UNIVERSITY OF GÄVLE

FACULTY OF ENGINEERING AND SUSTAINABLE DEVELOPMENT

THERMAL COMFORT ANALYSIS OF A NATURALLY VENTILATED BUILDING.

CASE STUDY:

COLLEGE OF ENGINEERING, DESIGN, ART & TECHNOLOGY (CEDAT) BUILDING, MAKERERE UNIVERSITY, KAMPALA-UGANDA

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OCTOBER/2013

Master's Thesis in Applied Thermodynamics and Refrigeration, HVAC Technologies.

MSc. Sustainable Energy Engineering

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Abstract

The main objective of the study was to analyze the thermal comfort of a naturally ventilated building in Kampala – Uganda. CEDAT building in Makerere University was selected as the case study representing an educational center which is a naturally ventilated building.

DesignBuilderEnergyPlus simulation program was used to model and perform simulations. Simulations for thermal comfort were done on the baseline model with a WWR of 30 % to attain the baseline model comfort data based on Simple ASHRAE 55-2004 throughout the year. Simulations for different natural ventilation improvement strategies were then done through parametric analysis. The strategies simulated for improving occupancy thermal comfort were lighting control, mechanical ventilation without cooling (fans), mechanical ventilation with cooling and variation of window to wall ratio from 0% to 100% to establish its effect on the thermal comfort of the building occupants.

Results for predicted thermal comfort sensation of occupants revealed that baseline thermal comfort sensation was between hot and slightly warm with 35.15% discomfort hours against 64.85% comfort throughout the year. Lighting control thermal comfort sensation improved to between hot and neutral with 0.55% improvement in baseline occupancy thermal comfort hours. Mechanical ventilation without cooling registered a negligible improvement in occupancy thermal comfort while on application of scheduled cooling thermal comfort improved between slightly warm and slightly cool with a 12% improvement in comfort hours. Variation of WWR revealed that thermal comfort generally increased negligible with increase in WWR.

It can be concluded that mechanical ventilation with cooling combined with lighting control can be great strategies and opportunity for improving the case study thermal comfort.

Key words: **Thermal comfort, Analysis, Naturally ventilated, Building.**

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ACEE – American Council for an Energy-Efficiency Economy

ASE - Alliance to Save Energy

ASHRAE - American Society of Heating, Refrigerating, and Air-Conditioning Engineers

CEDAT - College of Engineering, Design, Art and Technology

CIA - Central Inteligency Agency

CO_2 – Carbon dioxide

CSBR - Center for Sustainable Building Research

GPS - Global Positioning System

HVAC – Heating Ventilation & Air Conditioning

LBNL - Lawrence Berkeley National Laboratory

MAK – Makerere University Kampala

UBOS - Uganda Bureau of Statistics

UMD - Uganda Metrological Department

UN – United Nations

WWR – Window Wall Ratio

CHAPTER ONE

1.0 Introduction

1.1 Background

Uganda has one of the fastest growing economies in the region. There are an increasing number of commercial centers not only in the capital Kampala but in all the major urban centers. UBOS, (2012) published its finds indicating plans submitted and approved for residential and commercial buildings in Uganda almost doubled in 2011 compared to 2010.

The building sector encompasses a diverse set of end-use activities, which have different energy use implications. The amount of energy used for cooling and lighting, is directly related to the building design, building materials, the occupants' needs and behavior, and the surrounding micro-climate.

Majority of modern buildings in Uganda are replicas of buildings designed in western world (cold and temperate climates) and do not take into consideration the differences in climate.

People have always been in pursuit of creating comfort in their environment through natural ventilation due to its low cost. It is still one of the most important matters taken into account in the building design process.

Wang and Wong (2006), states that with the global emergence of energy shortages, climatic changes and sick building syndromes associated with the common usage of air-conditioning, authorities worldwide have recognized the necessity in finding strategies that can cultivate a more sustainable design with satisfactory indoor thermal comfort. This has led to the growing interest in low energy cooling strategies that take advantage of natural ventilation which has the potential to reduce first costs and operating costs for commercial buildings while maintaining ventilation rates consistent with acceptable indoor air quality.

Heiselberg (1990), states that the primary objective of ventilation in occupied space is to supply fresh air and remove contaminates in order to assure thermal comfort.

Globally agreed, Fanger (1970) defines thermal comfort as the condition of the mind which expresses satisfaction with the thermal environment. Thermal comfort is said to be achieved in a building when the highest possible percentage of all occupants are thermally comfortable.

Wang and Wong (2006), it's recommended that optimum WWR of 0.24 can improve indoor thermal comfort for full day ventilation and proved that symptoms of occupancy discomfort often show to be related to volume of air supplied to a building and type of ventilation provided.

Gail and Sam (2008), state that it has been demonstrated that naturally ventilated buildings in some climates can operate for the entire cooling season within adaptive comfort constrains without mechanical cooling.

New vision (28/July/2012), Uganda's population now at 34.5 million with a growth rate of 3.1% annually and above the sub-Sahara African regional average of 2.4%, growth rate is a factor that has imposed on the changing needs of its people for infrastructure (e.g., schools, hospitals, housing, roads) and resources (e.g., food, water, electricity).

This increased demand for buildings has to match with the goal of energy efficient buildings with productive, healthy indoor environments as occupant productivity is significantly improved when thermal comfort and indoor air quality are optimized.

In Uganda methods such as openings at the end of passageways to allow for a constant draft of fresh air through often crowded passages, considering large functional windows and grills/ventilation openings in and above entrance doors to create cross ventilation, even positioning of windows and doors in opposite walls of rooms, keeping windows and doors open to maximize cross ventilation are employed to improve natural ventilation of buildings.

The concept of natural ventilation doesn't seem to be complicated but it's a challenge to design naturally ventilated buildings due to the fact that naturally ventilation is difficult to control since it is a medium of passage for solar latent loads from the external environment.

1.2 Problem statement

To achieve the goal of energy efficiency in buildings, natural ventilation is one of the suggested practices emphasized and adopted in many buildings around the world of which educational facilities have been a major target as an opportunity of achieving thermal comfort and energy efficiency goals simultaneously.

When it comes to educational facilities, end users who are usually students, lecturers and other occupants spend almost 50% of the entire day within the buildings. To add on 50%, occupancy is predominantly during day time when environmental conditions are adverse to human survival hence creating thermal discomfort which in turn leads to low productivity and occupancy dissatisfaction.

Many educational facilities mostly in Africa have been built relying on natural climatic conditions for occupancy comfort throughout the year which has brought about discrepancies amongst users. Whilst natural ventilation can provide thermal comfort in some climates, a gap of thermal comfort improvement strategies in naturally ventilated buildings still exits to enhance suitable thermal condition in buildings thus avoiding occupant dissatisfaction, low productivity and overall building performance.

1.3 Project objectives

1.3.1 Main objective

The main objective of the study was to analyze the thermal comfort of a naturally ventilated building in Kampala – Uganda.

1.3. 2 Specific objectives

The study was defined by the following specific objectives;

1. To assess the case study/ baseline model components and external environment.
2. To develop CEDAT building baseline model.
3. To perform thermal comfort analysis of the baseline model.
4. To perform thermal comfort analysis of the different natural ventilation efficiency improvement and thermal comfort strategies.

CHAPTER TWO

2.0 Literature review

2.1 Thermal comfort analysis

"Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (Fanger, 1970).

2.1.1 Thermal comfort models

In the last decades, researchers have been exploring the thermal, physiological and psychological response of people in their environment in order to develop mathematical models to predict these responses. Researchers have empirically argued building occupants' thermal responses to the combined thermal effect of the environmental, personal and physiological variables that influence the condition of thermal comfort.

Environmental Variables

1. Air Temperature (Ta) - a direct environmental index, is the dry-bulb temperature of the environment,

2. Mean Radiant Temperature (Tr) - a rationally derived environmental index defined as the uniform black-body temperature that would result in the same radiant energy exchange as in the actual environment,

3. Relative air velocity (v) - a direct environmental index is a measure of the air motion,

4. Water vapor pressure in ambient air (Pa) - a direct environmental index.

Personal Variables

1. Thermal resistance of the clothing (Icl).

Thermal resistance of the clothing (Icl) is measured in units of "clo." The 1985 ASHRAE Handbook of Fundamentals (ASHRAE, 1985) suggests multiplying the summation of the individual clothing items clo value by a factor of 0.82 for clothing ensembles.

2. Metabolic rate (H/ADu).

Physiological Variables

1. Core or Internal Temperature (Tcr),
2. Skin Temperature (Tsk),
3. Skin Wettedness (w),
4. Sweat Rate,
5. Thermal Conductance (K) between the core and skin.

Where the Skin Temperature (Tsk), the Core Temperature (Tcr) and the Sweat Rate are physiological indices.

The Skin Wettedness (w) is a rationally derived physiological index defined as the ratio of the actual sweating rate to the maximum rate of sweating that would occur if the skin were completely wet. One more consideration is important in dealing with thermal comfort - the effect of asymmetrical heating or cooling. This could occur when there is a draft or when there is a radiant flux incident on a person.

Fanger (1986) noted that the human regulatory system is quite tolerant of asymmetrical radiant flux. According to ASHRAE (1984) reasonable upper limit on the difference in mean radiant temperature (Tr) from one direction to the opposing direction is 15. This limit is lower if there is a high air velocity in the zone.

2.1.2 Mathematical models for predicting thermal comfort

From the research done, some mathematical models that simulate occupants' thermal response to their environment have been developed. Most thermal comfort prediction models use a seven or nine point thermal sensation scale (Table 2.1 and 2.2)

Table 2. 1: Seven point thermal sensation scale

Scale	Sensation
3	Hot
2	Warm
1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

Source: Fanger (1970)

Table 2. 2: Nine point thermal sensation scale

Scale	Sensation
4	Very hot
3	Hot
2	Warm
1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold
-4	Very cold

Source: Fanger (1970)

According to Berglund (1978), the most developed and used models for predicting thermal comfort are;

1. Fanger Comfort Model – Developed by P.O. Fanger.
2. KSU Two-Node Model – Developed by Kansas State University.
3. Pierce Two-Node Model – Developed by J.B Pierce Foundation.

Similarities between the models

An energy balance is applied to a person where use of energy exchange mechanisms along with experimentally derived physiological parameters to predict the thermal feeling and the physiological response of a person due to their environment.

However there is a difference in the models which is mainly the representation of the human passive system and human control system.

Human passive system is represented by heat transfer all the way through and from the body and the control system is sweating, skin blood flow and shivering.

2.1.2.1 Fanger comfort model

According to Fanger (1967), the Fanger Comfort Model was the first one to be developed and published first in 1967. This publishment served as the basement for development of the other two models and it's considered to be the easiest to use due to its appearance in both chart and graphical output. Fanger comfort model is based on the assumption that a person is thermally at steady state with his environment.

2.1.2.2 KSU two-node model

According to Azer et al (1977), the KSU two-node model similar to the model of Pierce Foundation was developed at Kansas State University and published in 1977.

Inspite of the similarity, both models have a difference of KSU model predicting thermal sensation (TSV) differently for warm and cold environment. Theory behind the model is that its prediction is related to changes occurring in the thermal conductance between the core and the skin temperature in cold environments, and in warm environments it is based on changes in the skin wettedness.

Here metabolic heat production is generated in the core which exchanges energy with the environment by respiration and the skin exchanges energy by convection and radiation. In addition, body heat is dissipated through evaporation of sweat and/or water vapor diffusion through the skin.

Here, control signals, based on set point temperatures in the skin and core, are introduced into passive system equations and these equations are integrated numerically for small time increments or small increments in core and skin temperature.

The control signals modulate the thermoregulatory mechanism and regulate the peripheral blood flow, the sweat rate, and the increase of metabolic heat by active muscle shivering. The development of the controlling functions of skin conductance (KS), sweat rate (Esw), and shivering (Mshiv) is based on their correlation with the deviations in skin and core temperatures from their set points.

Base on Berglund (1978), KSU model's TSV was developed from experimental conditions in all temperature ranges and from clo levels between .05 clo to 0.7 clo and from activities levels of 1 to 6 mets.

2.1.2.3 Pierce two-node model

According to Gagge *et al* (1970), the Pierce Two-Node model was developed at the John B. Pierce Foundation at Yale University and initially published in 1970 then a revised version in 1986 (Gagge *et al, 1986)*. The theory behind this model is that the human body is lumped as; two isothermal, concentric compartments, one representing the internal section or core (where all the metabolic heat is assumed to be generated and the skin comprising the other compartment).

The boundary line between two compartments changes with respect to skin blood flow rate per unit skin surface area (SKBF in L/h•m^2) and is described by alpha – the fraction of total body mass attributed to the skin compartment (Doherty and Arens, 1988).

The model also accounts for deviations of the core, skin, and mean body temperature weighted by alpha from their respective set points.

Thermoregulatory effector mechanisms (Regulatory sweating, skin blood flow and shivering) are defined in terms of thermal signals from the core, skin and body (Doherty and Arens, 1988).

Standard Effective Temperature (SET) uses skin temperature as part of its limiting conditions, but uses skin wettedness (w) rather than sweat rate for the other limiting condition.

Values for Tsk and w are derived from the Pierce `two-node' model of human physiology. SET relates the real conditions to the (effective) temperature in standard clothing and metabolic rate and 50% RH which would give the same physiological response. Effective temperature can then be related to subjective response.

The latest version of the Pierce model (Fountain *et al*, 1997) uses the concepts of SET* and ET*. The Pierce model converts the actual environment into a "standard environment" at a Standard Effective Temperature, SET*. SET* is the dry-bulb temperature of a hypothetical environment at 50% relative humidity for subjects wearing clothing that would be standard for the given activity in the real environment.

Furthermore, in this standard environment, the same physiological strain, i.e. the same skin temperature and skin wettedness and heat loss to the environment, would exist as in the real environment. The Pierce model also converts the actual environment into a environment at an Effective Temperature, ET*, that is the dry-bulb temperature of a hypothetical environment at 50% relative humidity and uniform temperature (Ta = MRT) where the subjects would experience the same physiological strain as in the real environment.

In the latest version of the model it is suggested that the classical Fanged PMV be modified by using ET* or SET* instead of the operative temperature. This gives a new index PMV* which is proposed for dry or humid environments. It is also suggested that PMV* is very responsive to the changes in vapor permeation efficiency of the occupants clothing.

Besides PMV*, the Pierce Two Node Model uses the indices TSENS and DISC as predictors of thermal comfort. Where TSENS is the classical index used by the Pierce foundation, and is a function of the mean body temperature. DISC is defined as the relative thermoregulatory strain that is needed to bring about a state of comfort and thermal equilibrium. DISC is a function of the heat stress and heat strain in hot environments and equal to TSENS in cold environments. In summary, the Pierce Model, for our purposes, uses four thermal comfort indices; PMVET-a function of ET*, PMVSET- a function of SET*, TSENS and DISC.

2.1.2.4 Adaptive comfort model

ASHRAE developed an industry consent standard “ASHRAE Standard 55-2004 Thermal Environmental Conditions for Human Occupancy” for stating comfort requirements in naturally ventilated buildings to give the combined conditions of occupancy personal parameters and indoor thermal factors that yield acceptable majority comfort to occupancy in a given environment.

The ASHRAE Comfort Zone as portrayed on a modified psychrometric chart (Figure 2.1) given in. The Standard allows the comfort charts to be applied to spaces where the occupants have activity levels that result in metabolic rates between 1.0 met and 1.3 met and where clothing is worn that provides between 0.5 clo and 1.0 clo of thermal insulation. The comfort zone is based on the PMV values between -0.5 and +0.5.

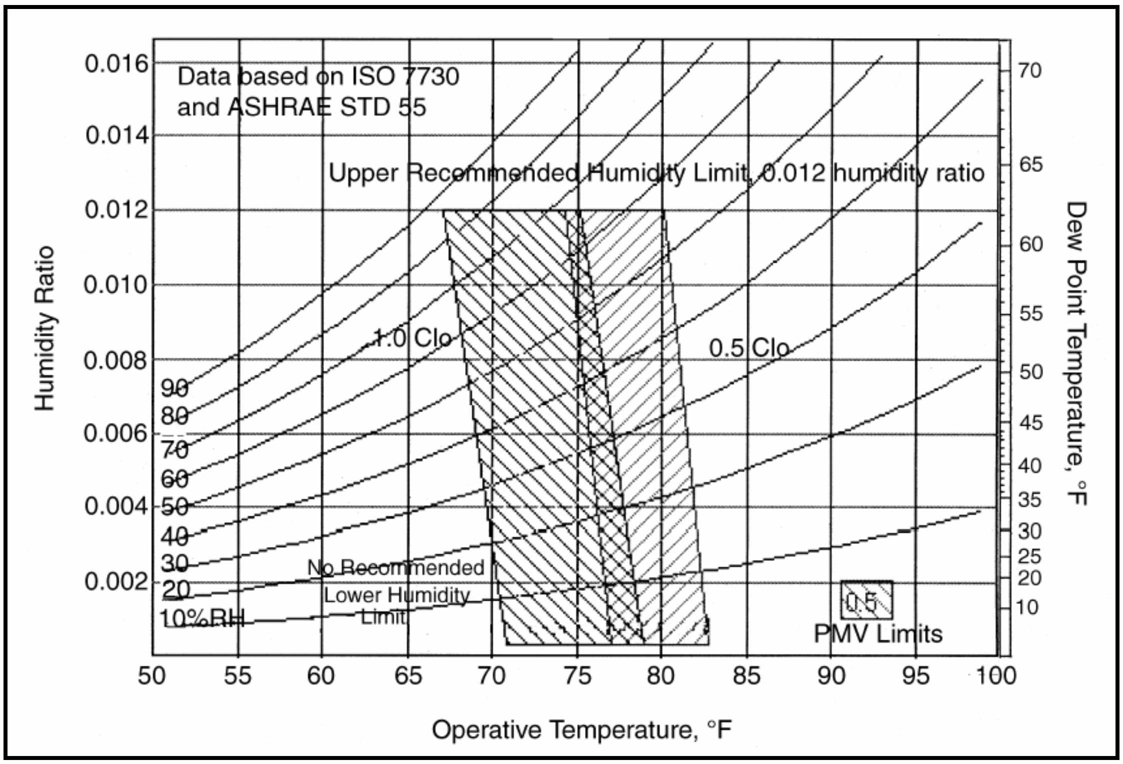


Figure 2. 1: ASHRAE comfort zone (ASHRAE Standard 55-2010)

The ASHRAE Standard 55 illustrates a way of predicting thermal conditions in naturally ventilated buildings. Here two limits of acceptability (80% and 90%) are adopted.

From simulations or measurements performed by a simulating software/tool, the indoor operative temperatures of each zone are obtained while the outdoor air temperature is represented by the climatic/ weather data of the study area.

To calculate discomfort/ comfort hours, the simulation results of operative temperatures are plotted on the ASHRAE Standard 55 (Figure 2.2). According to the limit selected, the results for the discomfort/ comfort hours are obtained in form of a percentage that indicates percentage hours of thermal comfort and thermal discomfort.

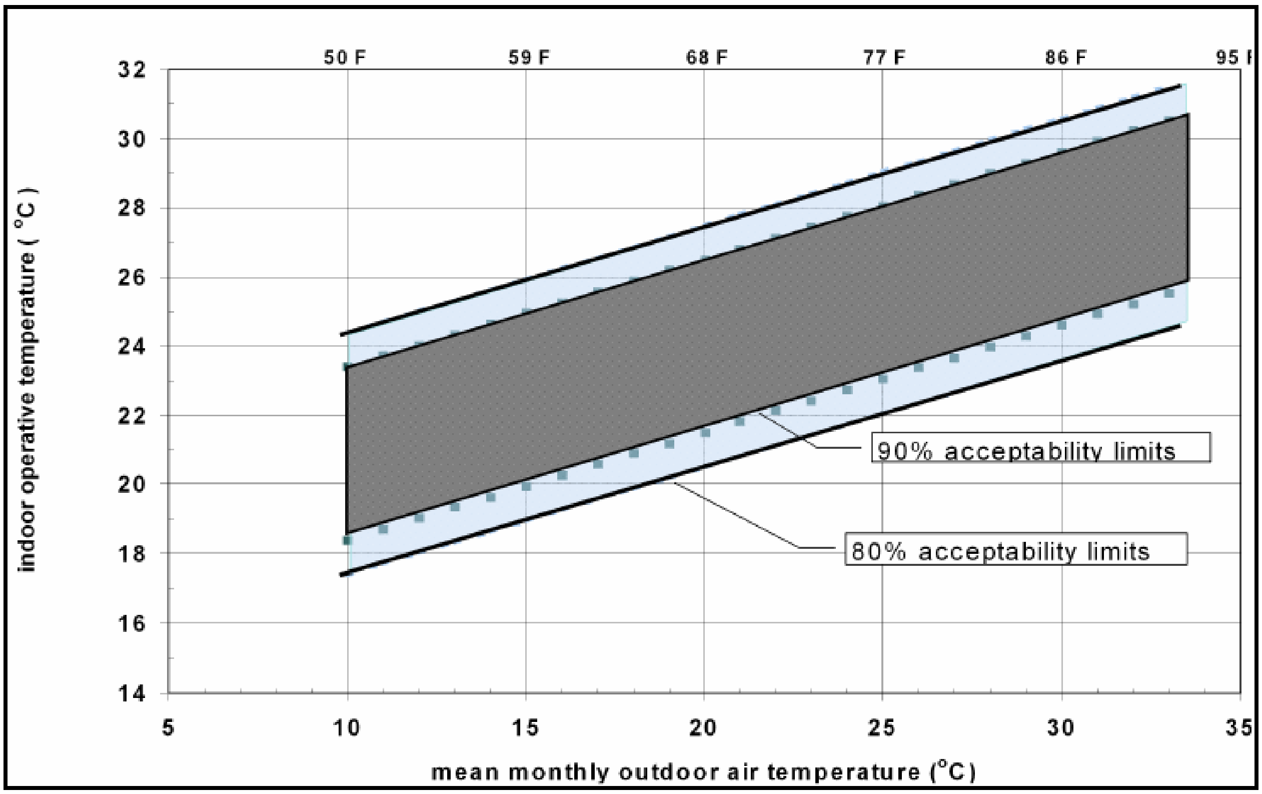


Figure 2. 2: Adaptive comfort standards (ACS) for ASHRAE Std. 55 (ASHRAE Standard 55-2010)

2.2 Natural ventilation

Natural Ventilation is where the airflow in a building is as a result of wind and buoyancy through openings or cracks within the building envelop (Hazim, 2010).

Natural ventilation can be defined as;

- **Single-sided ventilation** where the ventilation rate is limited to zones close to the openings. Wind turbulence and thermal buoyance are the main driving forces. On comparison with other principals, lower ventilation rates are registered with single-sided ventilation.
- **Cross ventilation** where two or more openings on opposite walls of a building cover a zone. The openings are usually windows or vents. Effect of cross ventilation is dependent on wind pressure and opening size.
- **Stack ventilation** is where buoyancy-driven gives larger flows. It relies on two principles which take the advantage of air density. I.e. As warms, it rises to the exit and the warm air is replaced by cool air hence ventilation. Here ventilation openings are at both high and low levels.

For the study, cross ventilation was used as the principal natural ventilation method.

2.3 Building modeling and simulation

Building modeling simulation is a discipline that has evolved of resent in the technological world. Modeling software is used to estimate the building's projected performance, water and energy use (ACEE, 2012)

Building performance efforts seek to improve the comfort, productivity and energy efficiency of buildings.

Many tools/ software have been developed and published for purposes of predicting and estimating building performance through modeling and simulation.

According to US-DOE - Building energy software tools directory (2011), a number of building simulation software have been developed.

Table A.1 in Appendix A presents summarized building software and applicability in relation to natural ventilation and thermal comfort simulation.

From appraisals for natural ventilation and thermal comfort in Table A.1, DesignBuilder and TAS software have the ability to perform thermal comfort and natural ventilation stimulations.

2.3.1 DesignBuilder software

DesignBuilder is a unique software tool for creating and assessing building designs. It provides a range of environmental performance data such as: energy consumption, carbon emissions, comfort conditions, maximum summertime temperatures and HVAC component sizes.

DesignBuilder use the latest EnergyPlus simulation engine to calculate building performance and is suitable for use by architects, building services engineers, energy consultants, and university departments. According to (DesignBuilder, 2010), some typical uses are:

- Thermal simulation of naturally ventilated buildings.
- HVAC design including heating and cooling equipment sizing.
- Calculating temperature, velocity and pressure distribution in and around buildings using CFD.
- Visualization of site layouts and solar shading.
- Checking for optimum use of natural light.
- Evaluating a range of façade options for effect on overheating, energy use and visual appearance.

2.3.2 TAS software

TAS is software is incorporated with; TAS building designer, TAS system and TAS ambiens used to:

- Simulate the dynamic thermal performance of buildings and HVAC systems.
- Trace the thermal state of the building through a series of hourly snapshots, with integrated zonal simulation of natural and forced airflow.

For the study, DesignBuilder will be used to model the case study and perform simulations.

2.4 Natural ventilation modeling and thermal comfort analysis using DesignBuilder

DesignBuilder EnergyPlus can be used generate extensive data on environmental conditions within the building and resultant occupant comfort levels (DesignBuilder, 2010).

2.4.1 Natural ventilation modeling

According to DesignBuilder (2010), two approaches scheduled and calculated natural ventilation can be used to model infiltration and natural ventilation.

2.4.1.1 Scheduled natural ventilation

Scheduled natural ventilation is when natural ventilation and infiltration change rate are defined for each zone using a fixed parameter of maximum ACH (infiltration air change rate) and the infiltration is always scheduled.

Infiltration is defined under airtightness and airflow is considered to be included in the natural ventilation set value.

Scheduled natural ventilation is used if one is able to estimate natural ventilation and infiltration rates.

2.4.1.2 Calculated natural ventilation

Calculated natural ventilation when natural ventilation and infiltration are calculated based on vents, window openings, cracks, buoyancy and wind driven pressure differences.

Calculated natural ventilation is used if one intents to estimate the real natural ventilation and infiltration.

Calculated natural ventilation will be used to model natural ventilation for the study case.

2.4.2 Thermal comfort analysis

The environmental conditions and occupant comfort listed below can be generated by DesignBuilder EnergyPlus simulations.

- Internal air temperature - the calculated average temperature of the air.
- Internal radiant temperature - the average Mean Radiant Temperature (MRT) of the zone, calculated assuming that the person is in the center of the zone, with no weighting for any particular surface.
- Internal operative temperature - The mean of the internal air and radiant temperatures.
- Outside dry-bulb temperature - site data.
- Relative Humidity - the calculated average relative humidity of the air.
- Fanger PMV - Fanger Predicted Mean Vote calculated according to ISO 7730.
- Pierce PMV ET - the Predicted Mean Vote (PMV) calculated using the effective temperature and the Pierce two-node thermal comfort model.
- Pierce PMV SET - the Predicted Mean Vote (PMV) calculated using the 'Standard' effective temperature and the Pierce two-node thermal comfort model.
- Pierce Discomfort Index (DISC) - the Discomfort index calculated using the Pierce two-node thermal comfort model.
- Pierce Thermal Sens. Index (TSENS) - the Thermal Sensation Index (PMV) calculated using the Pierce two-node thermal comfort model.
- Kansas Uni TSV - the Thermal Sensation Vote (TSV) calculated using the KSU two-node thermal comfort model.
- Discomfort hrs (summer clothing) - the time when the combination of zone humidity ratio and operative temperature is not in the ASHRAE 55-2004 summer clothes region.
- Discomfort hrs (winter clothing) - the time when the combination of zone humidity ratio and operative temperature is not in the ASHRAE 55-2004 winter clothes region.
- Discomfort hrs (all clothing) - the time when the combination of zone humidity ratio and operative temperature is not in the ASHRAE 55-2004 summer or winter clothes region.
- Mech Vent + Nat Vent + Infiltration - The sum of *outside air* (in ac/h) flowing into the zone through:

- The HVAC air distribution system +
- Infiltration +
- Natural ventilation

2.5 Natural ventilation and thermal comfort improvement strategies

Natural ventilation efficiency and building thermal comfort are affected by both internal and external factors (Cai and Wai, 2010).

Internal factors are majorly dependent on openings control setup and building designs and can be varied or engineered for the desired conditions while external factors include building orientation, location and prevailing weather conditions. These are usually natural and constrained.

2.5.1 Openings control

2.5.1.1 Manual window control

Adoption of manual control of windows is to have the window opening and closure left to the occupants. Windows in this strategy are opened by the occupants this usually happens whether or not the outside temperature is above the inside temperature.

Figure 2. 3: An occupant manual opening an office window

Though considered the lowest cost option, a challenge in this strategy is that at times occupants neglect or forget to open and close the windows when the outdoor conditions vary in unpredictable manner hence leading to thermal comfort problems (WindowMaster, 2012).

2.5.1.2 Automated window control

In automated window control, an automatic window control device is installed on the window (s). This device has a temperature sensor set to a set point temperature that opens the windows when the inside temperature is higher than the outside temperature and closes the window when the inside temperature is lower than the outside temperature (Carrilho et al, 2003).

Here windows can be opened to a variable width depending on the change in inside temperature as shown in figure 2.4.

