STUDY OF HOSPITAL BUILDING ENVELOPE TO FACILITATE PASSIVE COOLING INSIDE INPATIENT ROOMS IN THE CONTEXT OF RAJSHAHI, BANGLADESH

By

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The thesis titled 'STUDY OF HOSPITAL BUILDING ENVELOP TO FACILITATE PASSIVE COOLING INSIDE IN-PATIENT ROOMS IN THE CONTEXT OF RAJSHAHI, BANGLADESH' Submitted by Md. Sabbir Ahsan, Roll No- 0411012026 P, Session- April 2011, has been accepted as satisfactory in partial fulfillment of the requirements for the Degree of MASTER OF ARCHITECTURE on this day 29 March 2017.

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Signature:

Md. Sabbir Ahsan

DEDICATED TO MY PARENTS
Md. Ali Ahsan & Shamima Ahsan

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To my students who extend their myriad helping hand in collecting the vital data for research in my time of need.

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ABSTRACT

Depletion of biofuel at an increasing rate coupled with global warming give rise to the necessity of energy conservation as well as to search for alternative sources of energy. The particular importance on building is of pivotal importance because building on the face of planet is responsible for the consumption of almost half of the energy that is produced worldwide, most of which is used to maintain desired indoor artificial environment.

The environment of Bangladesh alongside with the other parts of the world moving towards extremities. North-Western part of Bangladesh is worst case scenario in this aspect. Maintaining thermal comfort inside inpatient room using mechanical means is expensive, energy intensive, and thus impractical. Adding to this already miserable condition Bangladesh is not self-sufficient in energy sector. Considering all these factor, this research would made an attempt to facilitate passive cooling inside inpatient room in the context of Rajshahi (a district and division of Bangladesh) through parametric study of hospital building envelope.

This research is a quantitative in nature. Literature review provided an overall frame work for the research, followed by field survey to obtain raw data and then OpenStudio plug-in in SketchUp was used to produce three dimensional model to simulate envelope condition for parametric study in EnergyPlus simulation engine.

The findings indicate a correlation exists between building envelope condition and thermal comfort. Hence an opportunity to provide passive cooling is a possibility inside inpatient room of hospital building.

It is expected that finding and expectation from this research for envelope condition will improve the thermal environment of inpatient room of hospital building and provide condition for thermal comfort to achieve the well-being of patients and the staff as well. It will also help in conserving energy for cooling purpose.

KEYWORDS

Building Envelope, Passive cooling, Inpatient room

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ABBREVIATIONS

ASHRAE:	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BNBC:	Bangladesh National Building Code
MRT:	Mean Radiant Temperature
AT:	Air Temperature
OP:	Operative Temperature
STD:	Standard Deviation
EP:	EnergyPlus
OS:	OpenStudio
PDF:	Probability Density Function
RH:	Relative Humidity
BMD:	Bangladesh Meteorological Department
DBT:	Dry Bulb Temperature
WBT:	Wet Bulb Temperature
Met:	Metabolic Rate
IGBC:	Indian Green Building Council
CIBSE:	Chartered Institute of Building Services Engineers

1 CHAPTER ONE: PREAMBLE

Background

Statement of the Problem

Aims and Objectives of the Study

Overview of the research methodology

Scope and Limitation

Structure of the research

Key findings

1.1 Background

During the course of its life buildings use high energy compared to other sectors, such as transportation and production. Buildings throughout the planet are responsible for the consumption of almost half of the energy produced. Most of this energy in buildings is used for lighting, heating, ventilation and air conditioning. Due to technological advancement and energy saving measures, many countries in the developed world greatly improved the performance of the buildings, especially in the heating sector. However in other parts of the world where cooling is of major concern especially in the hot humid, warm humid region; higher standard of life, availability of air conditioning and globalization of modern architecture promoted increased energy usage (Santamouris and kolokotsa, 2013).

The goal is now set as optimization of energy usage wherever possible, as it is one of the major contributors to global warming. Large buildings and business centers are given priorities because of their size, functional complexity and special requirements for microclimatic control inside the building. Despite its size, huge energy consumption due to its unique operational requirements and opportunities for savings hospitals have long been neglected in this regard. Hospitals are complex buildings and require years to plan, design and implement. If it can be planned and designed properly at its early stage by applying energy saving measures, then not only will it save energy in long term, but it will also provide healthier and comfortable indoor environment to the patients and staff (Congradac et al., 2012; Wu, 2011).

In recent years the shortage of conventional energy sources coupled with environmental concerns is forcing to rethink passive heating and cooling methods to achieve comfort condition, or at least reduce the load to assist mechanical systems. Therefore passive heating and cooling is now reaching a phase of maturity. Passive cooling is the use of techniques involving solar and heat gain control, heat modulation and finally heat dissipation to heat sinks , and it is done without energy usage other than renewable sources (Santamouris and kolokotsa, 2013; Geetha and Velraj, 2012). The effectiveness of passive cooling techniques depends on the site, climate, building type, occupants' behavior and expectation for comfort.

Rajshahi a major city, located in the western part of Bangladesh has a climate with hot and dry condition compared to other parts of the country, for example Dhaka, Chittagong and Khulna (Ahmed, 1995). Hospitals in this region therefore can be an appropriate case for applying passive cooling techniques to achieve thermal comfort and reduce energy consumption. Due to complex functional nature of the hospitals and their unique indoor environmental requirement, spaces that require rigorous control of temperature, humidity and pressure are avoided and for this reason this study only focuses on more flexible environments such as inpatient rooms with natural ventilation in order to facilitate passive cooling techniques.

1.2 Statement of the Problem

In view of the global climate change, future summers are going to be hot and dry and extreme temperature events are going to occur more frequently. The percentage of inpatient rooms equipped with mechanical cooling or air conditioning systems in Bangladesh are relatively low due to installation cost, operational cost, affordability of the patients, and energy shortage. A greater percentage of inpatient rooms are naturally ventilated and patients rely on fans and operable window to achieve comfort condition in the summer time. Considering the hot dry condition of Rajshahi, the likelihood of overheating of inpatient rooms during summers are very high. Especially during periods of hot spells hospital wards are expected to provide shelter for the patients, who are in vulnerable condition and susceptible to serious health hazards. Therefore, the thermal comfort is of utmost importance during both typical and extreme weather conditions, to assist the recovery process of the patient and to provide comfortable working environment to its normal healthy occupants, e.g. hospital staffs and visitors. It would not be wise to encourage, the installation of mechanical cooling indiscriminately as it is expensive, energy intensive and aggravates the climate change problem by increasing energy demand (Lomas and Giridharan, 2012). Energy demand aside, mechanical cooling is often responsible for indoor air quality problems if not regularly maintained. Condensate trays and cooling coils contamination, fungal and mould growth in fans, air contamination due to dirty filters are some of the causes of air quality problem (Santamouris and kolokotsa, 2013)**.** Particularly hospitals in Bangladesh are susceptible to this kind of air contamination from mechanical cooling and ventilation because in many cases buildings are retrofitted later with HVAC system while maintenance and servicing work is not done regularly.

Inpatients rooms are occupied 24 hours a day with diverse occupants having different comfort criteria. Of them most sensitive are the highly vulnerable patients usually with a short stay, but nurse and doctor though having greater tolerance, have to work for a longer period of time (Lomas and Giridharan, 2012)**.** Lack of adequate number of hospital beds, insufficient healthcare facility, the crisis become compounded during summer time when patient travel from rural area for secondary and tertiary level medical care.

In spite of these facts there have been very few studies on environments of hospital building in Bangladesh i.e. lighting (Joarder, 2011), hardly any study concentrates on impact of building Envelope on thermal environment of hospital and potential application of passive cooling inside inpatient room. Unlike the Energy Conservation Building Code (ECBC) and the Bureau of Energy Efficiency (BEE) in India, it is difficult to find any detailed guidelines about energy consumption, building envelope, mechanical systems and equipment, including heating, ventilation and air-conditioning system, lighting and thermal comfort criteria from Bangladesh National Building Code (HBRI and BSTI, 2006) or other published documents in context of Bangladesh.

The unique functionality and components of building envelope connect internal environment with the external environment hence offer an opportunity to incorporate passive cooling in building in order to achieve thermal comfort condition. Thus a detailed parametric study using simulation model can reveal the possibility and potential of facilitating passive cooling inside in-patient rooms in particular context of Rajshahi, Bangladesh.

1.3 Aims and Objectives of the Study

The aim, objective and methodology of this study were developed considering problem discussed above. This study aims to investigate building envelope of a hospital using simulation tools and parametric study to facilitate passive cooling inside inpatient room in the context of Rajshahi and to develop guidelines for implementation of those techniques to save energy for cooling purpose and improve thermal comfort inside hospital buildings. To achieve this aim following three objectives have been developed.

Objectives 1: To understand scopes and applications of passive cooling techniques for hospital building.

Objectives 2: To compare different passive cooling techniques in order to incorporate in hospital building design in the climatic context of Rajshahi.

Objectives 3: To identify parametric combination and configuration of envelope condition to facilitate passive cooling and to maximize comfort and minimize energy consumption.

1.4 Overview of the research methodology

A detailed description of the research methodology, used for this research, has been discussed in Chapter 3. This section provides a brief overview of the research methodology for the thesis. Figure 1.1 shows a flow diagram of the research process, which integrates the main research methods: literature review, case study and simulation analysis.

The research started with a literature review to gather knowledge and information on the different types of passive cooling techniques and their applications; existing thermal condition of hospital inpatient rooms; envelope materials and construction techniques; national and international standards and guidelines for hospital envelope design; and climate of Rajshahi to understand the appropriate passive cooling technique that can be implemented to the envelope of hospital building to provide thermal comfort to the patient.

Four inpatient rooms were selected from Rajshahi Medical college hospital wards for physical survey based on specific criteria (Section 3.2.2). Measurement of thermal comfort from patient survey; construction and materials of wall, floor, ceiling/roof window and shading device; lintel height, sill height, occupancy type and number of people and schedule of occupancy; number and types of electrical equipment and their schedule of usage; detail observations and related information were collected from these four inpatient rooms. From the four inpatient rooms, the most suitable one was selected as case inpatient room, for simulation.

