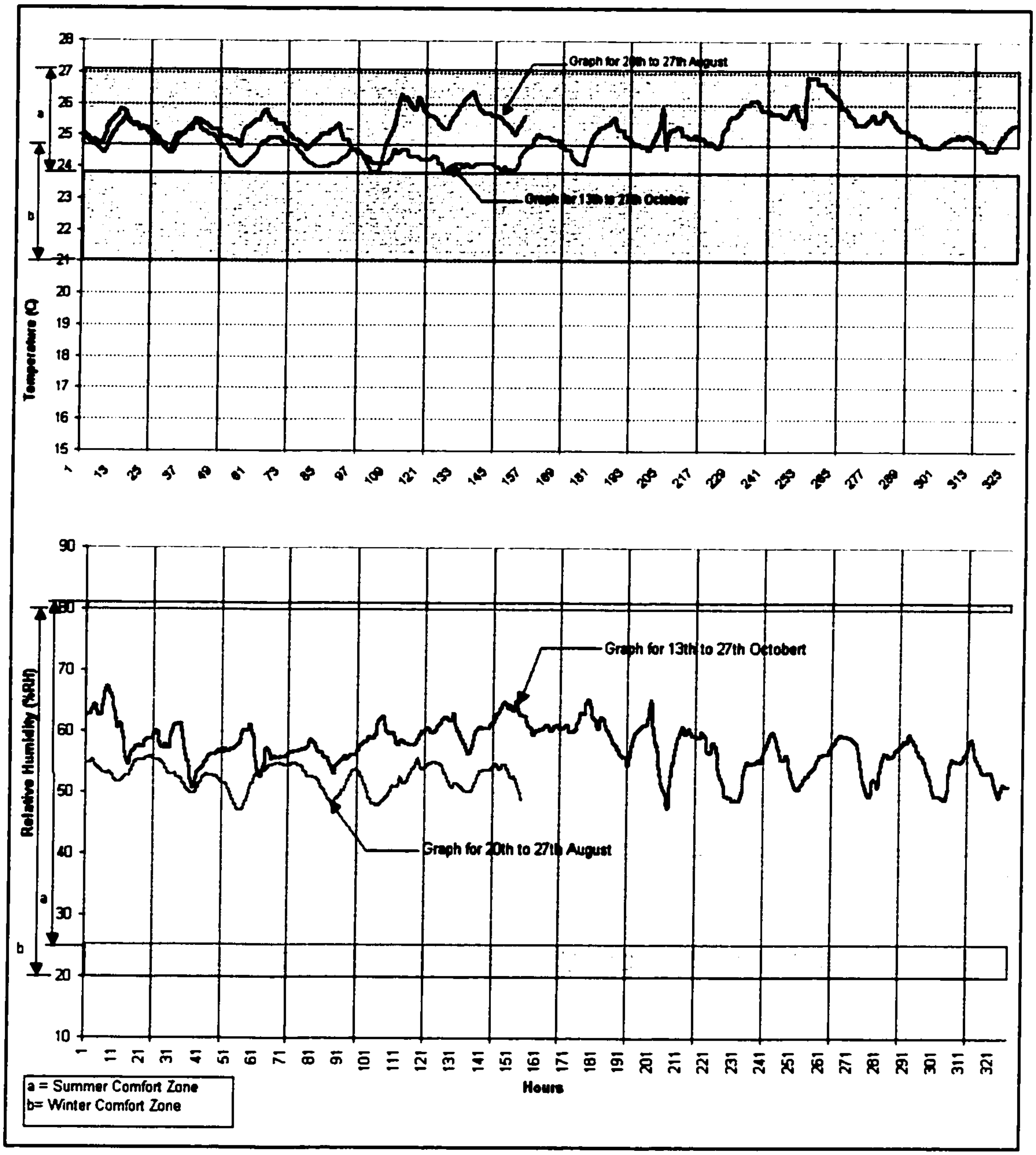


Figure 5.32: Temperature and Relative Humidity Profiles of Room 447

load, there is a need of air balancing, and thermostats should be repaired and installed where necessary.

Computer lab 452 is formed by partitioning the big computer lab into smaller labs. Alteration was performed in partitions as well as in internal load, but building's HVAC system has remained the same. To maintain space comfort conditions, supply airflow was increased to 4.40 $l/s/m^2$ from 3.64 $l/s/m^2$. This increased supply airflow is still not enough to maintain required thermal comfort. Temperature and relative humidity profiles of room 452 are shown in Figure 5.33. It is evident from the figure that an increase in space thermal load caused an increase in space temperature. The summer readings are at a higher side of the comfort limits; even the winter readings also show overheating. It is recommended that supply airflow should be adjusted and thermostats should be installed to meet the desired thermal comfort condition. Hence, it is concluded that, due to increase in heat generating sources over heating is taking place. Most of the occupants complained about high temperature level during the noon of summer and low temperature level in the evenings in winter. Moreover, it is observed that overall conditions of summer are better than winter. It is recommended to update the thermostat location in order to maintain the desired thermal comfort conditions. Furthermore, there is a need to adjust supply airflow at all the spaces in order to meet the existing cooling / heating requirement.

5.3.3 Unmodified Spaces

Thermal comfort analyses were also performed in the unmodified spaces to study the indirect impact of alterations in these spaces.

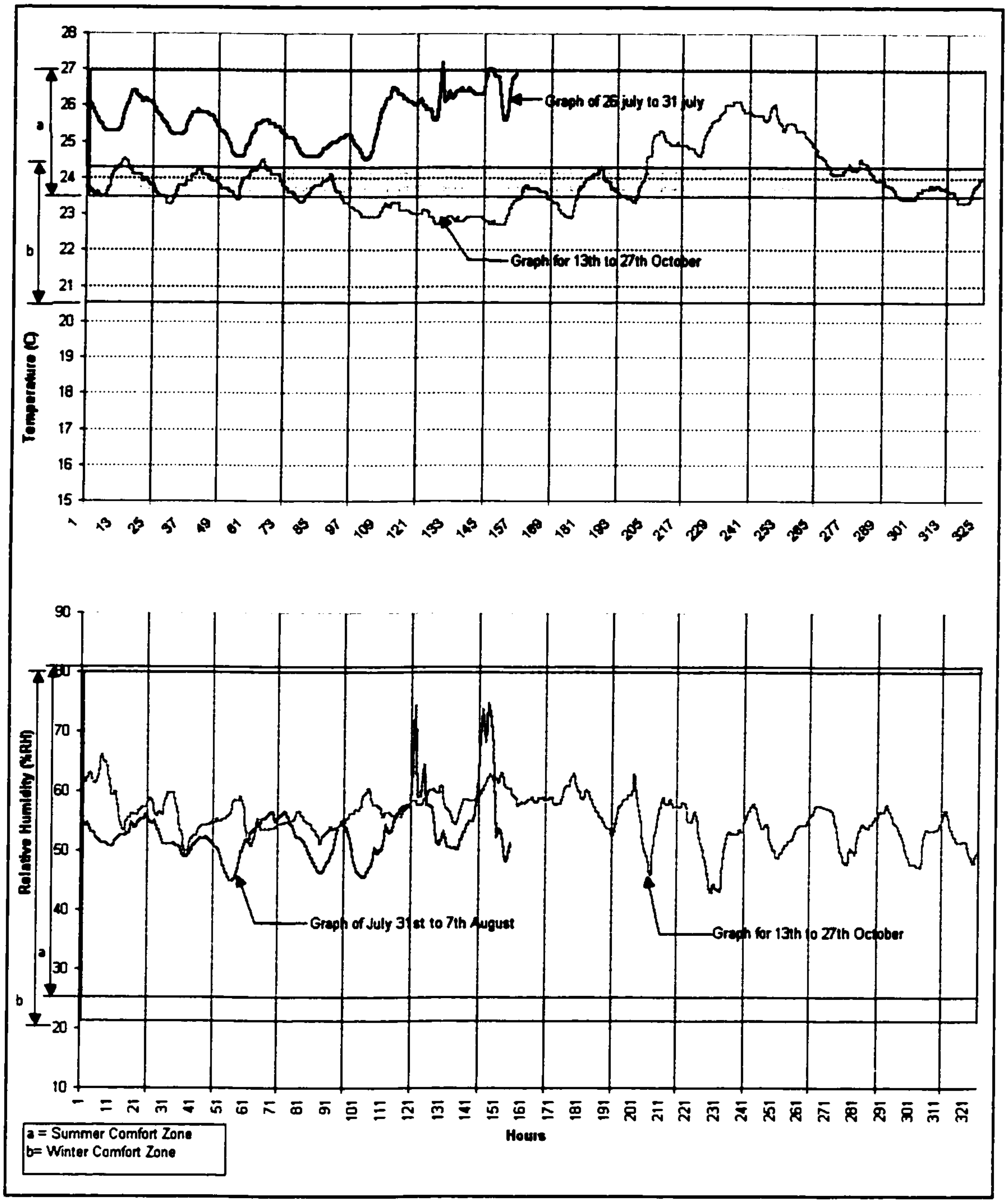


Figure 5.33: Temperature and Relative Humidity Profiles of Room 452

Response of the occupants for the space temperature is shown in Figure 5.34. It is observed that in both surveys, the majority of the occupants complained about cold indoor conditions while some complained about for feeling warm. For details see Figure 5.34.

Response of the occupants for space relative humidity is shown in Figure 5.35. It is observed that during the August survey, most of the occupants complained about humid conditions, while in October survey the majority of the occupants reported dry conditions. Response of the occupants for space air motion for unmodified spaces is shown in Figure 5.36. It is observed that in the August survey, most of the occupants complained about air draft. While in the October survey, 35% complained about the still air, a majority of the occupants reported feeling satisfied with air motion during October. This shows that partitions and adjustments of supply airflow of these spaces, causes an indirect effect on the supply airflow of unmodified spaces.

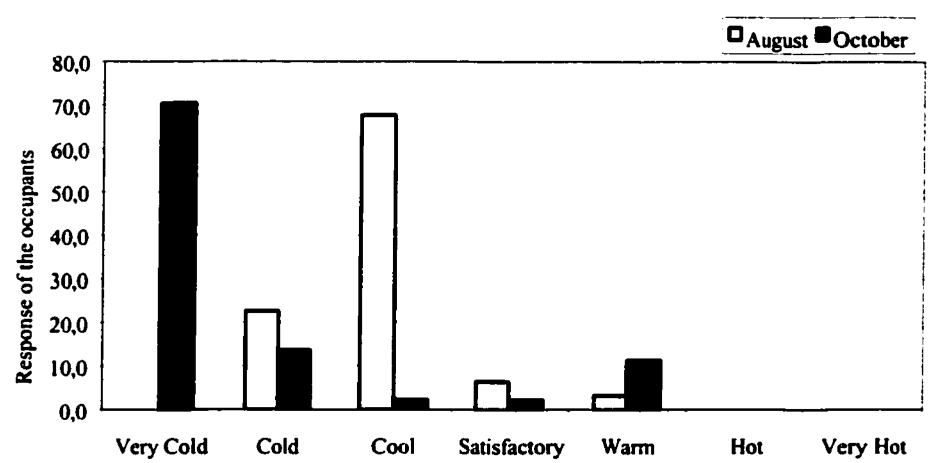


Figure 5.34: Response of the occupants for space temperature of unmodified spaces

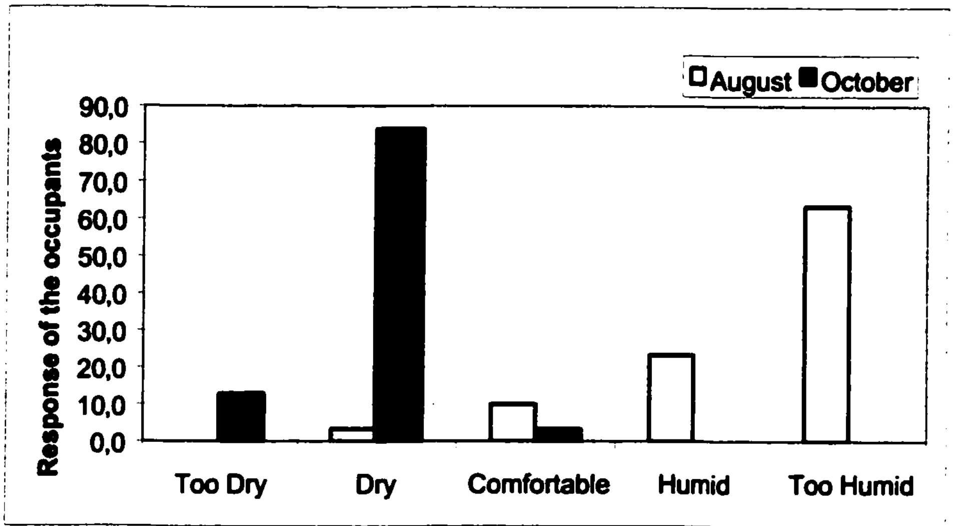


Figure 5.35: Response of the occupants for space relative Humidity of unmodified spaces.

The feeling of the occupants of unmodified spaces were inquired about space air motion. During the August survey, most of the occupants of unmodified spaces reported still and moderate air motion, while in the October survey, a majority of them reported drafty air motion. Moreover, it was observed during the site visit that because of the high air draft, few of the building occupants closed the air duct to prevent overcooling. Hence, there is a need for air balancing, not only the modified space but for unmodified spaces, in order to achieve a desired comfort level. For details see Figure 5.36.

In the August survey, there were few complaints of feeling uncomfortable (11 %) and 53 % of these reported comfort in the month of August. While for the October survey, a majority of the occupants

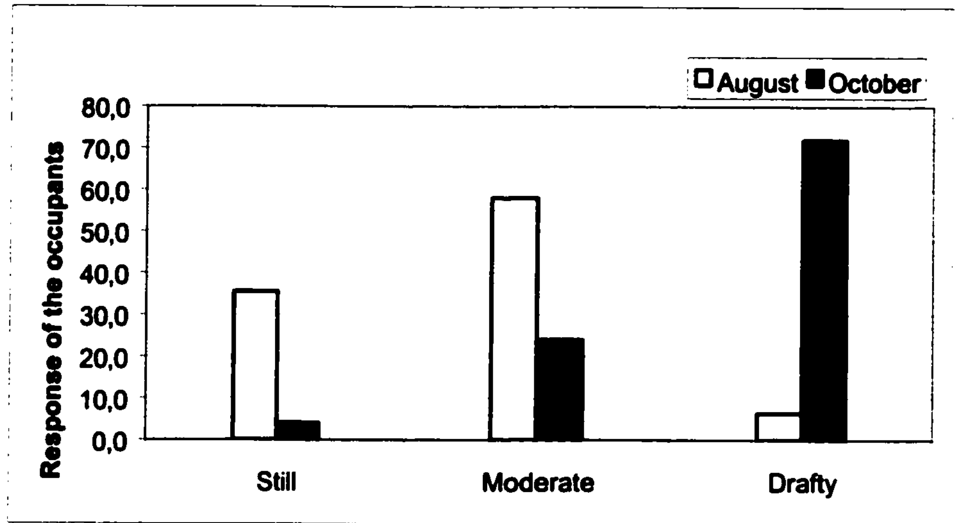


Figure 5.36: Response of the occupants for space air motion of unmodified spaces.