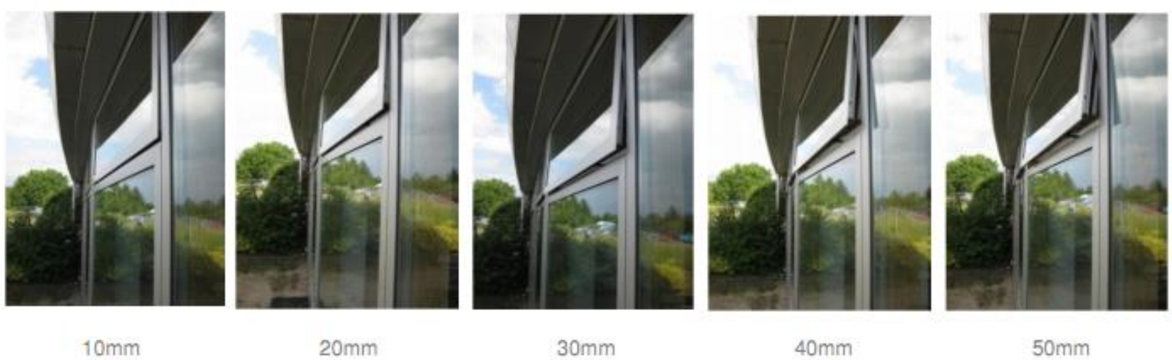


Figure 2. 4: Automated window opening with various opening width

2.5.2 Building designs

2.5.2.1 Window wall ratio (WWR)

According to CSBR (2011), window-to-wall ratio (WWR) also known as window area is considered as a very important parameter affecting the thermal performance of a building.

WWR is usually measured as the percentage area determined by dividing the building's total glazed area by its exterior envelope wall area. Optimized window design is vital in achieving thermal comfort with no additional financial investment and a reduction on dependence on air conditioning coupled with reduction of discomfort periods are realized

2.5.2.2 Lighting control

As a method of reducing internal loads generated from lights, electric lights can be controlled availability of natural daylight (DesignBuilder, 2010). Daylight luminance level in a zone depends on many factors, including sky condition, sun position and location, size, and glass transmittance of windows, window shades and reflectance of interior surfaces.

2.5.2.3 Mechanical ventilation

Mechanical ventilation is achieved by circulation of airflow into a building/ zone due to wind and buoyancy through installed openings in the building envelope supplemented, when necessary, by mechanical systems to increase the ventilation rate, and/or a heat exchanger for heating or cooling the outdoor supply air (Hazim, 2010).

Air is usually distributed through a duct which is centralized to the air conditioning systems or local fresh air systems. The air controlled by an HVAC system supplied with properties to either cool or heat the target hence achieving thermal comfort.

Mechanical ventilation has a tendency of introducing sensible cooling and heating on the zone heat balance.

Zone sensible heating will occur when warm air is introduced in a zone by means of a fan while sensible cooling is when cooler air is introduced in the zone.

In DesignBuilder this strategy can be modeled in two ways;

1. Room ventilation.
2. Ideal loads.

Room ventilation

Here mechanical ventilation is modeled in DesignBuilder by introduction of outside air by the assistance of fans is using the EnergyPlus zone ventilation.

Ideal loads

The ideal loads option includes mechanical ventilation is modeled in DesignBuilder with heating and cooling by the EnergyPlus zone HVAC ideal loads air system data.

For the study lighting control, mechanical ventilation without cooling, mechanical ventilation with cooling and window to wall ratio and are the strategies considered for thermal comfort analysis simulations in a natural ventilation building.

CHAPTER THREE

3.0 Methodology

The methodology of the projects consists of five main components;

1. Assessment of the case study/ baseline components and external environment.
2. Modeling of CEDAT building baseline model.
3. Thermal comfort analysis of the baseline model.
4. Simulation of the different natural ventilation efficiency improvement and building thermal comfort strategies.

3.1 Assessment of the case study/ baseline components and external environment

3.1.1 Case study components

The case study components were collected as follows;

3.1.1.1 Building Design and occupancy

Building plans were obtained from Technology Consults Ltd. From this plan, the building orientation, number of floor, number of classrooms/ offices, dimensions, construction materials & thickness of walls, floor and roof, window-wall-ratio was be established alongside other parameters required for modeling the building.
Parameters of the building and occupancy trends were physically collected from the building site.

3.1.1.2 External environment

Climatic data required for the project was collected from the Uganda Metrological Department (UMD).

Climatic data such as sunshine, relative humidity, wind speed and other related data of the case study area were collected, assessed and processed in averages format that that are compatible for DesignBuilder software simulation.

For purposes of simulation for hourly and daily weather conditions, Kisumu city close to Kampala which has hourly and daily weather partners was used for the simulations.

3.1.2 Case study

The study area/ building is a university building located in Makerere University Kampala that falls in the category of educational facilities. It is positioned on latitude 00°28'N and longitude 22°34'E at an elevation of 1148 m.

There is no air conditioning or mechanical ventilation system in the baseline model.

3.1.2.1 Building description and orientation

The building is made up of five floors with a total occupied floor area of 5,933.4 m^2 and total unoccupied area of 1,401.5 m^2. Building floor and elevation plan are attached in appendix A.

Each floor is partitioned into zones making up a total of 145 zones occupied zones. Table 3.1 shows the floor area, floor elevation and number of zones.

Table 3. 1: Building floor area, floor elevation and number of zones

Floor	**Floor Area (m^2)**	**Floor Elevation (m)**	**Number of Zones**
Ground (F_0)	1356.728	3.60	26
First (F_1)	1356.728	3.45	30
Second (F_2)	1356.728	3.45	41
Third (F_3)	1356.728	3.8	30
Fourth (F_4)	506.488	3.275	18

The building main façade is oriented in the south direction with the surroundings composed short plants and a parking ground besides it (Figure 3.1).

Figure 3. 1: Building main facade and surroundings

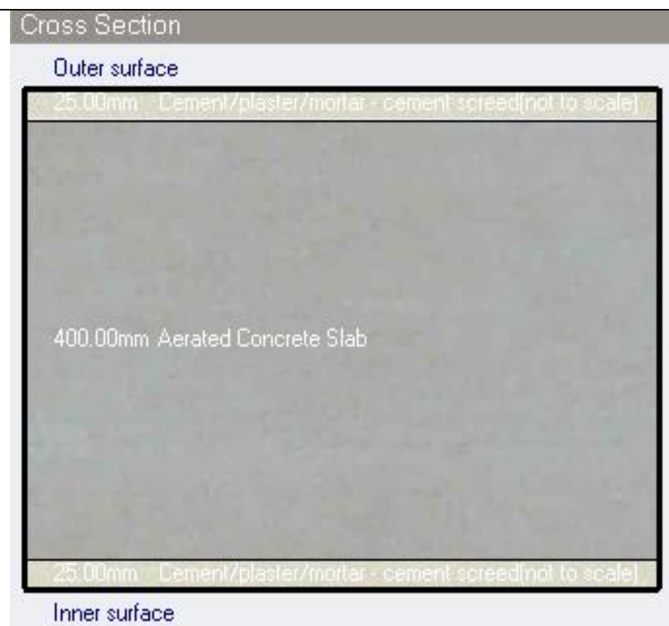
3.1.2.2 Building materials and construction

The window wall ratio (WWR) for the baseline model is 30%. Windows made out of generic clear glass of thickness 3 mm, 1.5 m height and sill height is 0.8 m.

Vents type is grille, small with light slats; the doors are made out of solid hard wood normally hanging and roofing pitched with tiles. Thermal properties of the building components were referenced to the International Energy Conservation Code (IECC, 2000).

Table 3. 2: Building materials, thickness of floors, walls and the roof

Component	Cross section
External walls • 100 mm Brickwork, Outer leaf. • 79.5 mm Concrete block (medium). • 25 mm Cement/plaster/mortar-cement screed.	
Internal walls/ partitions • 13 mm Plaster (lightweight). • 105 mm Brickwork, Inner leaf. • 13 mm Plaster (Lightweight).	

Roof • 25 mm Clay tile (Roofing). • 20 mm Air gap 10 mm. • 5 mm Roof felt.	
Ground floor • 132.7 mm miscellaneous materials – aggregate (sand/gravel/stone). • 100 mm cast concrete. • 70 mm floor/roof screed.	
Internal floor • 25mm 25 mm Cement/plaster/mortar- cement screed. • 400 mm aerated concrete slab. • 25mm 25 mm Cement/plaster/mortar- cement screed.	

3.1.2.3 Building occupancy

The building is fully occupied from 8:00 to 18:00 Monday to Saturday and open to all users. For simulations, the building was considered to be fully occupied from 1st January to 31st December.

From the building occupancy data attached in Appendix B, the occupancy of each zone was expressed in people/m2 then averaged and entered in the DesignBuilder activity platform at building level.

The average heat gain from computers and office equipment was taken to be 55.6 w (Christopher and Hosni, 2000). Appendix B shows gains from computers and office equipment for each zone expressed in w/m^2.

3.1.2.4 Climatic Conditions

As for the climatic data gathered from Uganda Meteorological Department (UMD), air temperatures range from 17 to 30 degrees C during the day but show little seasonal variation through the year. Table 3.3 shows the air temperatures, wind speeds and relative humidity.

Table 3. 3: Monthly statistics showing dry-bulb temperatures (°C), wind speed (miles/day) and relative humidity

(*Source: Kawanda Weather Station Climate Data 2011 - UMD Records)*

MONTH	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
T_{max}	28.6	28.6	28.2	27.1	26.4	26.2	25.7	26.2	26.9	27.2	27.4	27.6	27.2
T_{min}	15.5	15.9	16.6	16.9	16.6	15.6	15	15.3	15.5	16.1	16.2	15.7	15.9
Average	22.05	22.25	22.4	22	21.5	20.9	20.35	20.75	21.2	21.65	21.8	21.65	21.55
Wind speed	53.2	55.4	57.8	56.3	54.9	54.2	55.9	58.2	55.9	56.3	50.4	47.3	54.7
R/H0600	89	89	89	92	85	90	92	91	89	88	86	89	89
R/H1200	57	57	61	68	71	67	65	66	66	66	63	62	64
Solar													
Average	73	73	75	80	78	78.5	78.5	78.5	77.5	77	74.5	75.5	76.5

From Table 3.3, the hottest month is March with a mean temperature of 22.4°C. Maximum dry-bulb temperature is measured as 28.6°C in the months of January and February. While maximum wind speed reaches to the value of 58.2 miles/day in August. It was also noted that annual average relative humidity (RH) is 76.5%.

3.2 Modeling of CEDAT building baseline model

From the building plans presented in Appendix B, a baseline model was developed using DesignBuilder and the building floors were divided into different thermal zones.

After modeling, building model options were set as presented in Figure 3.2.

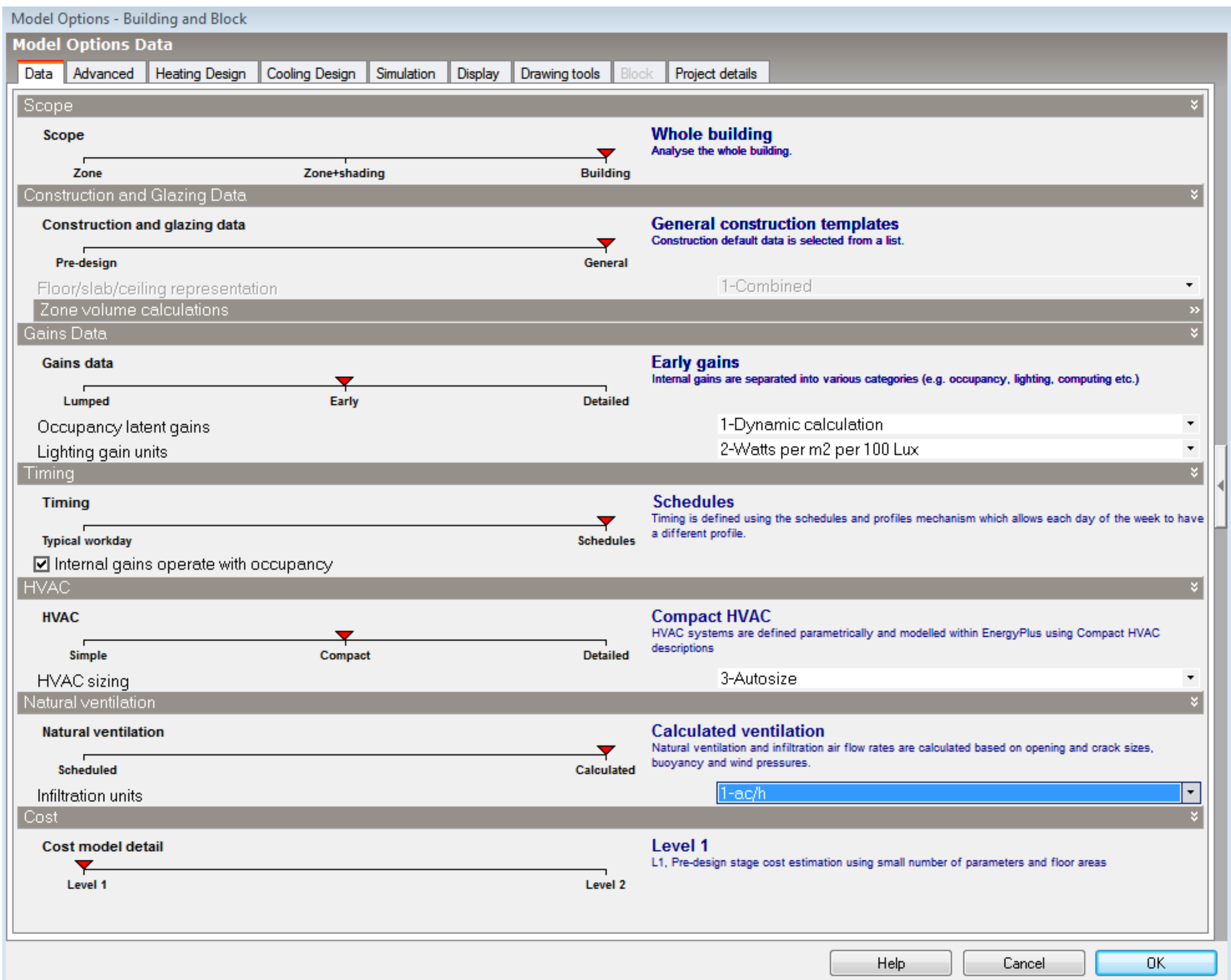


Figure 3. 2: Building and block model options

Model options included;

Scope

Analysis was set to the whole building.

Construction and glazing data

The general construction template was used to define the building construction and glazing.

Gains data

Early gains were selected which separate internal gains into various categories (i.e. computer, equipment, lighting etc.).

Timing

Scheduled timing was set to allow for typical days occupied by the university defined.

HVAC

Compact HVAC system was set to which is defined parametrically and modeled within energyplus.

Natural ventilation

Natural ventilation was set to calculated ventilation where ventilation and infiltration air flow are calculated based on opening, cracks, buoyancy and wind speed.

3.2.1 Building activity

Building activity was modeled at building level then inherited down to zones. Figure 3.3 shows a typical the activity template that was used in the DesignBuilder platform to model the building activity.

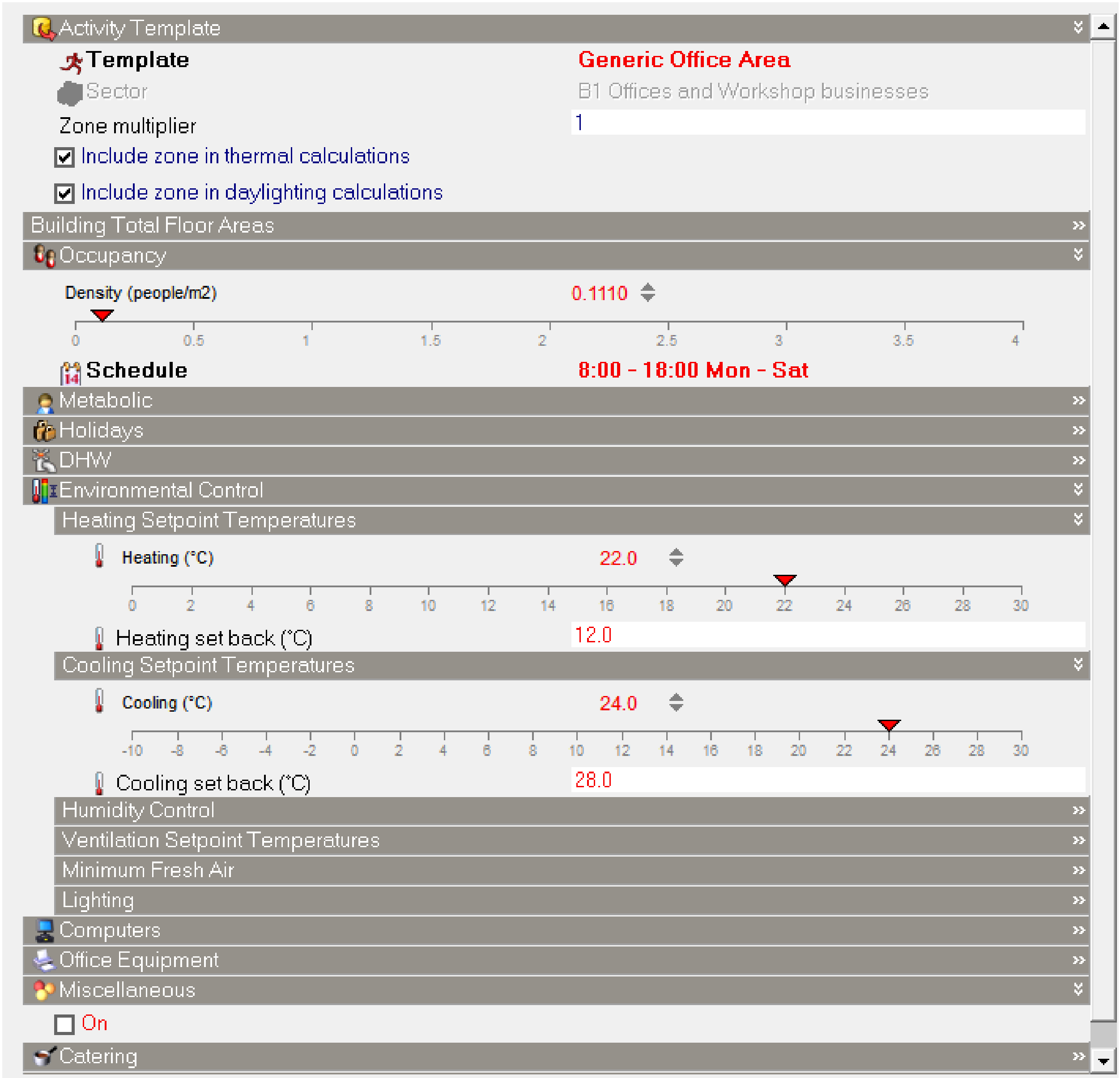


Figure 3. 3: Activity template used to model building activity in DesignBuilder

3.2.2 Building Construction

Building construction was modeled differently at floor level. Figure 3.4 shows a typical the construction template that was used in the DesignBuilder platform to model the construction of the building.

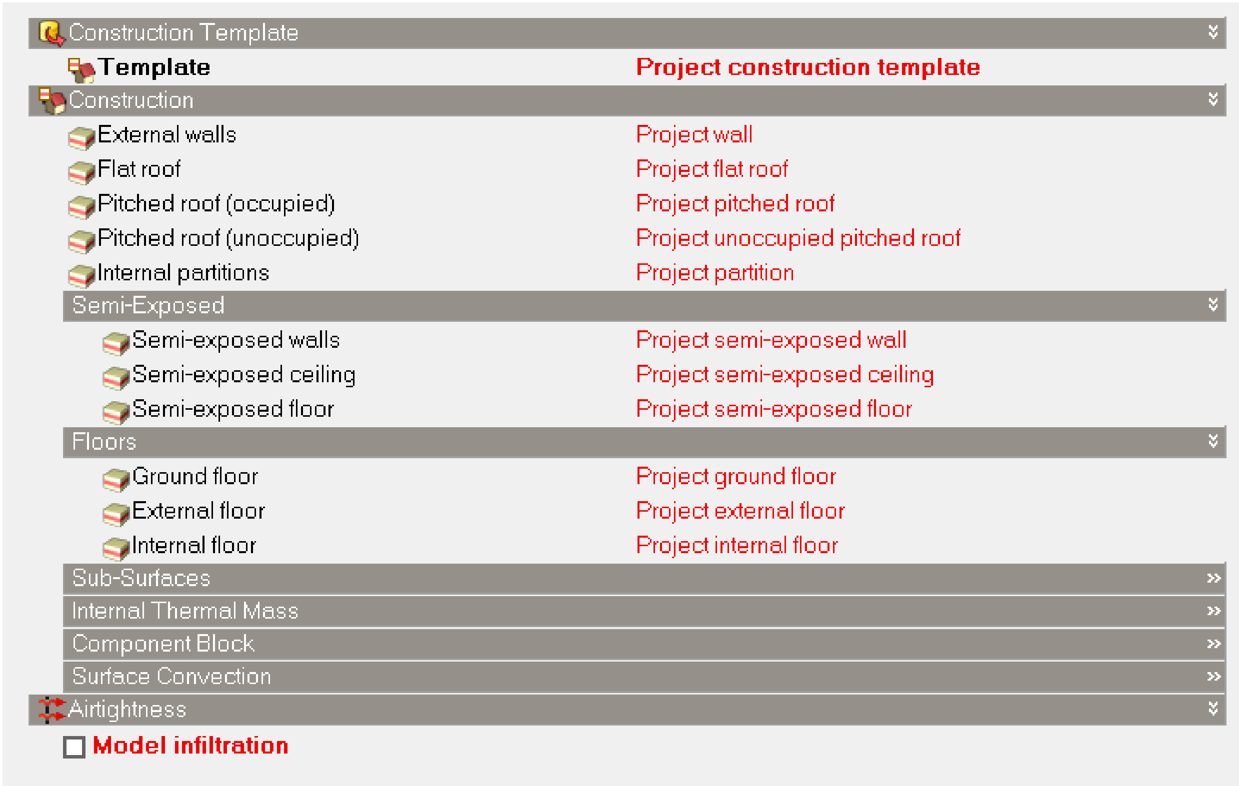


Figure 3. 4: Construction template used to model floor construction in DesignBuilder

3.2.3 Building openings

Building openings were modeled at building level with a baseline glazing of 30%. Figure 3.5 shows a typical the glazing template that was used in the DesignBuilder platform to model the glazing of the building.

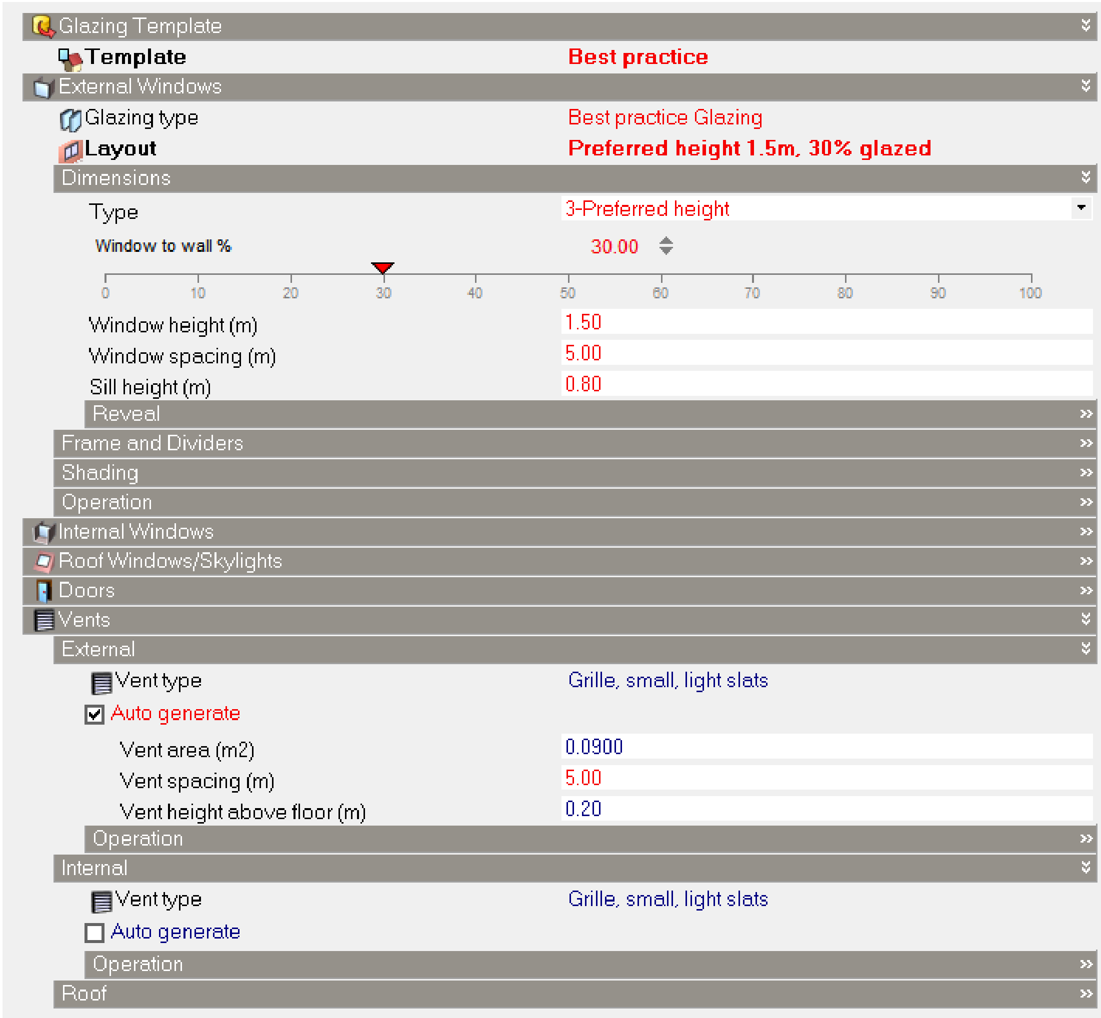


Figure 3. 5: Glazing template used to model openings in DesignBuilder

3.2.4 Building lighting

Building lighting was modeled as shown in Figure 3.6 using the lighting template in the DesignBuilder platform.

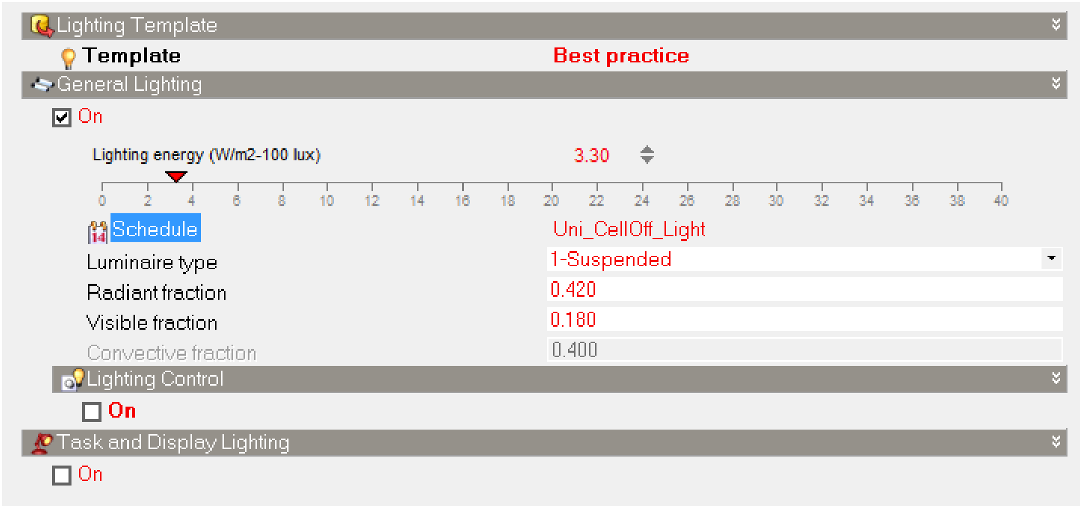


Figure 3. 6: Lighting template used to model building lighting in DesignBuilder

3.3 Thermal comfort analysis

After modeling of the baseline model as illustrated in section 3.3, thermal comfort analysis was performed for the baseline model in the DesignBuilder software under the simulation tab. Figure 3.7 shows the calculation options data used for the simulation, Figure 3.8 shows the calculation options used for the simulation and figure 3.8 shows the tab used to select the require output data after the simulation.