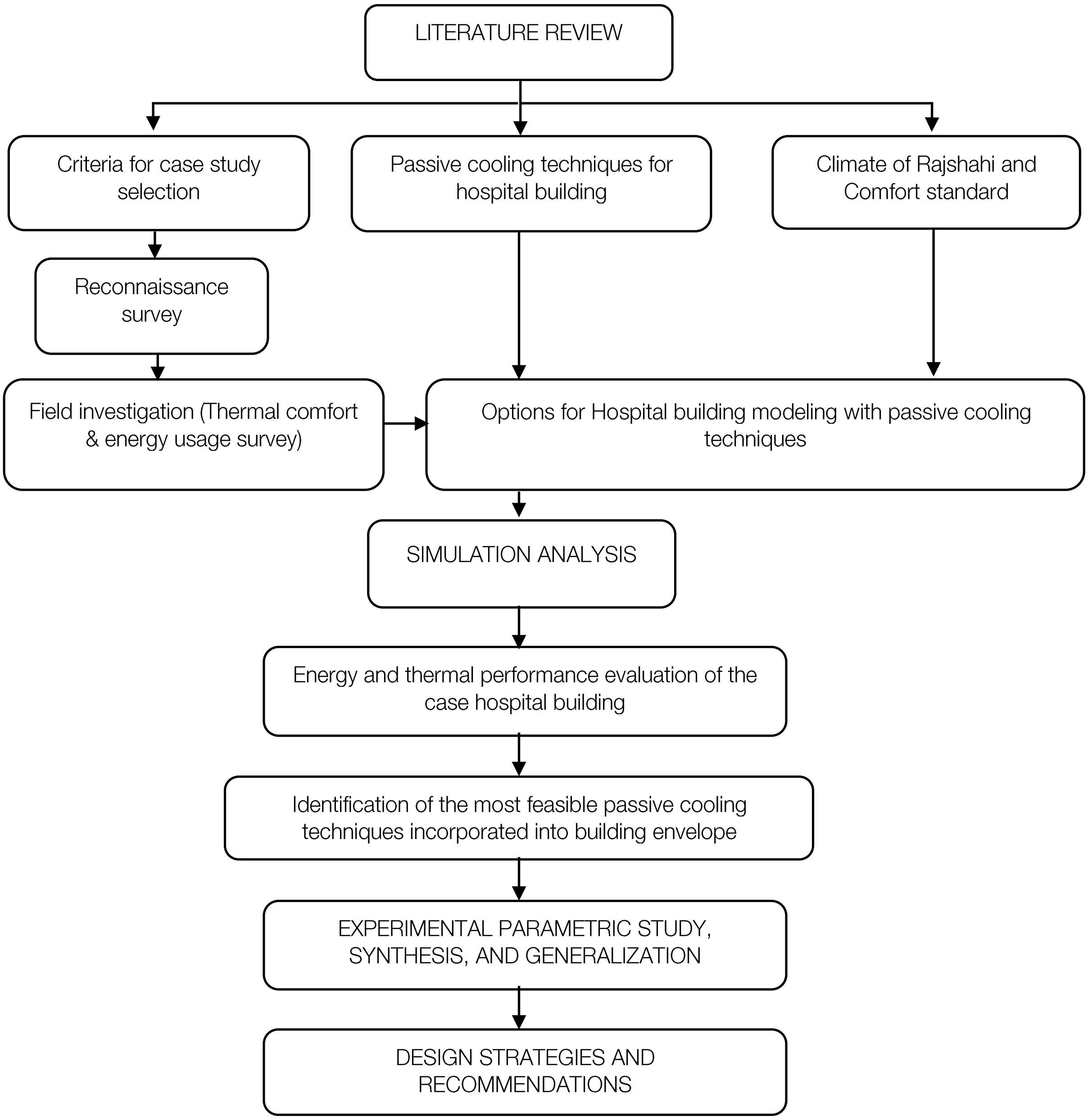

Figure 1.1 Structure of the research work

Through literature study and field survey it was found that, from the three tiers passive cooling methods and the wide array of techniques under each tier, the 1st tier - heat prevention can be achieved by microclimatic and solar control. Planners, architects and engineers generally deploy this techniques fairly and effectively. The 2nd tier involves heat modulation and 3rd tier deals with heat dissipation. It is the 2nd and 3rd tier where due to lack of up-to-date practical research and data, particularly in Bangladesh professionals working in built environment design are not confident enough to apply in practice and unlike developed countries are lagging behind. Therefore, in this study the 2nd tier – heat modulation and amortization techniques through building envelope study and simulation were conducted to find out the most effective one for the case of cooling inside inpatient room of hospital buildings. This study also sets scope for further study i.e. 3rd tier passive cooling techniques of dissipating heat to the surrounding environment.

1.5 Scope and Limitation

This research work focuses on performance evaluation of various construction types, of building envelope and material, to facilitate passive cooling inside inpatient rooms of hospitals under the climatic context of Rajshahi region. Five elements of the building envelope i.e. walls, windows, doors, floors and roofs have been considered for the research study. Characteristics of various local materials and their construction assemblies have been included from previous study and published standards.

Some degree of uncertainty has been presented in the data collections during field investigation due to air flow from ceiling fan. However given the limited time and scope of study, this research has concentrated on the inclusion of passive cooling techniques and the improvement of thermal condition only. Measurement of recovery rate of the patients and performance of hospital staff regarding HVAC system, heating, cooling, ventilation, lighting issues, acoustics, insulation, safety and security are beyond the scope of this research.

1.6 Structure of the research

This thesis is structured into six chapters. This Section provides an overview of each of the following chapters.

Chapter 1 is an introduction to the thesis; describes subjects that might be necessary for understanding this research, problem statement with the aim, objectives, brief methodology and limitations.

Chapter 2 provides the outcome of the literature review, based on established research and published sources, to provide a knowledge base for this research, which helped to focus on the issues on which the simulation is conducted later.

Chapter 3 describes the detailed steps of the methodology for field study and simulation for this research. This chapter also describes the criteria of the selection of the case space for simulation study. This chapter describes the existing thermal condition measured with thermo-anemometer and thermo-hygrometer to use as input for simulation engine to simulate thermal environment. This chapter provides the detailed description and methodology of the simulation exercise. At first the simulation process is described then parameters of the simulation and output variables are outlined in this chapter.

Chapter 4 discusses the results of the field survey and simulation of the envelop type in terms of the variables. It also compares and analyses the result for incorporation of passive cooling through building envelope of inpatient rooms of hospital building.

Chapter 5 summarizes the findings of the whole research. This chapter also provides recommendations for incorporation of passive cooling into building envelope of inpatient rooms of hospital building. The work ends by identifying research areas that need further investigation subsequent to this study Figure 1.2 shows the structure of the thesis with organization of the chapters.

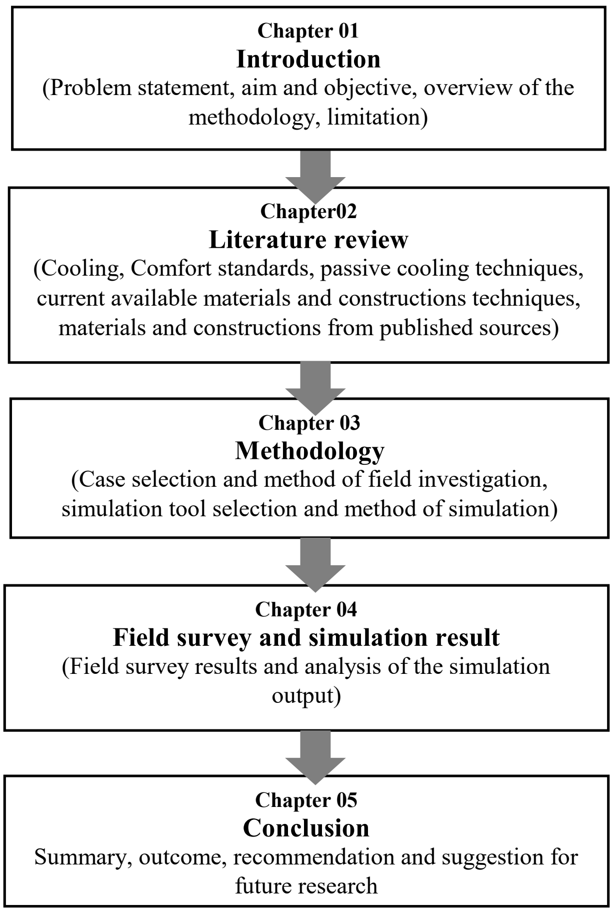

Figure 1.2 Organization of the chapters and structure of the thesis

1.7 Key findings

The research started to overcome some constraints mentioned in section 1.2. With the gradual development of the research from the literature review and incorporation of research findings at each stage made objectives, methodology and limitation of the research more defined, refined and detailed.

Table 1.1 presents a summary of the key findings of the research in relation to the objectives, methodologies and concerned chapters.

Table 1.1 Summary of the key findings of the research in relation to the objectives, methodologies and concerned chapters.

Objective	Method	Chapter	Key findings
Objective 1: To understand scopes and applications of passive cooling techniques for hospital building.	Literature review	Chapter 2	Passive cooling techniques can be broadly categorized into three tiers when applying them in building. The 1st tier involves heat gain protection, 2nd tier heat gain modulation and 3rd tier heat dissipation.
Objective 2: To compare different passive cooling techniques in order to incorporate in hospital building design in the climatic context of Rajshahi.	Literature review	Chapter 2	The 1st tier techniques can be easily deployed through microclimatic and solar control for any type of buildings. But the 2nd and 3rd tier techniques cannot be deployed easily as these techniques depend on climate, building and construction type, hence to utilize these techniques in hospital detailed study is required for the climatic context of Rajshahi. This study focuses on the 2nd tier as this can be integrated into building envelop with minimum intervention.
Objective 3: To identify parametric combination and configuration of envelope condition to facilitate passive cooling and to maximize comfort and minimize energy consumption.	Simulation Analysis	Chapter 5	Considering the climate of Rajshahi, available local construction techniques and nature of the hospital building i.e. naturally ventilated, two types of wall envelop found to be thermally performing well out of four configurations. Existing 10” brink construction and 11.5” cavity wall construction performed better than 5” brick construction with tiled and plastered finish and 4” light weight concrete block construction with tiled and plastered finish due to their better insulation.

2 CHAPTER TWO: LITERATURE REVIEW

Introduction

The climate of Bangladesh: An Overview

Climatic context of Rajshahi region

Design consideration in hot humid climate

Passive cooling

Codes and standards

Hospitals in Bangladesh

Building envelope

Key findings form literature review

Conclusion

2.1 Introduction

The first chapter introduces the research. This chapter discusses the outcomes of the literature review to find out the basic information required to study the hospital building envelope to facilitate passive cooling inside inpatient room in the context of Rajshahi. This chapter mainly consists of five major parts. The first part describes the climate of Rajshahi and compares it with climate of other region in Bangladesh. The second part discusses climate and comfort and how they are related. The third part highlights passive cooling techniques and their application in different climatic condition. The fourth part presents hospital buildings type, constructions, and current situation in Bangladesh, codes and standards for hospital construction, environmental control and comfort criteria for its occupants. The fifth part describes building envelope, construction assemblies, materials and their thermal properties, building envelope and thermal comfort. Finally, the key findings of this chapter have been highlighted. The methodology for field investigation and simulation studies are discussed in the next chapter (Chapter 3), developed with respect to the outcomes of this chapter.

2.2 The Climatic of Bangladesh: An overview

Bangladesh is considered one of the largest deltas in the world with a flat and low lying landscape. Bangladesh has a subtropical monsoon climate (Figure 2.1). It is characterized by wide seasonal variations in rainfall, moderately warm temperatures, and high humidity. Four meteorological seasons are recognized. They are pre-monsoon (March to May), monsoon (June to September), post-monsoon (October and November) and winter (December, January and February). Generally, Pre-monsoon months are hot and humid; monsoon months are humid and rainy, post-monsoon months are quite hot and dry but the winter months are cool and dry (Khatun, Rashid and Hygen, 2016). A classification in tropical region considering the environmental factors that affect human comfort directly was suggested by Atkinson (Atkinson, 1953) which has been widely accepted and useful. According to this classification the climate of Bangladesh can be defined as composite monsoon climate which has short and dry winters and long and wet summer (Koenigsberger et al., 2003; Ahmed, 1995).

Bangladesh is located between 20.57ºN to 26.63ºN and 88.02ºE to 92.68ºE. The country has border with India on the west, north and east side. In the southeast corner it shares a common border with Myanmar. Out of 230 rivers in Bangladesh 57 originated from outside the country. Most of the rivers flow to the Bay of Bengal from north to south. The main rivers are the Ganges (Padma), the Brahmaputra, and the Meghna. The coastline of Bangladesh is about 720 km long along the continental shelf which has a shallow bathymetry. The entire area of Bangladesh is about 1, 44,735 sq. km. The population of Bangladesh is about 160 million but about 80% of them live in the rural areas (Khatun, Rashid and Hygen, 2016).

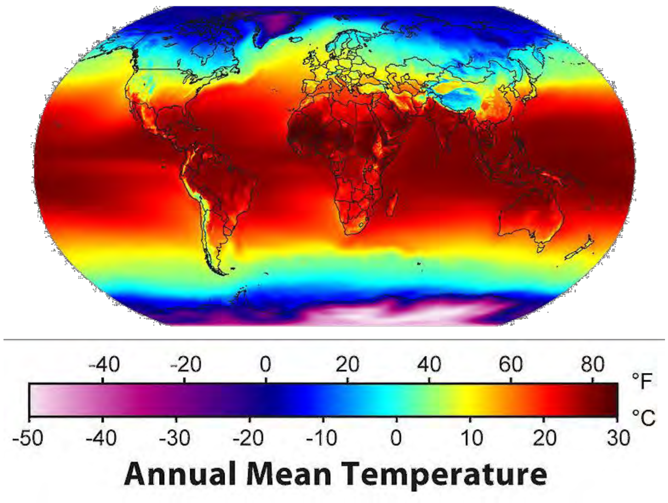

Figure 2.1 Annual mean temperature of the world (https://en.wikipedia.org/wiki/Temperature, accessed 2017)

January is the coldest month in Bangladesh. Average temperatures in January varies from about 17 deg C to 21 deg C. As the winter season advances into the summer, temperature rises, reaching the maximum in April. Average temperatures in April vary from about 27 deg C to 30 deg C in different regions. After April, temperature decreases slightly during the summer months, which coincides with the rainy season. Widespread cloud covers causes dampening of temperature during the latter part of the pre-monsoon season. Average temperatures in July vary from about 27 deg C to 29 deg C (Figure 2.2) (Chowdhury et al., 2012).