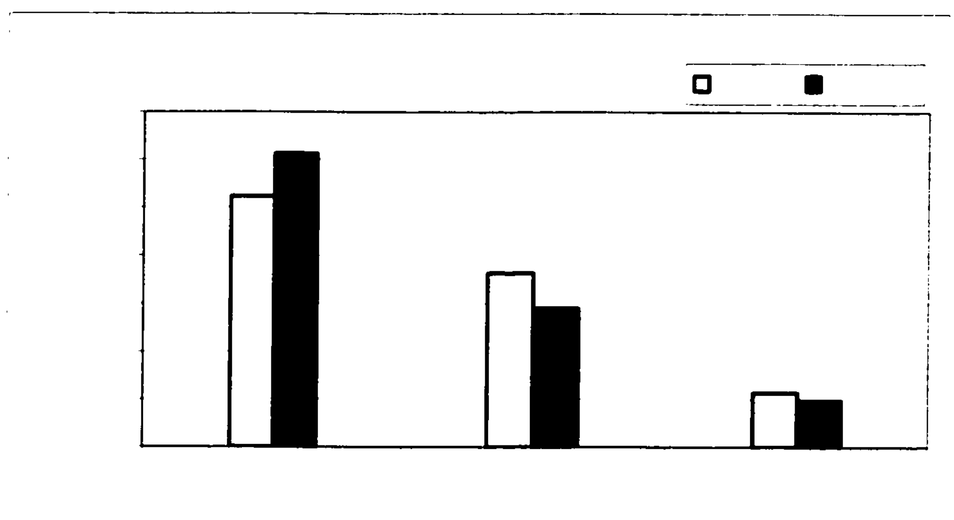


Figure 5.37: Response of the occupants for space over all conditions of unmodified spaces.

reported feeling comfortable and the percentage of feeling uncomfortable was decreased to 9%. For details see figure 5.37.

Overcooling is not only a problem of the occupants of those spaces that were modified, but it is also the problem of the occupants of unmodified spaces. A majority of the occupants reported uncomfortable feeling either in the winter or both of the seasons. It is observed that during summer the most uncomfortable time is noon and during winter the most uncomfortable time is evening. For details see Figure 5.39.

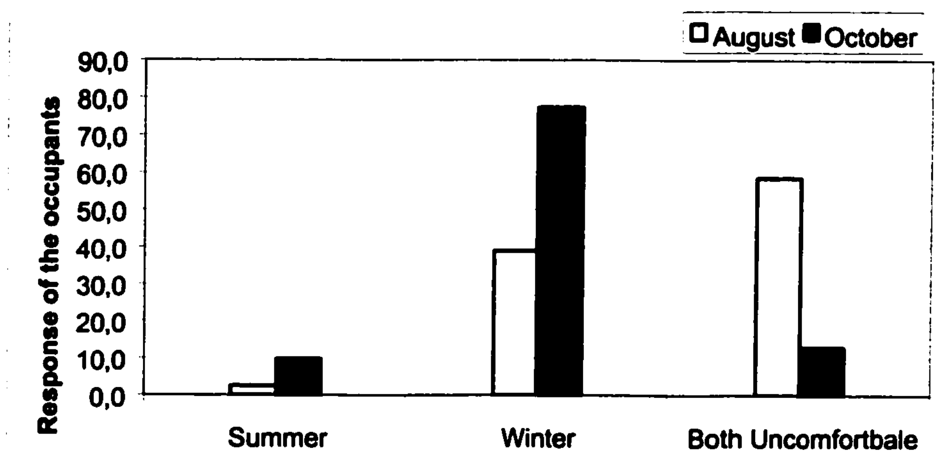


Figure 5.38: Response of the occupants for which season they feel most uncomfortable.

Quantitative analysis was performed in unmodified spaces also, to assess the indirect impact of alteration in unmodified spaces. For reference Faculty office 319, 330 and 333 and classroom 336 was selected Faculty offices 319, 330 and 333 are of same size and have the same internal load due to same usage. Faculty office 333 has one wall exposed to solar radiation (i.e. the Southwestern wall), while faculty offices

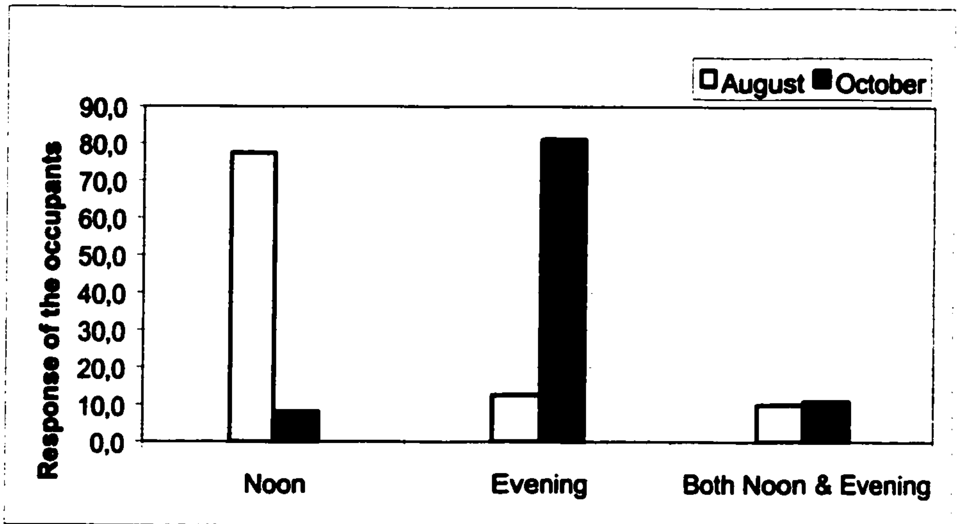


Figure 5.39: Response of the occupants for which time of the day they most uncomfortable

319 and 330 don't have any exposed walls. There may be some differences in the occupant's operating profile which affects the space internal heat gain. Since these are similar rooms, it was expected to have the same temperature profiles, except faculty office 333, which has one exposed wall, where some difference is expected. 3.87 l/s/m^2, 3.94 l/s/m^2 and 4.84 l/s/m^2 are the supply airflow for room 319, 330 and 333 respectively. Temperature and humidity profiles of these rooms are shown in figures 5.40, 5.41 and 5.42. For the case of faculty office 319 above mentioned supply airflow (i.e., 3.97 l/s/m^2) is not as per designed airflow. During the survey it was found that the occupant himself closed half of the diffuser, and the designed flow is 4.41 l/s/m^2, 14% more than the existing supply air flow. Both the temperature profiles of faculty office 319 as shown in figure 5.40 are well below their respective comfort limits (i.e. summer and winter comfort limits), which imply that overcooling is taking

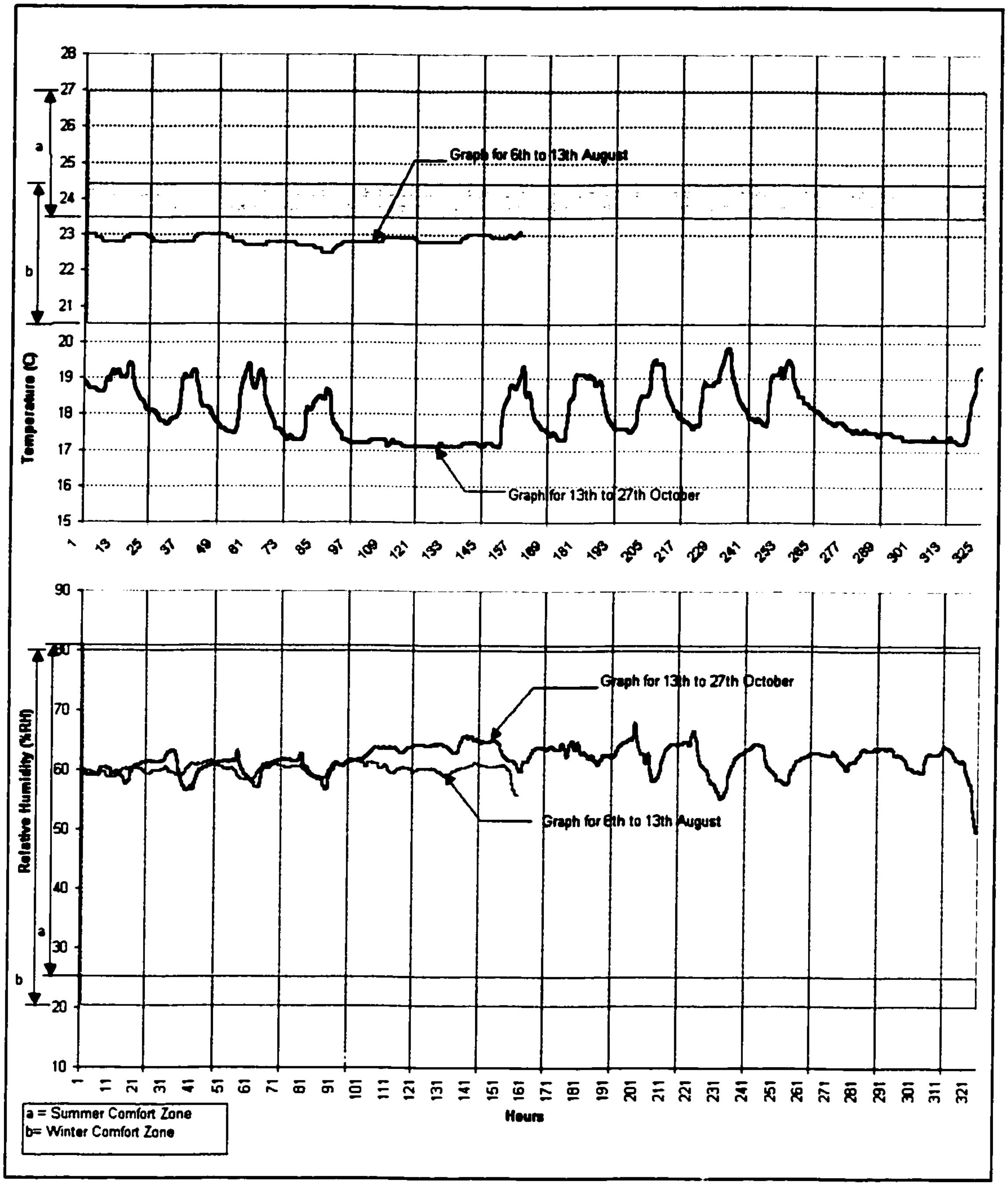


Figure 5.40: Temperature and Relative Humidity Profiles of Room 319

place in both the seasons. Even the supply airflow is less than the designed value.

For the case of faculty office 330, the supply airflow is almost the same as that of faculty office 319, but the summer temperature profile is above the summer thermal comfort limit, which implies over heating is taking place in the room. The winter temperature readings are well below the winter comfort limit, which implies overcooling. Hence, it is observed that during summer that this room is quite hot and during winter it is overcooled. This shows the poor performance of the control devices.

Temperature profiles of faculty office 333 are shown in figure 5.42. Summer readings of faculty office 333 are not in the winter comfort zone, while the profile is in the winter comfort zone, implying overcooling. Winter readings are at the top of the winter comfort limit, which shows heating. Hence, in both the seasons the thermal comfort conditions are not well maintained. Relative Humidity Profiles of these three similar spaces (faculty offices) are shown in figure 5.40, 5.41 and 5.42. These profiles are well within their respective comfort limits (i.e. summer and winter). Furthermore, it is supported by the feedback of the occupants, that the majority of the occupants are satisfied with the space thermal conditions. For details see Figure 5.37.

Classroom 336 was selected for the evaluation of thermal comfort conditions of unmodified spaces, since from the beginning this room was used as a classroom. There is a thermostat installed in this classroom, to control the space thermal conditions. There are two walls exposed to outside solar radiation (i.e. Northeast and Northwest walls), with the Northeast wall having a big glass area. The supply airflow to this classroom