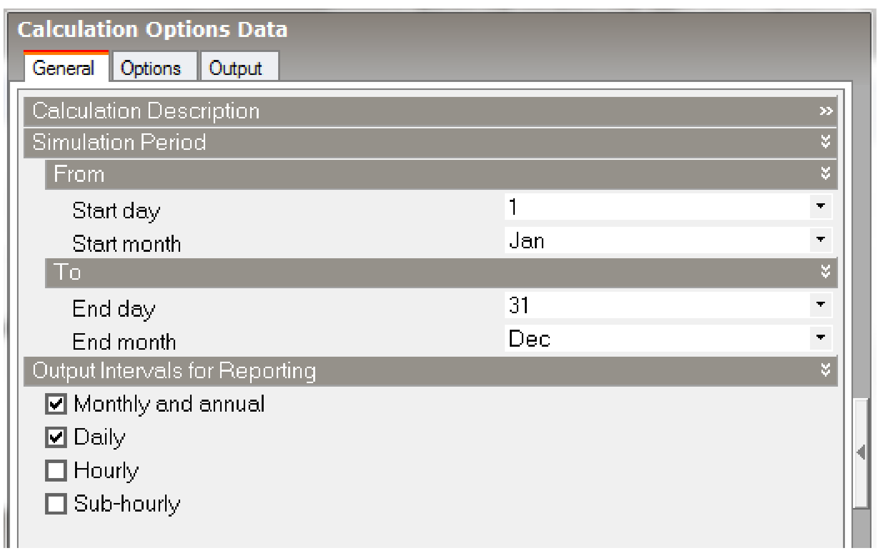


Figure 3. 7: Simulation template used to select the calculation options data in DesignBuilder

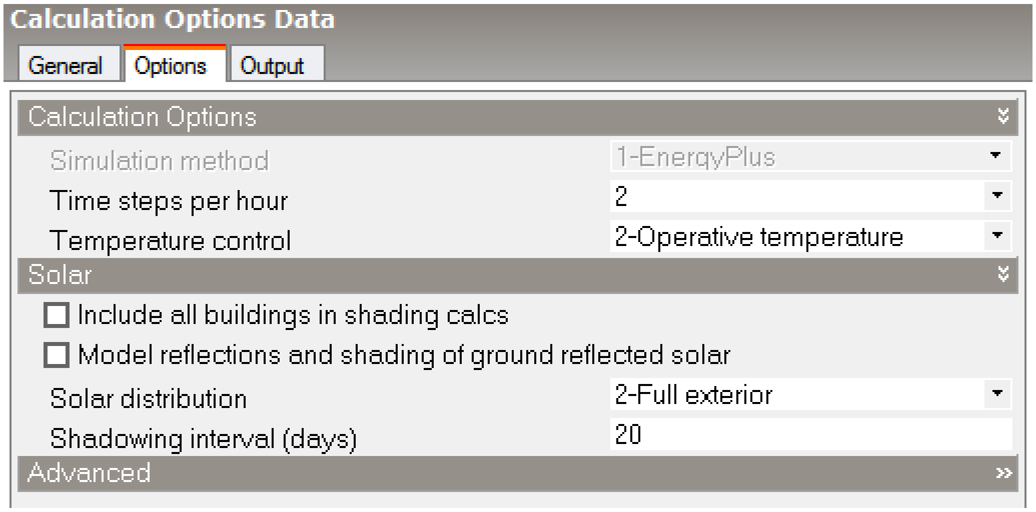


Figure 3. 8: Simulation template used to select the calculation options in DesignBuilder

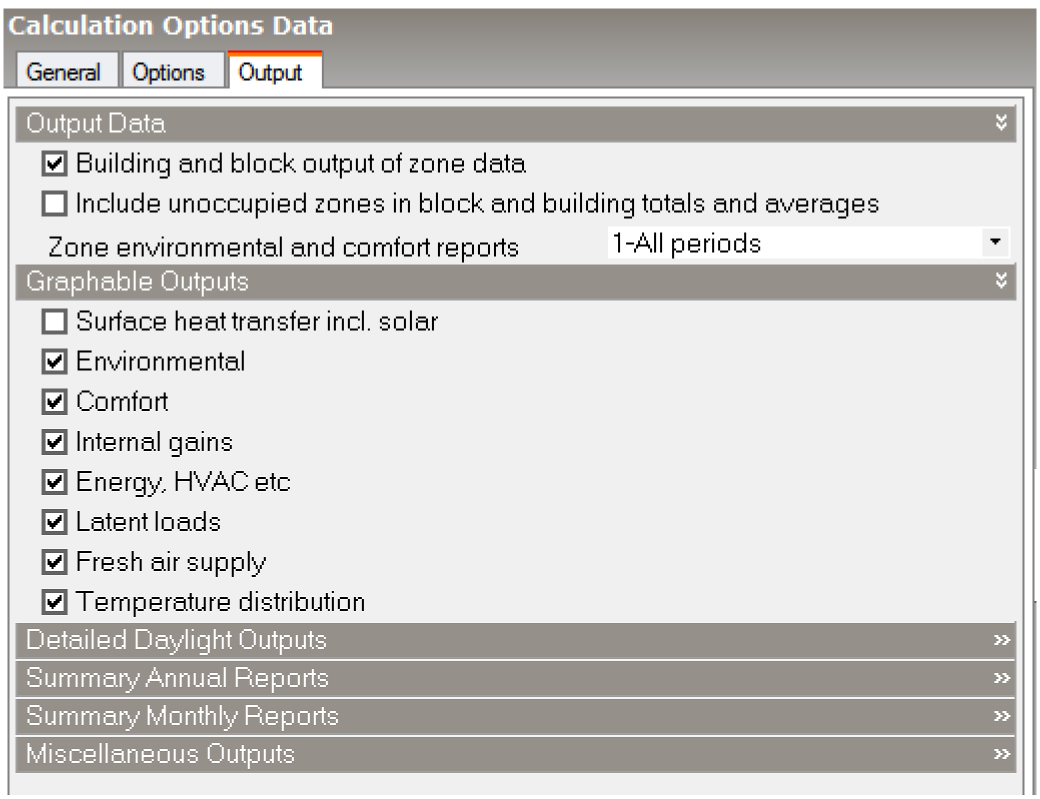


Figure 3. 9: Simulation template used to select the calculation options in DesignBuilder

3.4 Simulation of the different improvement strategies

After simulations for the base model, strategies to improve natural ventilation efficiency and corresponding thermal comfort were then simulated as below.

3.4.1 Lighting control

Lighting control was set using the lighting template (Figure 3.10) then simulations for thermal comfort performed for this strategy.

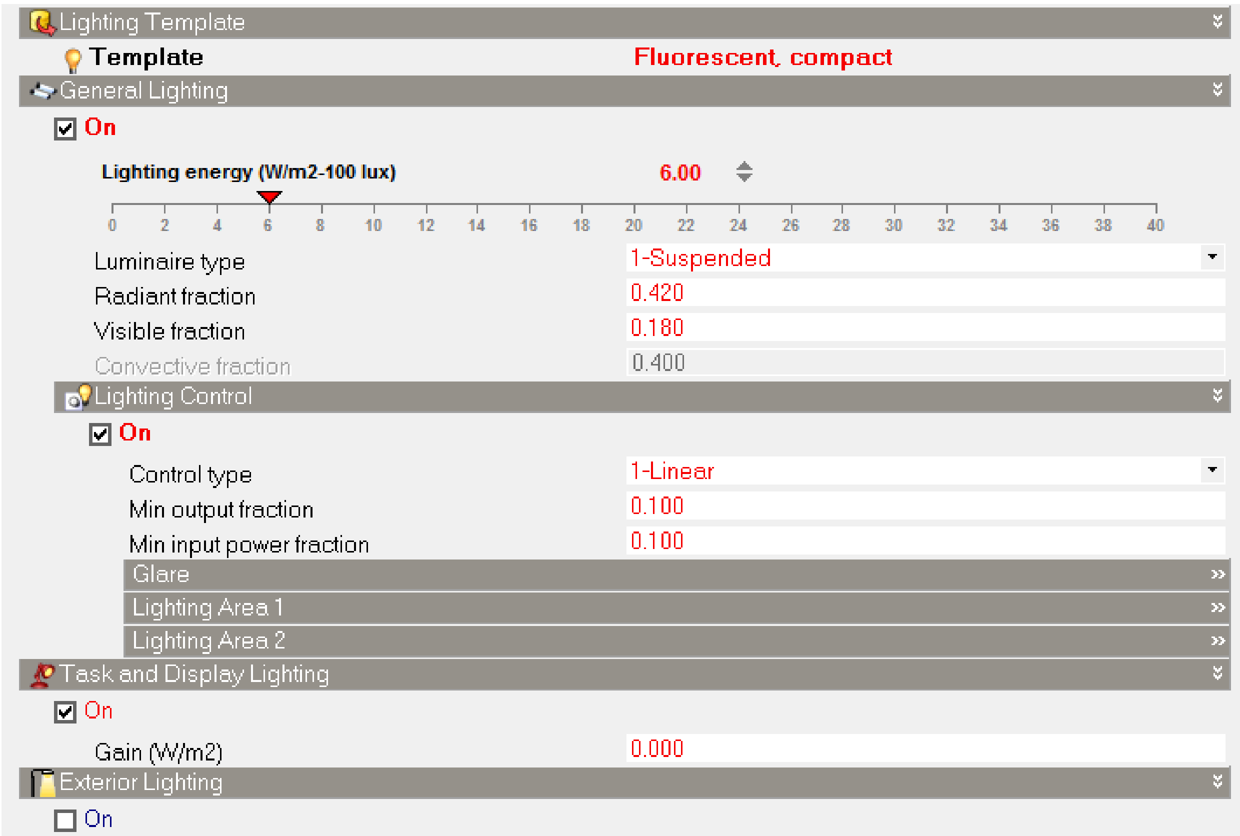


Figure 3. 10: Lighting control template

3.4.2 Mechanical ventilation without cooling

Mechanical ventilation was switched on in the HVAC system together with natural ventilation as a means of improving natural ventilation efficiency and then simulations for comfort were performed. In this strategy, fans were used to increase the air circulation in and out of the building.

Figure 3.11 shows the HVAC template used to select natural ventilation and mechanical ventilation strategies in DesignBuilder.

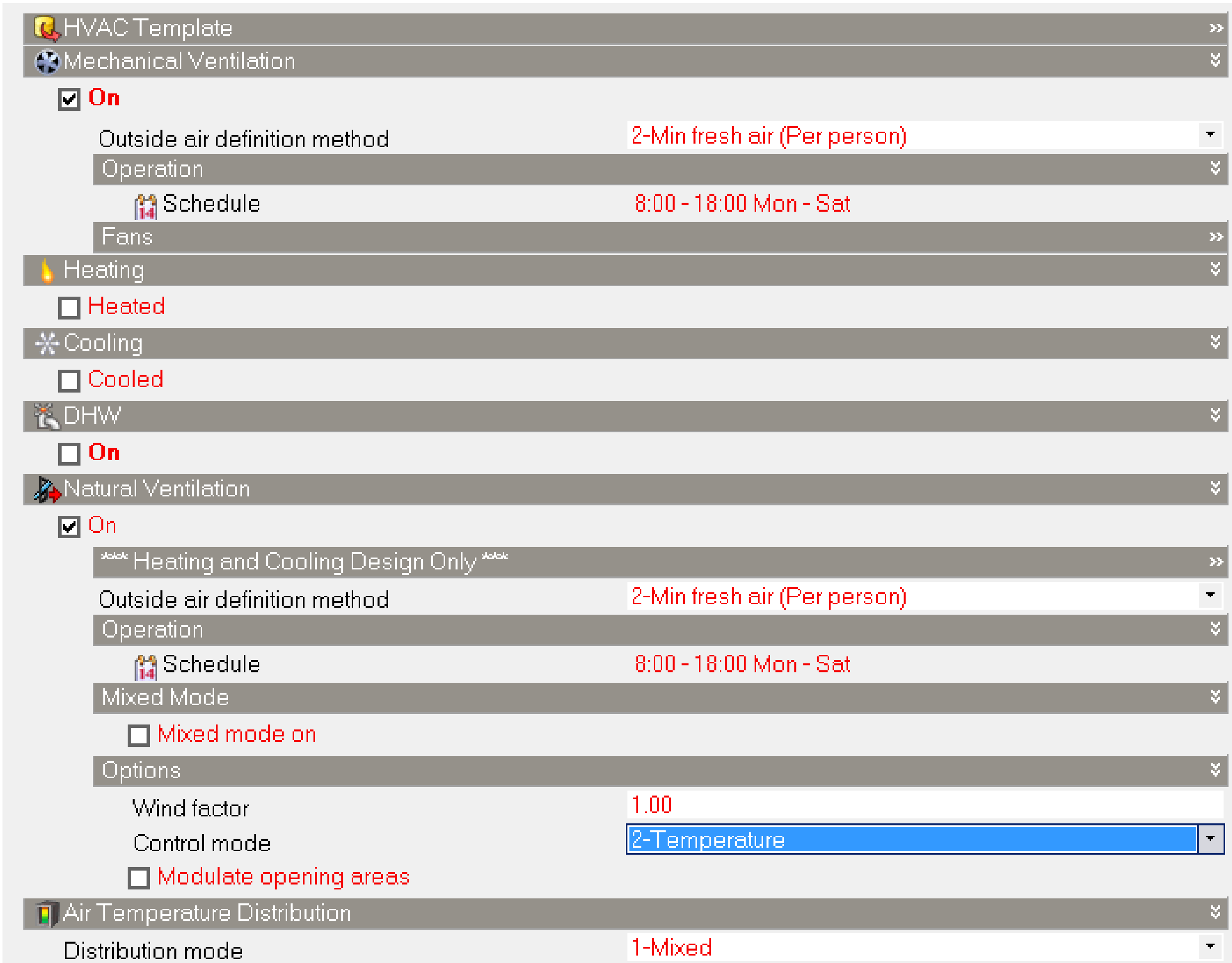


Figure 3. 11: HVAC template

3.4.3 Mechanical ventilation with cooling

Under the HVAC system, mechanical ventilation with the cooling effect was switched together with natural ventilation as a means of improving natural ventilation efficiency and then simulations for comfort were performed.

3.4.4 Window to wall ratio

Parametric analysis on the base was done using the parametric analysis tab in DesignBuilder platform.

Window to wall ratio was varied from 0% to 100% on the baseline model while it was only subjected to natural ventilation to establish the relationship between wwr and natural ventilation.

CHAPTER FOUR

4.0 Results and discussions

4.1 CEDAT building baseline model

The final 3D south and east orientation of the baseline model is presented in figure 4.1 and 4.2 respectively. Baseline model general building details and building envelop data are presented in Appendix E.

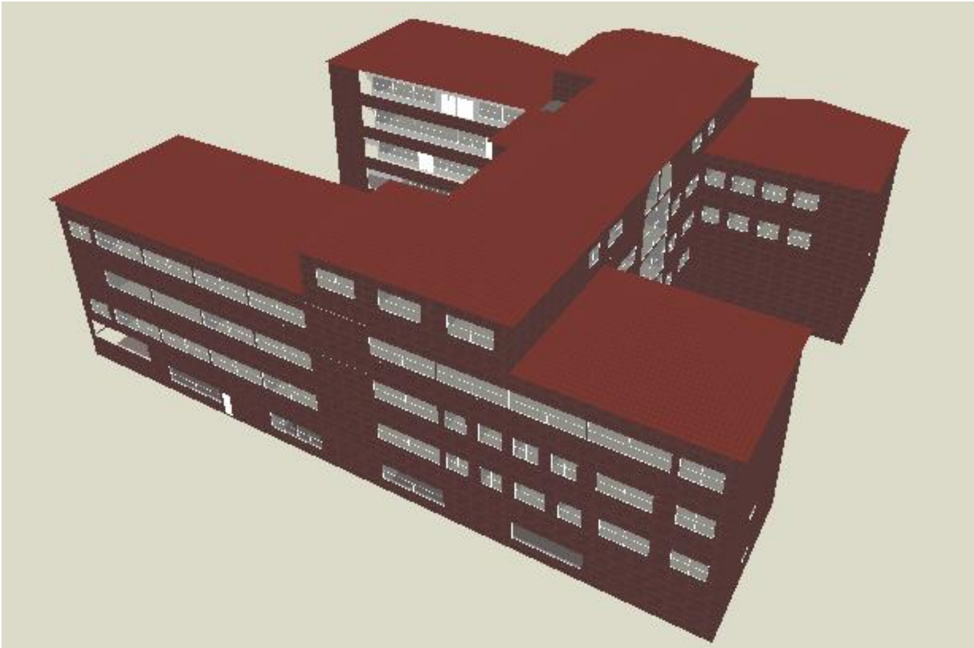


Figure 4. 1: South orientation of the building 3D model

Figure 4. 2: East orientation of the building 3D model

4.1.1 Site data

Figure 4.3 shows site data (outside dry-bulb temperature, outside dew-point temperature, wind speed, wind direction, solar altitude, solar azimuth, atmospheric, direct normal solar and diffuse horizontal solar energy) reported for occupied periods only with a maximum outside dry-bulb temperature of 24.03 ^{o}c in the month of February and a minimum of 21.63 ^{o}c in July. Maximum outside dew-point temperature is 18.11 ^{o}c in the month of May and the minimum being 15.05 ^{o}c in January.

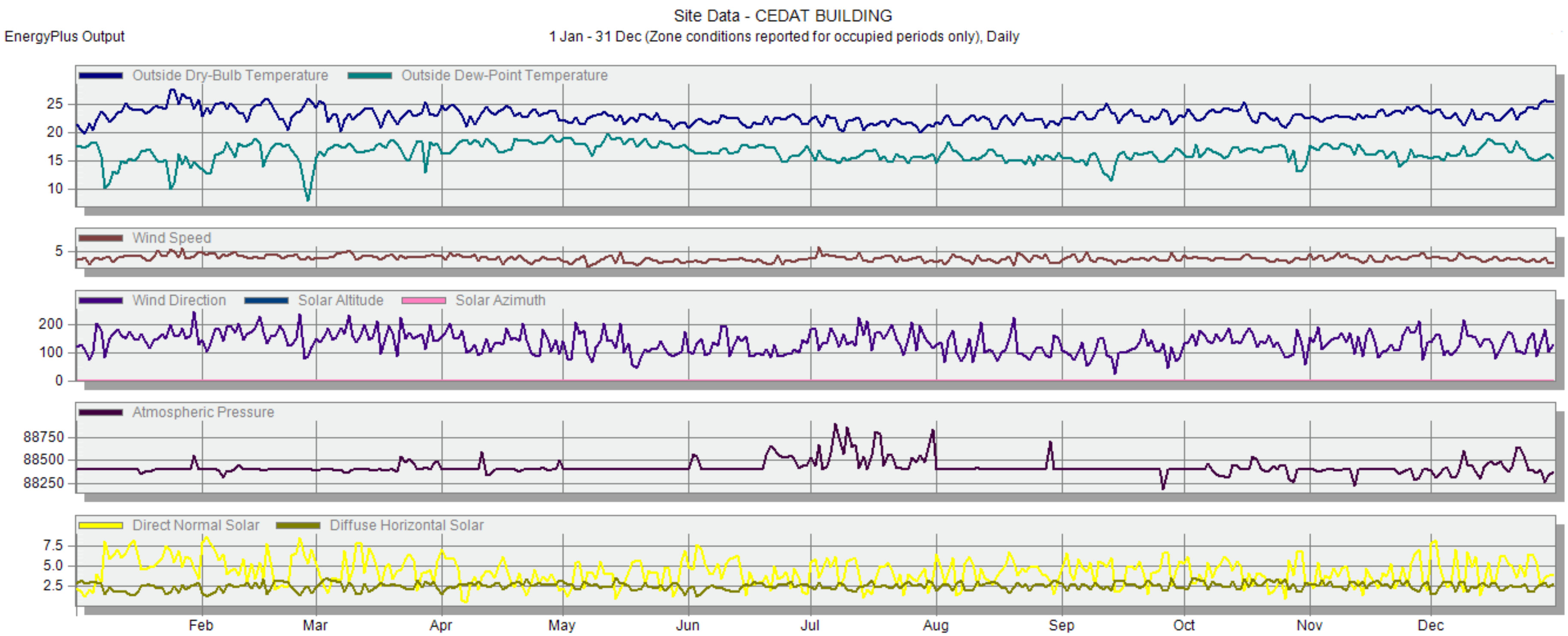


Figure 4. 3: Site data (1 Jan – 31 Dec) for zone conditions reported for occupied period

Wind speed reaches a maximum of 3.65 m/s during the month of February and the minimum of 2.25 m/s in May, while the maximum atmospheric pressure is 88570.97 Pa during the month of July and the minimum of 88384.59 Pa experienced in November.

Direct normal solar energy amounting to a maximum of 161.7 kWh is experienced in January and a minimum of 109.58 kWh in April, while the maximum diffuse horizontal solar energy is 84.09 kWh in October and the minimum of 63.76 kWh in February.

4.2 Baseline model thermal comfort analysis

Simulation for the baseline model thermal comfort was for a total period of 8760.00 hours for the total occupied area throughout the year.

Figure 4.4 presents the simulated environmental comfort data, maximum air temperature of 30.95 ^{o}c was registered in the month of January and a minimum of 28.72 ^{o}c in July. Radiant temperature reaches to a peak of 31.27 ^{o}c in January and a minimum of 29.07 ^{o}c in the month of July. Operative temperature is seen to reach its maximum of 31.11 ^{o}c in January and a minimum of 28.89 ^{o}c in the month of July.

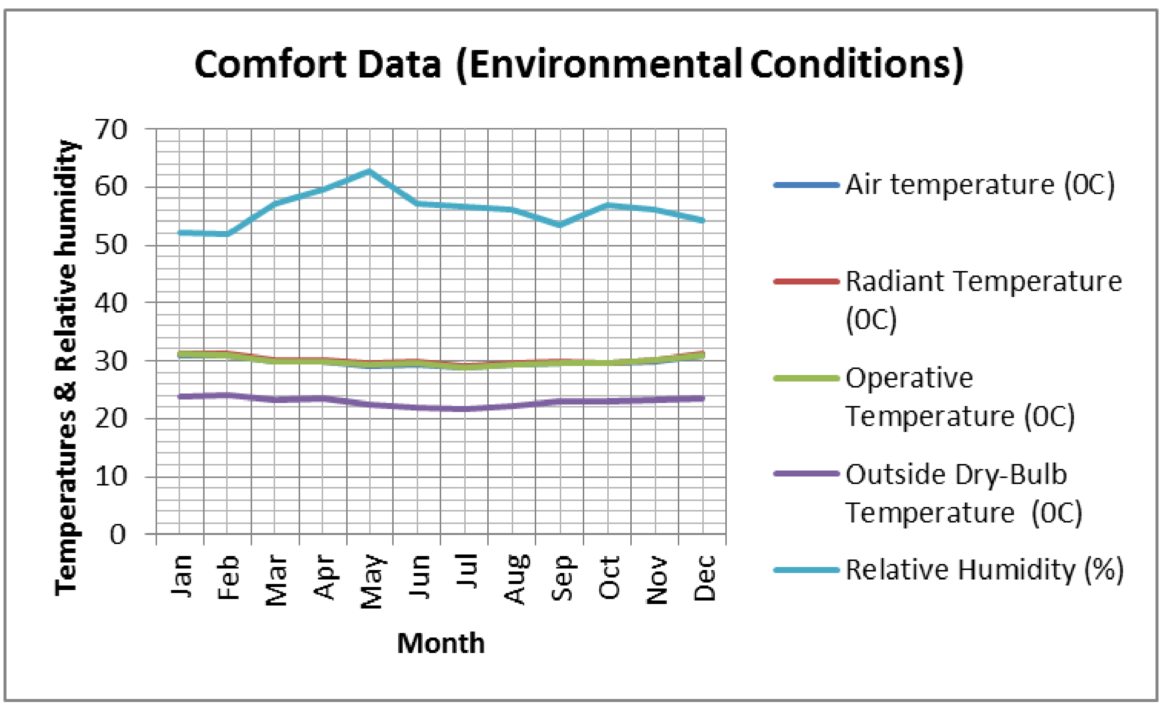


Figure 4. 4: Comfort data (Environmental conditions) (Baseline model)

Maximum relative humidity is 62.62 % in May and the lowest is 51.88% in February. It is generally observed that maximum temperatures are in the month of January.

On monthly comparison, the month of May had the highest number of discomfort hours of 268.41 hours and the lowest discomfort hours were in the month of February at 237.71hours as presented in Figure 4.5. This result could be attributed to the high relative humidity recorded in the month of May and lowest relative humidity in February.

From results of discomfort hours, it was reported that occupants experienced discomfort for 3078.74 hours throughout the year. This is 35.15% discomfort against 64.85% comfort hours out of the total simulation period.

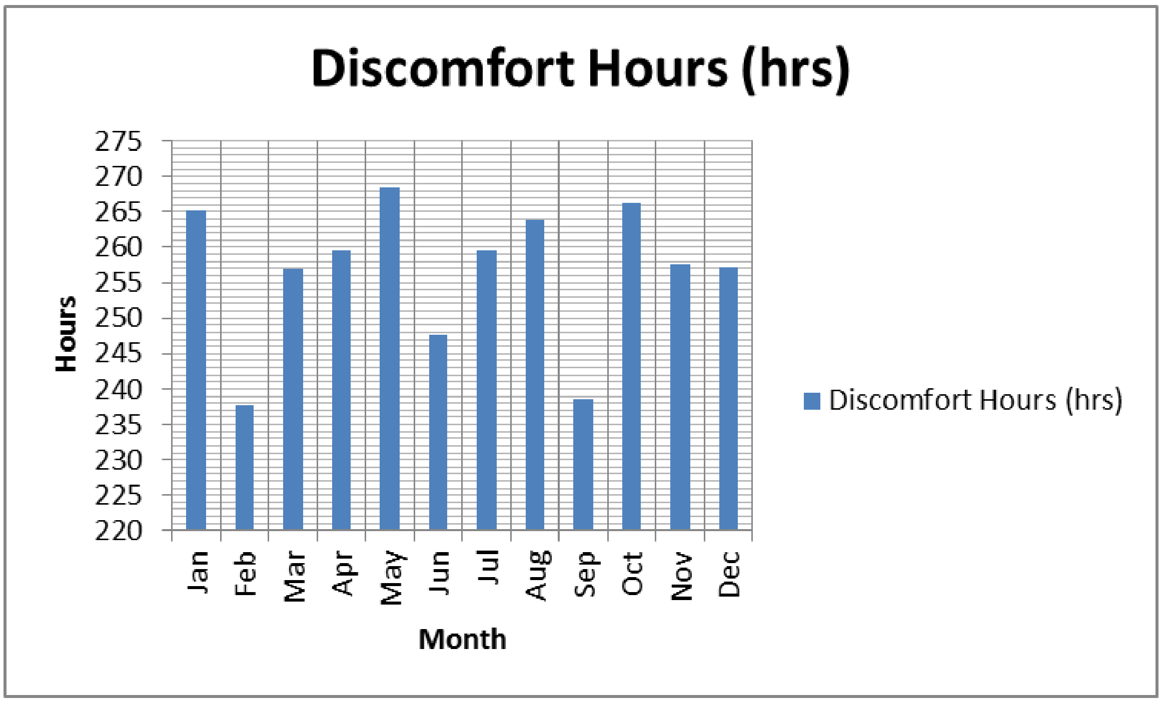


Figure 4. 5: Discomfort hours (Baseline model)

Figure 4.6 presents predicted thermal comfort sensation votes based Fanger PMV, Pierce PMV ET, Pierce PMV SET and Kansas Uni TSV thermal comfort predictive models. The Kansas Uni TSV model predicts thermal comfort close to neutral while the Pierce PMV SET model predicts the worst scenario of all models.

Based on the seven point thermal comfort scale, it is observed that the predicted votes place the comfort sensation between hot and slightly warm as presented in Figure 4.7. January is when occupants registered highest thermal comfort votes while July had the least.

Averaging predicted thermal comfort sensation votes on monthly basis gives 1.8.