Depending on the region the least humid months are usually from January to April in the country. The relative humidity is everywhere over 80% during June through September (Chowdhury et al., 2012).

In Bangladesh, the cloud cover has two opposing seasonal patterns. During the winter season, the cloud cover is about 10% almost all over the country. With the progression of the season, it reaches to 50-60% by the end of the pre-monsoon hot season. In the months of July and August, which is the middle of the rainy season, the cloud cover varies from 75 to 90% all over the country. After the withdrawal of the summer monsoon, the cloud cover decreases rapidly, dropping to 25-50% (Chowdhury et al., 2012).

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The single most dominant element of the climate of Bangladesh is the rainfall. Because of the country's location in the tropical monsoon region, the amount of rainfall is very high. However, there is a distinct seasonal pattern in the annual cycle of the rainfall. The winter season is very dry, and accounts for only 2%-4% of the total annual rainfall. As the winter season progresses into the pre-monsoon hot season, rainfall increases and accounts for 10%-25% of the total annual rainfall which is caused by the thunderstorms. Rainfall during the rainy season is caused by the tropical depressions that enter the country from the Bay of Bengal. These account for 70% - 85% of the total rainfall of Bangladesh. The following figure (Figure 2.2) show an overall climatic condition in terms of climatic elements in various regions of Bangladesh.

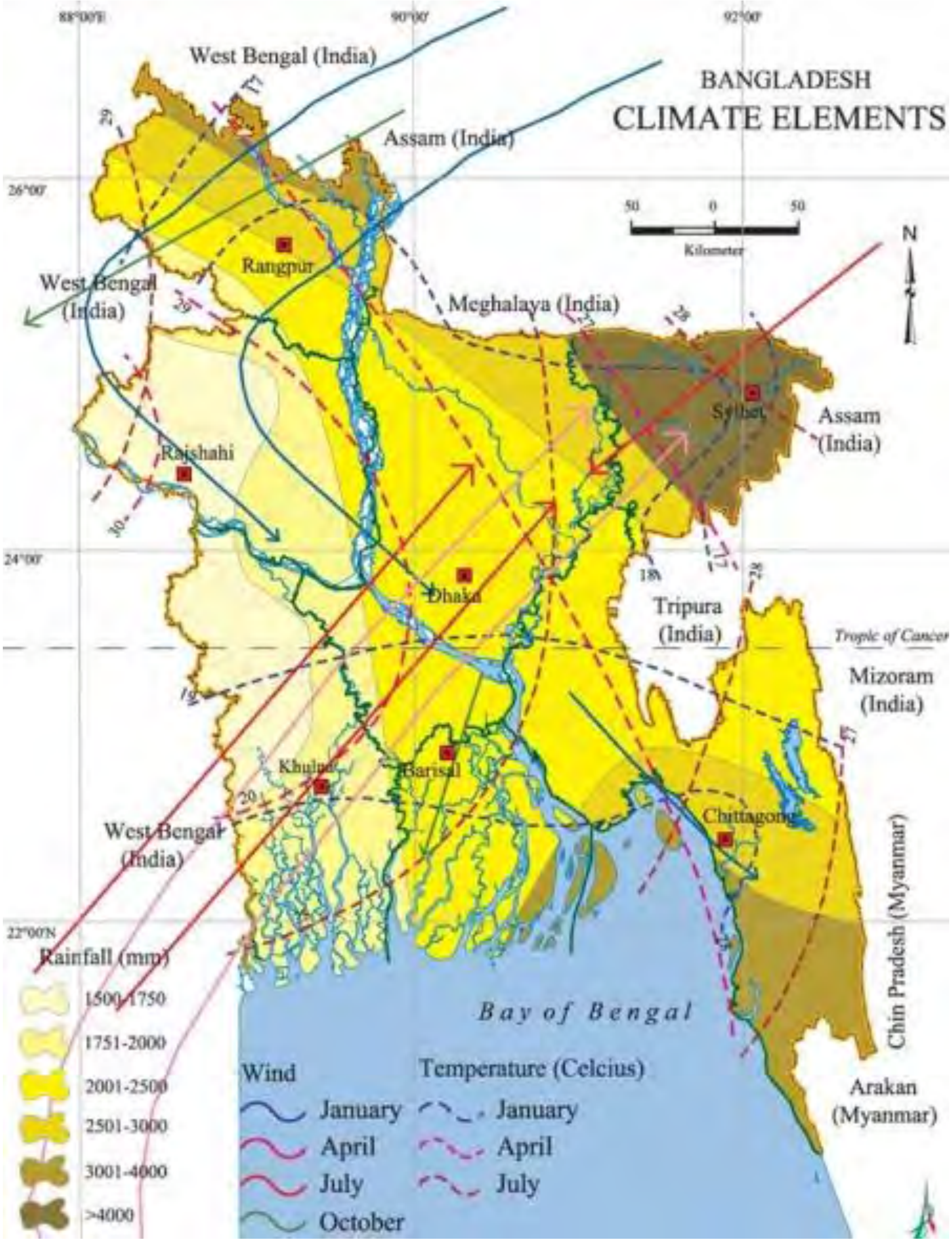


Figure 2.2 Climate of Bangladesh (http://en.banglapedia.org/index.php?title=File:ClimateRegion.jpg, accessed 2017)

2.3 Climatic context of Rajshahi region

To categorize the variation of the climate throughout the country, the whole region is subdivided into seven subzones (Figure 2.3). These are south east region, north east region, north west region, northern part of the northern region, west region, south west region and mid-south region (Chowdhury et al., 2012; Ahmed, 1995). These variations are due to the topography and surrounding geographic features.

Figure 2.3 Climatic sub regions of Bangladesh (http://en.banglapedia.org/index.php?title=File:ClimateRegion.jpg, accessed 2017)

The major cities such as Dhaka, Chittagong, Rajshahi, Sylhet and Khulna represents the sub climatic regions mid-south region, south east region, west region, north east region and south west region respectively. A comparative analysis of the climatic elements reveals the variations and their underlying reasons. This comparison is also necessary to understand the application of passive cooling in the context of Rajshahi compared to other climatic sub regions of Bangladesh.

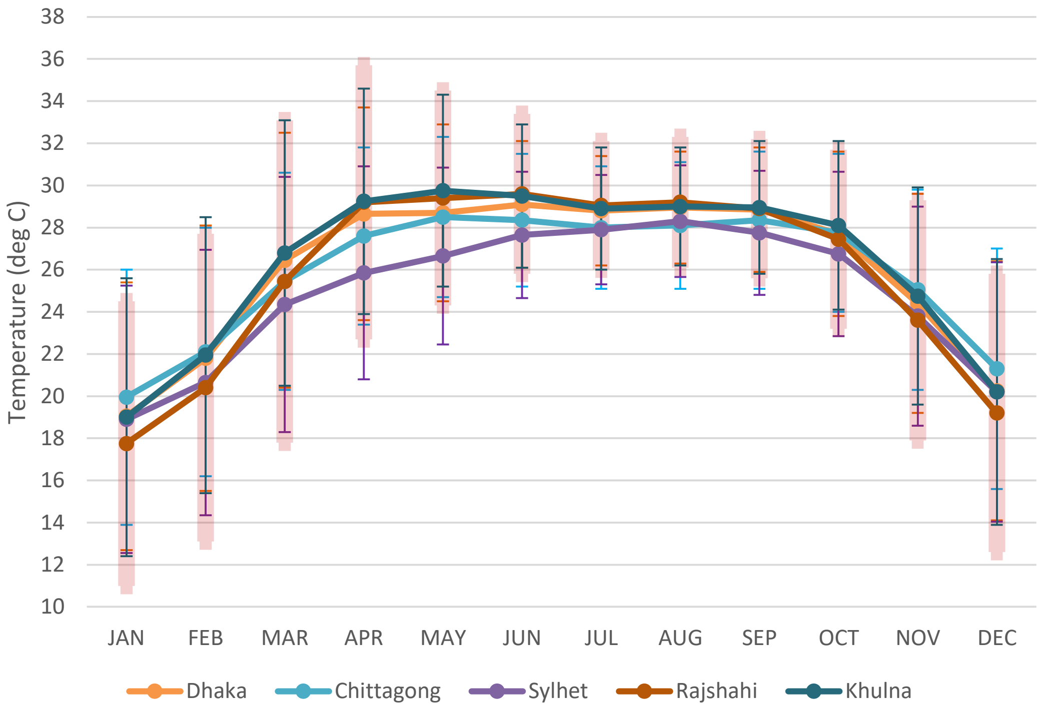


Figure 2.4 Mean temperature with max. and min. range of major cities in Bangladesh (Data Source: Bangladesh Meteorological Department)

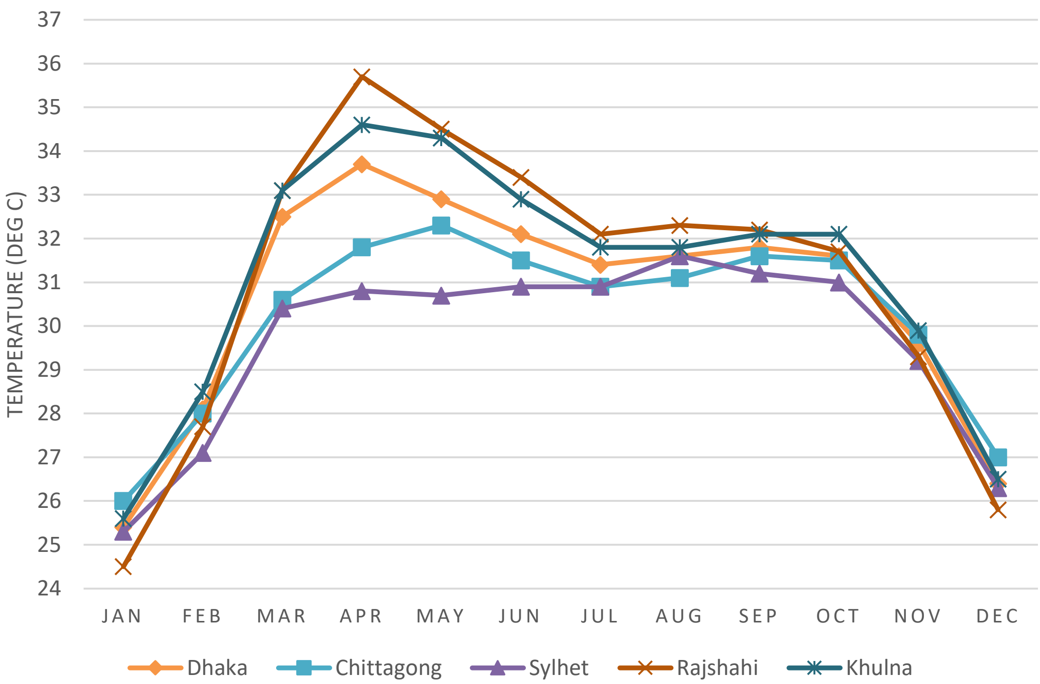


Figure 2.5 Mean maximum temperature of major cities in Bangladesh (Data Source: Bangladesh Meteorological Department)

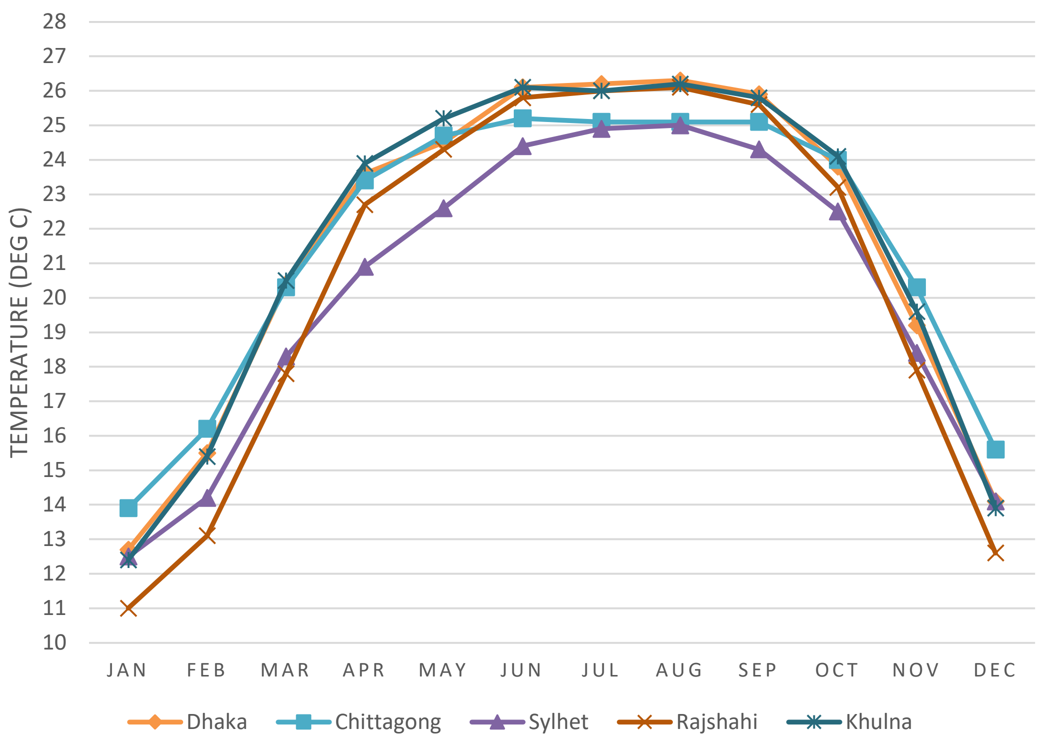


Figure 2.6 Mean minimum temperature of major cities in Bangladesh (Data Source: Bangladesh Meteorological Department)