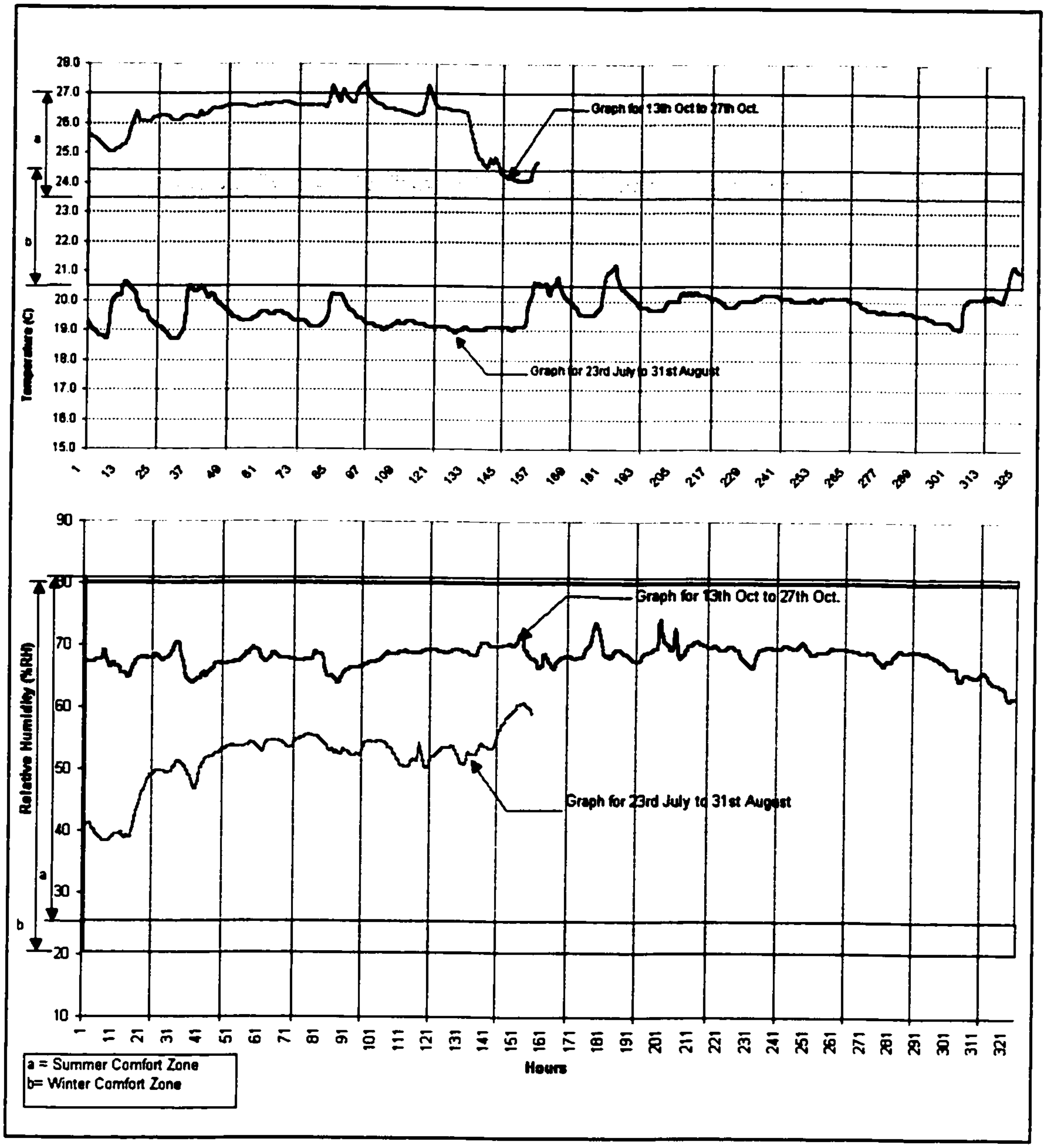


Figure 5.41: Temperature and Relative Humidity Profiles of Room 330

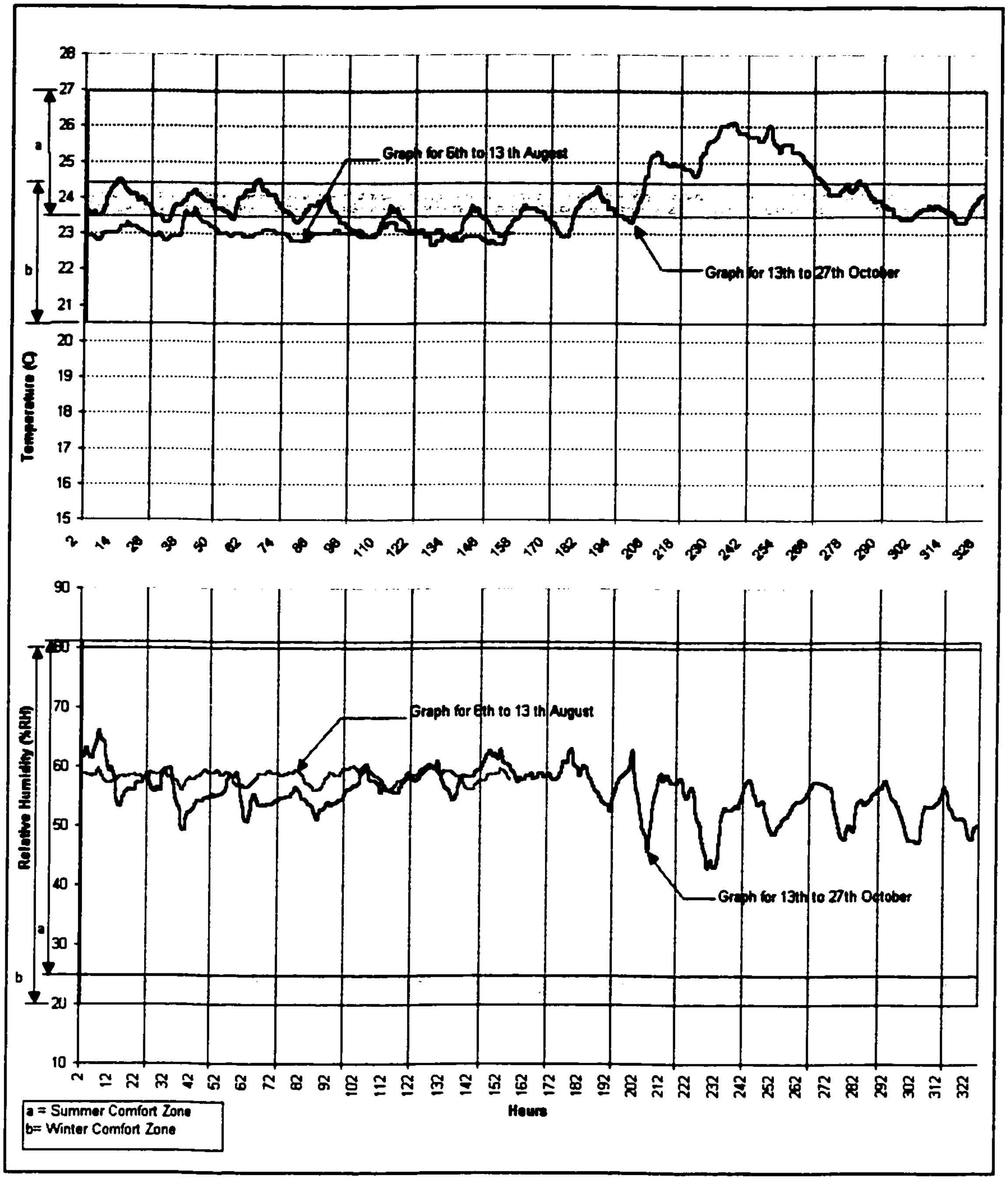


Figure 5.42: Temperature and Relative Humidity Profiles of Room 333

is 7.95 $l/s/m^2$. In comparison with the other spaces, the supply airflow to the classroom 336 is more; but still summer temperature readings are at the top of the thermal comfort limit, which shows a slight heating. For details see figure 5.43. The winter temperature readings are either at the bottom of the winter comfort limit or below the comfort limit, which shows over cooling, especially during evening. Relative humidity profiles of classroom 336 are shown in figure 5.43. Relative humidity readings recorded during summer and winter are within the comfort limit.

Hence, on the basis of quantitative and qualitative analysis of the unmodified spaces; it is concluded that, due to alterations in the building, those spaces, which remain unmodified, are also affected indirectly. The main reason behind this problem of thermal discomfort is the HVAC systems. Because of constant volume system, if settings of one space is altered it is affects the other spaces indirectly. As mentioned earlier, there is a need to balance the HVAC system of the unmodified spaces, although these spaces are not physically altered.

Energy and comfort analysis of the building under study was performed. Simulation results showed an increment in building annual energy consumption, as well as an increment found in the building peak cooling demand. While in the comfort analyses, complaints of the occupants was observed mostly for the overcooling, while in some places complaints of over heating and still air was also observed. Overall during summer, building occupants have comfort problems during noon time, and in winter overcooling was observed in evening.

The building's existing fresh air supply was found to be 2.4% of the total supply air, which is very small in comparison with original design

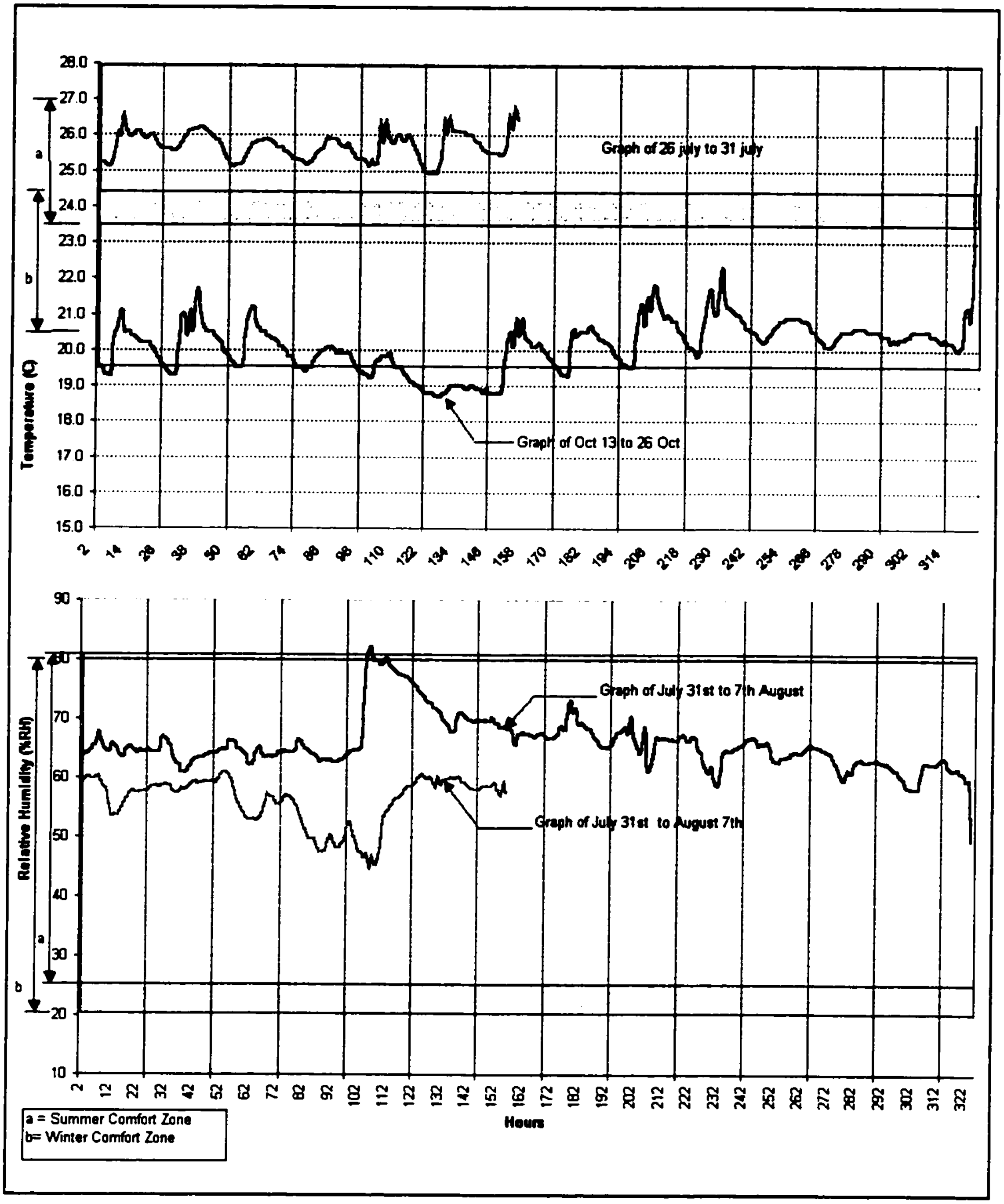


Figure 5.43: Temperature and Relative Humidity Profiles of Room 336

value. Original design value was 10% of the supply air, as per existing demand it would be very difficult to maintain comfort and indoor air quality (with 10% fresh air) with the same equipment. Hence, there is a need to install equipment of higher capacity to maintain comfort and indoor air quality. Equipment of higher capacity will increase both the first cost and energy consumption. The problem of over heating and cooling will not be solved completely by installing the higher capacity equipment. However, the ducting layout and diffuser location may need to be updated. Because change in partition affected the building's airflow pattern, the building's thermal zones should be revised by altering the partitions and updating the thermostats locations, to achieve a better comfort and energy efficient system.

It was found that energy and comfort analyses should be performed before retrofitting. There is a definite need of good overall planning including engineering and design skills to undergo modifications with quality of work and minimum interruption to the space activities.

CHAPTER-6

A SYSTEMATIC APPROACH FOR QUALITY COMFORT AND ENERGY EFFICIENCY IN BUILDING RETROFITTING PROJECTS

6.1 GENERAL

Retrofitting of a building may require major changes in its layout, zoning and services within the building. To accommodate these changes, the systems and services involved also need to be updated to maintain similar indoor environmental quality as was originally designed. Thus, properly planned and executed retrofitting is needed to balance the quality and quantity of change. The basic objectives of retrofitting for comfort and energy issues, can be fulfilled through efficient planning, good engineering and design skills.

6.2 PROPOSED SYSTEMATIC APPROACH

One of the objectives of the current research is to develop design guidelines in the form of a systematic approach for quality comfort and energy efficiency in retrofitting projects. Retrofitting a building is a very wide field; this varies from building to building, because of variation in building usage. These variations directly affect the retrofitting plan. For example, the retrofitting plan of a shopping mall will never be applicable for the retrofitting plan of a hospital. In some projects such as airports and markets it is strictly recommended not to interrupt the normal activities going on in the space. While in some other retrofitting projects, cost is a major issue. Hence, it is observed that in building retrofitting quality comfort and energy efficiency are very essential. Generally in depth analysis depends on the nature of the building, accuracy requirements, and on an allocated budget. For efficient thermal design, detailed building energy simulations are recommended. For the comfort analyses in small retrofitting projects a site visit with some quick measurement of indoor temperature and relative humidity are performed; while in some complex projects a need for accuracy, detail analyses may be needed to record environmental parameters like temperature and relative humidity along with the investigation of the building's occupants perception of the indoor thermal environment.

Based on the experiences and knowledge gained from the current research and from literature, a systematic approach is proposed to insure quality comfort and energy efficiency in retrofitting projects with emphasis on the performance of the HVAC systems as shown in the flow chat of Figure 6.1. This flow chart is a set of step-by-step activities, which are very essential in retrofitting projects. It would be very helpful for the designers and planners and those who are involved in retrofitting projects to schedule these tasks to achieve quality of work, comfort and better energy utilization. Hence, the depth of the analysis to be carried out depends on the nature of work needed to be performed as well as the allocated budget for this work.

6.3 BUILDING RETROFITTING

Shifting of partitions and change of space usage may require updating the following:

- Ducting system
- Diffuser locations
- Thermostat quantity and locations
- The building's energy management system
- Space access
- Data, power and communication cables
- Lighting control and distribution
- Fire escape routes

Following is a brief description of the various activities presented in the flow chart of Figure 6.1.