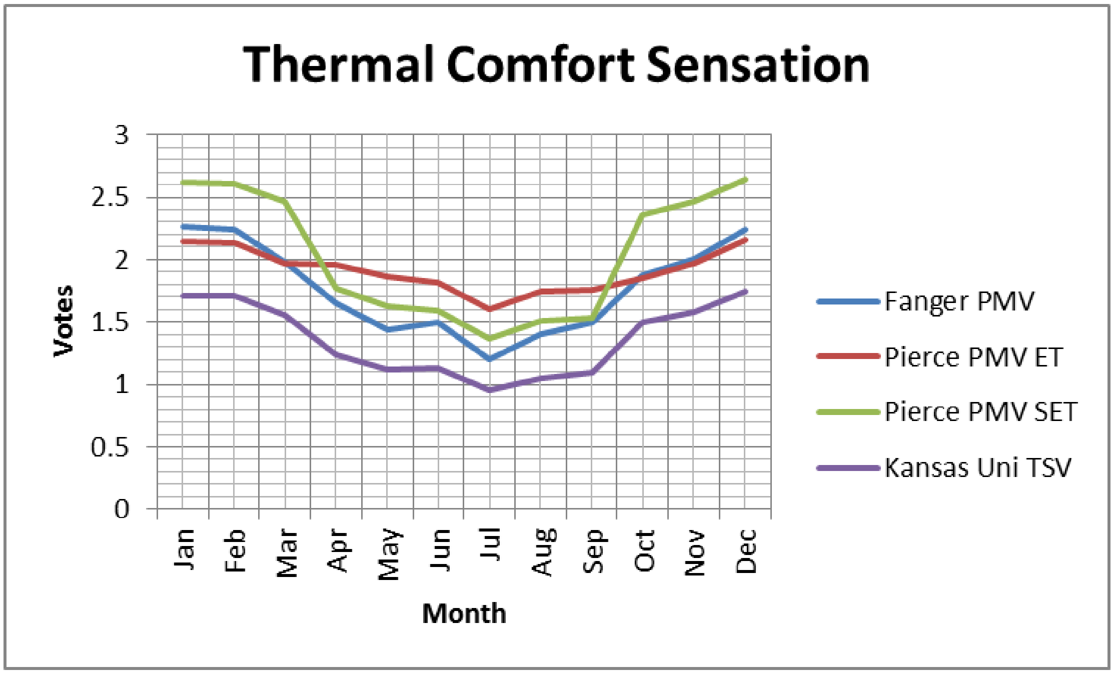


Figure 4. 6: Predicted thermal comfort sensation votes (Baseline model)

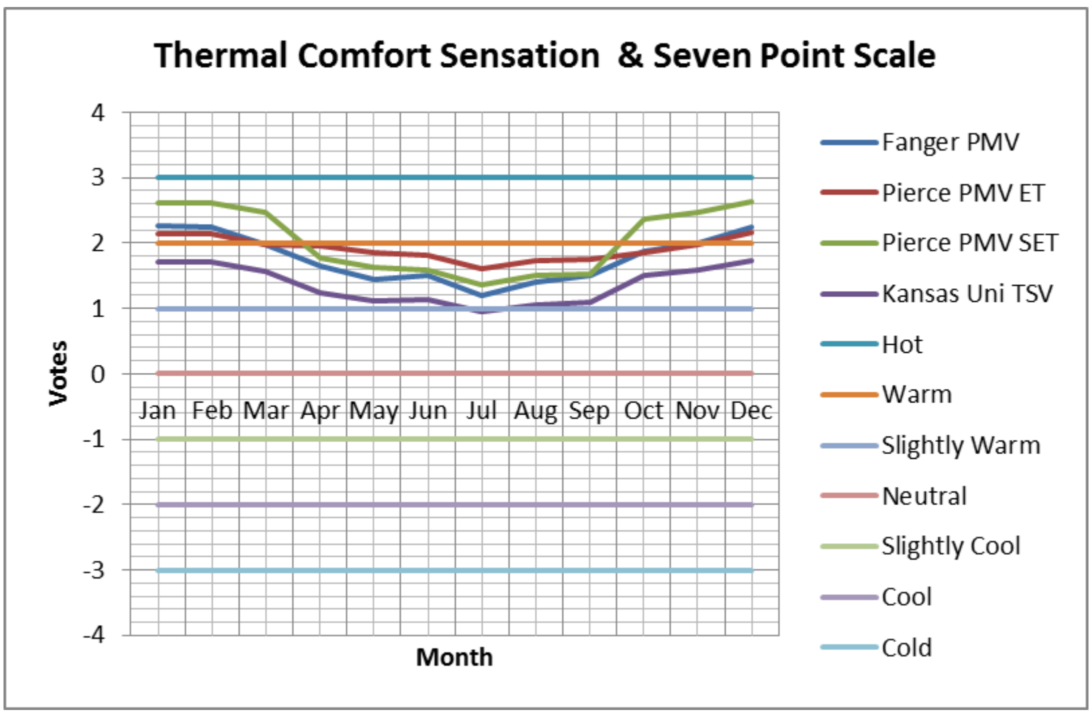


Figure 4. 7: Predicted thermal comfort sensation votes compared with the seven point thermal comfort prediction scale (Baseline model)

Figure 4.8 presents internal gains in the building. It is observed that gains due to solar and general lighting were highest. The month of January followed by December are seen to have the highest latent loads. It is also observed that these are the months with the highest temperature hence high latent loads resulting from solar gains.

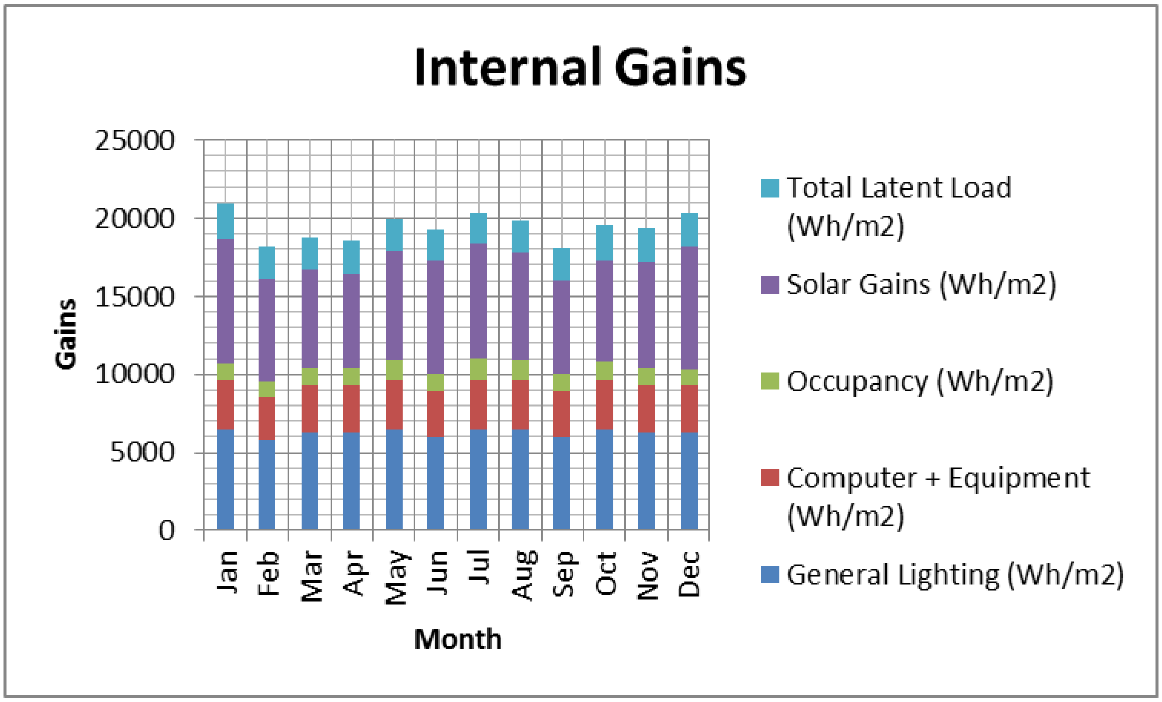


Figure 4. 8: Internal gains (Baseline model)

Baseline model results of ventilation energy loads, fabric & ventilation, electricity usage and carbon dioxide production are further presented in Appendix F.

4.3 Thermal comfort analysis of different natural ventilation efficiency improvement and thermal comfort strategies

Results for thermal comfort analysis of the different natural ventilation efficiency improvement and thermal comfort strategies are presented in the sections below.

4.3.1 Lighting control

Figure 4.9 presents simulated results for environmental comfort data when lighting control is applied. It is generally observed that on application of lighting control, air, radiant and operative temperatures reduced in the building as compared to the baseline model simulations.

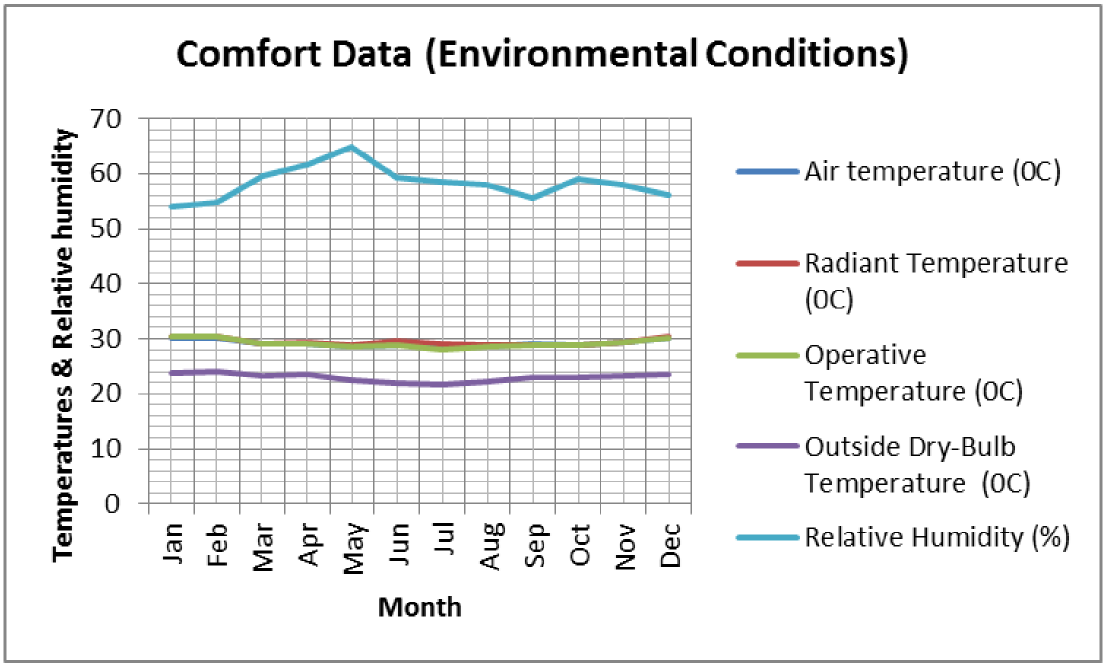


Figure 4. 9: Comfort Data (Environmental conditions (Lighting Control)

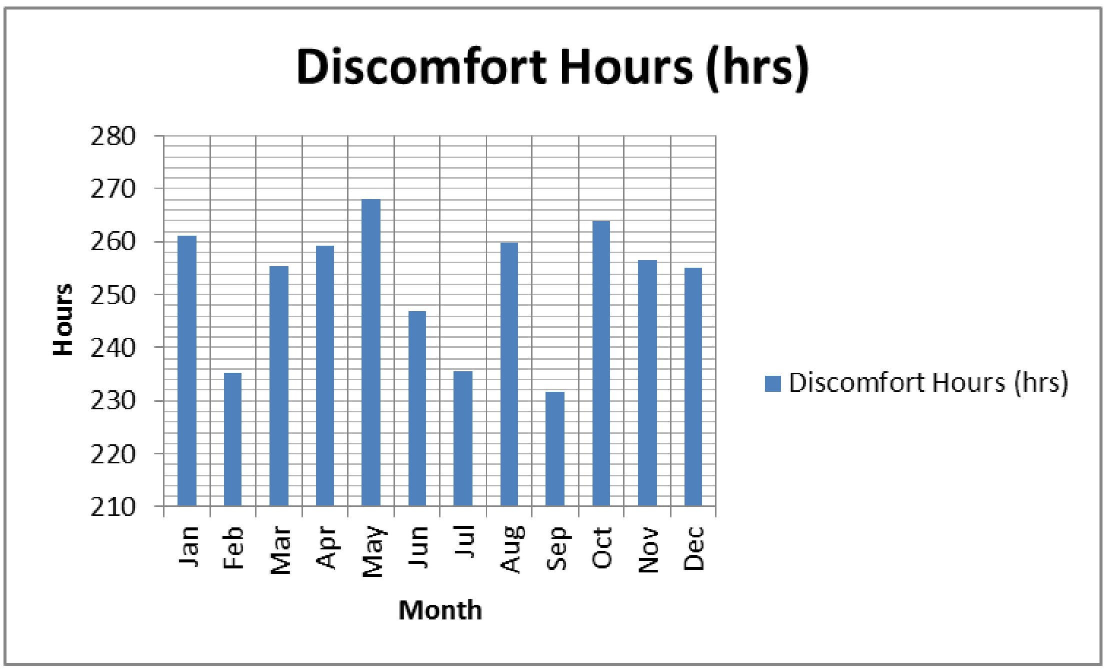


Figure 4. 10: Discomfort hours (Lighting control)

From results of discomfort hours, it was reported that occupants experienced discomfort for 3028.81 hours throughout the year. This is 34.60% discomfort against 65.40% comfort hours out of the total simulation period and hence reductions in the baseline model discomfort by 0.55%.

This reduction is attributed to reduced internal gains due to when lighting control is used in the building.

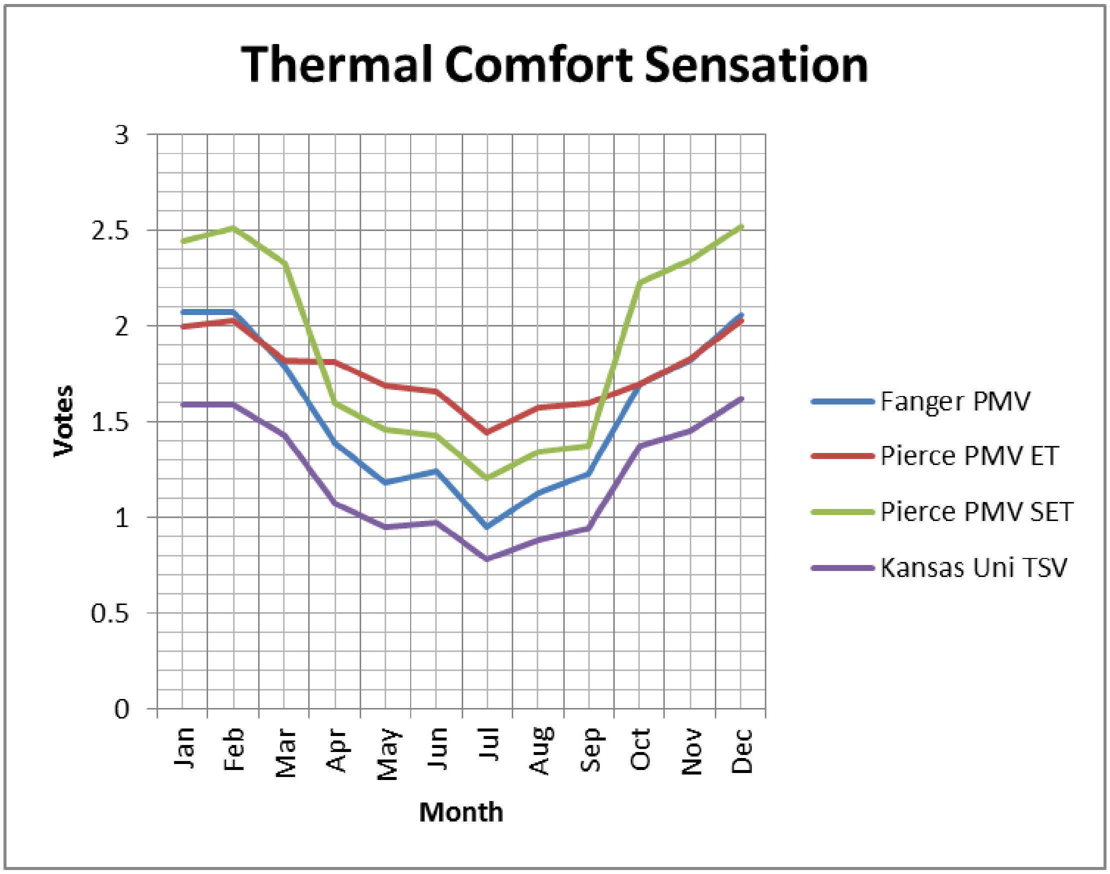


Figure 4. 11: Predicted thermal comfort sensation votes (Lighting control)

It's observed that predicted thermal comfort sensation is slightly improved on application of lighting control, Figure 4.11 presents predicted thermal comfort sensation votes based Fanger PMV, Pierce PMV ET, Pierce PMV SET and Kansas Uni TSV thermal comfort predictive model.

Based on the seven point thermal comfort scale, it is observed that the predicted votes place the comfort sensation between hot and neutral as presented in Figure 4.12.

Averaging predicted thermal comfort sensation votes on monthly basis gives 1.6 which is about 11.1% improvement in thermal comfort sensation when lighting control is adopted.

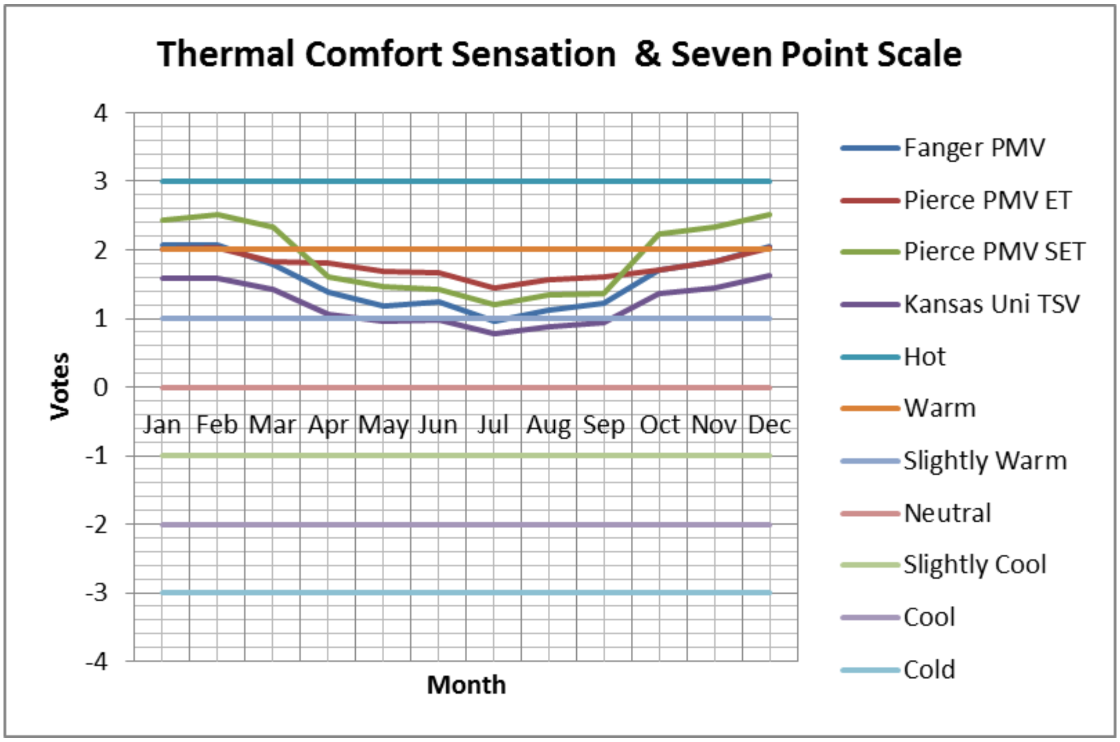


Figure 4. 12: Predicted thermal comfort sensation votes compared with the seven point thermal comfort prediction scale (Lighting control)

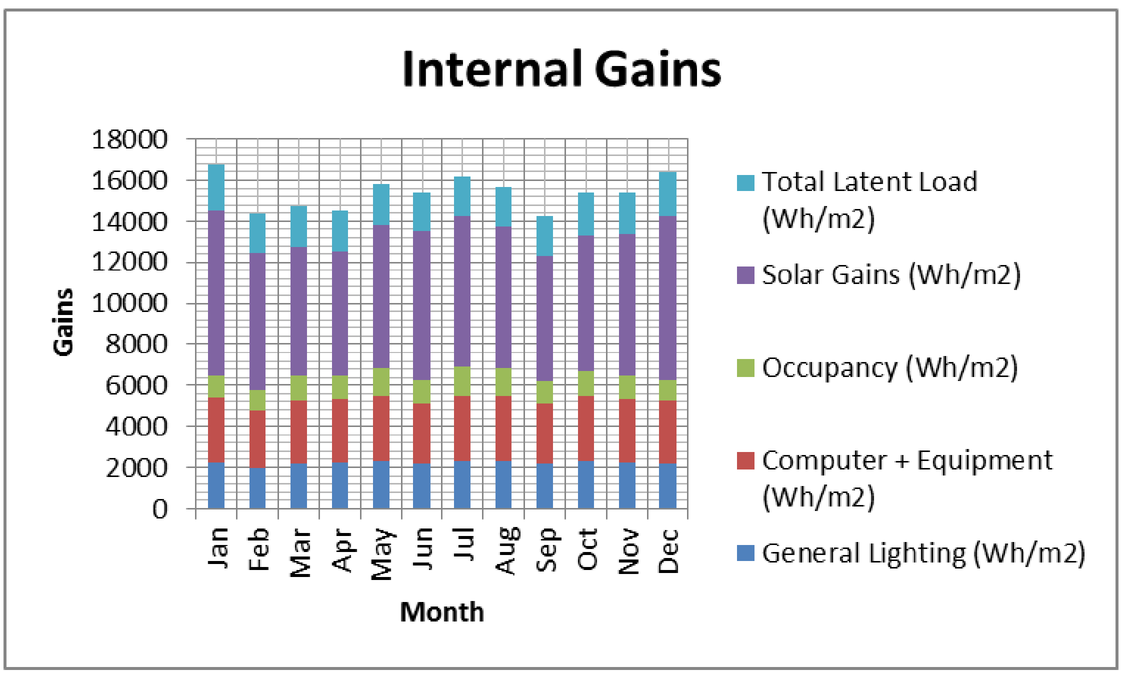


Figure 4. 13: Internal gains (Lighting control)

Figure 4.13 presents internal gains in the building. A 4 % reduction in latent load was realized on application of the lighting control strategy on the baseline model. This is attributed to reduction in gains due to lighting.

Lighting control strategy results for ventilation energy loads, fabric & ventilation, electricity usage and carbon dioxide production are further presented in Appendix G.

4.3.2 Mechanical ventilation without cooling

Results showing the effect of mechanical ventilation without cooling on the base mode are presented below;

Figure 4.14 presents simulated results for environmental comfort data when mechanical ventilation is applied. It is also observed that this strategy has an effect on reduction in, air, radiant, operative temperatures and relative humidity in the building as compared to the baseline model simulations.

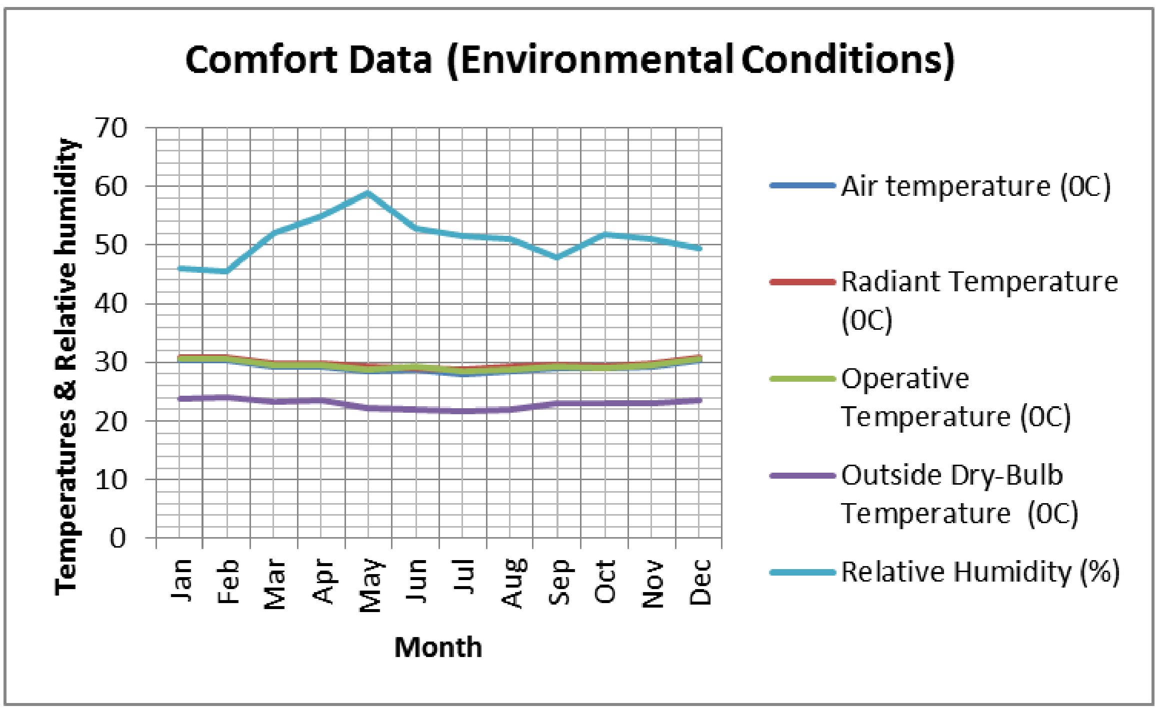


Figure 4. 14: Comfort Data (Environmental conditions - (Mechanical ventilation - Fans)

Figure 4.15 show that occupants experienced discomfort for 3073.92 hours throughout the year. This is 35.01% discomfort against 64.90% comfort hours out of the total simulation period, which represents a negligible reduction in the baseline model discomfort by 0.05%.

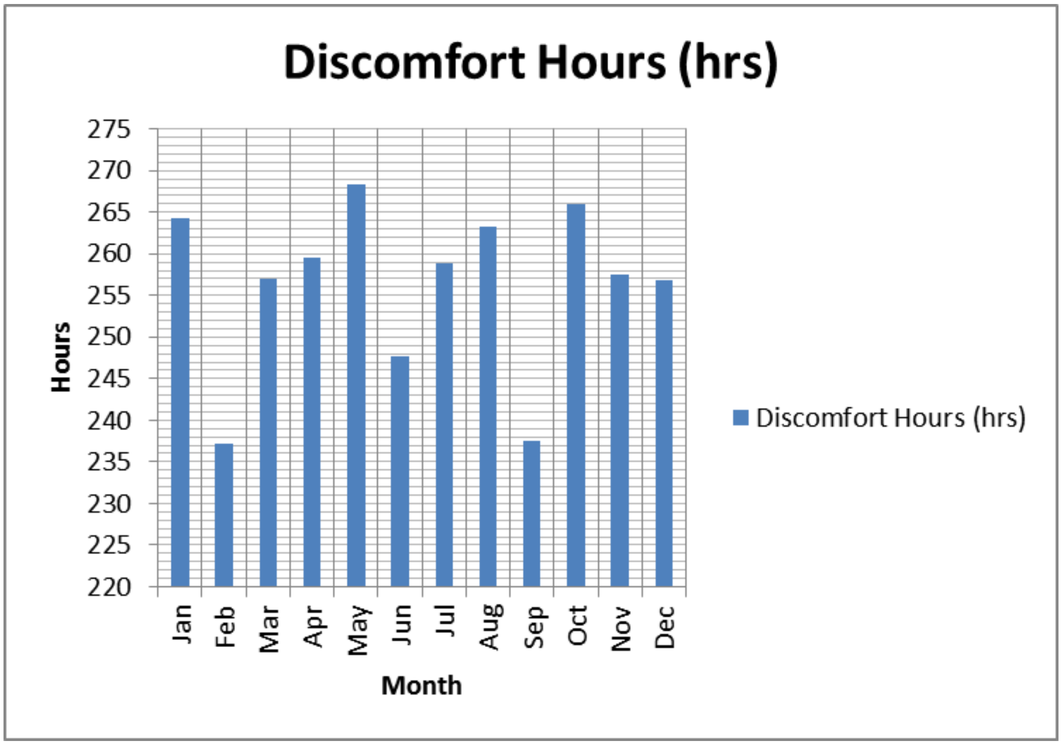


Figure 4. 15: Discomfort hours (Mechanical ventilation - Fans)

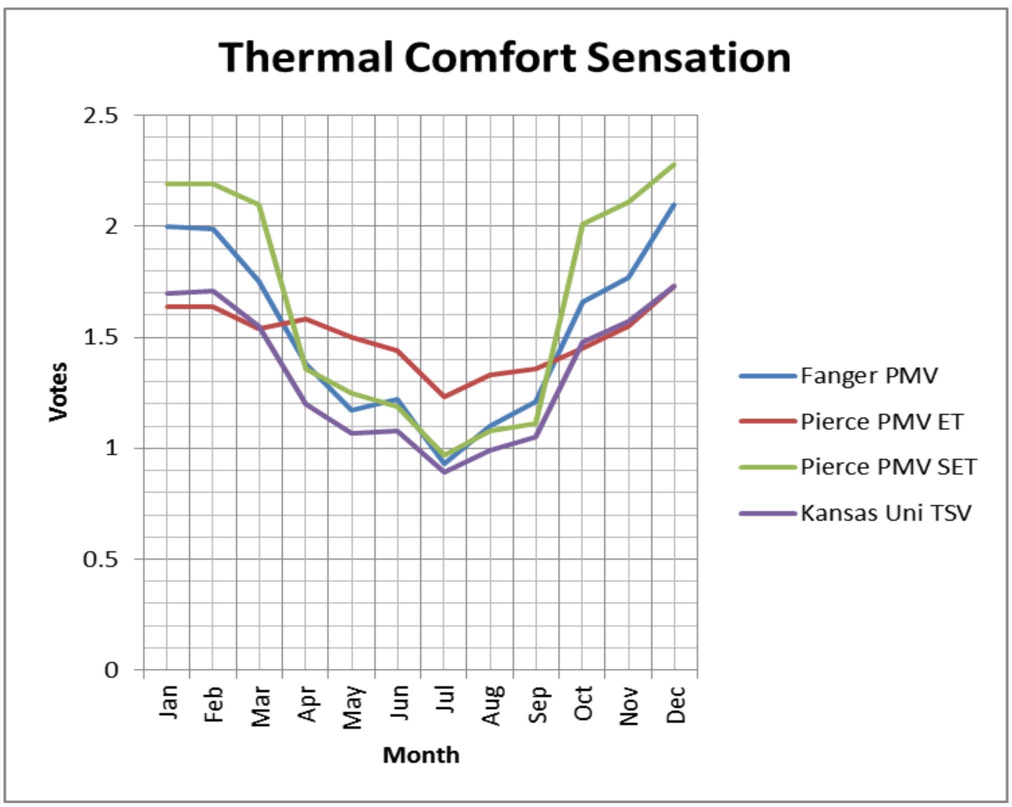


Figure 4. 16: Predicted thermal comfort sensation votes (Mechanical ventilation - Fans)

In Figure 4.16 shows that predicted thermal comfort sensation is majorly from hot to slightly warm on application of mechanical ventilation.