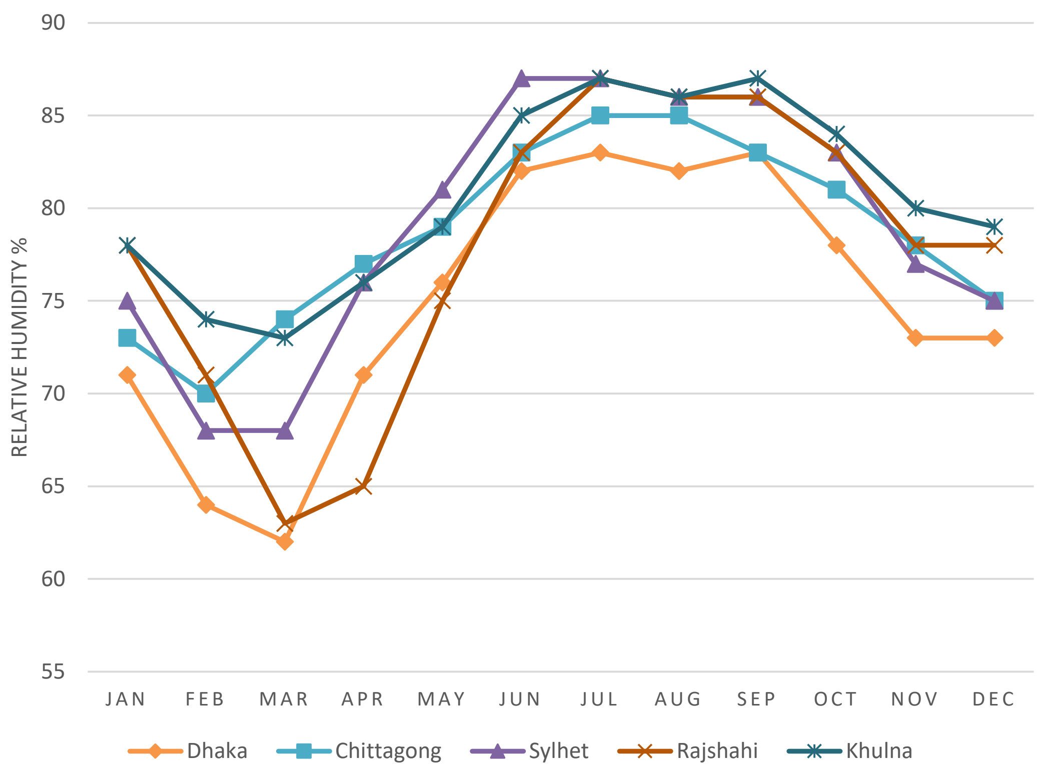


Figure 2.7 Relative humidity of major cities in Bangladesh (Data Source: Bangladesh Meteorological Department)

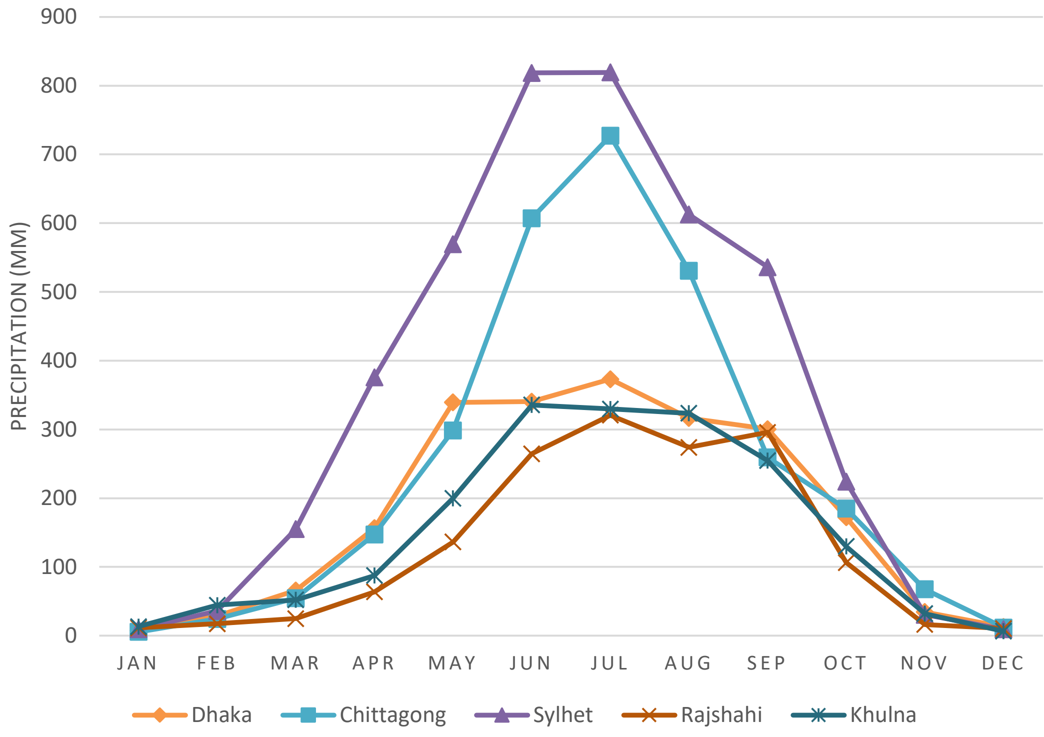


Figure 2.8 Mean monthly rainfall of major cities in Bangladesh. (Source: Bangladesh Meteorological Department)

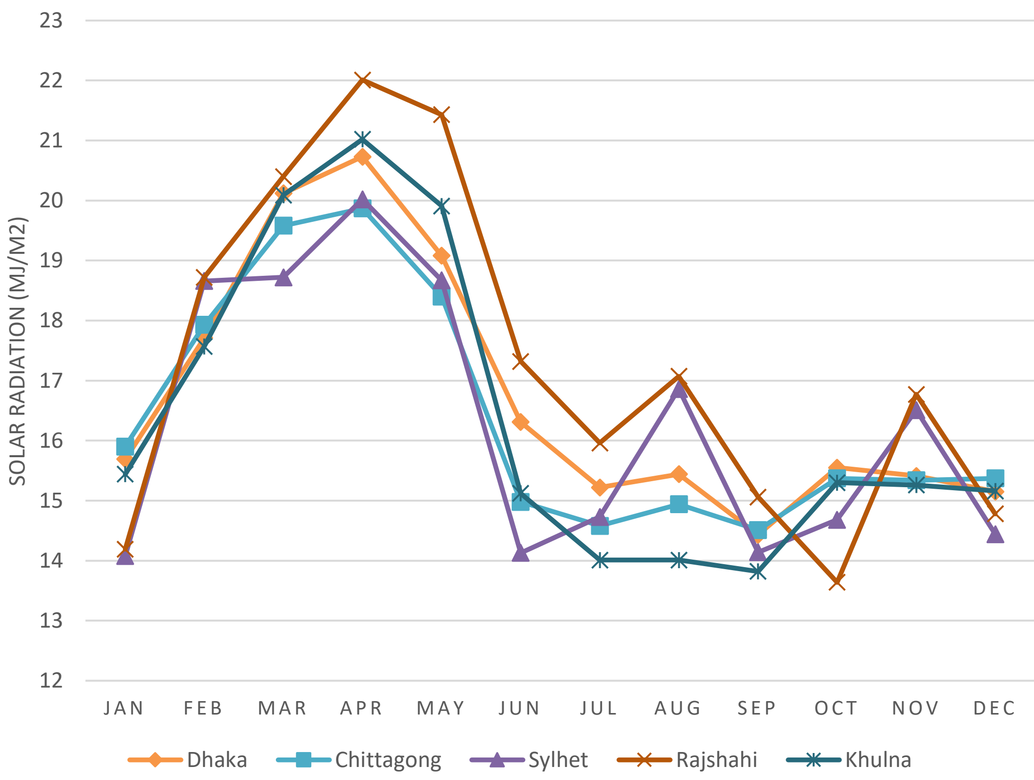
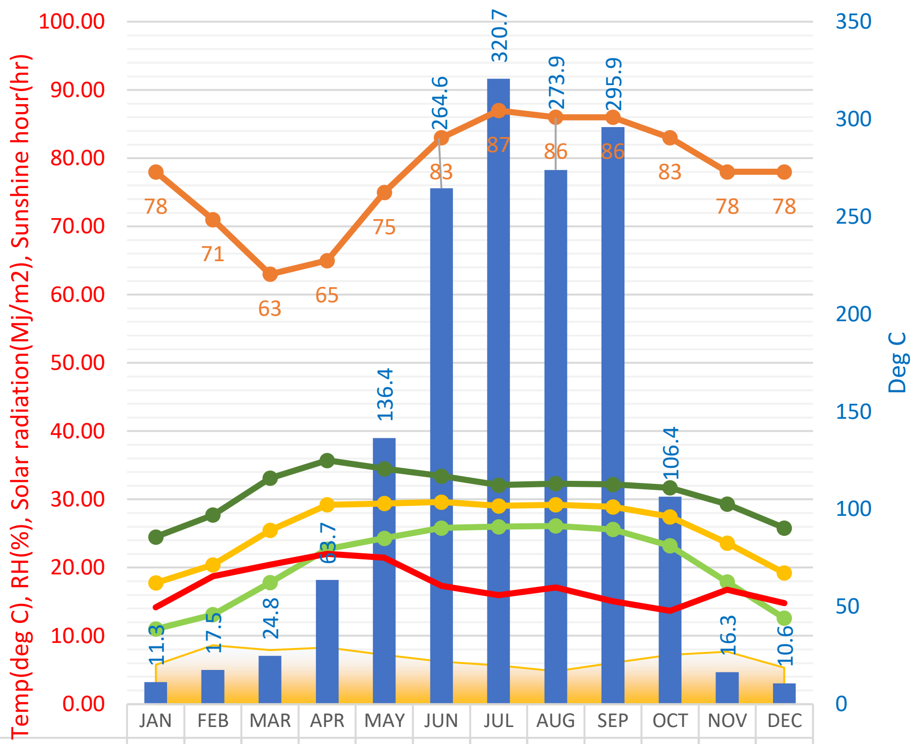


Figure 2.9 Monthly global solar radiation of major cities in Bangladesh. Source: (Debazit Datta, Datta and Chowdhury, 2014)

A comparative meteorological data analysis of the major cities i.e. Dhaka, Chittagong, Rajshahi, Sylhet and Khulna clearly shows the variations of different climatic elements. During the monsoon period (June to September) and post monsoon period (October to November) the temperature difference are the minimum due to cloud cover, reduced solar radiation and increased precipitation. The effect of precipitation on the temperature pattern is lowest from March to May during the pre-monsoon period (Ahmed, 1995). In the case of Rajshahi, pre monsoon period (March to May) experienced higher temperature than other parts of the country due to higher solar radiation in the region and this also coincide with minimum precipitation and lower humidity. Therefore the western zone with highest mean maximum temperature (Figure 2.5) and lowest recorded rainfall (Figure 2.8) is the driest part in Bangladesh. The relative humidity also in the summer stay low compare to other zone. (Figure 2.7 Relative humidity of major cities in Bangladesh (Data Source: Bangladesh Meteorological Department.