In the flow chart, the whole retrofitting project is divided into specific activities to make the operation simple. Once the decision to retrofit a facility is made, the next step is to evaluate the buildings and its systems. This activity requires the review of as-built documents, i.e., layouts and details of installed equipment, followed by a facility visit and investigation. For the case of major modifications it is recommended to generate a proposed plan, in order to have better understanding between what is available and what is required. For better quality and accuracy it is recommended to perform an energy analysis. After updating the building plans, the next step should be to investigate the compatibility of the building's existing thermal zones with the proposed plan. If required, the building's thermal zones could be re-arranged by shifting the partition walls and updating the thermostats' locations to meet the new thermal zoning requirements. Efficiently designed thermal zones not only provide better comfort but also help to consume less energy. After rearranging the thermal zones, the next step is to calculate the peak cooling load of the building according to the proposed plan. Meanwhile, an inventory of the building's existing equipment and systems (e.g. lighting, HVAC, electrical, etc.) should be carried out, so that the peak cooling load (obtained through calculations) could be compared with the capacity of installed equipment. If there is a need for additional equipment, selection and alteration can be done. At this stage of the retrofitting planning, a detailed inspection of the building is needed for both minor and major alterations to check ducting system, diffusers locations, lighting control and distribution, power communication data cables, and fire escape routes. If required, necessary alterations must be noted to meet the proposed requirements. Inspection of ducting system, diffusers locations and the amount of supply air will enable the designer to check the system for delivery of the required amount of air to maintain comfort with the new setup of partitions. If required, diffuser location or the height of partition should be altered.

Due to the technical and intuitive nature of these activities, it is essential that these tasks must be performed by experienced and qualified professionals, for example, an HVAC consultant, a facility engineer or an architectural engineer. After completing the planning, cost estimation or budgeting and a total cost of retrofitting must be calculated. Comfort issues should not be sacrificed in order to reduce cost. Energy conservation measures may increase the initial cost but life cycle costing should be performed to see the long run impact

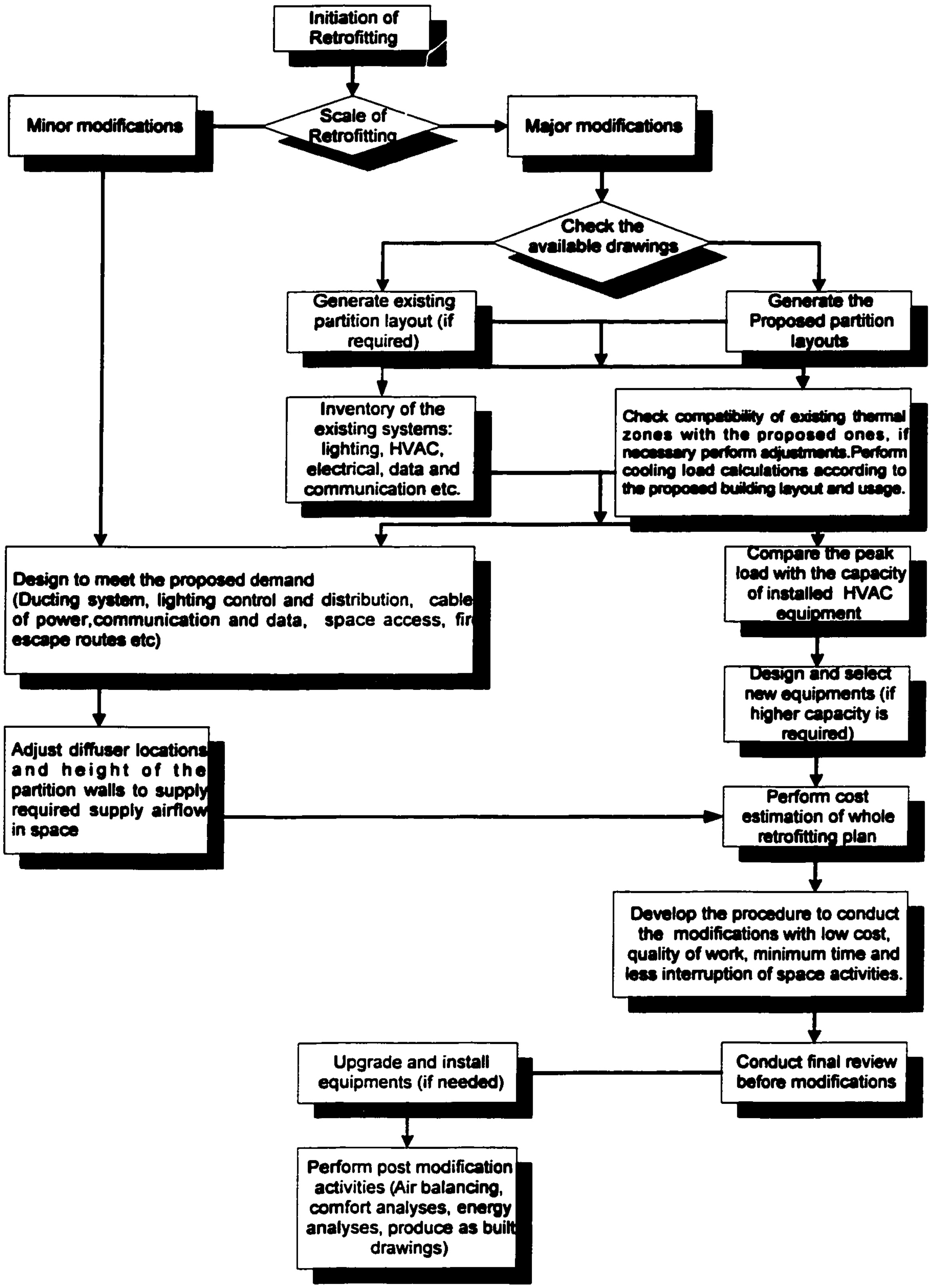


Figure 6.1: A systematic approach for assuring quality comfort and energy efficiency in building retrofitting projects.

After finalizing the cost estimations and before executing the retrofitting, the procedure to conduct these operations must be developed, to ensure

- Low cost
- Quality of work
- Minimum time
- Less interruption of space activities

Finally, before executing the project, all the activities must be carefully reviewed and the schedule of different activities with their duration must be developed to prevent the wastage of time. An efficient planning and selection of a good team might be helpful to complete the task on time with quality and the satisfaction of the building owners and its users. All the necessary documentations must be completed. Approval from the concerned authorities (if any) must take place before executing the modifications. After completing the modifications, the following activities must be performed to ensure quality comfort and energy efficiency.

- Air balancing
- Comfort analyses
- Energy Analyses

For future references and modifications, building as-built layouts must be developed. Post occupancy inspections of the facility and investigations of the building's occupants' satisfaction may be helpful to improve the quality of work in other similar projects.

CHAPTER-7

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

In the current research, the impact of the building's physical rezoning and change of use on energy consumption and occupants' thermal comfort was studied. Due to lack of research in this area, the aim was to develop a systematic approach for quality comfort and energy efficiency in building's retrofitting projects. Building – 19 at KFUPM was selected as a case study for the current research, due to the number of modifications carried out since the building was built. The objectives were to study the impact of the building's rezoning and change of use on the building's total energy consumption and occupants' thermal comfort conditions, and to develop guidelines for future retrofitting projects. The following conclusions are drawn based on the results of the building's energy simulation studies, occupants' survey, walkthrough inspection, questionnaire survey and measurement of environmental parameters:

- Due to change of space usage and modifications in the building's partitions, the building's annual energy consumption is raised to 13.6%
- Major components of the increment are occupancy and equipment load
- The building's peak cooling load increased by 15.7%
- The building's peak electricity usage is increased by 20.9%

- Existing supply airflow of the few zones were studied and found either more or less than the original designed value at the various spaces
- By using DOE 2.1-D required supply airflow as per existing load of all the zones were calculated and some variations were observed on compared with the original design values
- The building thermal comfort conditions were evaluated by measuring the environmental parameters and by collecting responses from the occupants using a questionnaire
- In the survey conducted in peak summer, most of the occupants complained about high temperature epically at noon.
- In the survey conducted in October, most of the occupants complained about low temperature in the evenings
- Due to the low capacity of installed HVAC equipment, peak cooling demand was not fulfilled
- Control devices were not functioning properly
- Location of thermostats were not updated as per new partition layouts
- Supply airflow of only a few of the zones were adjusted (upon receiving complaints) but these adjustments caused problems in other zones
- Fresh air supply to the air handling units was found to be 2.4% of the total supply air. As per the building's original design, it should be 10% of the supply air.
- There is a need of thermal rezoning and complete air balancing in all the zones
- Temperature profiles of various zones are out of comfort limits causing uncomfortable conditions

- Not only the profiles of the modified spaces but also the temperature profiles of the unmodified spaces were also affected.

7.2 RECOMMENDATIONS

Based on the results of this research, the following recommendations are made for future retrofitting projects:

- Before rezoning and change of the use of a building along with structural and architectural drawings and plans, the building's HVAC design should also be reviewed.
- For major modifications, building proposed partitions layouts must be developed.
- For better accuracy, energy efficiency and quality of the work building pre and post modification energy analysis must be performed.
- For minor modifications, an HVAC engineer should be consulted, so that adjustments if required could be done. These adjustments may include re-distribution and balancing of air, as well as changes in thermostats' locations.
- The systematic approach presented in Chapter 6 of this is highly recommended to be followed.
- Proper HVAC system design should be ensured to meet the proposed setup.
- The outside air dampers return air dampers and exhaust air dampers should be balanced to ensure proper proportional mixing.
- Proper temperature and humidity settings should be maintained for winter and summer because Improper temperature / humidity control can result in discomfort.

- Actual space temperature and humidity should be monitored, and compare this with set standards.
- All HVAC controls should be in proper working condition and well calibrated.
- Protocols of the building's management system should be updated, while minimum and maximum temperature and airflow should be in accordance with the existing zonal requirements.

REFERENCES

[1] Claridge and Haberl " Monitored Commercial Building Energy Data: Reporting The Results " ASHRAE Transactions, Volume 98, part 1, Page. 881-889, 1992.

[2] Marx and Stamper "Historical Development Of Building Energy Calculations" ASHRAE Transactions, Volume 101, Part 1, Page. 841-849, 1995.

[3] Nyuk et al.," The Use Of Performance Base Simulation Tools For Building Design And Evaluation - A Singapore Perspective" Building and Environment, Volume 35, 2000, Page 709-736.

[4] Radu et al., " Role Of Computers In The Design Of Energy-Responsive Buildings" Canadian Journal of Civil Engineering, Volume 16, Page 55-61, 1989.

[5] Said and Rahman "Energy Efficiency Of A Building In The Eastern Province Of Saudi Arabia: Parametric Analysis With DOE2.1A" ASHRAE Transactions, Volume 98, Page 147-152, 1992.

[6] Lawrence Berkeley Laboratory, DOE-2 Users Guide, Berkeley, CA, Supported by the US Department of Energy, 1979.

[7] Chow, "Airflow Studies In A Forced Ventilated Chamber With Low Partitions", ASHRAE Transactions, 1995, Volume 101, part 2, Page 125-135.

[8] Bauman et al., "Air Movement, Ventilation, And Comfort In A Partitioned Office Space" ASHRAE Transaction 1992, Volume 98, Part 1, Page 756-780.

[9] Bauman et al., "Performance Testing Of A Floor-Based, Occupant - Controlled Office Ventilation System" ASHRAE Transaction 1991, Volume 97, Part 1 Page 553-565.

[10] Ahart and Helm "A Test System To Measure Air Distribution And Comfort In A Open Plan Office" ASHRAE Journal 1989, Volume 31, Number 10.

[11] Haghihat et al., "Natural Convection And Airflow Pattern In A Partitioned Room With Turbulent Flow" ASHRAE Transaction 1989, Volume 95, Part 2, Page 600-610.

[12] Bauman et al., "Air Movement, Comfort, And Ventilation In Partitioned Workstation" ASHRAE Journal 1993, Volume 35, No 3, Page 42-50.

[13] Hahn and Hahn "Fast-Track HVAC Conversion" ASHRAE Journal Volume 41, No. 12, Page 41-44, December 1999.

[14] Joanna " Toys R Us Doesn't Kid Around With Renovation" Air Conditioning, Heating and Refrigeration News, Volume 210 issue 15. Aug 2000, Page 30-34.

[15] Ronald et al., " Principles Of Heating Ventilating And Air Conditioning" American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc. Page 1.4

[16] ASHRAE Fundamental 2001, GA: American Society of Heating, Ventilating and Air-Conditioning Engineers, (SI) 2001

[17] Hutcheon et al., "Building Science For A Cold Climate" John Wiley & Sons 1989, ISBN 0-471-79763-4

[18] Madsen "Measurement And Control Of Thermal Comfort In Passive Solar System", Proceedings of the 3rd International Congress on Building Engergy Management ICBEM '87 (edited by A. Faist, E. Fenanades and R.Sagelsdorff), Vol. IV, Page 489 – 496, Presses Poly-techniques Romandes, Lausanne (1987),

[19] Haghighat et al., "Thermal Comfort And Indoor Air Quality In A Partitioned Enclosure Under Mixed Convection". Building and Environment, Vol. 27, No. 1, Page 77-84.

[20] Fissore et al., " A Simple Empirical Model For Predicting Velocity Distribution And Comfort In A Large Slot-Ventilated Space". ASHRAE Transitions, Part 2, Page 1087-1095.

[21] Budaiwi "Thermal Comfort Requirements And Energy Conservation In Buildings" Al-Moandis, Issue-2, Volume 12, Shaban 1419 H

[22] Fountain "Laboratory Studies Of The Effect Of Air Movement On Thermal Comfort, A Comparison And Discussion Of Methods" ASHRAE Transactions, Part 1, Page 863-873.

[23] Bruel et al., "Innova Air Tech Instrument" Skodsborgvej 307, Naerum Denmark.

[24] Quiston et al., "Heating Ventilation And Design" second edition, John 1982 Wiley & Sons

[25] Kaiser "The Facilities Audit A Process For Improving Facilities Conditions", The Association of Higher Education Facilities Officers". 1993 Published by: APPA

[26] McCarthy et al., "HVAC Audits" Journal Of Property Management January-February 1997.

[27] Thumann "Hand Book Of Energy Audit" fifty edition, The Fairmont Press, Inc. 700 Indian Trail, Liburn, GA 30047.

[28] Krarti "Energy Audit Of Building Systems: An Engineering Approach" CRC Press, October 2000

[29] Al-Homoud "Computer-Aided Building Energy Analysis Techniques" Building and Environment, Volume 36, 2001 Page. 421-433.

[30] Lawrence Berkeley Laboratory, DOE-2 Users Guide, Berkeley, CA, Supported by the US Department of Energy, 1979.

[31] Nagengast "A History Of Comfort Cooling Using Ice" ASHRAE Journal Volume 41 no 2, Page 49-57, February 1999.

[32] Arnold "The Evolution Of Modern Office Buildings And Air Conditioning" ASHRAE Journal Volume 41 no 6, Page 40-54, June 1999.