Based on the seven points thermal comfort scale, it's observed that the predicted votes placed the comfort sensation between warm and neutral for almost the entire year as presented in Figure 4.17.

Averaging predicted thermal comfort sensation votes on monthly basis gives 1.5 which is about 16.7% improvement in thermal comfort sensation when mechanical ventilation is adopted.

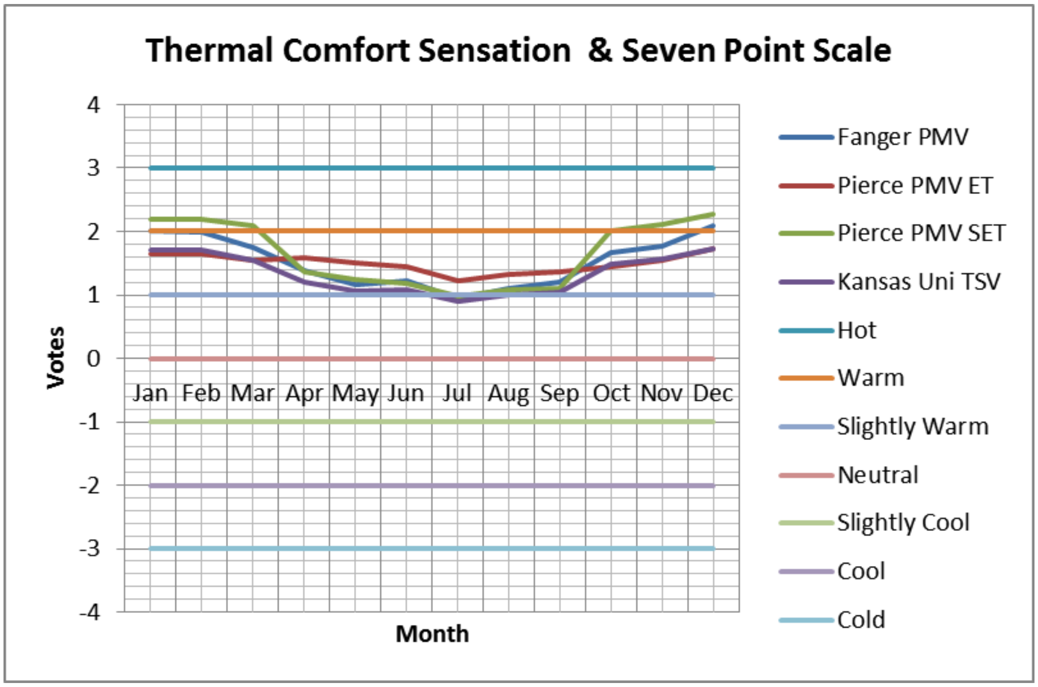


Figure 4. 17: Predicted thermal comfort sensation votes compared with the seven point thermal comfort prediction scale (Mechanical ventilation - Fans)

Figure 4.18 presents internal gains in the building. A 2 % reduction in internal gains was realized on the building heating balance when mechanical ventilation with fans strategy was applied on the baseline model. This is change is attributed to zone sensible cooling caused by the fans which increased the circulation of air within the building.

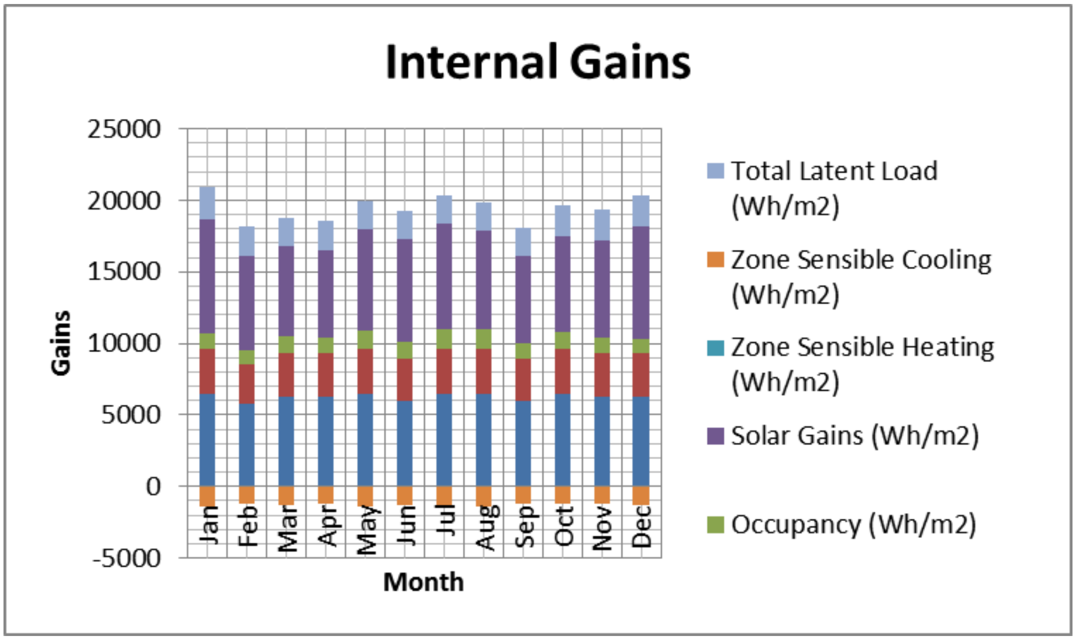


Figure 4. 18: Internal gains (Mechanical ventilation - Fans)

Mechanical ventilation with only fan aid strategy results for ventilation energy loads, fabric & ventilation, electricity usage and carbon dioxide production are further presented in Appendix H.

4.3.3 Mechanical ventilation with cooling

Results of the effect of mechanical ventilation with cooling are presented below;

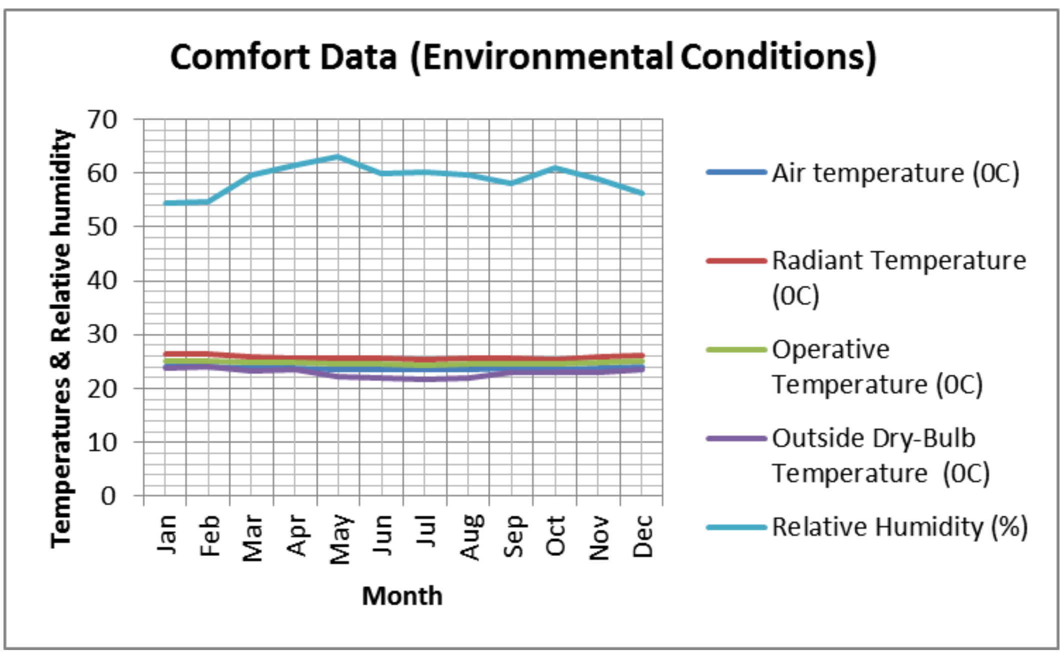


Figure 4. 19: Comfort Data (Environmental conditions - (Mechanical ventilation - Cooling)

From Figure 4.19, environmental comfort data results are presents showing building temperature significantly reduced as a result introduction of cooled air in the building. The scheduled introduction of cooled air is observed to keep the indoor temperatures close to the outside temperatures.

Figure 4.20 presents discomfort hours, occupants experienced discomfort for 2031.94 hours throughout the year. This is 23.2% discomfort against 76.8% comfort hours out of the total simulation period, which represents a significant reduction in the baseline model discomfort by 12%. This reduction is totally attributed to scheduled introduction of cooled air into the building.

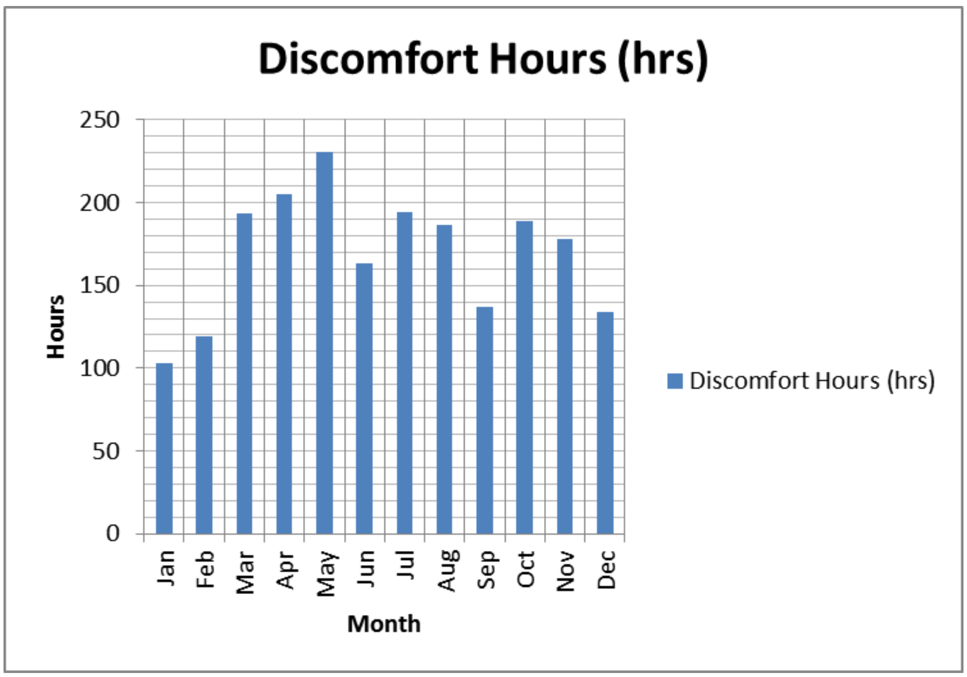


Figure 4. 20: Discomfort hours (Mechanical ventilation - Cooling)

Figure 4.21 presents predicted thermal comfort sensation results. It is observed that occupancy thermal sensation votes significantly reduced on application of mechanical ventilation with cooling.

Based on the seven points thermal comfort scale, it's observed that the predicted votes placed the comfort sensation between slightly warm and slightly cool for the entire year as presented in Figure 4.22. Averaging predicted thermal comfort sensation votes on monthly basis gives a vote of 0.32 which is about 82.2% improvement in the baseline model thermal comfort sensation when scheduled mechanical ventilation with cooling is adopted.

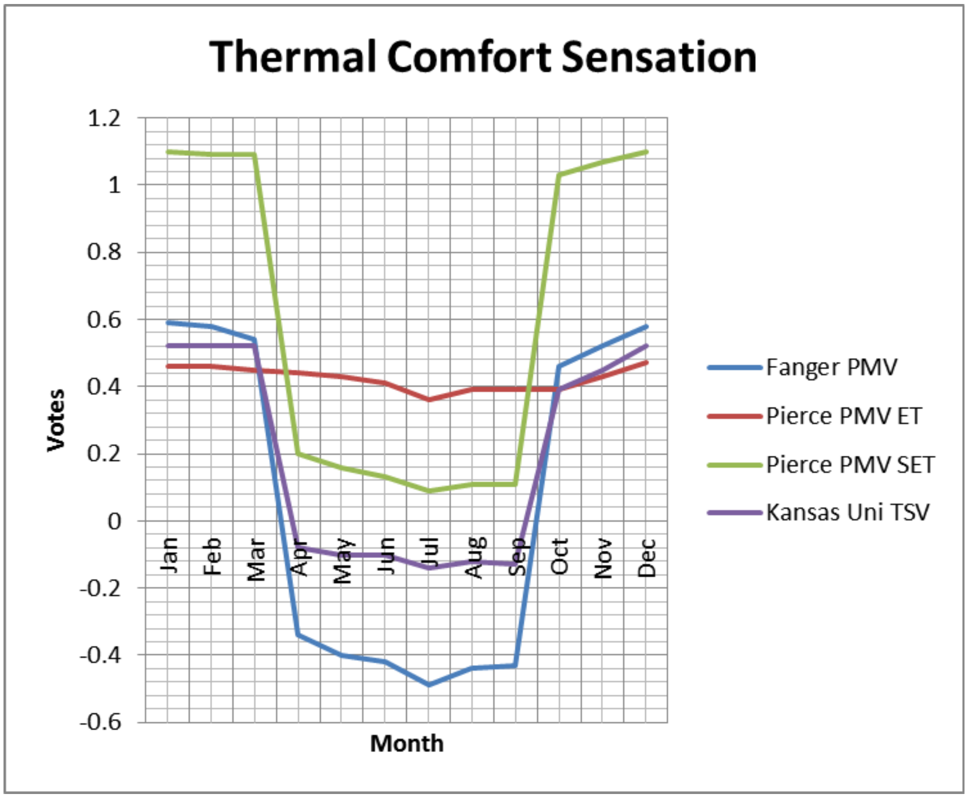


Figure 4. 21: Predicted thermal comfort sensation votes (Mechanical ventilation - Cooling)

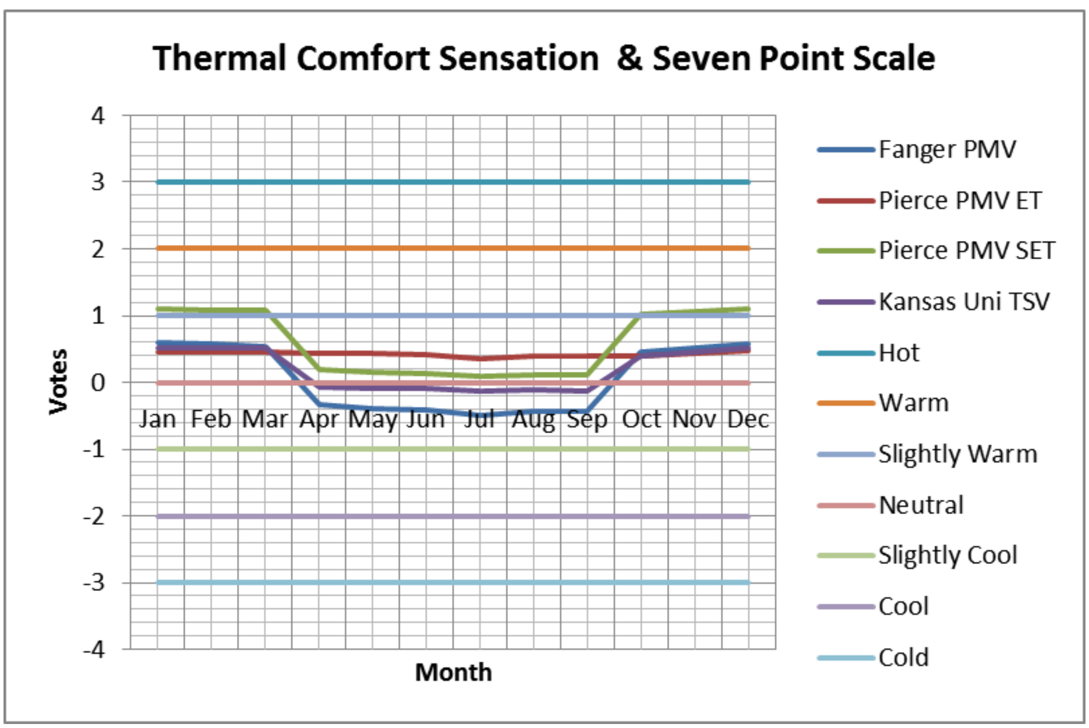


Figure 4. 22: Predicted thermal comfort sensation votes compared with the seven point thermal comfort prediction scale (Mechanical ventilation - Cooling)

Figure 4.23 presents internal gains in the building. A 55 % reduction in internal gains was realized on the building heating balance when mechanical ventilation with cooling strategy was applied on the baseline model.

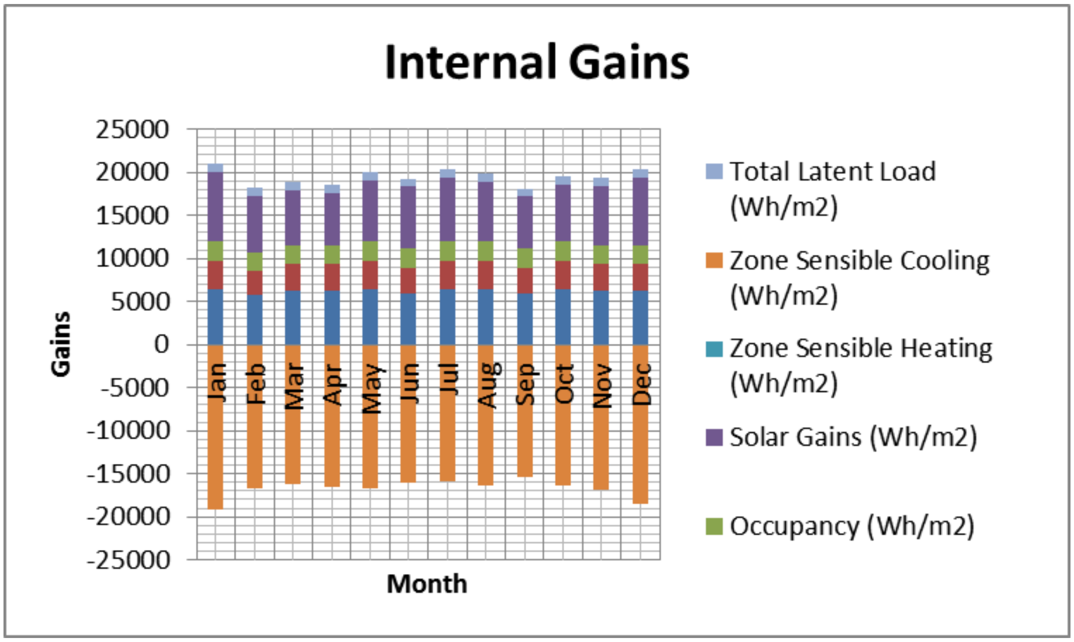


Figure 4. 23: Internal gains (Mechanical ventilation - Cooling)

Mechanical ventilation with cooling aid strategy results for ventilation energy loads, fabric & ventilation, electricity usage and carbon dioxide production are further presented in Appendix I.

4.3.4 Window wall ratio

Figure 4.24, presents results of parametric analysis used to establish the effect of wwr to comfort. It is generally observed that discomfort reduces with increase in wwr. This can be attributed to the availability of open area for air circulation into the building hence reduction in discomfort.

At wwr 0%, the highest discomfort hours where registered.

Variation of wwr from 0% to 20% had a sharp drop in discomfort hours. Beyond wwr 20% to 100%, the decline in discomfort hours is observed to be minimal and insignificant tending to a constant after wwr 60%.

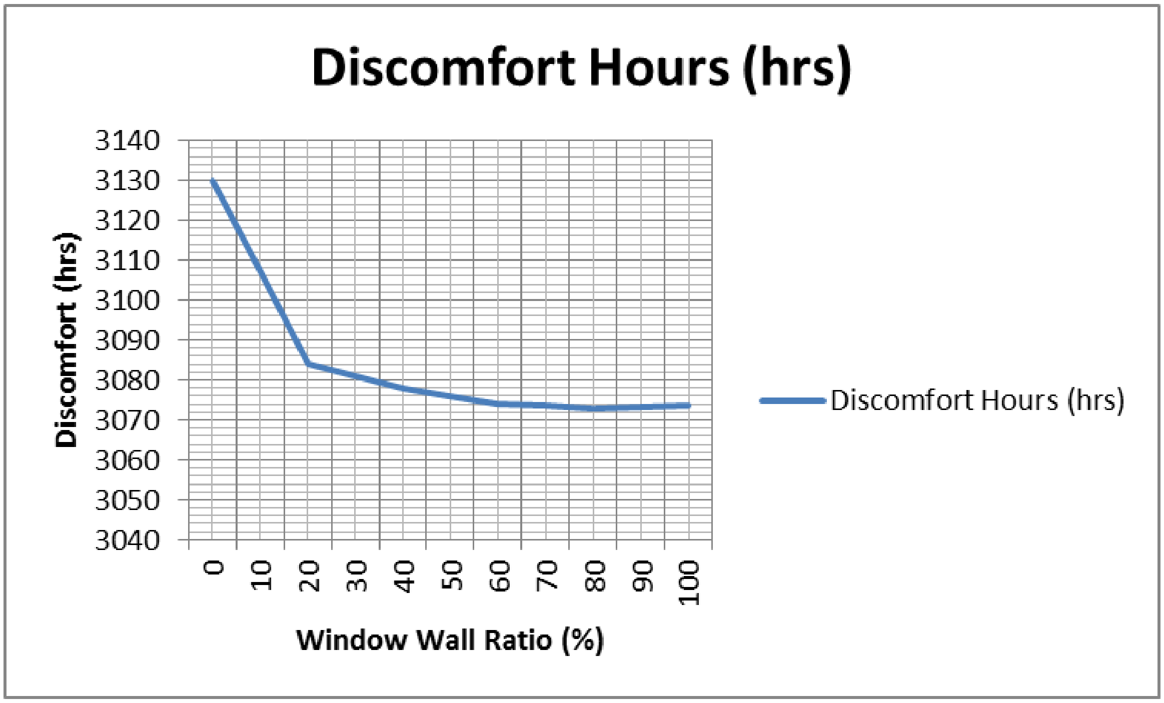


Figure 4. 24: Discomfort hours (window wall ratio)

Further doubling the wwr of the baseline model from 30% to 60% could have an effect on lighting but negligible effect on reduction of overall discomfort hours and thermal comfort.

CHAPTER FIVE

5.0 Conclusions and recommendations

Thermal comfort analysis of a naturally ventilated building was carried out in college of engineering, design, art & technology (CEDAT) building located in Makerere University, Kampala-Uganda.

DesignBuilderEnergyPlus software was use to model the building and perform simulations based on the Simple ASHRAE 55-2004 method for thermal comfort and their after its improvement.

Simulation results suggested that the baseline model predicted thermal comfort votes placed the occupancy thermal comfort sensation between hot and slightly warm based on the seven point thermal comfort sensation scale with occupants experiencing 35.15% discomfort hours against 64.85% comfort throughout the year.

On using the lighting control strategy, results revealed that occupants predicted thermal sensation moved between hot and neutral. Improvement was observed from slightly warm to neutral. This strategy brought about a negligible improvement of 0.55% in baseline occupancy thermal comfort hours.

Mechanical ventilation with the aid of fans to improve air circulation in the building also registered a negligible improvement of 0.05% in occupancy thermal comfort hours. This left the predicted thermal comfort sensation of occupants between hot and slightly warm.

Results for mechanical ventilation with scheduled cooling greatly improved the occupancy thermal sensation placing it between slightly warm and slightly cool with majority taking up the neutral position. This strategy improved the baseline thermal comfort by 12% comfort hours throughout the year.

Variation of WWR has very little noteworthy improvement to thermal comfort of the occupants with the occupancy thermal sensation predicted to be warm and some months tending to hot.

WWR 0% has the highest comfort hours and least natural ventilation rate. As WWR increased from 0% to 100%, occupancy thermal comfort increases but negligibly.
However while using the strategy of WWR for occupancy thermal comfort, variation from 20% beyond is recommended for naturally ventilated buildings within the same climatic region as the case study since it provides better comfort conditions if it's the available option and more lighting.

Natural ventilation combined with scheduled mechanical ventilation with cooling increased thermal comfort of occupants significantly.

It is however recommended that the strategy of scheduled mechanical ventilation with cooling be used together with lighting control as the control of building lighting reduces internal gains due to lighting by 4% and also electricity usage seen to reduce by 43%. If opportunity taken, energy saved from lighting control can be used to run the HVAC system hence improving occupancy thermal comfort significantly.

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APPENDICES

Appendix A: Building modeling & simulation software

Table A. 1: Building performance modeling & simulation software/ tools for thermal comfort and natural ventilation simulation

Software/ Tool	Application
3E Plus	Insulation and insulation thickness.
AcousticCalc	HVAC acoustics, sound level prediction and noise level.
Acoustics Program	HVAC acoustics, sound level prediction and noise level.
AFT Fathom	Design, pump selection, pipe analysis, duct design, duct sizing, chilled water systems and hot water system.
AFT Mercury	Optimization, pipe optimization, pumps selection, duct design, duct sizing, chilled water systems and hot water systems.
AIRWIND Pro	Air Conditioning Load Calculation.
Analysis Platform	Heating, cooling, and SWH equipment and commercial buildings.
Apache	Thermal design, thermal analysis, energy simulation, dynamic simulation, system simulation.
ApacheHVAC	Buildings, HVAC, simulation, energy performance.
AUDIT	Operating cost, bin data, residential, commercial.
BEES	Environmental performance, green buildings, life cycle assessment, life cycle costing, sustainable development.
BSim	Building simulation, energy, daylight, thermal and moisture analysis, indoor climate.
Building Energy Analyzer	Air-conditioning, heating, on-site power generation, heat recovery, CHP, BCHP.
BuildingAdvice	Whole building analysis, energy simulation, renewable energy, retrofit analysis, sustainability/green buildings.
BuildingSim	Thermostat, simulation, energy cost.
C-MAX	Pumps, fans, chillers, compressors, energy conservation, facility design
CBE UFAD Cooling Design Tool	UFAD, under floor, Cooling load calculator, cooling, stratification, thermal comfort.

COLDWIND Pro	Refrigeration, Heat Load Calculation.
COMSOL	Multiphysics, simulations, modeling, heat transfer, finite element.
CONTAM	Airflow analysis; building controls; contaminant dispersal; indoor air quality, Multizone analysis, smoke control, smoke management, ventilation.
CtrlSpecBuilder	HVAC controls, specifications, CSI Section 15900 HVAC Instrumentation and Controls.
Cymap Electrical	BS 7671 Main/Sub Main and Final Circuit distribution, generators, UPS, lighting design, emergency lighting, day lighting, floodlighting, cable sizing, discrimination studies, LV and HV capabilities, fire alarm, CAD symbol library based small power design, Cable Tray/Basket/Raceways/Conduit. Lightning protection risk assessment to EN62305 in 10 languages.
Cymap Mechanical	Load calculation, Pipe sizing & Radiator selection, Duct sizing, Hot and cold water design, SAP, iSBEM, EPCs, Psychometrics.
CYPE-Building Services	Building services, single model, energy simulation, sizing, HVAC, plumbing, sewage, electricity, solar, analysis of acoustic behavior.
Czech National Calculation Tool	EPBD, Energy Performance Certificate, Delivered energy, Energy Demand Calculation.
DD4M Air Duct Design	Duct design, air-conditioning, heating.
DesiCalc	Desiccant system, air-conditioning, system design, energy analysis, dehumidification, desiccant-based air treatment.
DesignBuilder	Building energy simulation, visualization, CO_2 emissions, solar shading, natural ventilation, day lighting, comfort studies, CFD, HVAC simulation, pre-design, early-stage design, building energy code compliance checking, OpenGL EnergyPlus interface, building stock modeling, hourly weather data, heating and cooling equipment sizing
DeST	Building simulation, design process, calculation, building thermal properties, natural temperature, graphical interfaces, state space method, and maximum load.
DOLPHIN	Duct sizing, duct and fitting pressure loss, fan pressure.