In the following review, climatic factors of Rajshahi city form various studies and meteorological data are discussed in detail.



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Sunshine hour (hr)	5.74	8.63	7.90	8.29	7.20	6.22	5.65	4.80	6.01	7.22	7.70	5.34
Prec. (mm/month)	11.3	17.5	24.8	63.7	136.4	264.6	320.7	273.9	295.9	106.4	16.3	10.6
Max. Temp. (°C)	24.5	27.7	33.1	35.7	34.5	33.4	32.1	32.3	32.2	31.7	29.3	25.8
Min. Temp. (°C)	11	13.1	17.8	22.7	24.3	25.8	26	26.1	25.6	23.2	17.9	12.6
Mean Temp. (°C)	17.75	20.4	25.45	29.2	29.4	29.6	29.05	29.2	28.9	27.45	23.6	19.2
RH (%)	78	71	63	65	75	83	87	86	86	83	78	78
Radiation (MJ/m2)	14.19	18.72	20.4	22.01	21.43	17.32	15.96	17.07	15.06	13.64	16.77	14.78

Figure 2.10 Climate graph, Rajshahi, Bangladesh

2.3.1 Temperature

A temperature is an objective comparative measurement of hot or cold. Temperature is one of the principal quantities in the study of thermodynamics. Many temperature scales were developed throughout history. Some of them are empirically defined e.g. Fahrenheit, Celsius and some are theoretically e.g. kelvin. (Wikipedia, 2017). A compiled meteorological data (Figure 2.10) of Rajshahi indicates the relationship between the climatic elements and the overall climatic profile of the region. The profile shows that the highest temperatures are registered from March to May (pre monsoon period) and are very close to each other. April is the hottest month in this region with a mean max temperature of 35.7 deg C. In Bangladesh the highest ever recorded temperature was 45.1 deg C which was recorded in Rajshahi on May 19, 1972. (Khatun, Rashid and Hygen, 2016). The diurnal variation is high during the pre-monsoon and winter period and became low during the monsoon and post monsoon period. Precipitation and cloud cover reduce the effect of solar radiation. Figure 2.11 and Table 2.1 represents daily temperature profile for a typical year of Rajshahi, derived from ASHRAE Fundamental 2013 prescribed method to calculate daily temperature profile.

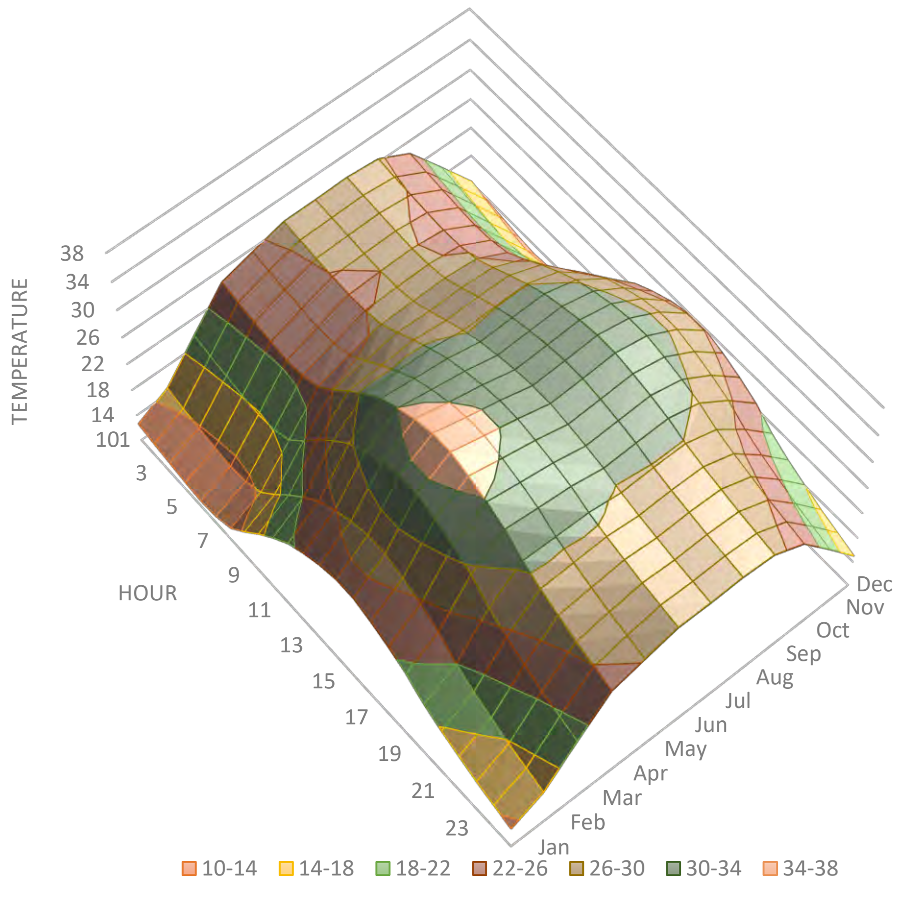


Figure 2.11 Daily temperature profile for a typical year of Rajshahi

Figure 2.11 shows the diurnal as well as annual variation in temperature. The mean temperature increases from January to April as winter season progresses to pre monsoon period. During these four months the diurnal variation ranging from 13-15 deg C is also high and influenced strongly by solar radiation. From April to May before the monsoon season the trend of mean temperature increase slows down and diurnal range also decreases to 10-13 deg C. The temperature form June to September changes very little and almost remains same with a diurnal range of 6-7 deg C. Then the temperature gradually decreases as winter approaches from October to December and the diurnal range stays within 8-13 deg C. Figure 2.12 shows the annual maximum and minimum temperature distribution pattern over the region of Bangladesh.

Table 2.1 Daily temperature profile of a typical year in Rajshahi

Month	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Season	Cool Dry			Hot Dry			Hot Wet					
Hour	Winter			Pre Monsoon			Monsoon				Post Monsoon	
1	14.2	12.6	14.9	19.6	24.3	25.5	26.7	26.7	26.8	26.4	24.2	19.3
2	13.7	12.1	14.3	19.0	23.7	25.1	26.4	26.5	26.6	26.2	23.9	18.8
3	13.3	11.7	13.8	18.6	23.4	24.8	26.2	26.3	26.4	26.0	23.6	18.5
4	12.9	11.3	13.4	18.1	23.0	24.5	26.0	26.1	26.2	25.7	23.4	18.1
5	12.6	11.0	13.1	17.8	22.7	24.3	25.8	26.0	26.1	25.6	23.2	17.9
6	12.9	11.3	13.4	18.1	23.0	24.5	26.0	26.1	26.2	25.7	23.4	18.1
7	13.8	12.2	14.4	19.2	23.9	25.2	26.5	26.5	26.7	26.2	24.0	18.9
8	16.0	14.5	16.9	21.8	26.1	27.0	27.8	27.6	27.7	27.4	25.4	20.9
9	18.5	17.1	19.7	24.7	28.6	28.9	29.2	28.7	28.9	28.8	27.0	23.0
10	20.8	19.4	22.2	27.3	30.8	30.6	30.5	29.8	29.9	29.9	28.5	25.0
11	22.8	21.4	24.3	29.6	32.7	32.2	31.7	30.7	30.9	31.0	29.7	26.7
12	24.1	22.7	25.8	31.1	34.0	33.2	32.4	31.3	31.5	31.7	30.6	27.8
13	25.1	23.8	27.0	32.3	35.1	34.0	33.0	31.8	32.0	32.3	31.3	28.7
14	25.8	24.5	27.7	33.1	35.7	34.5	33.4	32.1	32.3	32.6	31.7	29.3
15	25.8	24.5	27.7	33.1	35.7	34.5	33.4	32.1	32.3	32.6	31.7	29.3
16	25.0	23.7	26.8	32.2	34.9	33.9	32.9	31.7	31.9	32.2	31.2	28.6
17	24.0	22.6	25.7	31.0	33.9	33.1	32.3	31.2	31.4	31.6	30.5	27.7
18	22.6	21.3	24.2	29.4	32.6	32.1	31.6	30.6	30.8	30.9	29.7	26.6
19	20.7	19.2	22.0	27.1	30.6	30.5	30.4	29.7	29.9	29.9	28.4	24.9
20	19.2	17.8	20.4	25.5	29.2	29.4	29.6	29.1	29.2	29.1	27.5	23.6
21	18.0	16.5	19.1	24.1	28.0	28.5	28.9	28.5	28.6	28.5	26.7	22.6
22	16.8	15.3	17.8	22.7	26.9	27.6	28.2	28.0	28.1	27.8	25.9	21.5
23	15.9	14.4	16.8	21.6	26.0	26.9	27.7	27.5	27.7	27.4	25.3	20.8
24	15.0	13.4	15.7	20.6	25.0	26.1	27.2	27.1	27.2	26.9	24.7	20.0
Max	25.8	24.5	27.7	33.1	35.7	34.5	33.4	32.1	32.3	32.6	31.7	29.3
Min	12.6	11.0	13.1	17.8	22.7	24.3	25.8	26.0	26.1	25.6	23.2	17.9
Range	13.2	13.5	14.6	15.3	13.0	10.2	7.6	6.1	6.2	7.0	8.5	11.4

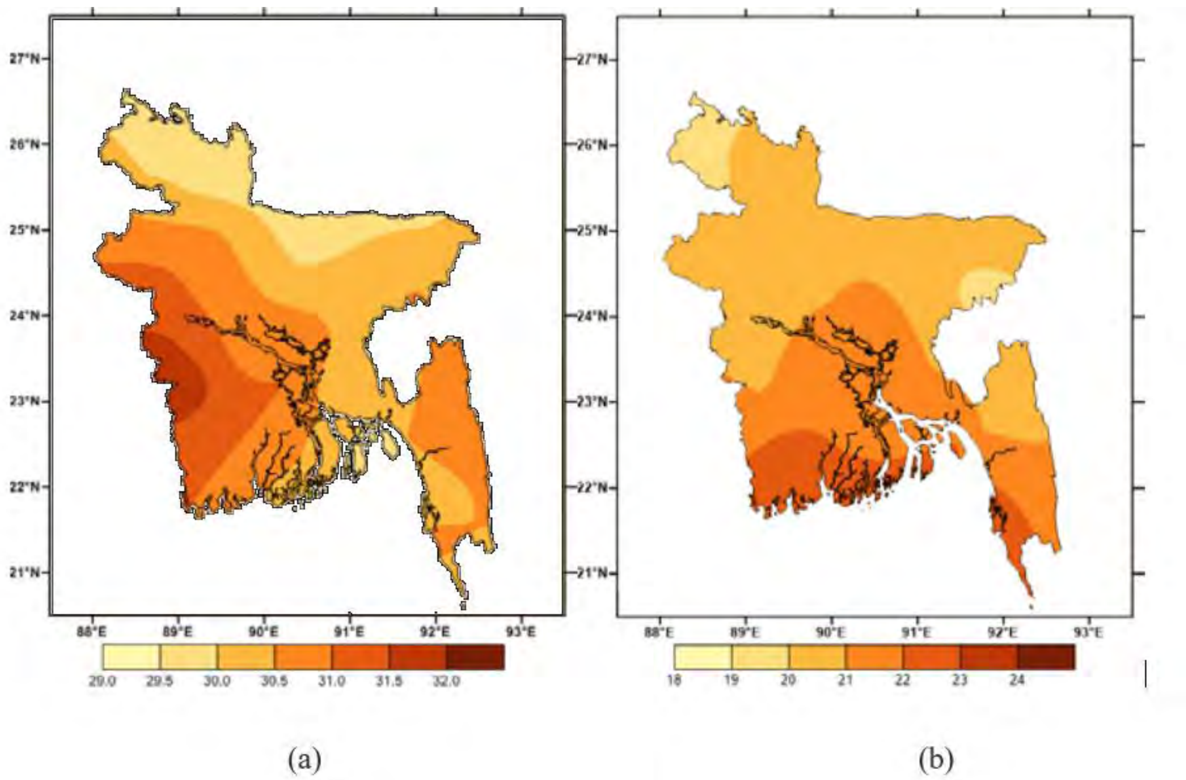


Figure 2.12 Spatial distribution of (a) annual maximum temperature during 1981-2010 (b) a minimum temperature during 1981-2010. Source: (Khatun, Rashid and Hygen, 2016)