[33] Pita "Air Conditioning Principles And Systems An Energy Approach" 1981 by John Wiley & Sons. Inc.

[34] ASHRAE handbook: Fundamentals. Atlanta, GA: American Society of Heating, Ventilating and Air-Conditioning Engineers, (SI) 1997 Page 8.15

[35] ANSI/ASHRAE Standard 55-1992 "Thermal Environmental Conditions For Human Occupancy". American Society of Heating, Ventilating and Air-Conditioning Engineers

[36] Parker et al., " Heating, Ventilation And Air Conditioning Analysis And Design" 1982 by John Wiley & Sons. Inc.

APPENDICES

A Architectural Drawings

A1 Building –19 KFUPM 3rd floor original design layout

A2 Building –19 KFUPM 3rd floor existing layout

A3 Building – 19 KFUPM 4th floor design layout

A4 Building –19 KFUPM 4th floor existing layout

A5 Building – 19 KFUPM 3rd floor thermal zones

A6 Building – 19 KFUPM 4th floor thermal zones

A7 Building – 19 KFUPM 3rd floor locations of data loggers

A8 Building – 19 KFUPM 4th floor locations of data loggers

B Occupancy Schedules

B1 Large Classrooms

B2 Small classrooms

B3 Secretary rooms

B4 Library

B5 Faculty offices

B6 Corridor

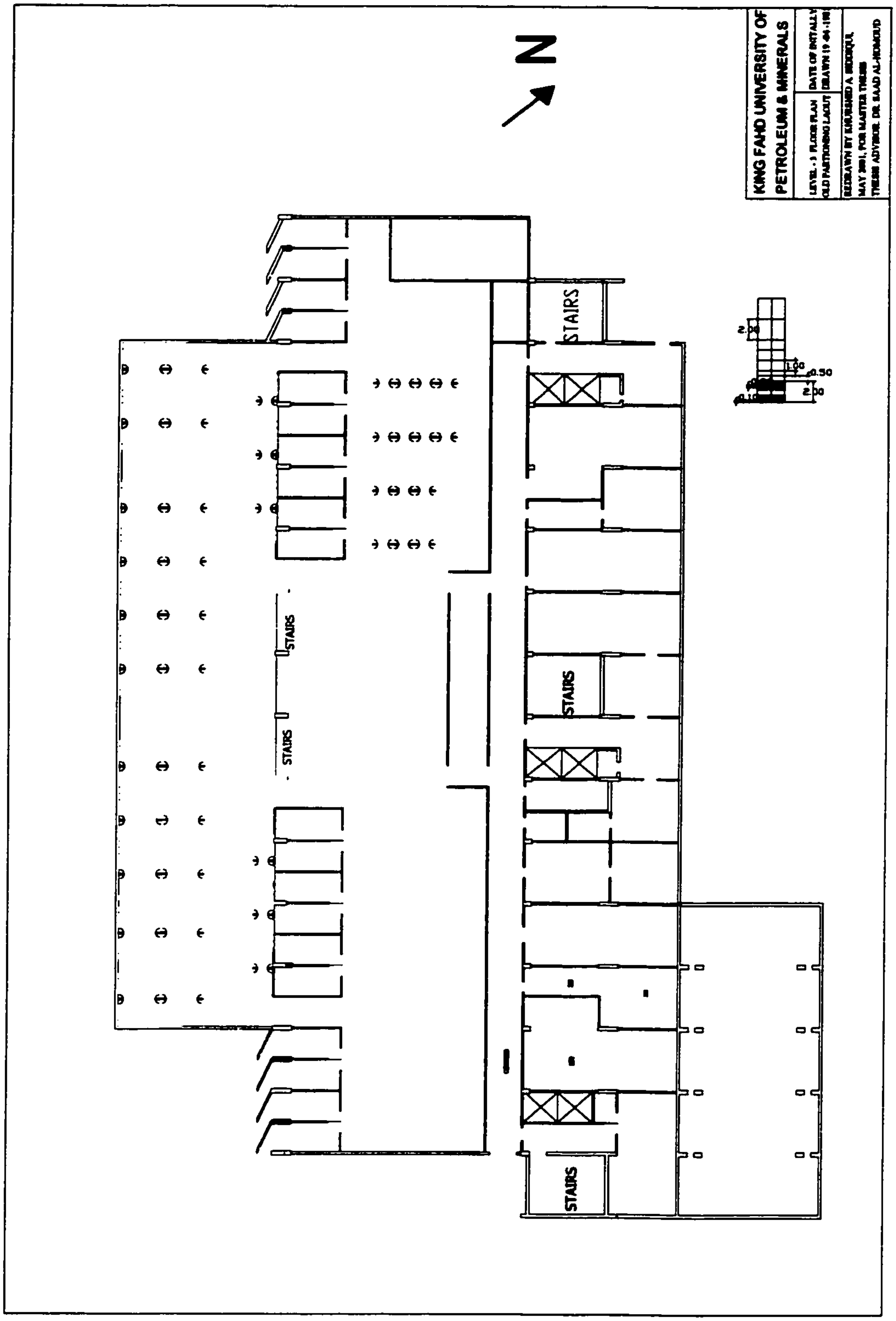
B7 Graduate labs

C Building Energy Audit Form

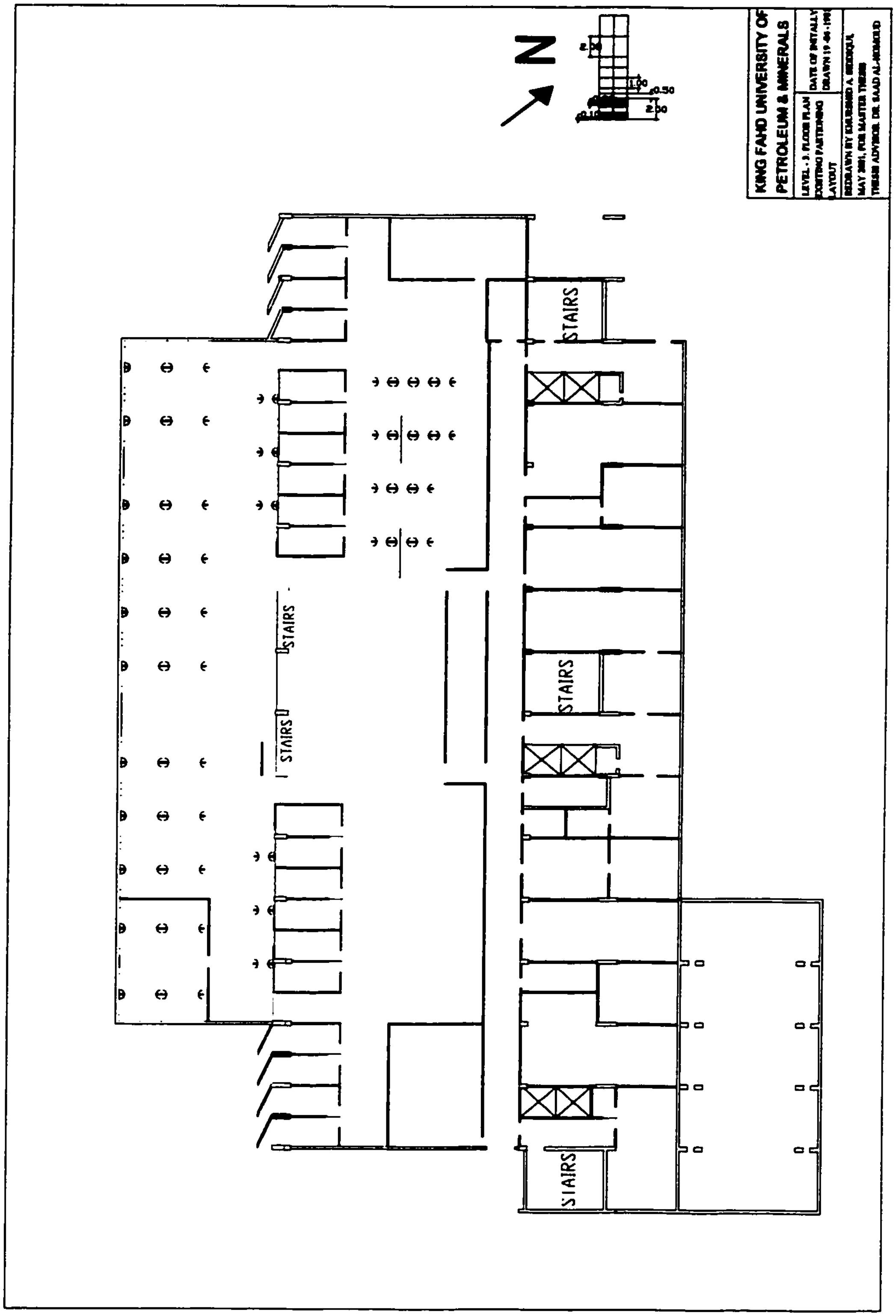
D Thermal Comfort Assessment Questionnaire

APPENDIX - A

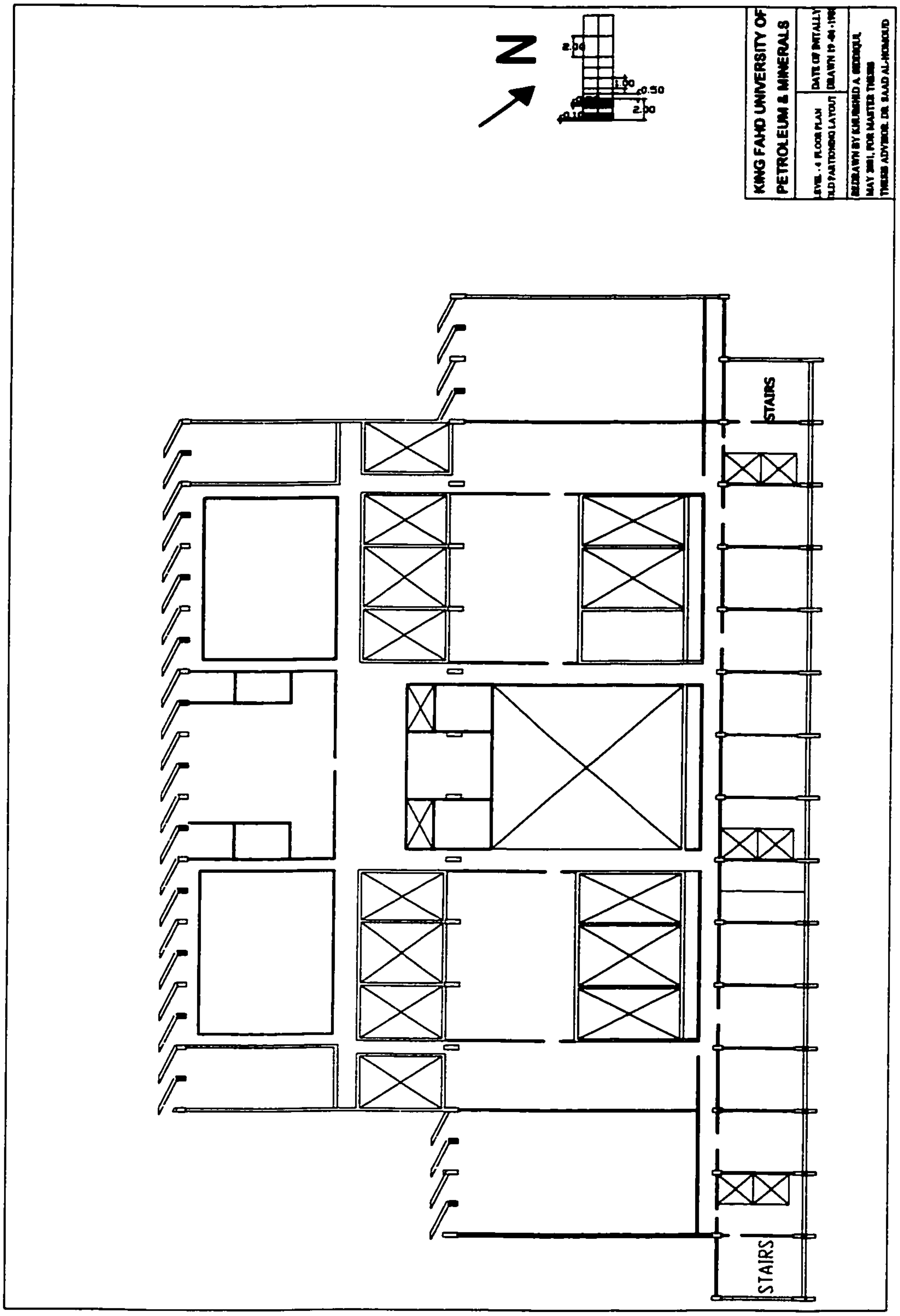
CASE STUDY BUILDING ARCHITECTURAL DRAWINGS