DONKEY	Duct sizing, equal friction, static regain, balanced pressure drop, duct acoustics, self-generated noise, room sound pressure level.
DPClima	Thermal load calculation, equipment sizing.
Duct Calculator	Duct-sizing, design, engineering, calculation.
DUCTSIZE	duct sizing, equal friction, static regain
E.A.S.Y. - Energy Accounting System for Your Buildings	Energy Accounting, OMV System, Building baseline development, Energy and Emissions Savings.
EnergyPlus	Models heating, cooling, lighting, ventilation, other energy flows, and water use.
ecasys	Energy program management.
EcoAdvisor	Online interactive training, online multimedia training, sustainable commercial buildings, lighting, HVAC.
ecoInsight Energy Audit & Analysis Software	Retrofit Analysis, Energy Audit Software, Building Analysis, Lighting Retrofit.
ECOTECT	Environmental design, environmental analysis, conceptual design, validation; solar control, overshadowing, thermal design and analysis, heating and cooling loads, prevailing winds, natural and artificial lighting, life cycle assessment, life cycle costing, scheduling, geometric and statistical acoustic analysis.
EffTrack	Chiller efficiency, chiller performance.
Energy Estimation Software with Carbon Footprint Calculation	Variable frequency drive, energy savings, fans, pumps, carbon footprint
Energy Profile Tool	Benchmarking, energy efficiency screening, end-use energy analysis, building performance analysis, utility programs.
Energy Trainer for Energy Managers HVAC Module	Training, HVAC, operation and maintenance, existing buildings.
EnergyGauge Summit	Building simulation, energy simulation, building energy modeling, ASHRAE

Premier	Standard 90.1, commercial code compliance, LEED NC 2.2 EA Credit 1, federal commercial building tax deductions, EPACT 2005 qualified software, Florida code compliance, ASHRAE Standard 90.1 Appendix G, DOE 2.1E, AHSRAE advanced building design guidelines, automatic reference building generation, automatic EA Credit 1 PDF generation, buildings research.
EnergyPro	California Title 24, LEED, ASHRAE 90.1, compliance software, energy simulation, commercial, residential.
EnergyWitness	Large building; energy efficiency.
Engineering Toolbox	Refrigerant line sizing, air properties, fluid properties, power factor correction, duct sizing.
ESP-r	Energy simulation, environmental performance, commercial buildings, residential buildings, visualization, complex buildings and systems.
FLOVENT	airflow, heat transfer, simulation, HVAC, ventilation
Flownex	Gas flow; liquid flow; dynamic; heat transfer; two phase; slurry.
Gas Cooling Guide PRO	Gas cooling, hybrid HVAC systems.
GLHEPRO	Ground heat exchanger design, ground source heat pump system, and geothermal heat pump system.
Ground Loop Design	Geothermal, borehole, heat exchanger design.
HAMLab	Heat air and moisture, simulation laboratory, hydrothermal model, PDE model, ODE model, building and systems simulation, MatLab, SimuLink, Comsol, optimization.
HAP	Energy performance, load calculation, energy simulation, HVAC equipment sizing.
HAP System Design Load	Cooling and heating load calculation, HVAC equipment sizing, zoning and air distribution.
Heat Pump Design Model	Heat pump, air conditioner, air-to-air heat pump, equipment simulation.
Home Energy Tune-up	Home energy audit, energy efficiency, administration, conservation, consulting, energy savings, home performance, inspection, low income, renewable energy,

	residential retrofit, training, weatherization, whole house.
HPSIM	Heat pump, research.
HVAC 1 Toolkit	Energy calculations, HVAC component algorithms, energy simulation, performance prediction.
HVAC Solution	Boilers, chillers, heat exchangers, cooling towers, pumps, fans, expansion tanks, heat pumps, fan coils, terminal boxes, louvers, hoods, radiant panels, coils, dampers, filters, piping, valves, ductwork, schedules.
HVACSIM+	HVAC equipment, systems, controls, EMCS, complex systems
Hydronics Design Studio	Hydronic heating, radiant heating, simulation, design, piping.
IDA Indoor Climate and Energy	Design, energy performance, thermal comfort, indoor air quality, commercial buildings.
INDUS	Ductwork sizing, ductwork design, HVAC.
ISE	Thermal model, building zone simulation, MatLab/SimuLink.
J-Works	Load calculation, commercial buildings, and residential buildings.
kW-Field	Commercial Energy Auditing Field Software.
LESOSAI	Heating energy, cooling energy, energy simulation, load calculation, standards, life cycle analysis, and gbxml.
Load Express	Design, light commercial buildings, heating and cooling loads, HVAC.
LoopDA	Airflow analysis, indoor air quality, multizone analysis, natural ventilation.
Maintenance Edge	CMMS, Maintenance, Work Order, Planned Maintenance, LEED, ENERGY STAR®, benchmarking, Critical Alarm.
ManagingEnergy	Building energy management; energy efficiency strategies, energy accounting.
MarketManager	Building energy modeling, design, and retrofit.
MC4Suite 2009	HVAC project design, sizing, calculations, energy simulation, and commercial, residential, solar.
ModEn	object-oriented simulation, energy simulation, controls, energy audit, energy-saving, energy performance, dynamic simulation, research, education, heating, air conditioning.
MotorMaster+	motors, premium efficiency, motor management, industrial efficiency

National Energy Audit (NEAT)	Retrofit, energy, audit, efficiency measures.
NewQUICK	Passive simulation, load calculations, natural ventilation, evaporative cooling, energy analysis.
OHVAP	Venting design, oil-fired equipment.
Pervidi	Building systems, performance, preventative maintenance, and analysis, residential and commercial buildings.
PHPP	Energy balance, high-performance houses, passive houses.
Pipe Designer	Fluid systems, piping design, existing systems.
Pipe Flow Expert	Pipe flow, pipe pressure loss.
Pipe-Flo	Piping analysis, pump selection, piping design, hydraulic analysis, pump sizing, pressure drop calculator, hydraulic modeling, steam distribution, chilled water, sprinkler system.
Pisces	Pipe work, heating, cooling.
PocketControls	PDA, controls, front end, handheld.
Polysun	Solar System Design Simulation Software (and Heat Pump).
PsyCalc	Psychrometric, temperature, moisture content, atmospheric pressure.
PsyChat	Moist air state, dry bulb, wet bulb, relative humidity, sensible heat, moisture content.
Psychrometric Analysis	Psychrometric analysis, HVAC.
PYTHON	pipe sizing, pump sizing, control valve selection.
QwickLoad	Design, residential to large commercial buildings, heating load, cooling load, HVAC.
RadTherm	Convection, conduction, radiation, weather, solar, transient.
RHVAC	Residential HVAC, residential load calculations.
Right-Suite Residential for Windows	Residential loads calculations, duct sizing, energy analysis, HVAC equipment selection, system design.
RIUSKA	Energy calculation, heat loss calculation, system comparison, dimensioning, 3D modeling.
Room Air Conditioner	Air conditioner, life-cycle cost, energy performance, residential buildings,

Cost Estimator	energy savings.
SIMBAD Building and HVAC Toolbox	Transient simulation, control, integrated control, control performance, graphical simulation environment, modular, system analysis, HVAC.
SMILE	Object-oriented simulation environment, building and plant simulation, complex energy systems, time continuous hybrid systems.
SolarPro 2.0	Solar water heating, thermal processes, alternative energy, simulation.
SPARK	Object-oriented, research, complex systems, energy performance, short time-step dynamics.
T*SOL	Solar thermal heating, swimming pool heating, solar planning and design.
TAS	Building dynamic thermal simulation, building simulation, comfort, CFD, thermal analysis, energy simulation.
TRACE 700	Energy performance, load calculation, HVAC equipment sizing, energy simulation, commercial buildings.
TRACE Load 700	Heating and cooling load calculation, air distribution simulation, HVAC equipment sizing, and commercial buildings.
TRANSOL	Powerful, flexible, complete
Trend Importer	trend, importer, data, spreadsheet, UTF
TRNSYS	Energy simulation, load calculation, building performance, simulation, research, energy performance, renewable energy, emerging technology.
Varitrane Duct Designer	Duct sizing, static regain, equal friction, fitting loss.
WISE	Hydrothermal model, building simulation, MatLab/SimuLink Tool.

Source: US-DOE - Building energy software tools directory, 2011

Appendix B: Building floor and elevation plans

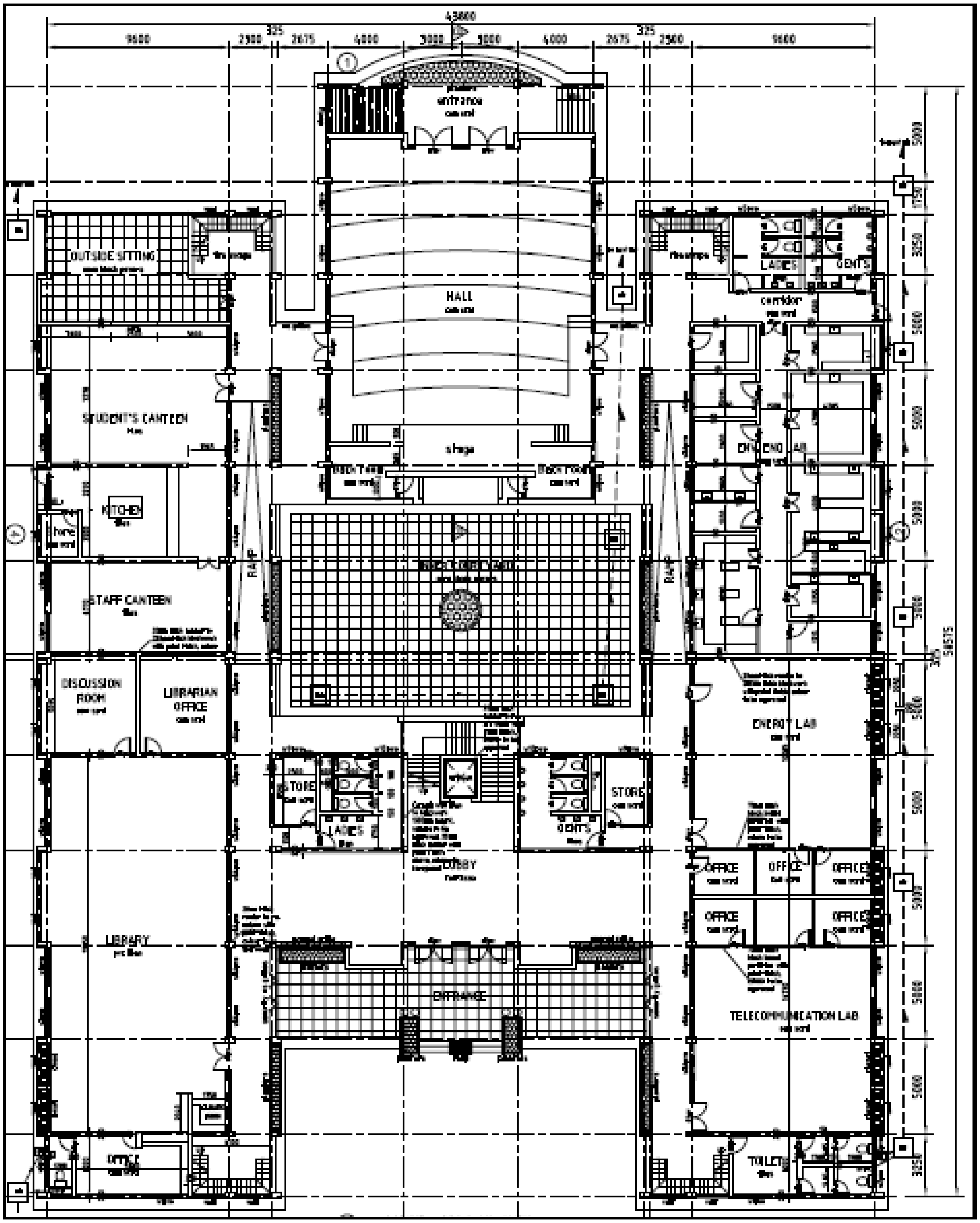


Figure B. 1: Ground floor (F_0) plan layout

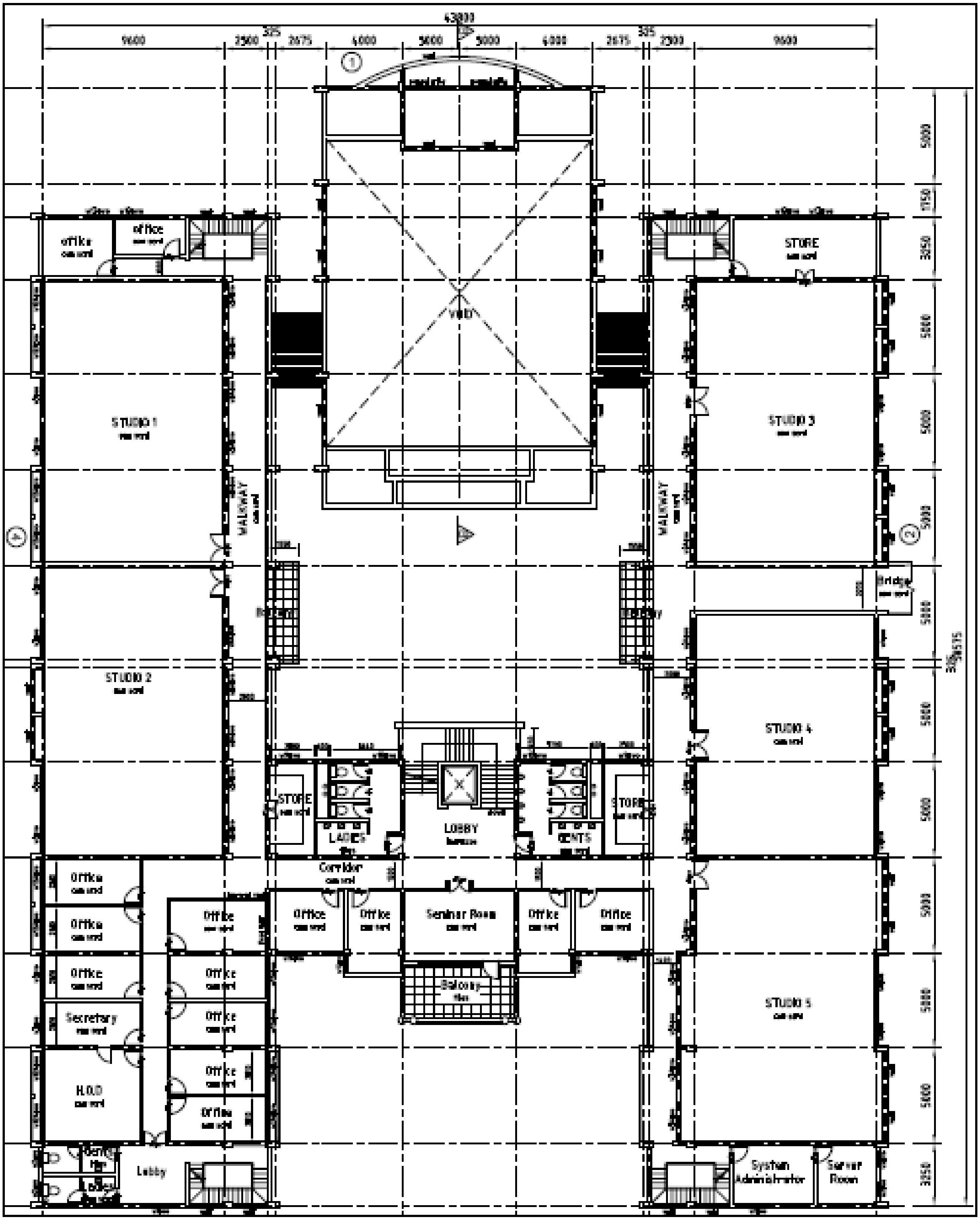


Figure B. 2: First floor (F_1) plan layout

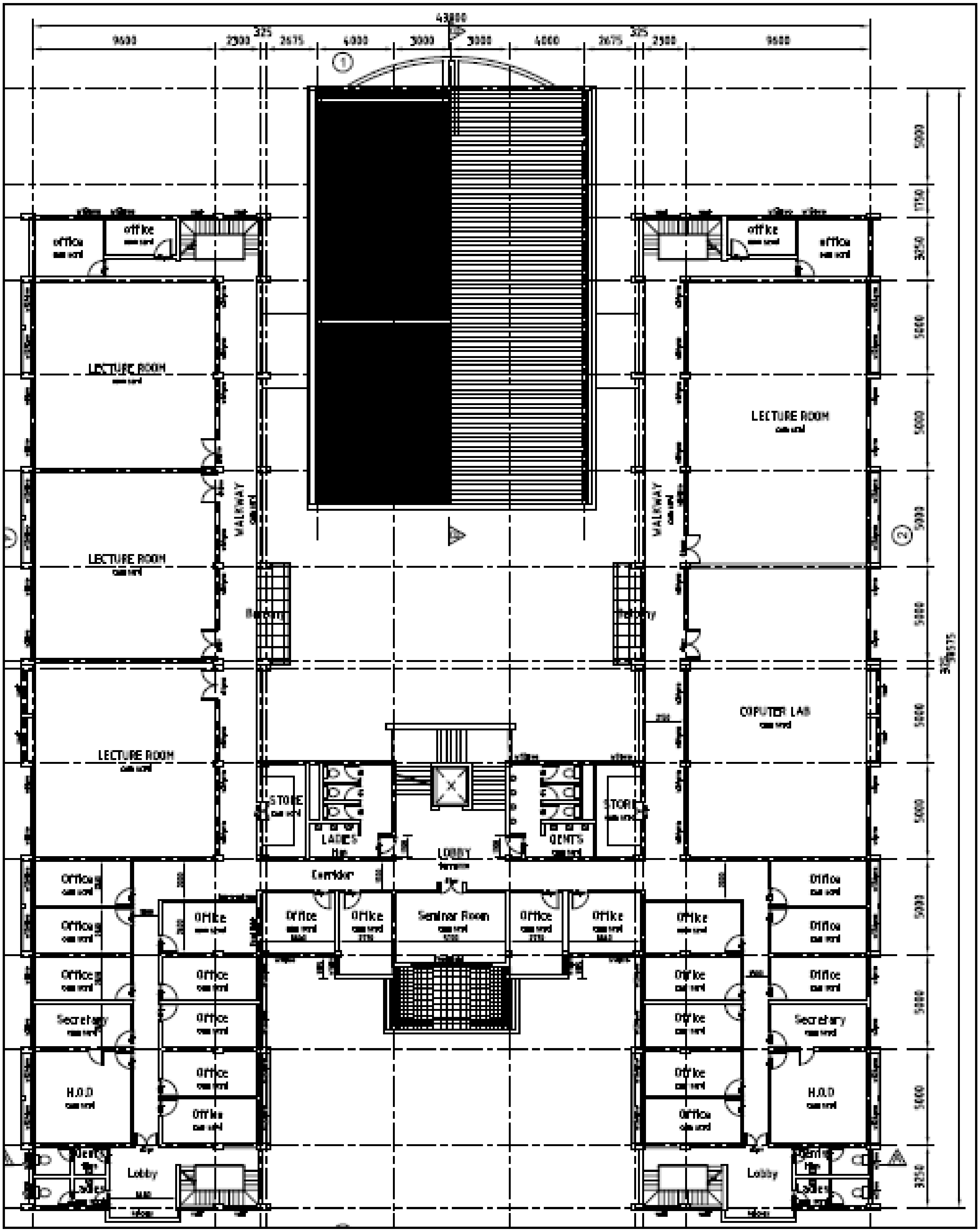


Figure B. 3: Second floor (F_2) plan layout

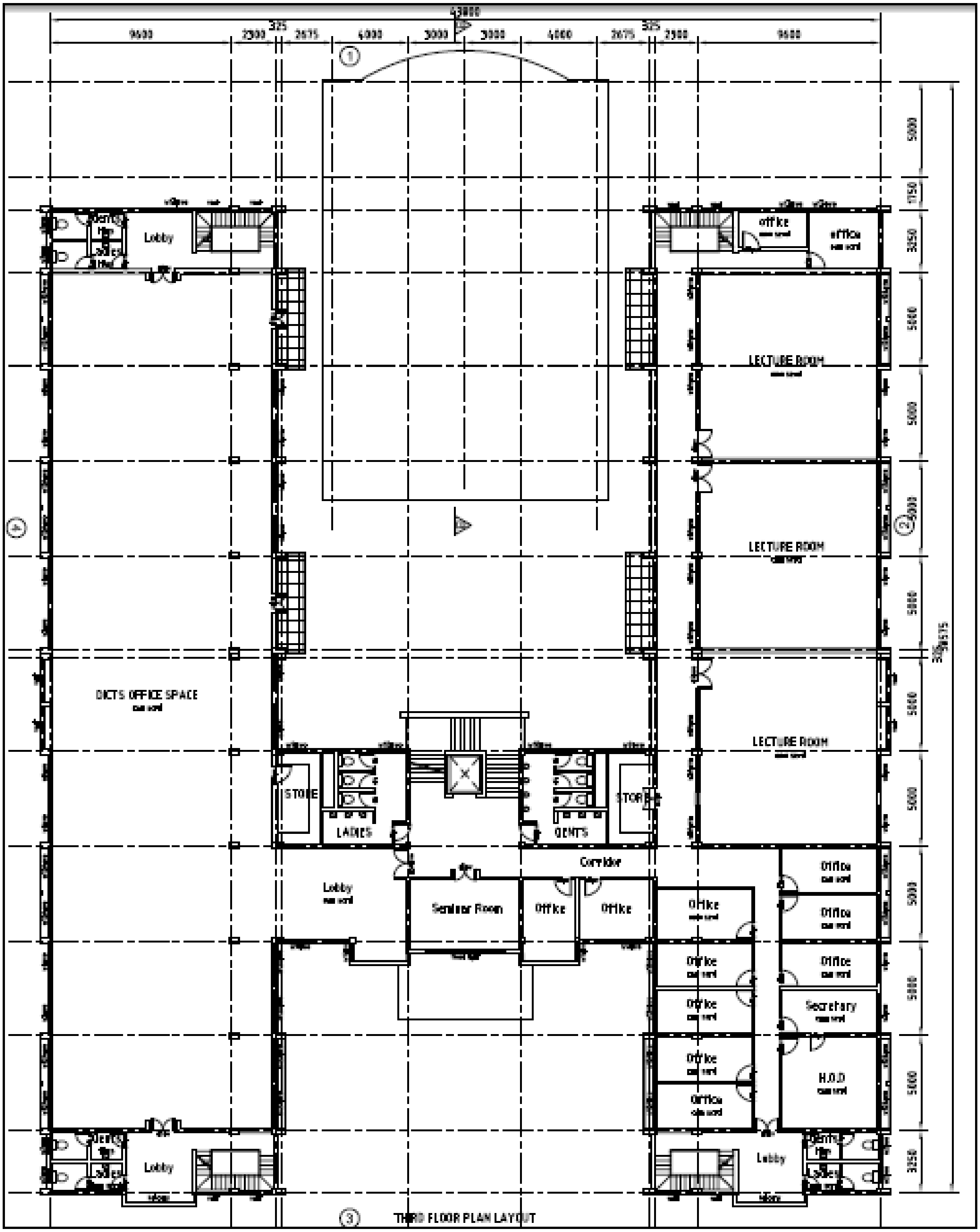


Figure B. 4: Third floor (F_3) plan layout

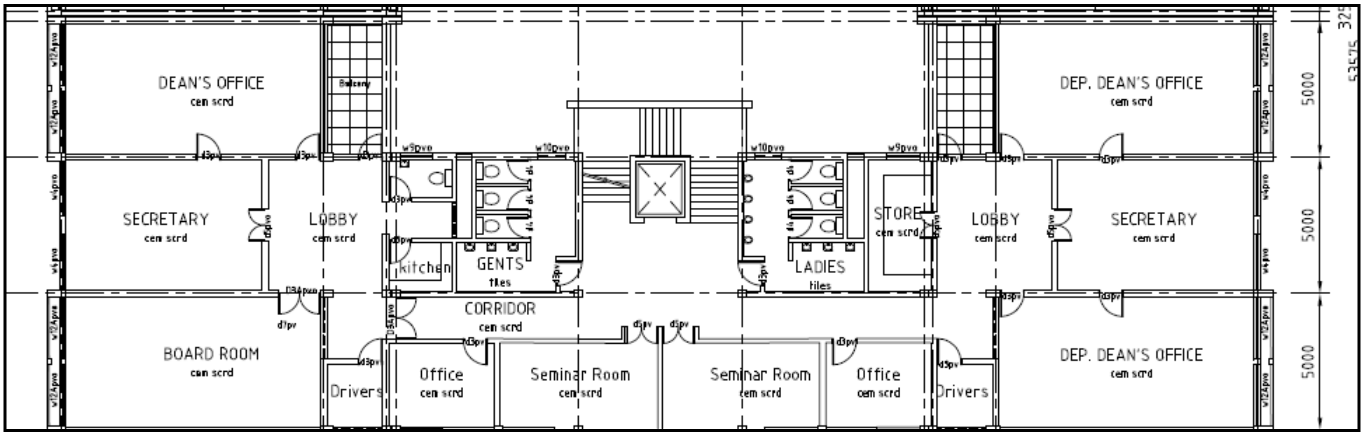


Figure B. 5: Fourth floor (F_4) plan layout

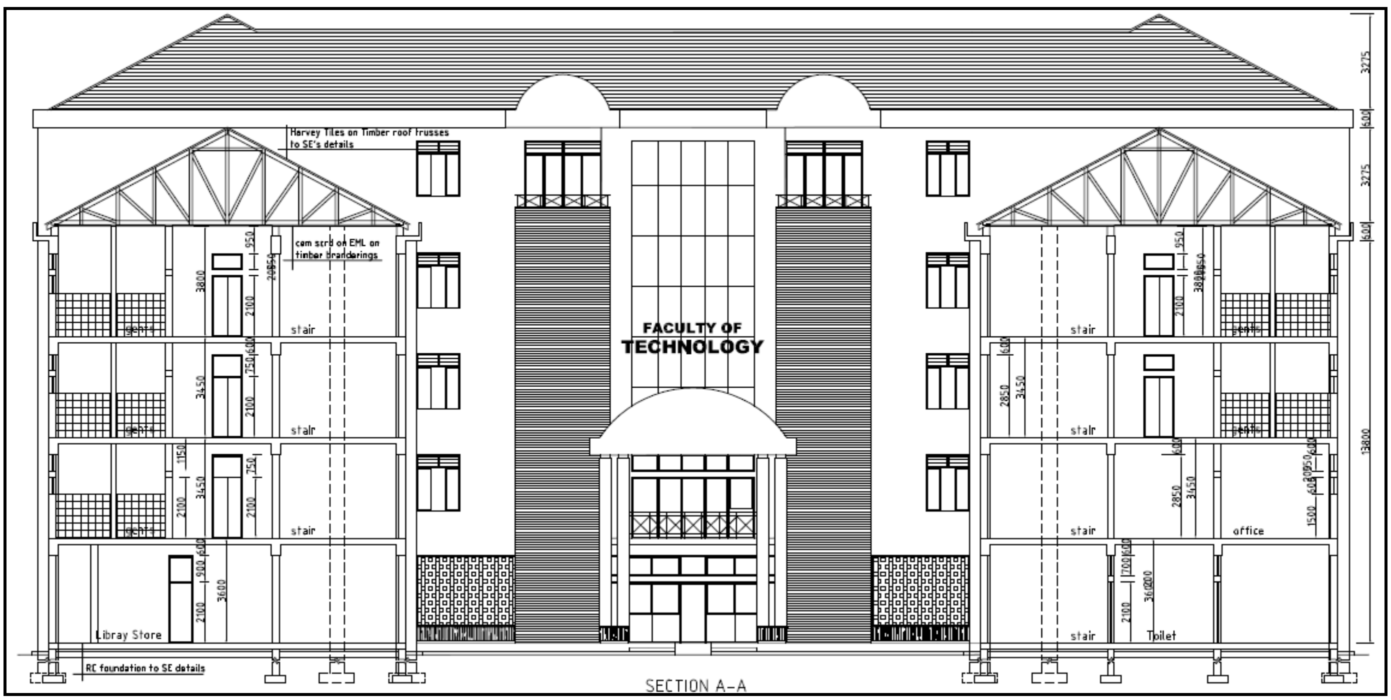


Figure B. 6: Building elevation view

Appendix C: Building Occupancy data

Table C. 1: Building occupancy data and heat gains by zone (Source: CEDAT, 2011/2012 Class Lists and Muhangi, 2012)

NO	Zone	Total number of Occupants	Area (m^2)	Number of computers	Gains from computers (w)	Gains from computers w/m^2	Number of office equipment	Gains from office equipment (w)	Gains from office equipment w/m^2	Occupancy (People/m^2)
Ground Floor (F_0)										
1	Corridor	30	410.176	0	0	0	0	0	0	0.073139335
2	Counter	10	9.39	1	55.6	5.921192758	1	55.6	5.921192758	1.064962726
3	Discussion Room	18	22.778	2	111.2	4.881903591	2	111.2	4.881903591	0.790236193
4	Energy Lab	22	90.306	20	1112	12.31368901	15	834	9.23526676	0.24361615
5	Env Eng. Lab	24	151.537	20	1112	7.33814184	10	556	3.66907092	0.158377162
6	Kitchen	6	32.63	0	0	0	0	0	0	0.183879865
7	Librarian's Office	4	22.778	4	222.4	9.763807182	2	111.2	4.881903591	0.175608043
8	Library	60	178.391	10	556	3.116749163	5	278	1.558374582	0.336339838
9	Office - 1	1	7.458	1	55.6	7.455081791	1	55.6	7.455081791	0.134084205
10	Office – 2	1	7.46	1	55.6	7.45308311	1	55.6	7.45308311	0.134048257
11	Office - 3	2	18.06	2	111.2	6.157253599	1	55.6	3.0786268	0.110741971
12	Office - 4	1	7.458	1	55.6	7.455081791	1	55.6	7.455081791	0.134084205
13	Office - 5	1	6.571	1	55.6	8.461421397	1	55.6	8.461421397	0.152183838
14	Office - 6	1	6.569	1	55.6	8.463997564	1	55.6	8.463997564	0.152230172
15	Office - 7	2	6.569	2	111.2	16.92799513	1	55.6	8.463997564	0.304460344
16	Sitting Area	10	51.654	0	0	0	0	0	0	0.193595849
17	Staff Canteen	15	42.691	0	0	0	1	55.6	1.302382235	0.351362114