2.3.2 Humidity

The humidity of the air can be described in terms of absolute value or relative value. The absolute humidity is the amount of moisture actually present in unit mass or unit volume of air, e.g. g/kg or g/m^3. The relative humidity (RH) is a much more meaningful way to describe humidity as it gives a direct indication of evaporation potential. Relative humidity is the ratio of the actual amount of moisture present to the amount of moisture the air could hold at the given temperature expressed as a percentage (Koenigsberger et al., 2003).

$$RH = \frac{AH}{SH} \times 100(\%)$$

Thus the relative humidity depends on two factors, the air temperature and the presence of moisture in the air. When the air temperature increases, the relative humidity decreases as the capacity of air to hold moisture increases, given that the moisture content of the air stays unchanged, and if the temperature decreases the opposite occurs. Therefore relative humidity has an inversely relationship with the temperature, the relative humidity increases when the moisture content of the air increases and the relative humidity decreases when the moisture content of the air decreases (Koenigsberger et al., 2003). The humidity profile of Rajshahi reflect this phenomena. During the pre-monsoon period from March to May, high temperature and low precipitation yielded a comparative low relative humidity with a mean value of 63-75%. Relative humidity dramatically increases during monsoon season from June to

September under the influence of high precipitation and decreasing temperature. During this time the mean relative humidity varies from 83-87%. In spite of temperature decrease in post monsoon period mean relative humidity decreases to 78-83% as the precipitation dropped significantly during October to November. Mean relative humidity, regardless of low precipitation, remain moderately high (71-78%). This is due to the temperature drop in winter (Figure 2.10)

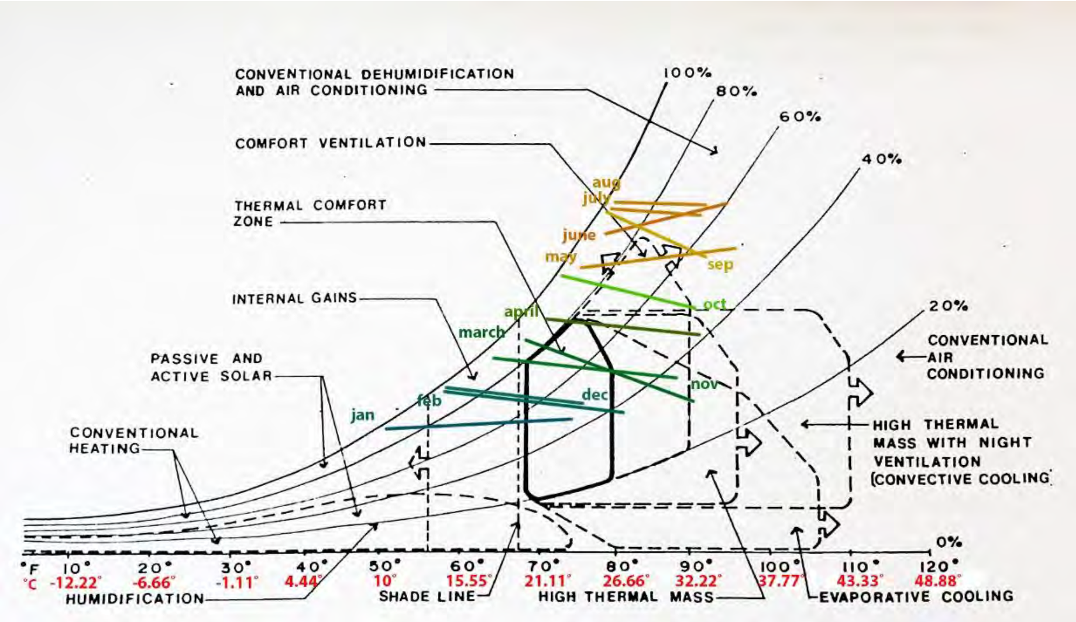


Figure 2.13 Combined effect of temperature and relative humidity on outdoor environment

A combined effect of temperature and relative humidty of a typical year of Rajshahi is shown in Figure 2.13 in a psychrometric chart.

2.3.3 Precipitation

Precipitation is a collective term for any sort of water depositions from the atmosphere. It is measured in millimetre per a time unit e.g. mm/month, mm/day, mm/hr. In Rajshahi rainfall and dew are the only form of precipitations that are deposited from the atmosphere.The numbers of rainy days for different rainfall ranges, i.e., light rain (1-10 mm), moderate rain (11-22 mm), moderately heavy rain (23-43 mm), heavy rain (44-88 mm), and very heavy rain (greater than 88 mm) are calculated for Rajshahi.

Table 2.2 shows frequency of rainy days over Rajshahi. Rainfalls are higher in the monsoon months and it is the highest in July. Highest recorded 24 hour rainfall is 247 mm recorded on June 22, 2014. Rainfalls are significantly lower during the winter months and it is the lowest in December. Monthly normal rainfall of Rajshahi are 11.3 mm (January), 17.5 mm (February), 24.8 mm (March), 63.7 mm (April), 136.4 mm (May), 264.6 mm (June), 320.7 mm (July), 273.9 mm (August), 295.9 mm (September), 106.4 mm (October), 16.3 mm (November) and 10.6 mm (December).

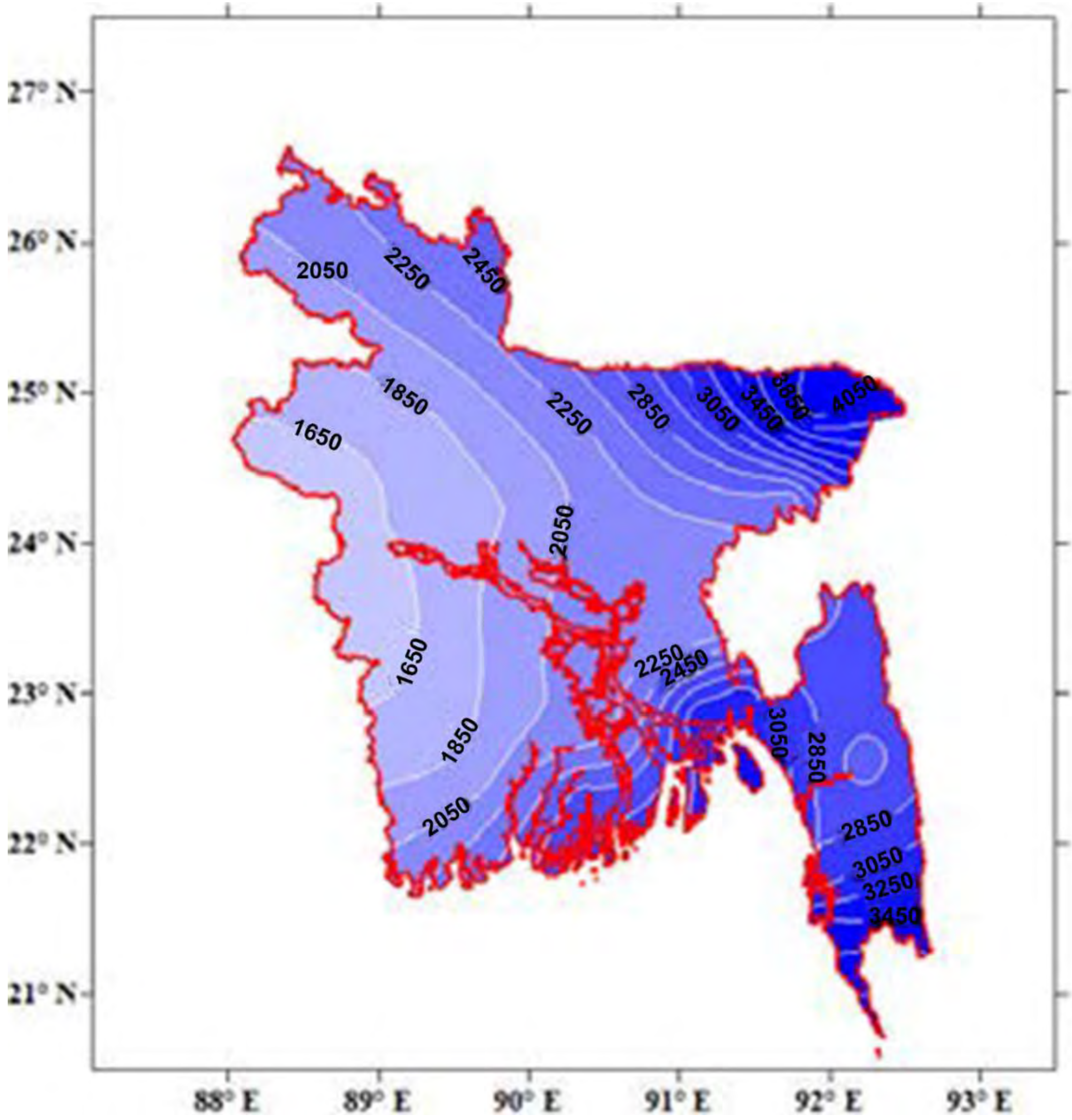


Figure 2.14 Spatial distribution of annual normal rainfall during 1981-2010 in Bangladesh. Source: (Khatun, Rashid and Hygen, 2016)

Spatial distributions of annual rainfall for the duration 1981-2010 are shown in Figure 2.14. Distribution pattern shows that western part of the country has the least annual rainfall. The rainfall gradually increases as it moves to the eastern region of the country. Average monthly rainfall in Figure 2.10 depicts that amounts of rainfall gradually increases in February, March, April, May, June and July; decreases in October, November, December and January; and remained nearly unchanged during Rest of the monsoon period.

Table 2.2 Frequency of rainy days over Rajshahi for different rainfall ranges during the period 1981-2010. Source: (Khatun, Rashid and Hygen, 2016)

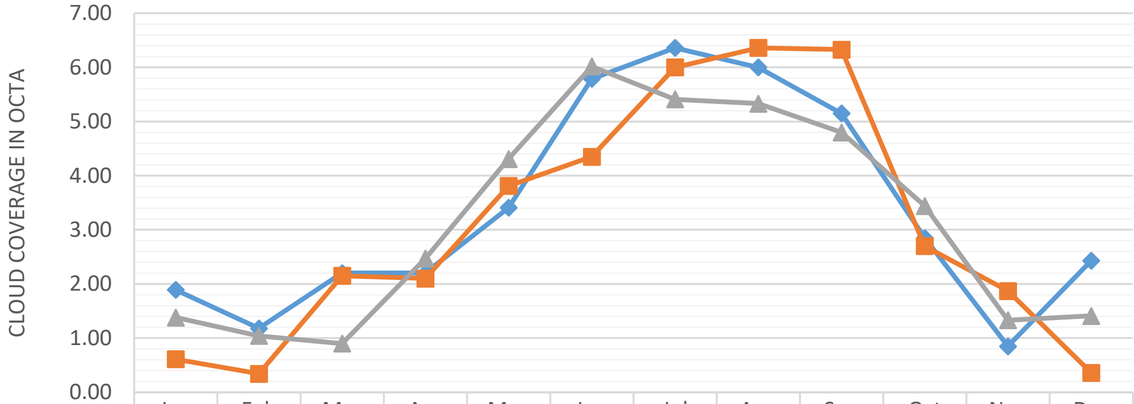
Rainfall (mm)	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Total
Season	Cool Dry			Hot Dry			Hot wet						
	Winter			Pre monsoon			Monsoon				Post Monsoon		
Dry days	905	887	781	832	739	639	459	325	386	439	726	866	7984
Light rain 1-10	18	37	52	75	92	160	244	373	333	253	104	24	1765
Moderate rain 11-22	3	4	11	18	41	68	80	100	109	83	43	5	565
Moderate heavy 23-43	2	2	3	4	20	47	67	80	57	79	39	2	402
Heavy rain 44-88	2			1	2	15	37	44	38	36	14	3	192
Very heavy rain > 89						1	6	8	5	10	4		34
Very heavy rain 100-199						1	1	7	3	9	1		22
Very heavy rain 200-299													0
Very heavy rain > 300													0

2.3.4 Sky condition

Sky condition is described in terms of presence or absence of clouds. Sky covered in cloud is expressed as a percentage or 'tenths' or 'eighths' or 'octets'. Cloud coverage of 50% can be also expressed as five-tenths or four-eighths (Koenigsberger et al., 2003).During the monsoon season the average cloud coverage across the country is 5.42 okta. Compared to other parts of the country, Rajshahi is one of the regions which has the lowest cloud coverage, with readings varying from 0.34 to 6.36 okta (Khan, Rahman and Hossain, 2012). Figure *2.15* shows the cloud coverage in Rajshahi during the period of 2008-2010. It is evident from the data that during the late pre-monsoon (May) and early post-monsoon period the sky remains moderately overcast. However, the monsoon period (June-September) the sky becomes considerably overcast. The rest of the period (early pre-monsoon, late post monsoon and winter) the sky remains clear with some exception during thunderstorm, hail or heavy rain (Figure *2.15*).