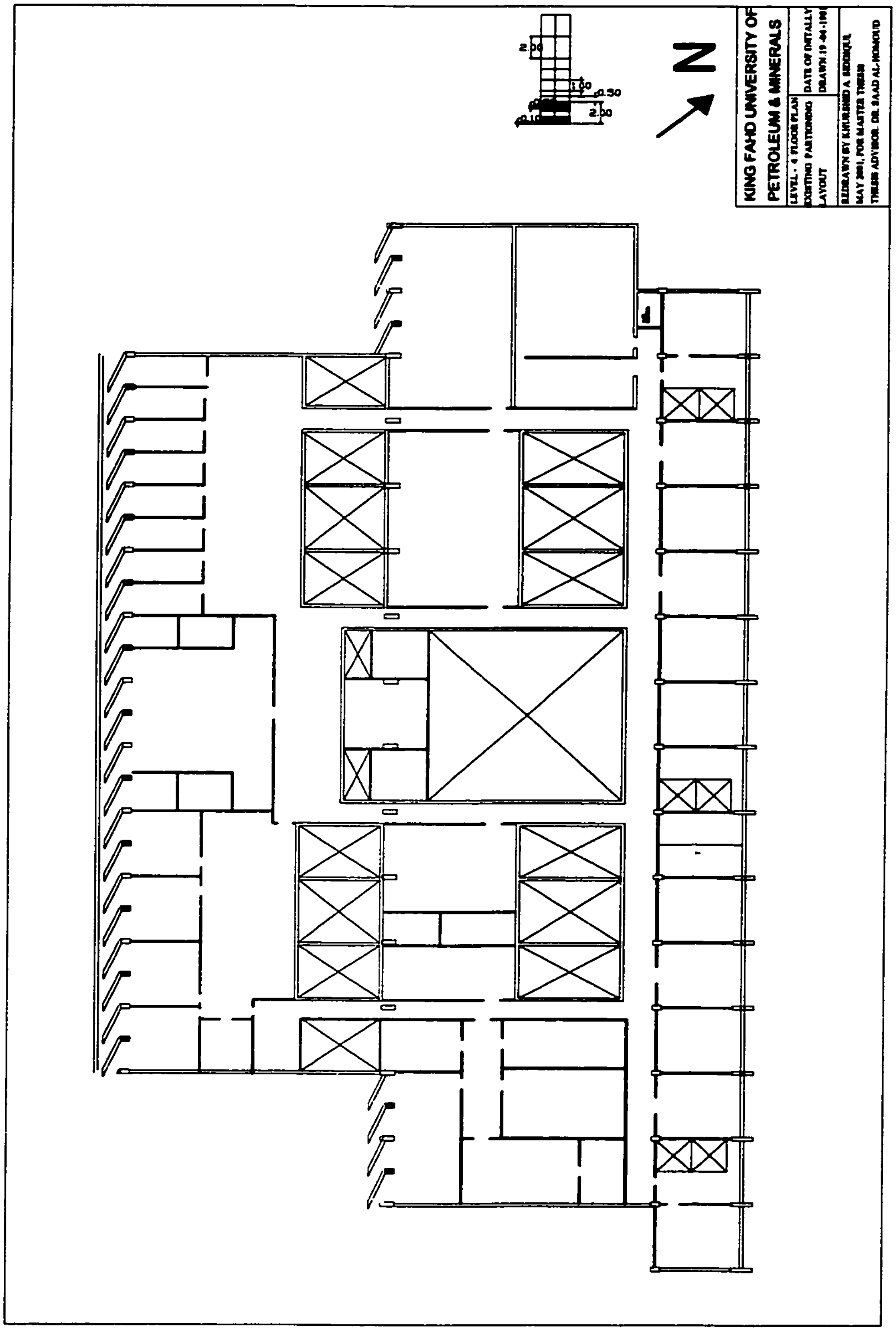
Appendix A1: Building –19 KFUPM 3rd floor original design layout



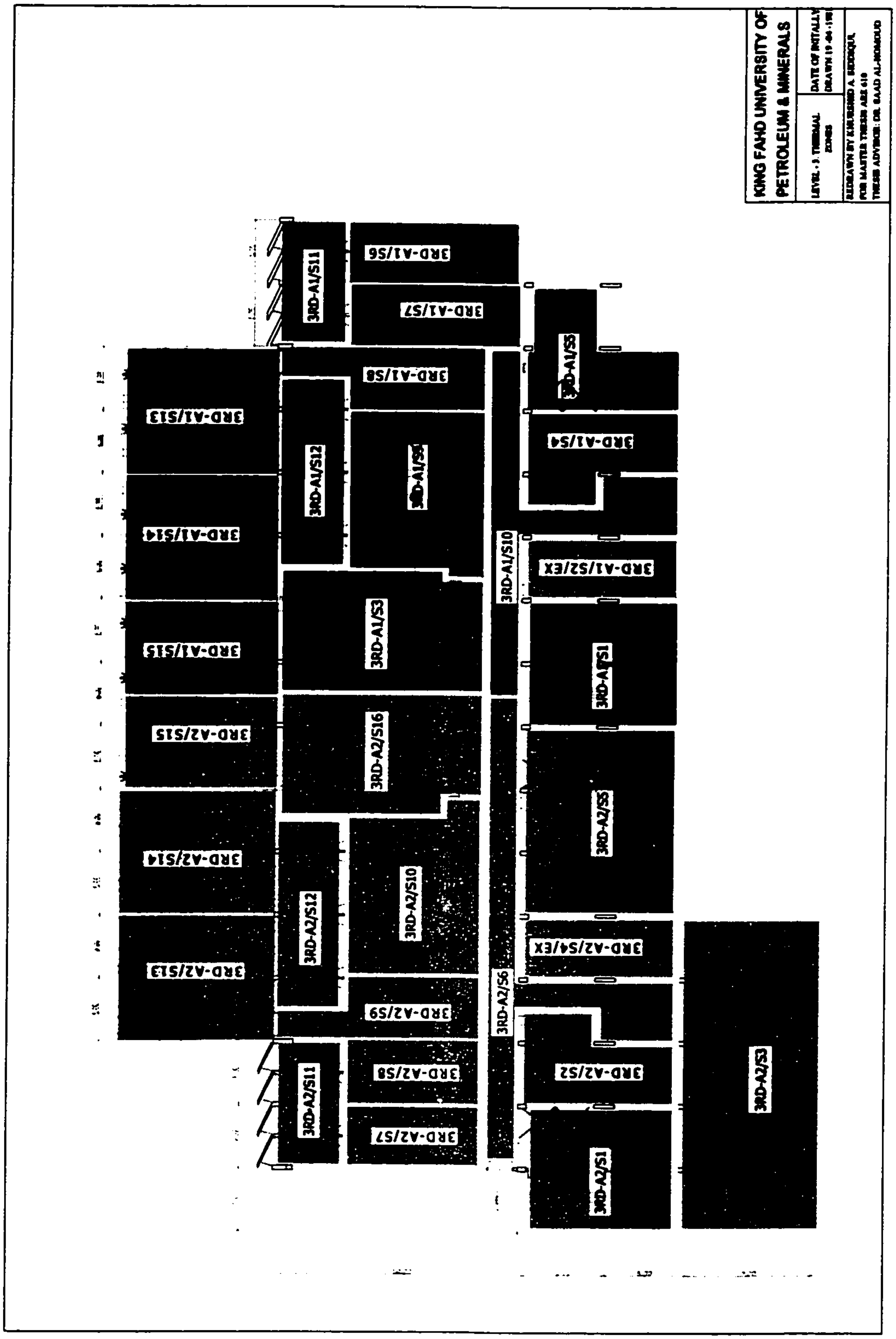
Appendix A2: Building –19 KFUPM 3rd floor existing layout



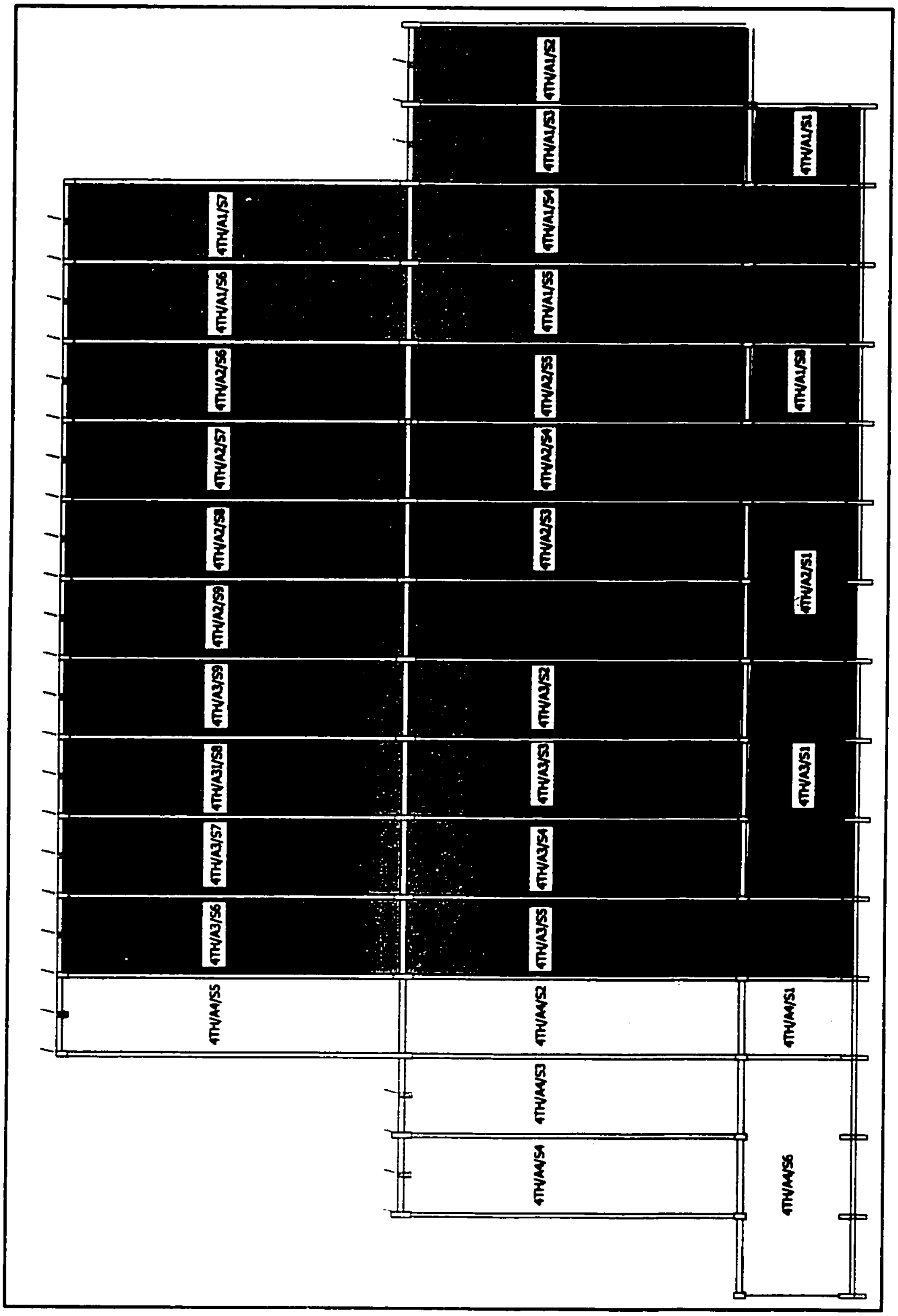
Appendix A3: Building – 19 KFUPM 4th floor design layout



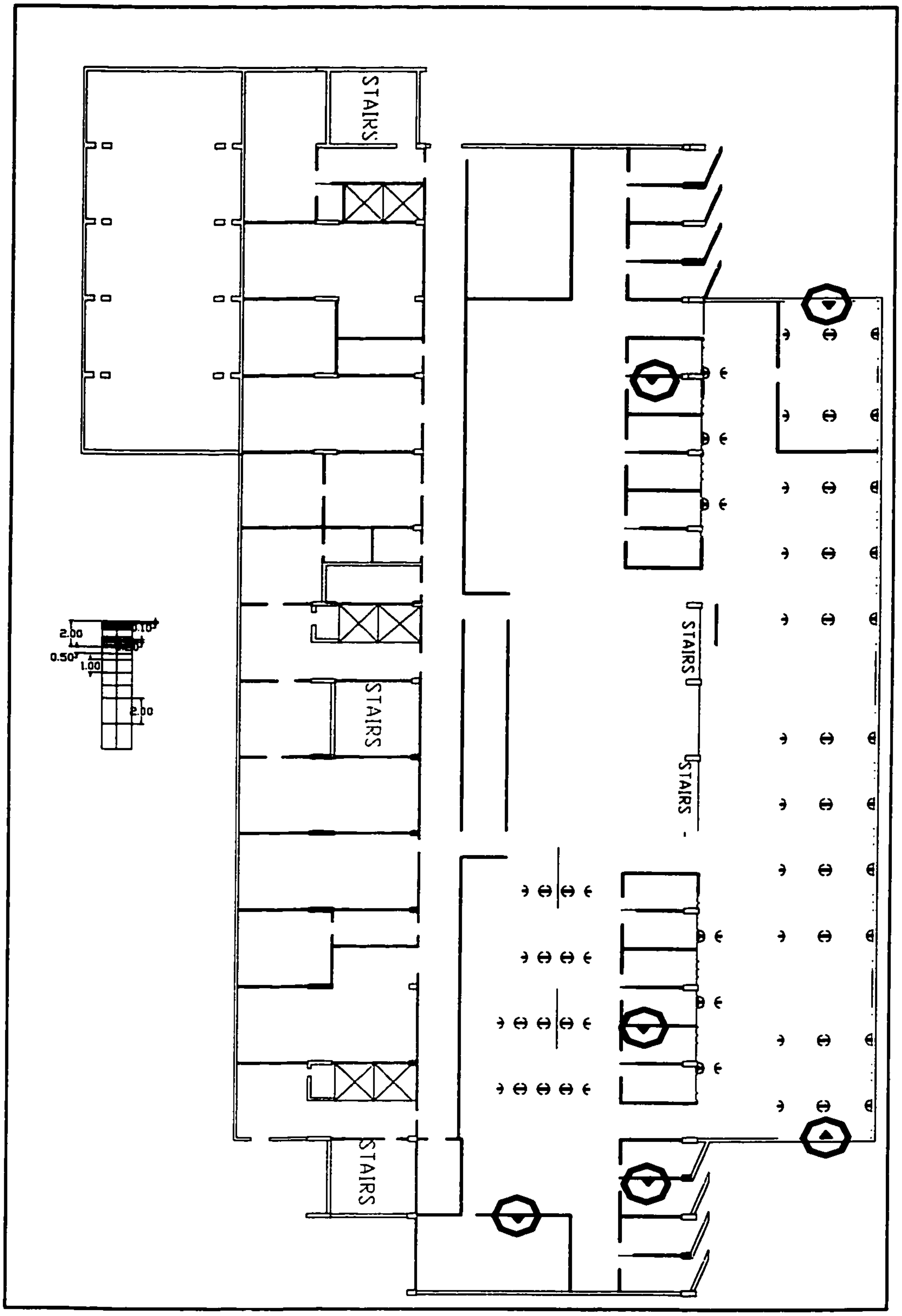
Appendix A4: Building –19 KFUPM 4th floor existing layout