18	Store - 1	1	8.797	0	0	0	0	0	0	0.113675117
19	Store - 2	1	8.797	0	0	0	0	0	0	0.113675117
20	Students Canteen	35	65.066	0	0	0	1	55.6	0.854516952	0.537915347
21	Telecom Lab	25	91.559	20	1112	12.14517415	15	834	9.108880613	0.27304798
22	Toilet - 1	0	25.125	0	0	0	0	0	0	0
23	Toilet - 2	0	25.125	0	0	0	0	0	0	0
24	Toilet - 3	0	25.593	0	0	0	0	0	0	0
25	Toilet - 4	0	30.566	0	0	0	0	0	0	0
26	Toilet - 5	0	3.624	0	0	0	0	0	0	0
	Total	**270**	**1356.728**	**86**	**4781.6**	**117.8545721**	**59**	**3280.4**	**92.24478202**	**5.731263828**
First Floor (F_1)										
1	Corridor	30	325.334	0	0	0	0	0	0	0.092212926
2	HOD's Office	1	22.984	2	111.2	4.838148277	1	55.6	2.419074139	0.043508528
3	Office – 1	2	11.492	2	111.2	9.676296554	1	55.6	4.838148277	0.174034111
4	Office – 2	2	15.273	2	111.2	7.280822366	1	55.6	3.640411183	0.130950043
5	Office – 3	2	11.492	2	111.2	9.676296554	1	55.6	4.838148277	0.174034111
6	Office – 4	2	12.641	2	111.2	8.796772407	1	55.6	4.398386204	0.158215331
7	Office - 5	2	11.492	2	111.2	9.676296554	1	55.6	4.838148277	0.174034111
8	Office – 6	2	11.492	2	111.2	9.676296554	1	55.6	4.838148277	0.174034111
9	Office – 7	2	11.492	2	111.2	9.676296554	1	55.6	4.838148277	0.174034111
10	Office – 8	1	15.273	1	55.6	3.640411183	1	55.6	3.640411183	0.065475021
11	Office – 9	2	14.925	2	111.2	7.450586265	1	55.6	3.725293132	0.13400335
12	Office – 10	4	15.264	4	222.4	14.57023061	1	55.6	3.642557652	0.262054507
13	Office – 11	1	9.282	1	55.6	5.990088343	1	55.6	5.990088343	0.107735402
14	Office – 12	1	9.282	1	55.6	5.990088343	1	55.6	5.990088343	0.107735402
15	Office – 13	4	15.264	4	222.4	14.57023061	1	55.6	3.642557652	0.262054507
16	Office – 14	1	9.75	1	55.6	5.702564103	1	55.6	5.702564103	0.102564103

17	Office – 15	1	9.56	1	55.6	5.815899582	1	55.6	5.815899582	0.10460251
18	Seminar Room	10	17.928	4	222.4	12.40517626	0	0	0	0.557786702
19	System Admin	2	23.563	6	333.6	14.15778976	4	222.4	9.438526503	0.084878835
20	Store - 1	1	23.563	0	0	0	0	0	0	0.042439418
21	Store - 2	1	11.157	0	0	0	0	0	0	0.089629829
22	Store - 3	1	11.157	0	0	0	0	0	0	0.089629829
23	Studio - 1 (Arch-1)	39	138.75	0	0	0	0	0	0	0.281081081
24	Studio - 2 (Arch – 2)	31	137.32	0	0	0	0	0	0	0.225750073
25	Studio - 3 (Arch – 3)	39	138.75	0	0	0	0	0	0	0.281081081
26	Studio - 4 (Arch – 4)	26	116.374	0	0	0	0	0	0	0.223417602
27	Studio - 5 (Arch – 5)	25	147.372	0	0	0	0	0	0	0.169638737
28	Toilet - 1	0	24.376	0	0	0	0	0	0	0
29	Toilet - 2	0	24.376	0	0	0	0	0	0	0
30	Toilet - 3	0	9.75	0	0	0	0	0	0	0
	Total	**235**	**1356.728**	**41**	**2279.6**	**159.5902909**	**20**	**1112**	**82.2365994**	**4.486615371**
Second Floor (F_2)										
1	Computer Lab	40	140.852	45	2502	17.76332604	10	556	3.947405788	0.283986028
2	Corridor	30	321.529	0	0	0	0	0	0	0.093304181
3	HOD's Office	1	24.875	2	111.2	4.470351759	1	55.6	2.235175879	0.040201005
4	HOD's Office	1	24.875	2	111.2	4.470351759	1	55.6	2.235175879	0.040201005
5	HOD’s Secretary	1	12.437	2	111.2	8.941062957	1	55.6	4.470531479	0.080405242
6	HOD’s Secretary	1	12.437	2	111.2	8.941062957	1	55.6	4.470531479	0.080405242
7	Lecture Rm (Sur - 1)	60	140.839	0	0	0	1	55.6	0.394777015	0.426018361
8	Lecture Rm (Sur - 2)	50	93.902	0	0	0	1	55.6	0.592106664	0.532470022
9	Lecture Rm (Sur - 3)	50	93.901	0	0	0	1	55.6	0.59211297	0.532475692
10	Lecture Rm (Sur - 4)	45	93.901	0	0	0	1	55.6	0.59211297	0.479228123
11	Office – 1	2	12.438	2	111.2	8.940344107	1	55.6	4.470172053	0.160797556

12	Office – 2	2	12.067	2	111.2	9.215215049	1	55.6	4.607607525	0.165741278
13	Office – 3	2	12.067	2	111.2	9.215215049	1	55.6	4.607607525	0.165741278
14	Office – 4	2	12.437	2	111.2	8.941062957	1	55.6	4.470531479	0.160810485
15	Office - 5	2	12.437	2	111.2	8.941062957	1	55.6	4.470531479	0.160810485
16	Office – 6	2	12.437	2	111.2	8.941062957	1	55.6	4.470531479	0.160810485
17	Office – 7	2	12.438	2	111.2	8.940344107	1	55.6	4.470172053	0.160797556
18	Office – 8	2	14.184	2	111.2	7.839819515	1	55.6	3.919909757	0.141003948
19	Office – 9	3	15.264	3	166.8	10.92767296	1	55.6	3.642557652	0.196540881
20	Office - 10	1	9.282	1	55.6	5.990088343	1	55.6	5.990088343	0.107735402
21	Office - 11	1	9.238	1	55.6	6.018618749	1	55.6	6.018618749	0.108248539
22	Office - 12	3	15.264	3	166.8	10.92767296	1	55.6	3.642557652	0.196540881
23	Office - 13	2	14.184	2	111.2	7.839819515	1	55.6	3.919909757	0.141003948
24	Office – 14	2	12.438	2	111.2	8.940344107	1	55.6	4.470172053	0.160797556
25	Office - 15	2	12.437	2	111.2	8.941062957	1	55.6	4.470531479	0.160810485
26	Office - 16	2	12.437	2	111.2	8.941062957	1	55.6	4.470531479	0.160810485
27	Office - 17	2	12.437	2	111.2	8.941062957	1	55.6	4.470531479	0.160810485
28	Office - 18	1	12.578	1	55.6	4.4204166	1	55.6	4.4204166	0.079503896
29	Office - 19	2	12.438	2	111.2	8.940344107	1	55.6	4.470172053	0.160797556
30	Office - 20	2	12.067	2	111.2	9.215215049	1	55.6	4.607607525	0.165741278
31	Office - 21	2	12.067	2	111.2	9.215215049	1	55.6	4.607607525	0.165741278
32	Office - 22	2	12.578	2	111.2	8.840833201	1	55.6	4.4204166	0.159007791
33	Office - 23	1	3.908	1	55.6	14.2272262	1	55.6	14.2272262	0.255885363
34	Office - 24	1	3.908	1	55.6	14.2272262	1	55.6	14.2272262	0.255885363
35	Seminar room	6	17.928	2	111.2	6.20258813	0	0	0	0.334672021
36	Store - 1	1	13.631	0	0	0	0	0	0	0.073362189
37	Store - 2	1	13.631	0	0	0	0	0	0	0.073362189
38	Toilet - 1	0	21.902	0	0	0	0	0	0	0

39	Toilet - 2	0	21.902	0	0	0	0	0	0	0
40	Toilet - 3	0	12.578	0	0	0	0	0	0	0
41	Toilet - 4	0	12.578	0	0	0	0	0	0	0
	Total	**332**	**1356.728**	**100**	**5560**	**268.3167522**	**42**	**2335.2**	**147.0931648**	**6.982465558**
Third Floor (F_3)										
1	Corridor	30	193.68	0	0	0	0	0	0	0.154894672
2	DICTS Office/ Lab	20	502.898	30	1668	3.316775966	15	834	1.658387983	0.039769496
3	HOD - Office	1	24.875	2	111.2	4.470351759	1	55.6	2.235175879	0.040201005
4	HOD's Secretary	1	12.437	2	111.2	8.941062957	1	55.6	4.470531479	0.080405242
5	Lecture room – LE - 4 & QS – 4	73	93.906	0	0	0	0	0	0	0.777373118
6	Lecture room – LE - 3 & QS – 3	75	93.906	0	0	0	0	0	0	0.798671011
7	Lecture room – CM – 3	44	93.907	0	0	0	0	0	0	0.46854867
8	Lobby - 1	5	23.985	0	0	0	0	0	0	0.208463623
9	Lobby - 2	5	23.985	0	0	0	0	0	0	0.208463623
10	Lobby - 3	5	23.985	0	0	0	0	0	0	0.208463623
11	Office – 1	2	12.437	2	111.2	8.941062957	1	55.6	4.470531479	0.160810485
12	Office – 2	2	12.067	2	111.2	9.215215049	1	55.6	4.607607525	0.165741278
13	Office – 3	2	12.067	2	111.2	9.215215049	1	55.6	4.607607525	0.165741278
14	Office – 4	2	12.437	2	111.2	8.941062957	1	55.6	4.470531479	0.160810485
15	Office – 5	2	12.437	2	111.2	8.941062957	1	55.6	4.470531479	0.160810485
16	Office – 6	2	12.437	2	111.2	8.941062957	1	55.6	4.470531479	0.160810485
17	Office – 7	2	12.437	2	111.2	8.941062957	1	55.6	4.470531479	0.160810485
18	Office – 8	2	14.184	2	111.2	7.839819515	1	55.6	3.919909757	0.141003948
19	Office – 9	4	15.264	4	222.4	14.57023061	1	55.6	3.642557652	0.262054507
20	Office – 10	1	9.282	1	55.6	5.990088343	1	55.6	5.990088343	0.107735402

21	Office – 11	2	12.578	2	111.2	8.840833201	1	55.6	4.4204166	0.159007791
22	Office – 12	1	4.81	1	55.6	11.55925156	0	0	0	0.207900208
23	Seminar room	12	17.928	2	111.2	6.20258813	0	0	0	0.669344043
24	Store - 1	1	13.631	0	0	0	0	0	0	0.073362189
25	Store - 2	1	13.631	0	0	0	0	0	0	0.073362189
26	Toilet - 1	0	12.578	0	0	0	0	0	0	0
27	Toilet - 2	0	12.578	0	0	0	0	0	0	0
28	Toilet - 3	0	12.577	0	0	0	0	0	0	0
29	Toilet - 4	0	21.902	0	0	0	0	0	0	0
30	Toilet - 5	0	21.902	0	0	0	0	0	0	0
	Total	**297**	**1356.728**	**60**	**3336**	**134.8667469**	**28**	**1556.8**	**57.90494014**	**5.814559342**
Fourth Floor (F_4)										
1	Board Room	12	43.416	1	55.6	1.280633868	0	0	0	0.276395799
2	Corridor	10	124.298	0	0	0	0	0	0	0.080451817
3	Dean's Office	1	41.6	2	111.2	2.673076923	1	55.6	1.336538462	0.024038462
4	Dean’s Secretary	1	35.412	2	111.2	3.140178471	1	55.6	1.570089235	0.028239015
5	Dep. Dean	1	41.623	2	111.2	2.671599837	1	55.6	1.335799918	0.024025178
6	Dep. Dean	1	43.441	2	111.2	2.559793743	1	55.6	1.279896872	0.023019728
7	Dep. Dean’s Secretary	3	35.412	2	111.2	3.140178471	1	55.6	1.570089235	0.084717045
8	Drivers Office – 1	2	7.862	0	0	0	0	0	0	0.254388196
9	Drivers Office – 2	2	7.862	0	0	0	0	0	0	0.254388196
10	Kitchen	2	4.637	0	0	0	0	0	0	0.431313349
11	Office – 1	1	12.868	1	55.6	4.320795772	1	55.6	4.320795772	0.077712154
12	Office – 2	1	12.868	1	55.6	4.320795772	1	55.6	4.320795772	0.077712154
13	Seminar room – 1	8	19.101	0	0	0	0	0	0	0.418826239
14	Seminar room – 2	8	19.101	0	0	0	0	0	0	0.418826239

15	Store	1	13.631	0	0	0	0	0	0	0.073362189
16	Toilet - 1	0	19.404	0	0	0	0	0	0	0
17	Toilet - 2	0	19.404	0	0	0	0	0	0	0
18	Toilet - 3	0	4.548	0	0	0	0	0	0	0
	Total	**54**	**506.488**	**13**	**722.8**	**24.10705286**	**7**	**389.2**	**15.73400527**	**2.547415762**

Averaged parameters		
Gains from computers w/m^2	**Gains from office equipment w/m^2**	**Occupancy (People/m^2)**
4.860244241	**2.725610287**	**0.176291861**

Appendix D: Model variables for natural ventilation improvement strategies

Table D. 1: Natural ventilation improvement strategies

Strategy	Variable
Case - 1 (Baseline model)	• WWR 30% + Natural ventilation
Case - 2 (Lighting control)	• WWR 30% + Natural ventilation + Lighting control
Case - 3 (Mechanical ventilation – fans only)	• WWR 30% + Natural ventilation + Mechanical ventilation (fans)
Case - 4 (Mechanical ventilation – fans and cooling)	• WWR 30% + Natural ventilation + Mechanical ventilation (cooling)
Case - 5 (Window wall ratio)	• WWR (0% to 100%) + Natural ventilation

Appendix E: General building details and building envelop data (Baseline model)

Table E. 1: General building details

Parameter	Value
Program Version and Build	EnergyPlusDLL-32 7.0.0.036
Weather	UNTITLED
Latitude (deg)	-0.1
Longitude (deg)	34.75
Elevation (m)	1146
Time Zone	3
North Axis Angle (deg)	270
Rotation for Appendix G (deg)	0

Table E. 2: Building envelop data

Parameter	Total	North (315 to 45 deg)	East (45 to 135 deg)	South (135 to 225 deg)	West (225 to 315 deg)
Gross wall area (m^2)	4339.89	1423.01	746.94	1423.01	746.94
Window opening area (m^2)	1282.68	422.08	221.29	422.08	217.23
Window-wall ratio (%)	29.56	29.66	29.63	29.66	29.08

Appendix F: Baseline model simulation results

Table F. 1: Comfort data environmental conditions (Baseline model)

Comfort Data (Environmental Conditions)												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Air temperature (^{0}C)	30.95	30.92	29.81	29.85	29.21	29.48	28.72	29.27	29.68	29.53	29.91	30.83
Radiant Temperature (^{0}C)	31.27	31.2	30.04	30.06	29.56	29.86	29.07	29.57	29.81	29.67	30.19	31.15
Operative Temperature (^{0}C)	31.11	31.06	29.93	29.96	29.38	29.67	28.89	29.42	29.74	29.6	30.05	30.99
Outside Dry-Bulb Temperature (^{0}C)	23.83	24.03	23.18	23.45	22.34	22.05	21.63	22.07	22.92	23.01	23.15	23.43
Relative Humidity (%)	52.18	51.88	57.16	59.63	62.62	57.26	56.61	56.06	53.37	56.8	56.21	54.34

Table F. 2: Comfort data (Time comfort not met) (Baseline model)

Comfort Data (Time Comfort Not Met)												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Discomfort Hours (hrs)	265.19	237.71	257.03	259.6	268.41	247.76	259.62	263.87	238.58	266.21	257.56	257.2

Table F. 3: Predicted thermal comfort sensation (Baseline model)

Predicted Thermal Comfort Sensation												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Fanger PMV	2.26	2.24	1.98	1.65	1.44	1.5	1.2	1.4	1.5	1.88	2	2.24
Pierce PMV ET	2.15	2.14	1.97	1.96	1.86	1.81	1.6	1.74	1.76	1.85	1.97	2.16
Pierce PMV SET	2.62	2.61	2.47	1.77	1.63	1.59	1.37	1.51	1.53	2.36	2.47	2.64
Kansas Uni TSV	1.71	1.71	1.56	1.24	1.12	1.13	0.95	1.05	1.1	1.5	1.58	1.74

Table F. 4: Internal gains (Baseline model)

Internal Gains												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
General Lighting (Wh/m^2)	6480	5760	6240	6240	6480	6000	6480	6480	6000	6480	6240	6240
Computer + Equipment (Wh/m^2)	3177.9	2824.8	3060	3060.2	3177.9	2942.5	3177.9	3177.9	2942.5	3177	3060.2	3060.2
Occupancy (Wh/m^2)	1028.07	913.34	1119.24	1069.66	1240.57	1121.87	1324.47	1252.39	1030.25	1110.52	1076.42	977.47
Solar Gains (Wh/m^2)	7936.92	6602.97	6300.02	6051.28	6999.88	7232.78	7375.3	6906.66	6070.29	6552.06	6819.76	7869.48
Total Latent Load (Wh/m^2)	2289.61	2035.71	2075.57	2125.14	2077.11	1950.05	1993.2	2065.29	2041.67	2207.15	2118.38	2217.33

Table F. 5: Ventilation loads (Baseline model)

Ventilation Energy Loads												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Internal Natural Ventilation (Wh/m^2)	-69.04	-72.75	-91.9	-95.57	-78.73	-86.43	-127.4	-94.13	-71.21	-81.64	-71.13	-51.86
External Air (Wh/m^2)	-8285.4	-7219.3	-7573.7	-7201	-8339.9	-7964	-8498.1	-8140.6	-6609.7	-7115.5	-7619.6	-7874.9

Table F. 6: Fabric and ventilation (Baseline model)

Fabric and Ventilation												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mech Vent + Nat Vent + Infiltration (ac/h)	11.15	13.4	13.14	11.55	9.15	9.5	11.16	10.1	10.99	10.92	12.03	11.3

Table F. 7: Electricity Usage (Baseline model)

Electricity Usage												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lighting (Wh/m^2)	6480	5760	6240	6240	6480	6000	6480	6480	6000	6480	6240	6240
Others (Wh/m^2)	3177.9	2824.8	3060.2	3060.2	3177.9	2942.5	3177.9	3177.9	2942.5	3177.9	3060.2	3060.2
Total Electricity (Wh/m^2)	9657.9	8584.8	9300.2	9300.2	9657.9	8942.5	9657.9	9657.9	8942.5	9657.9	9300.2	9300.2

Table F. 8: Carbon dioxide production (Baseline model)

Carbon dioxide Production												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
CO_2 (kg)	6615.66	5880.59	6370.64	6370.64	6615.66	6125.61	6615.66	6615.66	6125.61	6615.66	6370.64	6370.64

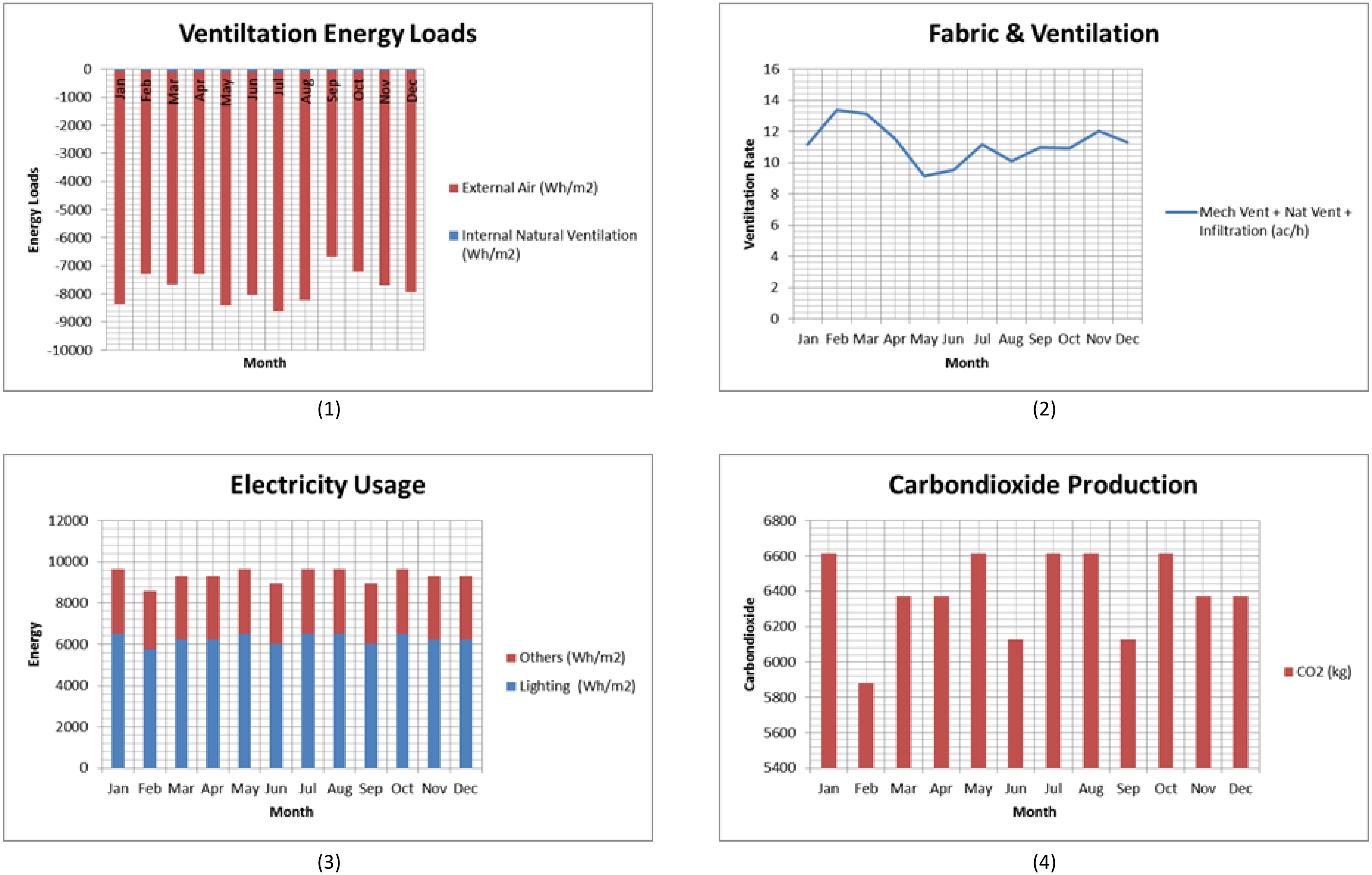


Figure F. 1: (1)-Ventilation energy loads, (2)-Fabric & ventilation, (3)-Electricity usage & (4)-Carbon dioxide production (Baseline Model)

Appendix G: Lighting control model simulation results

Table G. 1: Comfort data environmental conditions (Lighting control)

Comfort Data (Environmental Conditions)												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Air temperature (^{0}C)	30.27	30.24	29.12	29.19	28.53	28.81	28.81	28.57	28.98	28.85	29.26	30.17
Radiant Temperature (^{0}C)	30.43	30.35	29.18	29.22	28.71	29.61	29.01	28.7	28.93	28.81	29.37	30.33
Operative Temperature (^{0}C)	30.35	30.3	29.15	29.2	28.62	28.91	28.15	28.63	28.95	28.83	29.31	30.25
Outside Dry-Bulb Temperature (^{0}C)	23.83	24.03	23.18	23.45	22.34	22.05	21.63	22.07	22.92	23.01	23.15	23.43
Relative Humidity (%)	53.98	54.71	59.43	61.7	64.86	59.29	58.43	57.97	55.47	58.96	58.08	56.21

Table G. 2: Comfort data (Time comfort not met) (Lighting control)

Comfort Data (Time Comfort Not Met)												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Discomfort Hours (hrs)	261.3	235.43	255.48	259.26	268.03	246.88	235.45	259.68	231.85	264.02	256.44	254.99

Table G. 3: Predicted thermal comfort sensation (Lighting control)

Predicted Thermal Comfort Sensation												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Fanger PMV	2.07	2.07	1.79	1.39	1.18	1.24	0.95	1.13	1.23	1.7	1.82	2.06
Pierce PMV ET	2	2.03	1.82	1.81	1.69	1.66	1.44	1.57	1.6	1.7	1.83	2.03
Pierce PMV SET	2.44	2.51	2.33	1.6	1.46	1.43	1.2	1.34	1.37	2.23	2.34	2.52
Kansas Uni TSV	1.59	1.59	1.43	1.07	0.95	0.97	0.78	0.88	0.94	1.37	1.45	1.62

Table G. 4: Internal gains (Lighting control)

Internal Gains												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
General Lighting (Wh/m^2)	2218.67	1969.42	2197.5	2247.43	2336.13	2158.83	2303.33	2304.9	2155.08	2338.06	2250.54	2183.83
Computer + Equipment (Wh/m^2)	3177.9	2824.8	3060	3060.2	3177.9	2942.5	3177.9	3177.9	2942.5	3177	3060.2	3060.2
Occupancy (Wh/m^2)	1118.56	993.58	1200.7	1152.37	1326.05	1200.99	1404.1	1337.98	1115.9	1200.45	1157.04	1062.64
Solar Gains (Wh/m^2)	8032.88	6653.61	6311.24	6056.45	7002.58	7224.79	7372.75	6912.57	6074.6	6581.77	6892.23	7971.94
Total Latent Load (Wh/m^2)	2199.12	1955.47	1994.1	2042.43	1991.63	1870.94	1913.58	1979.7	1956.02	2117.28	2037.76	2132.16

Table G. 5: Ventilation loads (Lighting control)

Ventilation Energy Loads												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Internal Natural Ventilation (Wh/m^2)	-50.32	-57.92	-73.43	-76.34	-66.42	-70.75	-106.16	-73.25	-50.87	-62.92	-62.92	-38.81
External Air (Wh/m^2)	-5734.4	-4943.4	-5095.2	-4779.3	-5783.9	-5565.9	-5909.9	-5574.4	-4318	-4647.9	-5203.7	-5456.7

Table G. 6: Fabric and ventilation (Lighting control)

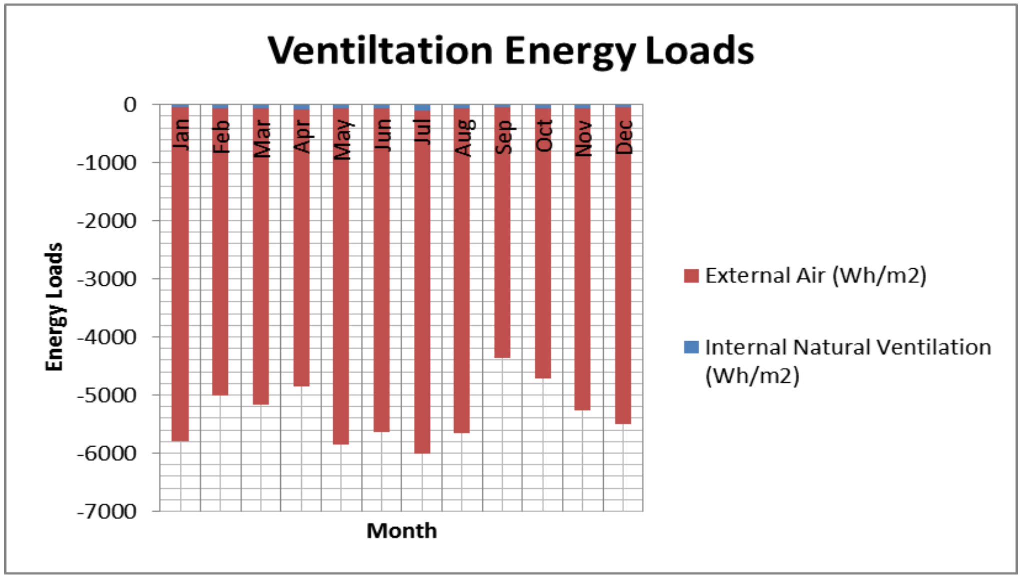
Fabric and Ventilation												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mech Vent + Nat Vent + Infiltration (ac/h)	10.6	12.64	12.57	11.06	8.79	9.14	10.69	9.57	10.07	10.17	11.6	10.85

Table G. 7: Electricity Usage (Lighting control)