2.3.5 Solar radiation

Average daily amounts of solar radiation for each month of the year would give a fair indication of climatic conditions and seasonal variations (Koenigsberger et al., 2003). The western zone where Rajshahi is located shows the trend of receiving a higher than average amount of solar radiation (Figure *2.16*) when compared to the rest of the country. A decreasing trend of insolation can be observed during the monsoon, post monsoon and winter seasons. Overcast sky condition is responsible for reduced solar radiation during the monsoon and post monsoon period. Winter experiences a reduced solar radiation because of the shorter duration of day, in spite of a clear sky. Figure *2.17* shows monthly mean sunshine hour in Rajshahi recorded during the period 2008-2010. Sunshine hour reflects inverse pattern observed in cloud coverage.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2008	1.89	1.18	2.2	2.2	3.41	5.79	6.36	6	5.15	2.85	0.85	2.43
2009	0.61	0.34	2.15	2.1	3.81	4.35	6	6.36	6.33	2.7	1.87	0.36
2010	1.38	1.04	0.9	2.47	4.31	6.02	5.41	5.33	4.8	3.44	1.33	1.41

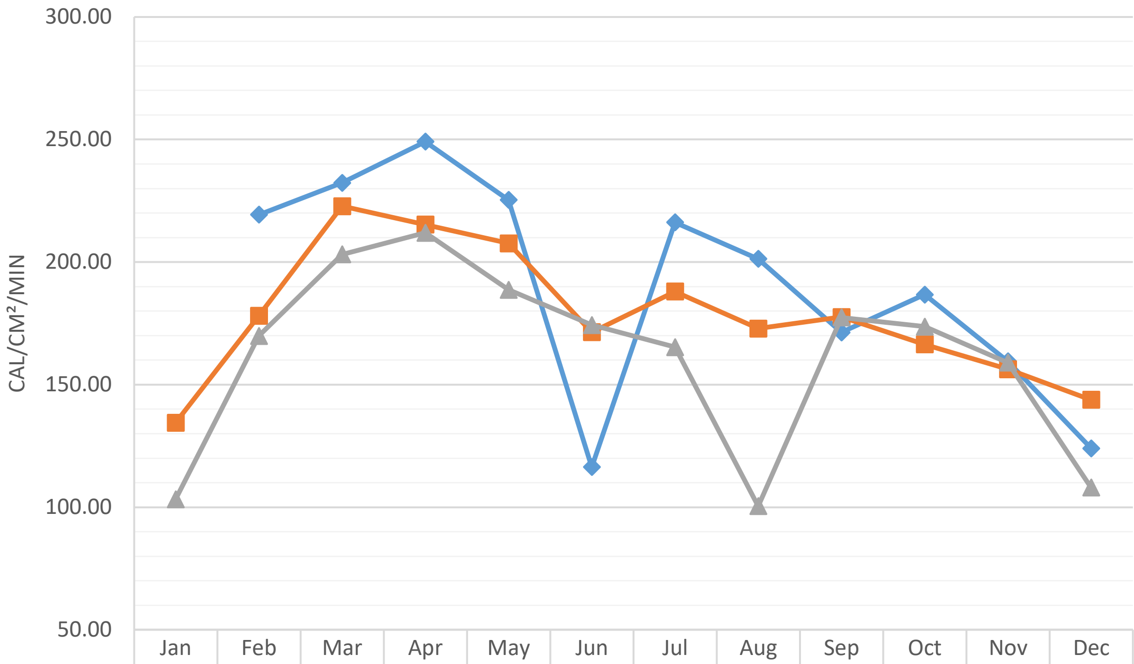
Figure 2.15 *Cloud coverage in Rajshahi (2008-2010). Source: (Khan, Rahman and Hossain, 2012)*

2.3.6 Wind speed and direction

Wind speed is the rate of movement of air in its instantaneous direction and is measured as kilometer per hour or meter per second or knots. Wind direction is the direction from which wind blows and expressed in degrees and measured clockwise from the geographical north or in terms of the points of the compass. Though there are different methods of wind speed measurement, the rotating cup anemometer is commonly used for wind speed measurement. Seasonal wind pattern and distribution of wind speed of Rajshahi are shown in the Figure 2.18, Figure 2.19, Figure 2.20 and Figure 2.21.

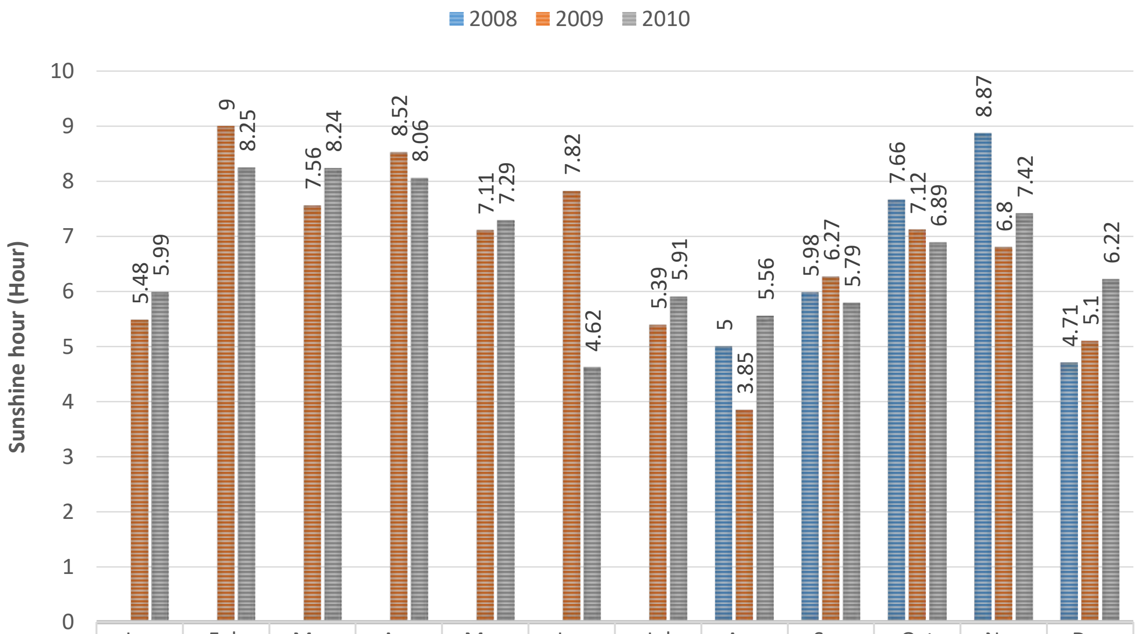
During winter the northern winds prevail over Rajshahi. Clear sky, low temperatures, low humidity and light winds are the common weather phenomenon of winter season.

The summer months (March to May) experience high temperature and falling of air pressure over the country. Circulation of air begins to set in around this low pressure area, resulting in strong gusty, hot, dry wind blowing during the day. Wind blows to Rajshahi from east, west and south during this period and wind from north is infrequent and weak (Figure 2.19). Thunderstorms are very common during this season. In this season, localized thunderstorms associated with violent winds, torrential downpours and occasionally hail occur. These are locally known as the 'Kalbaishakhi' (Nor 'wester) are the common weather phenomena.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2008		219.30	232.30	249.10	225.30	116.40	216.20	201.30	171.30	186.70	159.50	124.00
2009	134.50	178.10	222.80	215.30	207.60	171.40	188.00	172.90	177.60	166.4	156.30	143.80
2010	103.27	169.85	203.10	211.93	188.70	174.35	165.30	100.43	177.39	173.69	158.97	108.00

Figure 2.16 Monthly mean solar radiation in Rajshahi (2008-2010). Source: (Khan, Rahman and Hossain, 2012). Data for January 2008 is not available.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2008								5	5.98	7.66	8.87	4.71
2009	5.48	9	7.56	8.52	7.11	7.82	5.39	3.85	6.27	7.12	6.8	5.1
2010	5.99	8.25	8.24	8.06	7.29	4.62	5.91	5.56	5.79	6.89	7.42	6.22

Figure 2.17 Monthly mean daily sunshine hour in Rajshahi (2008-2010). Source: (Khan, Rahman and Hossain, 2012). Data for January to July in 2008 is not available.

Generally monsoon season arrives in early June and withdraws by the end of September in Bangladesh. During this season, the persisting low pressure attracts the trade winds of the southern hemisphere. These trade winds blow in a southwesterly direction entering the Indian peninsula and the Bay of Bengal. After that, it covers the whole Bangladesh as a southwest monsoon. However, the monsoon winds enters Rajshahi region from southeasterly direction (Figure 2.20).

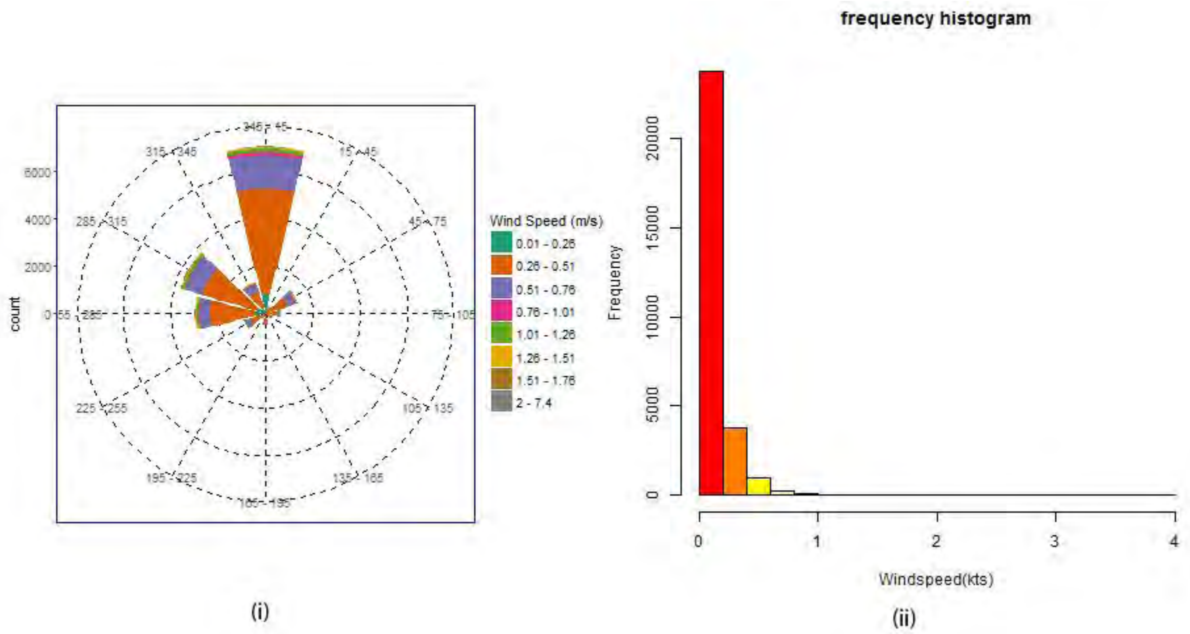


Figure 2.18 Distribution of (i) wind direction and (ii) wind speed of Rajshahi during Winter Season. Source: (Khatun, Rashid and Hygen, 2016)