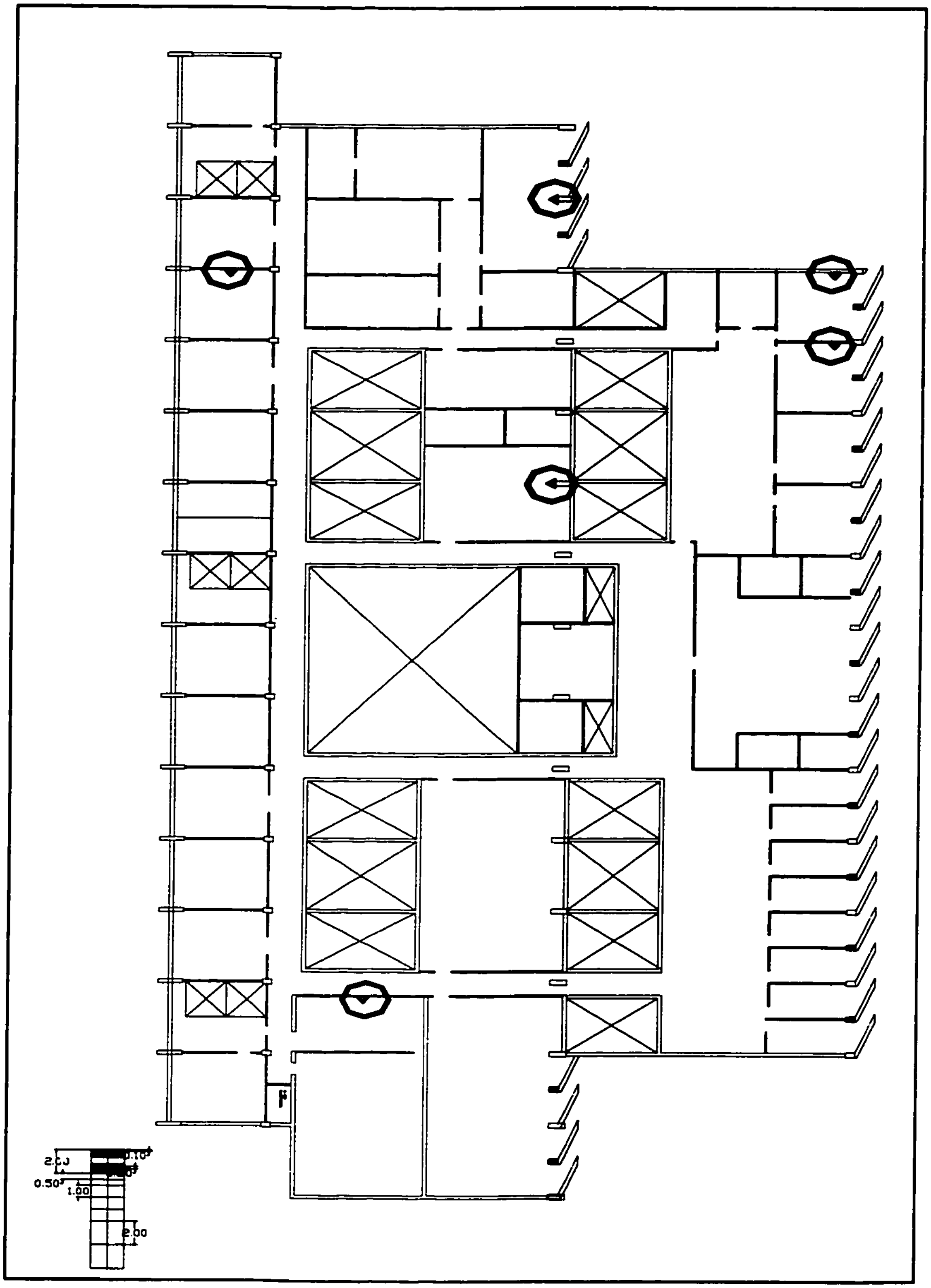
Appendix A5: Building – 19 KFUPM 3rd floor thermal zones



Appendix A6: Building – 19 KFUPM 4th floor thermal zones



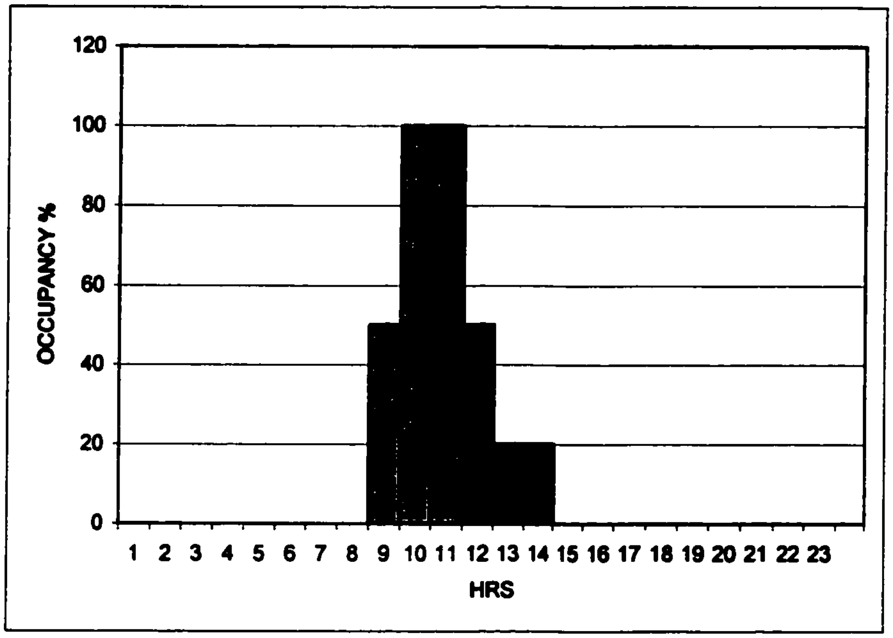
Appendix A7: Building – 19 KFUPM 3rd floor locations of data loggers



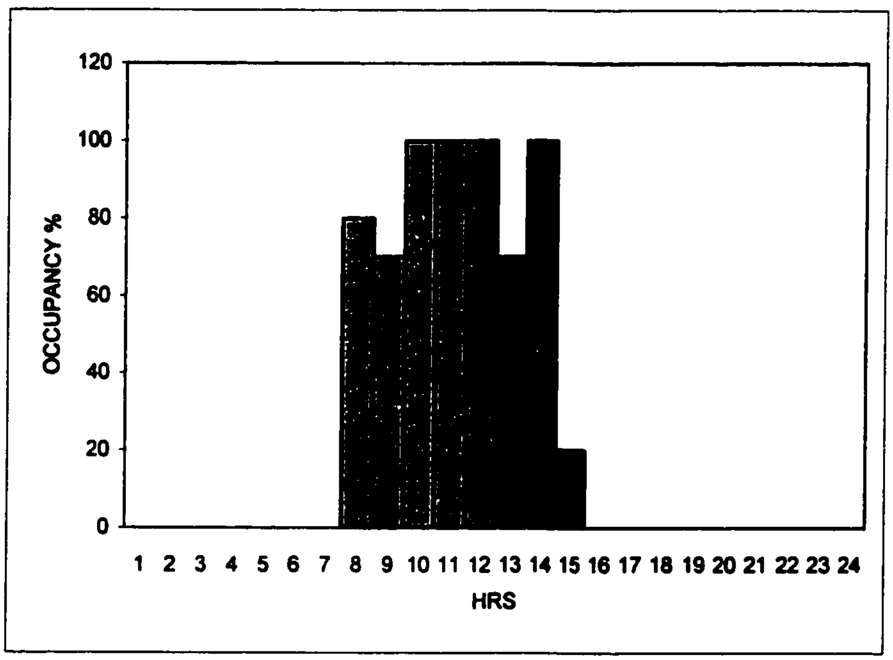
Appendix A8: Building – 19 KFUPM 4th floor locations of data loggers

APPENDIX - B

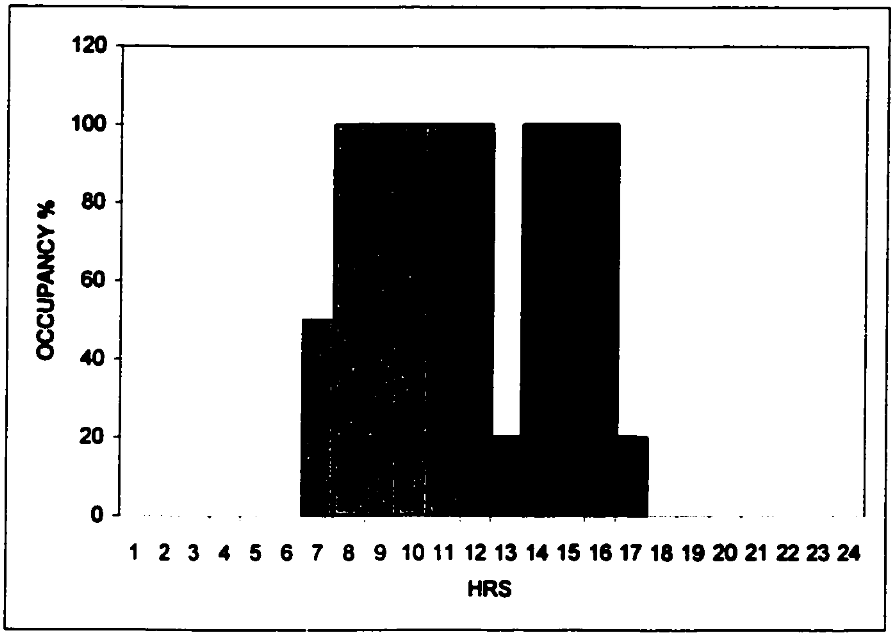
OCCUPANCY SCHEDULES



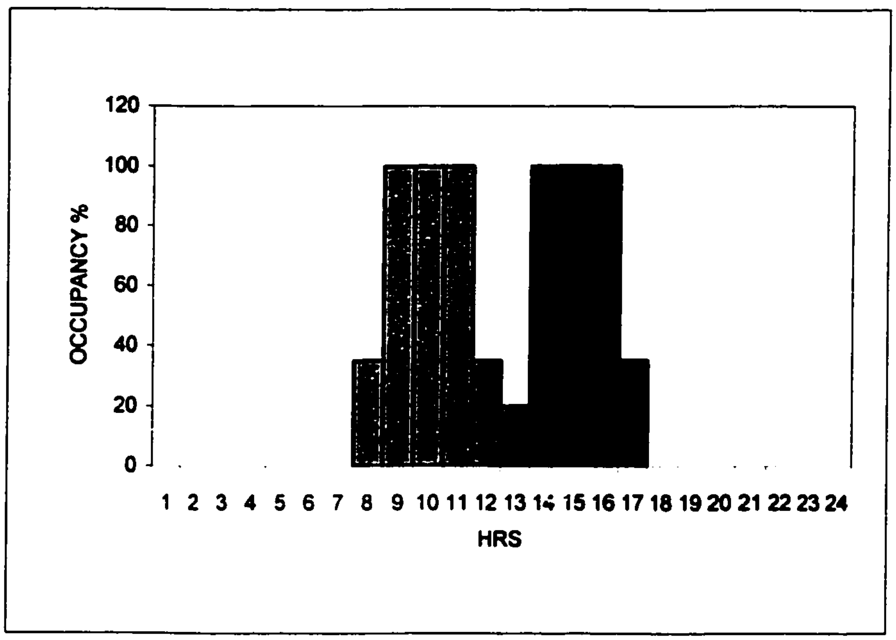
Appendix B-1: Occupancy schedule for large classrooms



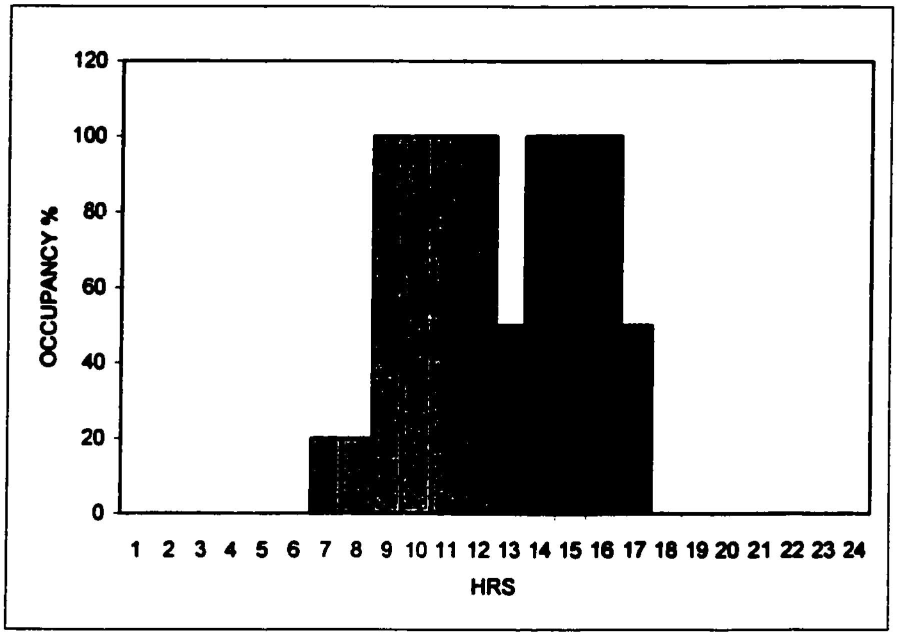
Appendix B-2: Occupancy schedule for small classrooms



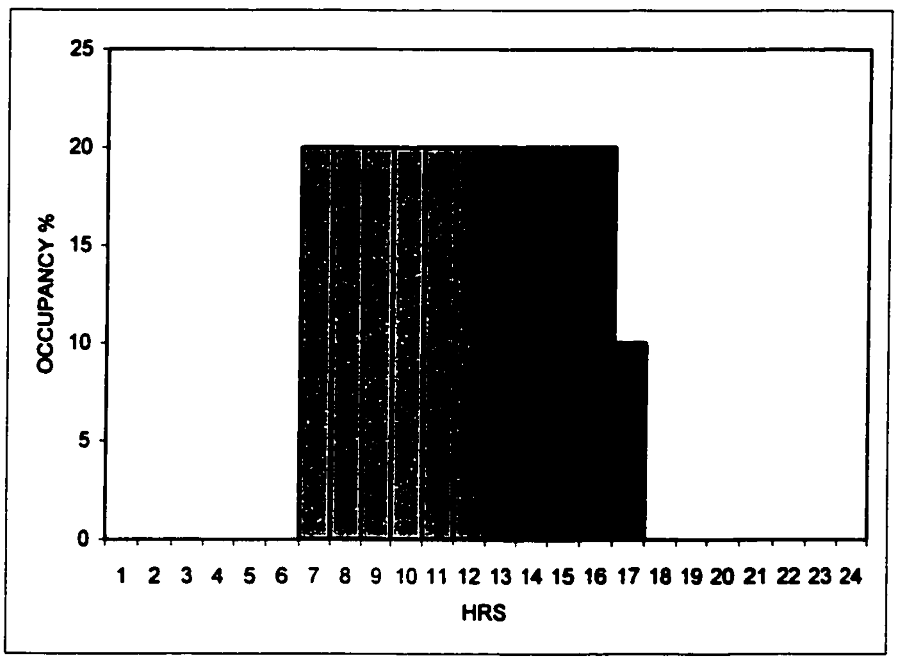
Appendix B -3: Occupancy schedule for secretary rooms