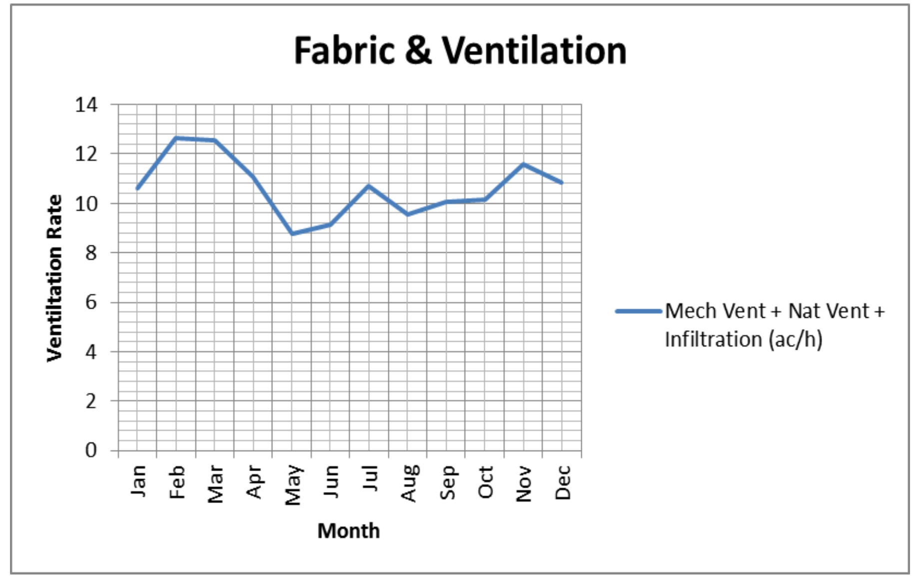
Electricity Usage												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lighting (Wh/m^2)	2218.6	1969.42	2197.5	2247.43	2336.13	2158.83	2303.33	2304.9	2155.08	2338.06	2550.54	2183.83
Others (Wh/m^2)	3177.9	2824.8	3060.2	3060.2	3177.9	2942.5	3177.9	3177.9	2942.5	3177.9	3060.2	3060.2
Total Electricity (Wh/m^2)	5396.5	4794.22	5257.7	5307.63	5514.03	5101.33	5481.23	5482.8	5097.58	5515.96	5610.74	5244.03

Table G. 8: Carbon dioxide production (Lighting control)

Carbon dioxide Production												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
CO2 (kg)	3696.65	3284.04	3601.53	3635.73	3777.11	3494.41	3754.64	3755.72	3491.84	3778.48	3637.86	3592.16



(1)



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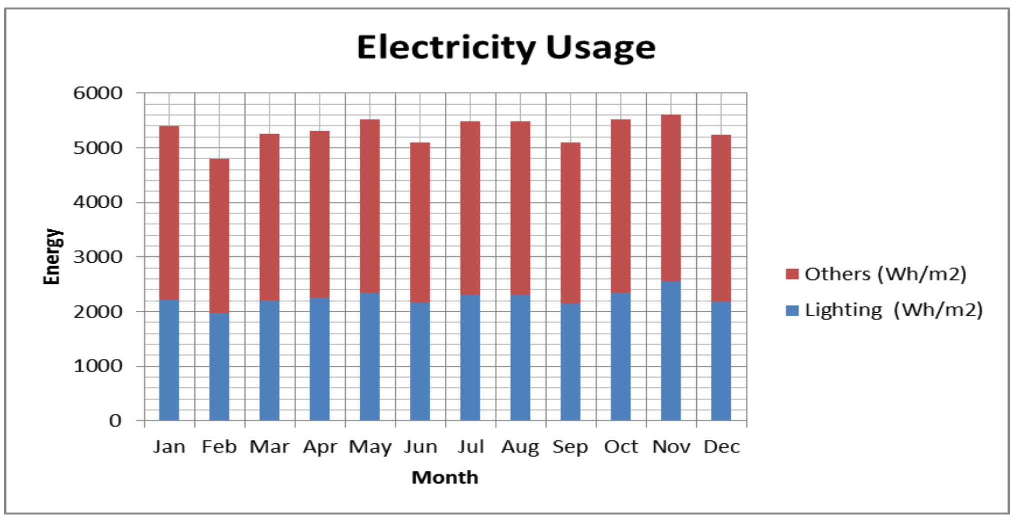

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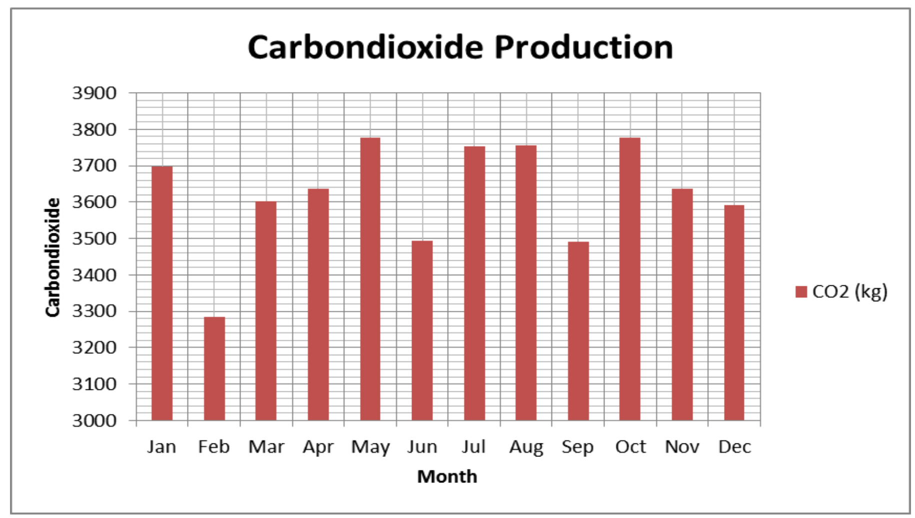


(4)

Figure G. 1: (1)-Ventilation energy loads, (2)-Fabric & ventilation, (3)-Electricity usage & (4)-Carbon dioxide production (Lighting control)

Appendix H: Mechanical ventilation (Fans) model simulation results

Table H. 1: Comfort data environmental conditions (Mechanical ventilation -Fans)

Comfort Data (Environmental Conditions)												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Air temperature (^{0}C)	30.32	30.31	29.21	29.26	28.58	28.86	28.11	28.61	29.08	28.96	29.32	30.23
Radiant Temperature (^{0}C)	30.93	30.87	29.71	29.74	29.2	29.05	28.73	29.2	29.46	29.35	29.86	30.81
Operative Temperature (^{0}C)	30.62	30.59	29.46	29.5	28.89	29.18	28.42	28.9	29.27	29.15	29.59	30.52
Outside Dry-Bulb Temperature (^{0}C)	23.83	24.03	23.18	23.45	22.34	22.05	21.63	22.07	22.92	23.01	23.15	23.43
Relative Humidity (%)	46.06	45.58	52.11	55.01	58.75	52.8	51.62	50.96	47.93	51.91	51.12	49.43

Table H. 2: Comfort data (Time comfort not met) (Mechanical ventilation-Fans)

Comfort Data (Time Comfort Not Met)												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Discomfort Hours (hrs)	264.28	237.16	256.96	259.54	268.32	247.68	258.81	263.34	237.5	266	257.44	256.89

Table H. 3: Predicted thermal comfort sensation (Mechanical ventilation-Fans)

Predicted Thermal Comfort Sensation												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Fanger PMV	2	1.99	1.75	1.38	1.17	1.22	0.93	1.1	1.21	1.66	1.77	2.1
Pierce PMV ET	1.64	1.64	1.54	1.58	1.5	1.44	1.23	1.33	1.36	1.45	1.55	1.73
Pierce PMV SET	2.19	2.19	2.1	1.36	1.25	1.19	0.97	1.08	1.11	2.01	2.11	2.28
Kansas Uni TSV	1.7	1.71	1.55	1.2	1.07	1.08	0.89	0.99	1.05	1.48	1.57	1.73

Table H. 4: Internal gains (Mechanical ventilation-Fans)

Internal Gains												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
General Lighting (Wh/m^2)	6480	5760	6240	6240	6480	6000	6480	6480	6000	6480	6240	6240
Computer + Equipment (Wh/m^2)	3177.9	2824.8	3060	3060.2	3177.9	2942.5	3177.9	3177.9	2942.5	3177	3060.2	3060.2
Occupancy (Wh/m^2)	1070.4	948.89	1156.73	1108.19	1287.65	1163.94	1373.62	1295.42	1064.91	1154.46	1114.48	1015.26
Solar Gains (Wh/m^2)	7936.92	6602.97	6300.02	6051.28	6999.88	7232.78	7375.3	6906.66	6070.29	6662.06	6819.76	7889.48
Zone Sensible Heating (Wh/m2)	0.5	0.54	0.09	0.03	0.003	0.03	0.01	0.1	0.39	0.34	0.14	0.21
Zone Sensible Cooling (Wh/m2)	-1370.4	-1180.9	-1273.8	-1249.6	-1420.6	-1323.6	-1382.2	-1434.2	-1205.9	-1250.7	-1245.4	-1299.7
Total Latent Load (Wh/m^2)	2247.28	2000.16	2038.07	2086.61	2030.03	1907.98	1944.06	2022.26	2007.01	2163.22	2080.32	2179.54

Table H. 5: Ventilation loads (Mechanical ventilation-Fans)

Ventilation Energy Loads												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Internal Natural Ventilation (Wh/m^2)	-62.35	-67.33	-84.35	-88.29	-73.19	-80.53	-119.17	-88.04	-65.78	-74.88	-65.18	-48.45
External Air (Wh/m^2)	-7801.7	-6807.8	-7133.1	-6766	-7808.5	-7472.4	-7980	-7625.7	-7625.7	-6202.2	-7170.4	-7405.8

Table H. 6: Fabric and ventilation (Mechanical ventilation-Fans)

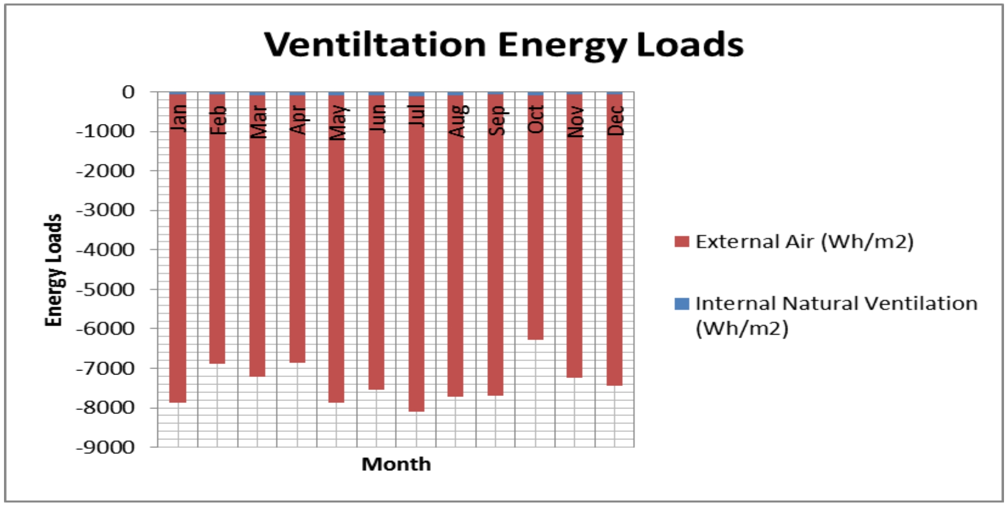
Fabric and Ventilation												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mech Vent + Nat Vent + Infiltration (ac/h)	11.56	13.81	13.55	11.96	9.56	9.9	11.57	10.5	11.37	11.33	12.45	11.71

Table H. 7: Electricity Usage (Mechanical ventilation-Fans)

Electricity Usage												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lighting (Wh/m^2)	6480	5760	6240	6240	6480	6000	6480	6480	6000	6480	6240	6240
Others (Wh/m^2)	3177.9	2824.8	3060.2	3060.2	3177.9	2942.5	3177.9	3177.9	2942.5	3177.9	3060.2	3060.2
Total Electricity (Wh/m^2)	9657.9	8584.8	9300.2	9300.2	9657.9	8942.5	9657.9	9657.9	8942.5	9657.9	9300.2	9300.2

Table H. 8: Carbon dioxide production (Mechanical ventilation-Fans)

Carbon dioxide Production												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
CO2 (kg)	6615.66	5880.59	6370.64	6370.64	6615.66	6125.61	6615.66	6615.66	6125.61	6615.66	6370.64	6370.64



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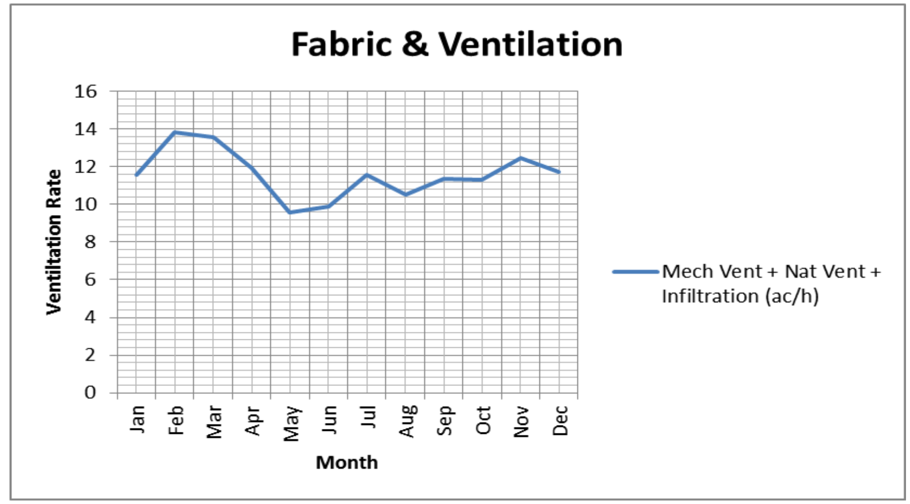

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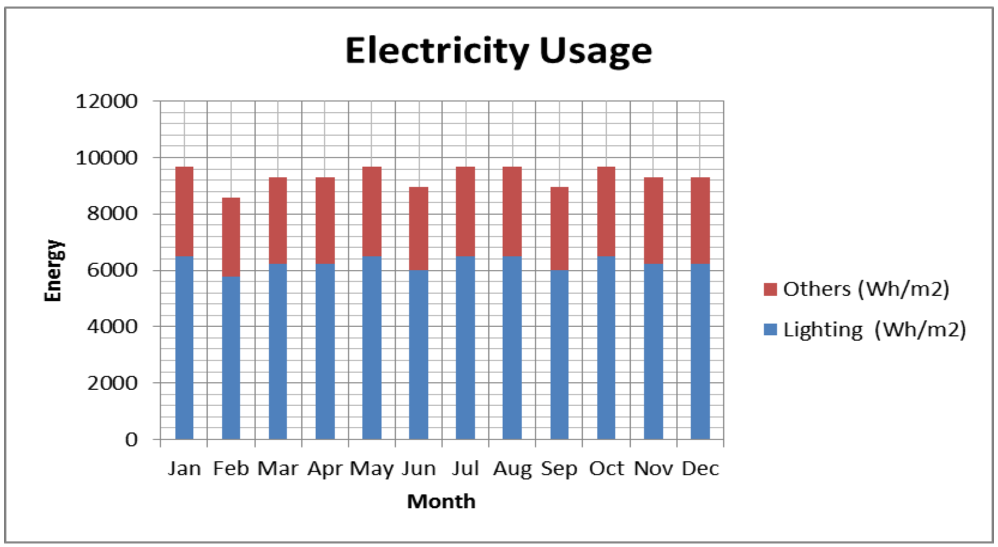

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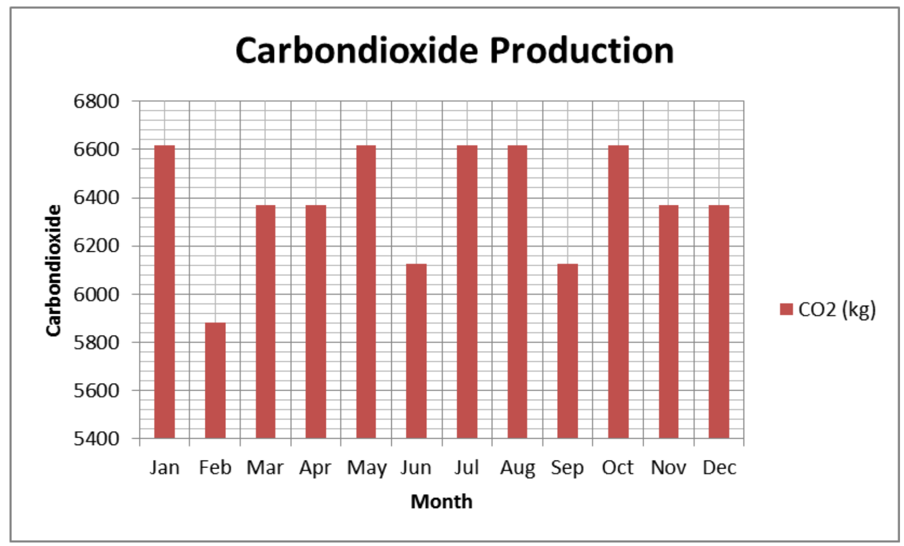

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Figure H. 1: (1)-Ventilation energy loads, (2)-Fabric & ventilation, (3)-Electricity usage & (4)-Carbon dioxide production (Mechanical ventilation - Fans)

Appendix I: Mechanical ventilation (with cooling) model simulation results

Table I. 1: Comfort data environmental conditions (Mechanical ventilation - Cooling)

Comfort Data (Environmental Conditions)												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Air temperature (^{0}C)	24.08	24.11	23.92	23.76	23.64	23.63	23.47	23.58	23.69	23.57	23.81	24.05
Radiant Temperature (^{0}C)	26.38	26.32	25.84	25.76	25.63	25.66	25.41	25.59	25.58	25.5	25.86	26.26
Operative Temperature (^{0}C)	25.23	25.21	24.88	24.76	24.63	24.65	24.44	24.59	24.64	24.53	24.84	25.15
Outside Dry-Bulb Temperature (^{0}C)	23.83	24.03	23.18	23.45	22.34	22.05	21.63	22.07	22.92	23.01	23.15	23.43
Relative Humidity (%)	54.54	54.66	59.59	61.37	63.11	59.94	60.14	59.62	58.14	61.05	58.99	56.28

Table I. 2: Comfort data (Time comfort not met) (Mechanical ventilation-- Cooling)

Comfort Data (Time Comfort Not Met)												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Discomfort Hours (hrs)	103.32	119.05	193.1	204.8	230.65	163.1	194.05	186.07	137.04	189.01	177.82	133.93

Table I. 3: Predicted thermal comfort sensation (Mechanical ventilation - Cooling)

Predicted Thermal Comfort Sensation												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Fanger PMV	0.59	0.58	0.54	-0.34	-0.4	-0.42	-0.49	-0.44	-0.43	0.46	0.52	0.58
Pierce PMV ET	0.46	0.46	0.45	0.44	0.43	0.41	0.36	0.39	0.39	0.39	0.43	0.47
Pierce PMV SET	1.1	1.09	1.09	0.2	0.16	0.13	0.09	0.11	0.11	1.03	1.07	1.1
Kansas Uni TSV	0.52	0.52	0.52	-0.08	-0.1	-0.1	-0.14	-0.12	-0.13	0.39	0.45	0.52

Table I. 4: Internal gains (Mechanical ventilation - Cooling)

Internal Gains												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
General Lighting (Wh/m^2)	6480	5760	6240	6240	6480	6000	6480	6480	6000	6480	6240	6240
Computer + Equipment (Wh/m^2)	3177.9	2824.8	3060	3060.2	3177.9	2942.5	3177.9	3177.9	2942.5	3177	3060.2	3060.2
Occupancy (Wh/m^2)	2361.76	2092.87	2243.08	2242.18	2336.81	2185.71	2344.44	2340.23	2152.66	2322.5	2249.82	2276.49
Solar Gains (Wh/m^2)	7936.92	6602.97	6300.02	6051.28	6999.88	7232.78	7375.33	6906.66	6070.29	6552.06	6819.76	7869.48
Zone Sensible Heating (Wh/m2)	16.28	19.36	14.63	4.66	13.37	17.37	41.96	25.95	5.57	12.6	2.88	3.88
Zone Sensible Cooling (Wh/m2)	-19201	-16777	-16204	-16481	-16688	-16111	-15854	-16374	-15436	-16308	-16924	-18566
Total Latent Load (Wh/m^2)	955.92	856.7	951.72	952.62	980.87	886.22	973.28	977.45	919.26	995.18	944.98	918.31

Table I. 5: Ventilation loads (Mechanical ventilation - Cooling)

Ventilation Energy Loads												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Internal Natural Ventilation (Wh/m^2)	-5.93	-3.7	-4.52	-3.36	-3.28	-2.79	-8.41	-7.69	-3.42	-5.1	-4.22	-2.92
External Air (Wh/m^2)	-465.6	-308.78	-308.78	-167.17	-384.06	-537.94	-938.06	-698.85	-226.4	-356.3	-121.49	-165.55

Table I. 6: Fabric and ventilation (Mechanical ventilation- Cooling)

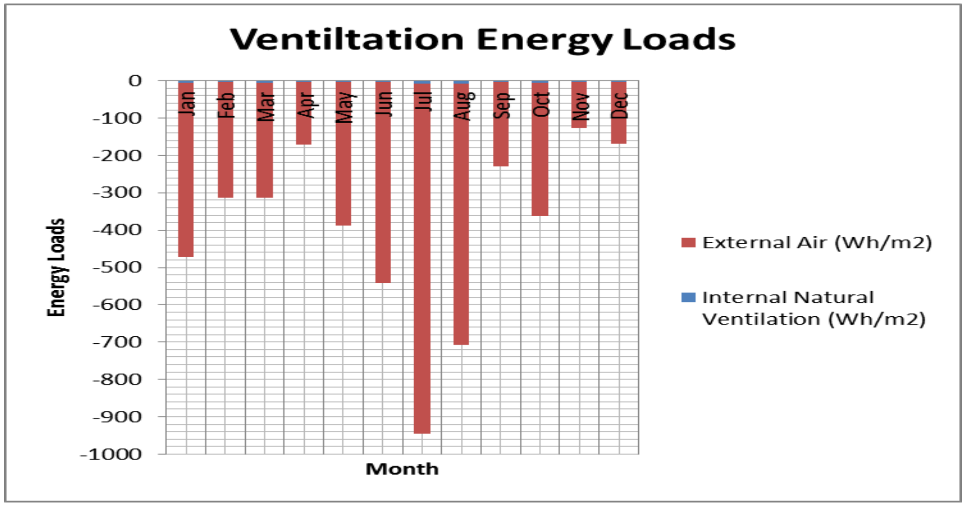
Fabric and Ventilation												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mech Vent + Nat Vent + Infiltration (ac/h)	1.11	0.85	0.91	0.88	1	1.15	1.44	1.24	0.86	0.99	0.73	0.63

Table I. 7: Electricity Usage (Mechanical ventilation- Cooling)

Electricity Usage												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lighting (Wh/m^2)	6480	5760	6240	6240	6480	6000	6480	6480	6000	6480	6240	6240
System pumps (Wh/m^2)	1027.46	913.3	989.41	989.41	1027.46	951.35	1027.46	1027.46	951.35	1027.46	989.41	989.41
Chiller (Wh/m^2)	4407.32	3915.25	3884.59	4010.69	4085.73	3759.7	3751.89	3875.38	3569.56	3919.2	3947.35	4253.97
Heat rejection (Wh/m^2)	201.6	187.93	191.05	206.3	206.52	174.38	159.07	168.68	155.36	182.61	189.34	207
Others (Wh/m^2)	3177.9	2824.8	3060.2	3060.2	3177.9	2942.5	3177.9	3177.9	2942.5	3177.9	3060.2	3060.2
Total Electricity (Wh/m^2)	15294.3	13601.3	14365.3	14506.6	14977.6	13827.9	14596.3	14729.4	13618.8	14787.2	14426.3	14750.6

Table I. 8: Carbon dioxide production (Mechanical ventilation- Cooling)

Carbon dioxide Production												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
CO_2 (kg)	10476.6	9316.88	9840.19	9937.02	10259.7	9472.14	9998.47	10089.7	9328.86	10129.2	9882.02	10104.2



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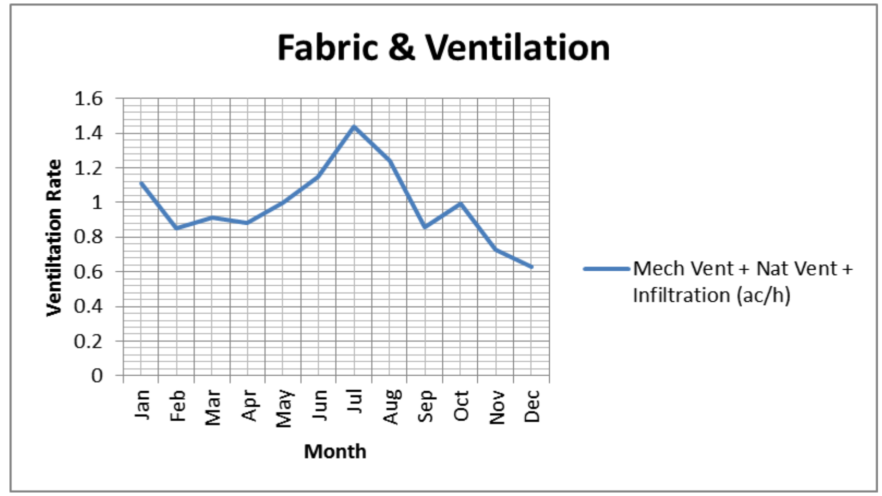

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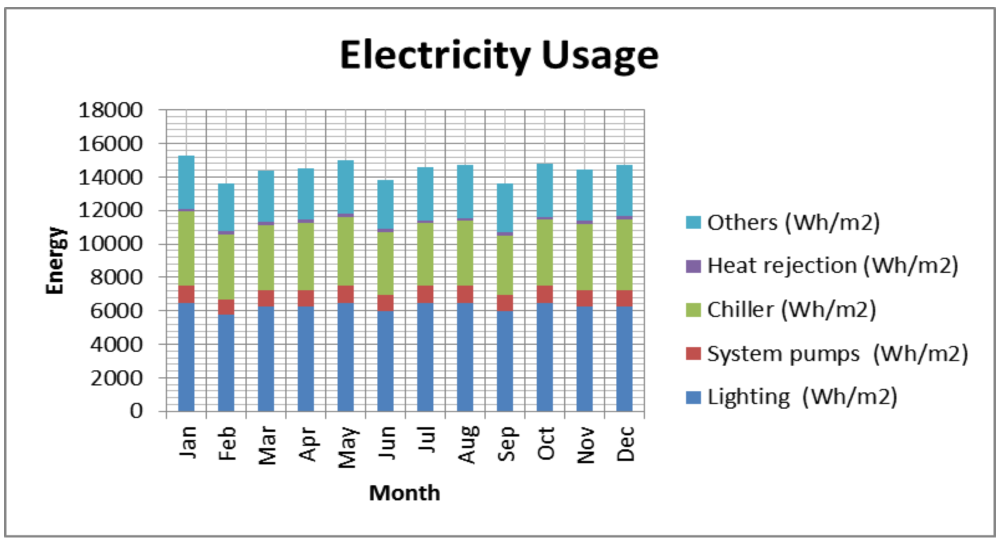

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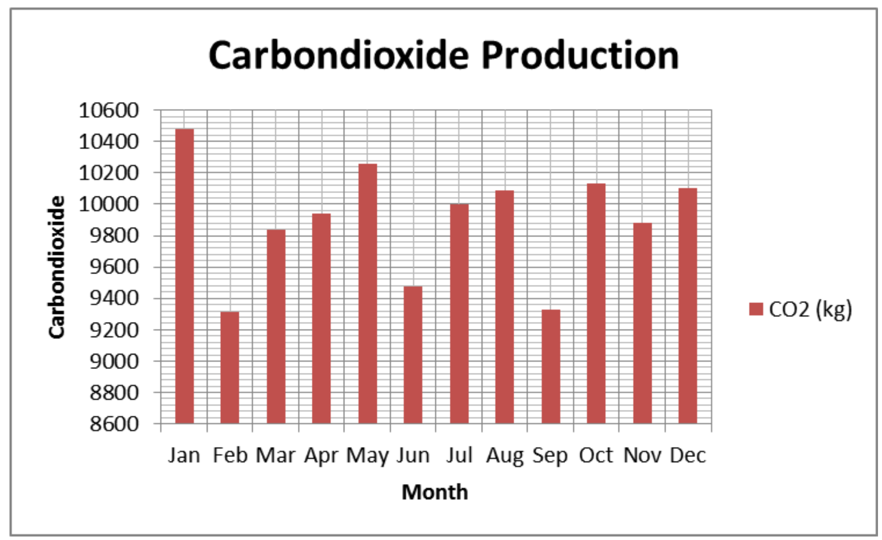

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Figure I. 1: (1)-Ventilation energy loads, (2)-Fabric & ventilation, (3)-Electricity usage & (4)-Carbon dioxide production (Mechanical ventilation - Cooling)