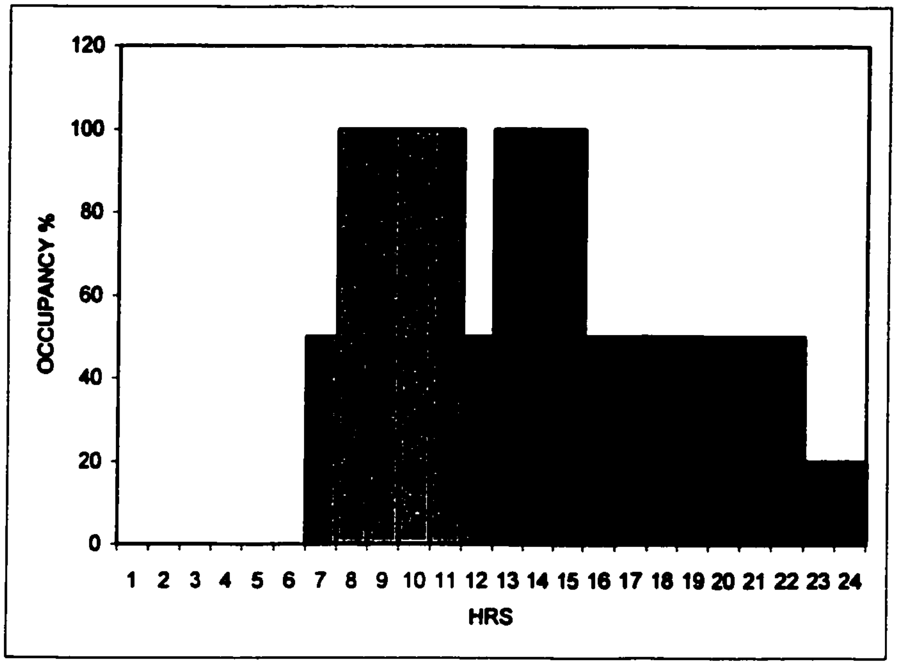
Appendix B - 4: Occupancy schedule Library



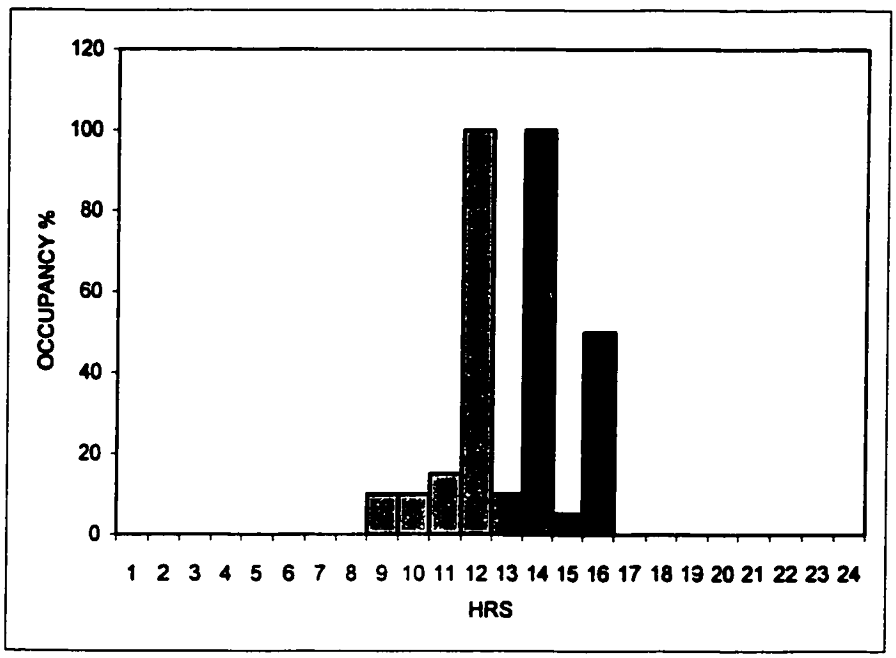
Appendix B - 5: Occupancy schedule for faculty offices.



Appendix B - 6: Occupancy schedule for corridor



Appendix B - 7: Occupancy schedule for graduate labs.



Appendix B - 8: Occupancy schedule toilet and ablution area

APPENDIX C

BUILDING ENERGY AUDIT FORM

EZDOE
BUILDING LOADS DATA

Elite Software Development 409-846-2340

Default Space Data

Default Space Data

Area: ____________
Volume: ____________
X: ____________
Y: ____________
Z: ____________
Azimuth: ____________
Mult: ____________
Flr Mult: ____________
Temp: ____________
Type: ____________
Sunspace: O Yes O No
Box: O Yes O No
Height: ____________
Width: ____________
Depth: ____________

People Schedule: ____________
# of People: ____________
Area/Person: ____________
Light Schedule: ____________
Lighting (kW): ____________
Lighting (W/ft^2): ____________
Light Type: ____________
Equip Schedule: ____________
Equipment (kW): ____________
Equipment (W/ft^2): ____________
Infil Schedule: ____________
Infil Method: ____________
Infiltration (changes/hr): ____________
Infiltration (cfm/ft^2): ____________

Default Miscellaneous Space Data

People Heat Gain: ____________
People Sensible: ____________
People Latent: ____________
Light to Space: ____________
Light to Other: ____________
Light to Return: ____________
Lt Heat to Space: ____________
Light Rad Fract1: ____________
Light Rad Fract2: ____________
Task Light Sched: ____________
Task Lighting: ____________
Task Lighting: ____________
Equipment Sens: ____________
Equipment Latent: ____________

Neutral Zone Ht: ____________
Neutral Level: ____________
Horiz Leak Fract: ____________
Frac. Leak Area: ____________
Resid Infil Coef1: ____________
Resid Infil Coef2: ____________
Resid Infil Coef3: ____________
Source Sched: ____________
Source Type: ____________
Source Btu/Hr: ____________
Source Sensible: ____________
Source Sensible: ____________
Source Latent: ____________
Floor Weight: ____________
Furniture Type: ____________
Furniture Weight: ____________
Furn Fraction: ____________

EZDOE
BUILDING LOADS DATA
Elite Software Development 409-846-2340

Default Space Data (continued)

Default Space Daylighting

Daylighting:	O Yes O No
Daylight Rep Schedule:	______
Max Glare:	______
View Azimuth:	______
Light Ctrl Prob:	______
Light Ctrl Steps:	______
Light Ctrl Type 1:	O Continuous O Stepped
Light Ctrl Type 2:	O Continuous O Stepped
Light Set Point 1:	______
Light Set Point 2:	______
Zone Fraction 1:	______
Zone Fraction 2:	______
Min Power Fraction:	______
Min Light Fraction:	______
Light Ref Point 1 (x, y & z):	(, ,)
Light Ref Point 2 (x, y & z):	(, ,)

Default Roof Data

Construction:	______		
Height × Width:	×		
Azimuth:	______		
Tilt:	______		
X, Y, Z:	(, ,)		
Multiplier:	______	Solar Fraction:	______
Gnd Reflectance:	______	Infil Coef:	______
Sky Form Factors:	______	Shading Division:	______
Gnd Form Factors:	______	Shanding Surfaces:	O Yes O No
Inside Sol Abs:	______	Inside Vis Refl:	______
Location:	O Left (1) O Right (2) O Front (3) O Back (4) O Top (5) O Bottom (6)		

EZDOE
BUILDING LOADS DATA

Elite Software Development 409-846-2340

Default Space Data (continued)

Default Exterior Wall Data

Construction: ______________
Height × Width: ______ × ______
Azimuth: ______________
Tilt: ______________
X, Y, Z: (, ,)
Multiplier: ______________
Gnd Reflectance: ______________
Sky Form Factors: ______________
Gnd Form Factors: ______________
Inside Sol Abs: ______________
Solar Fraction: ______________
Infil Coef: ______________
Shading Division: ______________
Shanding Surfaces: O Yes O No
Inside Vis Refl: ______________
Location: O Left (1) O Right (2) O Front (3) O Back (4) O Top (5) O Bottom (6)

Default Interior Wall Data

Construction: ______________
Height × Width: ______ × ______
Azimuth: ______________
Tilt: ______________
X, Y, Z: (, ,)
Next to Space #: ______________
Solar Fraction 1: ______________
Solar Fraction 2: ______________
Inside Sol Abs 1: ______________
Inside Sol Abs 2: ______________
Inside Vis Refl 1: ______________
Inside Vis Refl 2: ______________
Int. Wall Type: O Standard (1) O Air (2) O Adiabatic(3) O Internal (4)
Location: O Left (1) O Right (2) O Front (3) O Back (4) O Top (5) O Bottom (6)

EZDOE
BUILDING LOADS DATA

Elite Software Development 409-846-2340

Default Space Data (continued)

Default Underground Wall/Floor Data	
Construction:	______
Height × Width:	___ × ___
U-Effective:	______
Tilt:	______
X, Y, Z:	(, ,)
Multiplier:	______
Solar Fraction:	______
Inside-Vis-Refl:	______
Inside Sol Abs	______
Location:	O Left (1) O Right (2) O Front (3) O Back (4) O Top (5) O Bottom (6)

Default Window Data			
Glass Type:	______		
Height × Width:	___ × ___		
Multiplier:	______	Shading Sched:	______
X, Y:	(,)	Open Shade Sched:	______
Setback:	______	Max Solar Sched:	______
Infil Coef:	______	Solar Trans Sch:	______
Shading Division:	______	Conduct Sched:	______
Glare Ctrl Prob:	______	Conduct TMin Sch:	______
Inside Vis Refl:	______	Vis Trans Sched:	______
Sky Form Factor	______	Gnd Form Factor:	______
Win Shade Type:	O Movable-Int (1) O Fixed-Int (3)	O Mov-Ext (2) O Fixed-Ext (4)	

EZDOE

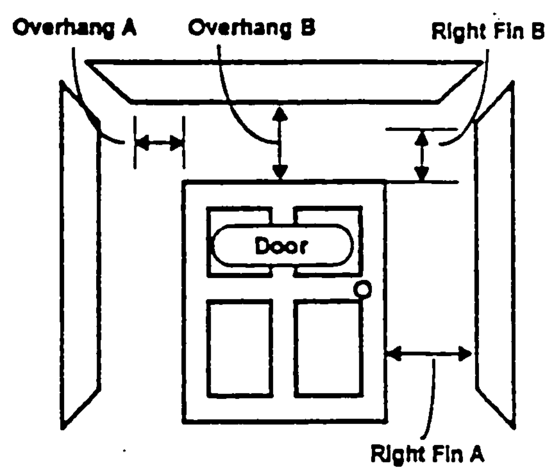
BUILDING LOADS DATA

Elite Software Development 409-846-2340

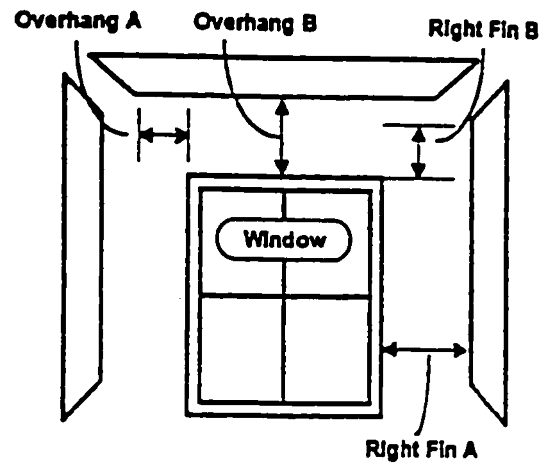
Default Space Data (continued)

Default Door Data	
Construction:	
Height × Width:	×
Multiplier:	
X, Y:	(,)
Setback:	
Infil Coef:	
Shading Division:	
Inside Vis Refl:	
Sky Form Factor:	
Gnd Form Factor:	

Default Door Overhang Data	
Overhang	
A Distance:	
B Distance:	
Width:	
Depth:	
Angle:	
Left Fin	
A Distance:	
B Distance:	
Height:	
Depth:	
Right Fin	
A Distance:	
B Distance:	
Height:	
Depth:	



Default Window Overhang Data	
Overhang	
A Distance:	________
B Distance:	________
Width:	________
Depth:	________
Angle:	________
Left Fin	
A Distance:	________
B Distance:	________
Height:	________
Depth:	________
Right Fin	
A Distance:	________
B Distance:	________
Height:	________
Depth:	________



APPENDIX D

THERMAL COMFORT ASSESSMENT QUESTIONNAIRE

Questionnaire for the Assessment of "The Thermal Comfort Status in Various Spaces of Building 19 KFUPM"

Please write or check the most appropriate answer for the following questions:

General Information

Age:

- ❑ Less than 20 years
- ❑ 20 to 30
- ❑ 30 to 40
- ❑ Above 40

Room number or location: __________

No. of Persons/ Students in the room/ space:________ ,

Nature of your work

- ❑ Faculty
- ❑ Student
- ❑ Other (please specify): ____________________________
- ❑ Secretarial / Lab works

How long have you been using this room / space?

- ❑ Less than a semester
- ❑ A year
- ❑ More than one year

Approximately how long do you stay in this room / space each day?

- ❑ Less than 1 hr
- ❑ 1-4 hrs
- ❑ 4-6 hrs
- ❑ 6-8 hrs
- ❑ More Than 8 hrs

Thermal Comfort Assessment:

How do you feel about the room / space temperature?

- ❑ Very Cold
- ❑ Cold
- ❑ Cool
- ❑ Satisfactory
- ❑ Warm
- ❑ Hot
- ❑ Very Hot

How do you feel about the humidity in the room / space?

- ❑ Too dry
- ❑ Dry
- ❑ Comfortable
- ❑ Humid
- ❑ Too humid

How do you feel about the movement of the air in the room / space?

- ❑ Still
- ❑ Moderate
- ❑ Drafty

What is your overall rating for the room/ space thermal conditions?

- ☐ Comfortable
- ☐ Moderately comfortable
- ☐ Uncomfortable

Which season do you feel most uncomfortable in your room / space?

☐ Summer ☐ Winter ☐ Both

Which time of the day do you feel most uncomfortable in your room / space?

☐ Morning ☐ Noon ☐ Both

Has the layout of your room/space been changed?

☐ Yes ☐ No

If the answer of the above question is "YES", kindly answer the following question:

What effect you think space layout changes have on the quality of its thermal conditions?

- ☐ No effect
- ☐ Improve
- ☐ Become worse (How? ______________________________)

Please add any additional comments below:

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Thanks for your cooperation,

Kindly return this questionnaire back to

Mr. Khurshid Alam in Bldg. 19, Room no. 234 or post it to P.O. Box # 591.