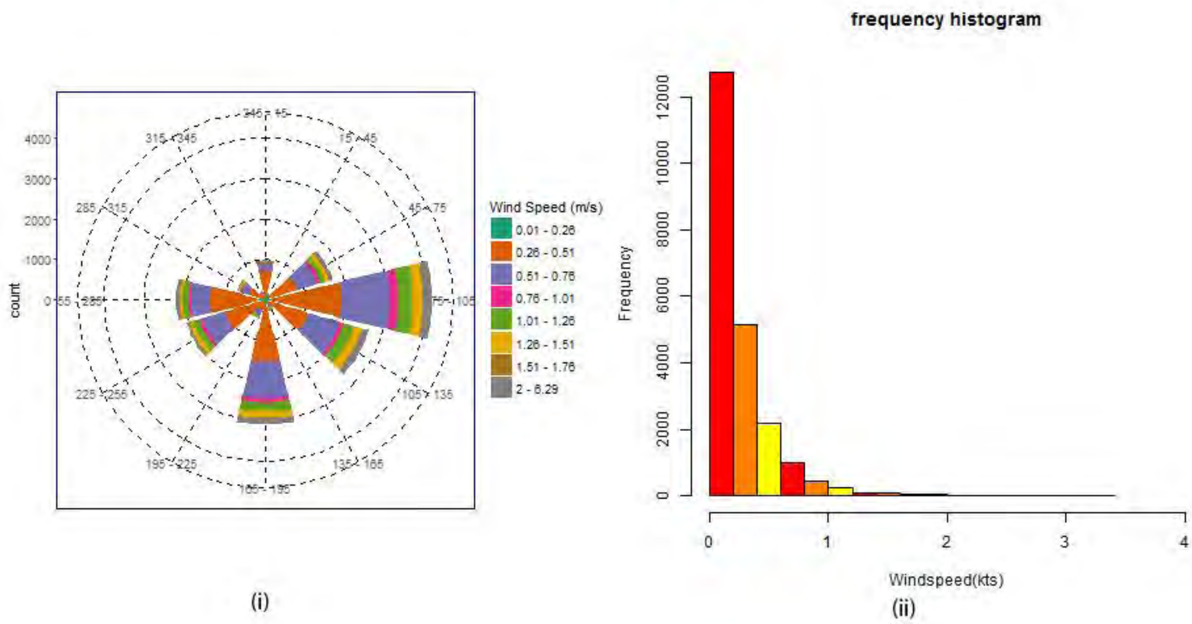


Figure 2.19 Distribution of (i) wind direction and (ii) wind speed of Rajshahi during Pre-monsoon Season. Source: (Khatun, Rashid and Hygen, 2016)

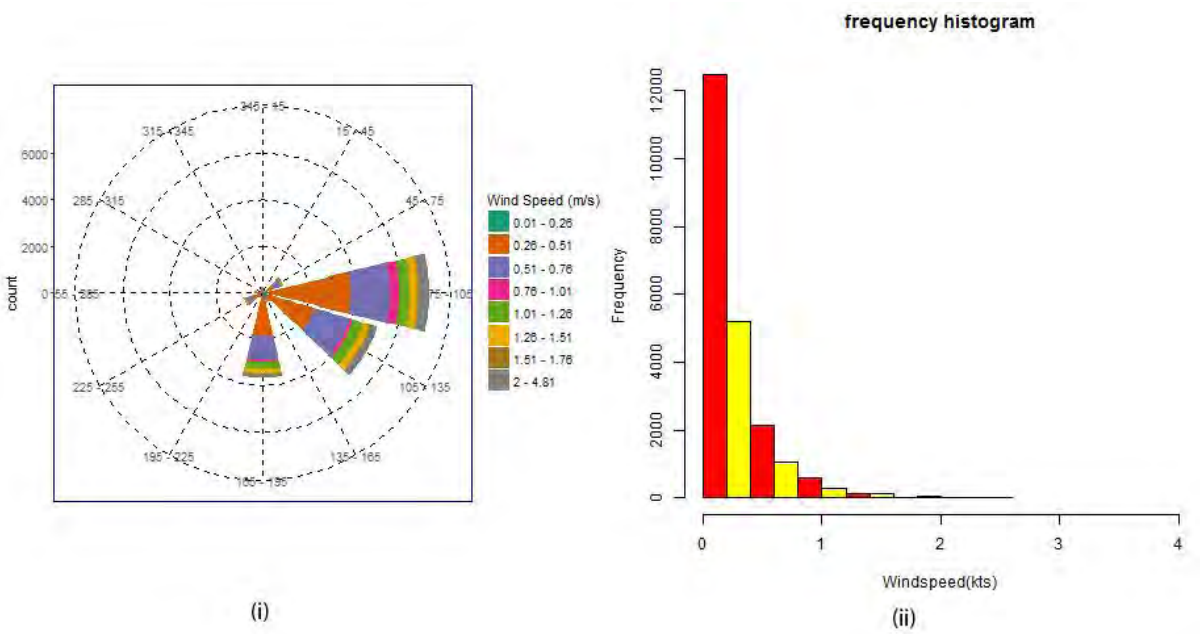


Figure 2.20 Distribution of (i) wind direction and (ii) wind speed of Rajshahi during Monsoon Season. Source: (Khatun, Rashid and Hygen, 2016)

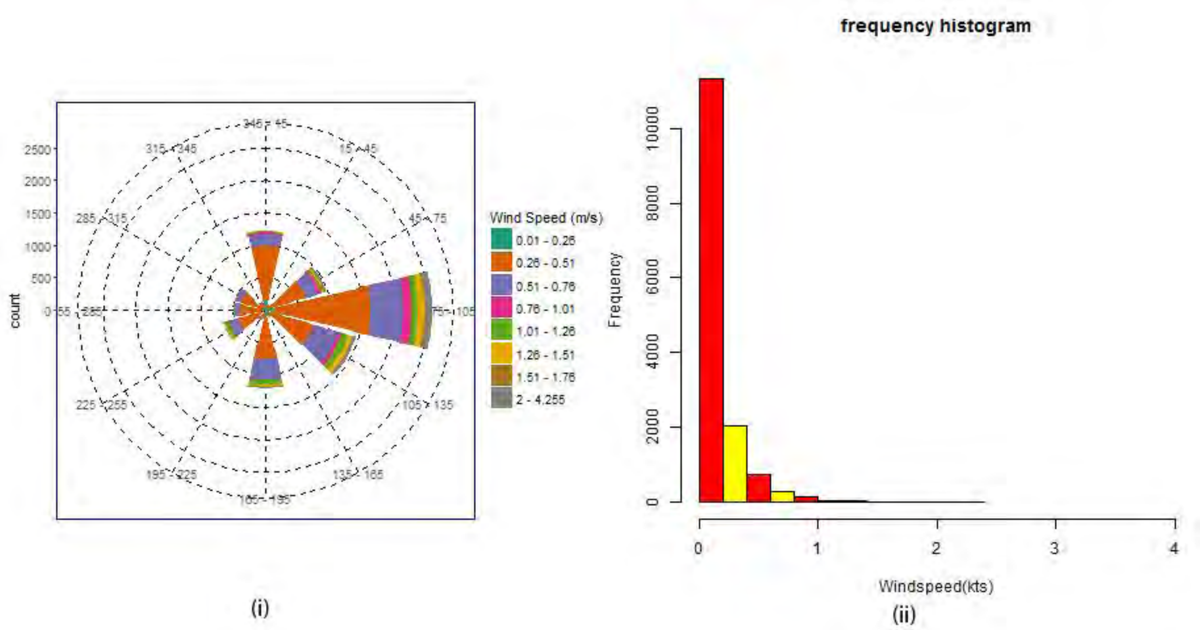


Figure 2.21 Distribution of (i) wind direction and (ii) wind speed of Rajshahi during Post-monsoon Season. Source: (Khatun, Rashid and Hygen, 2016)

During post monsoon season (October to November) the low pressure trough over Bangladesh becomes weak, gradually replaced by a high pressure system. After withdrawal of monsoon, the period of October and November months acts as a transition from hot rainy season to dry winter conditions. In this period winds blow in from all directions with a predominant blow from eastern direction (Figure 2.21).

The maximum wind speed was 3.19 m/s but its occurrence was only 0.20%, on the other hand the maximum occurrence 12.80% was of speed 2.00 m/s from 1300. The other notable percentages, direction, speeds are 11.58%, 900, 2.15 m/s; 9.61%, 3600, 1.26 m/s and 9.37%, 1800, 1.97 m/s. (Hossain, Hossain and Isalm, 2002; Khatun, Rashid and Hygen, 2016)

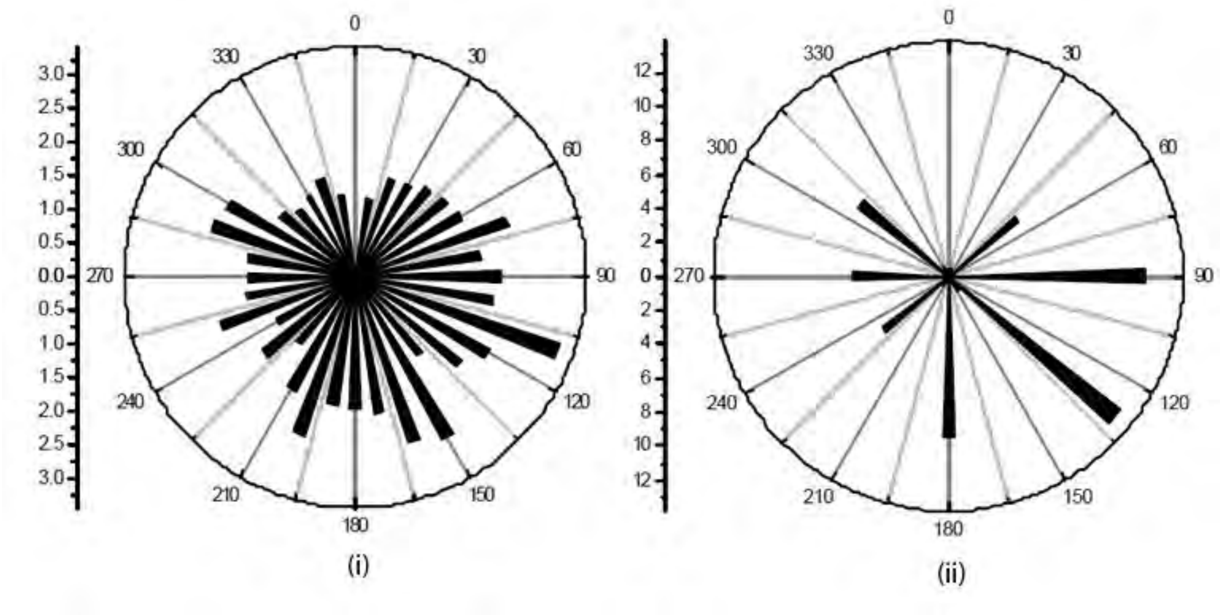


Figure 2.22 Wind roses of Rajshahi: wind speed (left) and percentage of occurrences (right).

2.4 Design considerations in Hot Humid Climate

From climate study of Rajshahi in the preceding sections, it can be said that climatic parameters differ from the country average and it has a drier and hotter climate during the pre-monsoon period and this region experience lesser rainfall even during the monsoon period.

Unlike hot dry climates, where massive walls are used for their time lag effect and small windows to prevent hot outdoor air along with intense sun, hot and humid climates favor very different kind of buildings. Moreover, annual seasonal cycle between hot dry pre monsoon period and warm wet monsoon period makes it difficult to design building to perform equally in both seasons. Additionally the third season, winter complicated the situation with a much lower temperature than the warmer seasons. Many construction features may be suitable for all seasons. But complications arise when incompatible requirements are to be satisfied. In order to develop suitable design that will fulfill most of the requirements of the seasons, some form of weighting of the seasons can be performed to prioritize the strategies. This can be done by taking into account of the length of the different season and the relative severity of the conditions (Koenigsberger et al., 2003). Table 2.3, Figure *2.23* and Table 2.4 shows the calculation to determine the relative severity of the different seasons.

Table 2.3 Effective temperature calculation from DBT, WBT and wind speed

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean max. DBT: deg C	24.5	27.7	33.1	35.7	34.5	33.4	32.1	32.3	32.2	31.7	29.3	25.8
RH p.m.: %	56.6	47.2	34.1	41.0	59.2	72.7	77.3	75.9	75.6	69.0	60.1	57.7
WBT: deg C	18.5	18.5	21.1	24.7	27.6	29.1	28.6	29.0	28.4	26.9	23.2	19.8
Monthly mean wind speed m/s	0.45	0.45	0.82	1.34	1.30	1.27	1.15	1.16	0.69	0.55	0.36	0.82
ET: max.: deg C	21.2	23	25.6	27.9	28.6	29.6	28.6	28.7	28.7	28	25.6	21.8
Mean min. DBT: deg C	11	13.1	17.8	22.7	24.3	25.8	26	26.1	25.6	23.2	17.9	12.6
RH a.m.: %	99.4	94.8	91.9	89.0	90.8	93.3	96.7	96.1	96.4	97.0	95.9	98.3
WBT: deg C	10.9	12.6	16.9	21.4	23.1	24.9	25.2	25.6	25.1	22.8	17.5	12.4
Monthly mean wind speed m/s	0.45	0.45	0.82	1.34	1.30	1.27	1.15	1.16	0.69	0.55	0.36	0.82
ET:min.: deg C	9.2	11.5	15.2	19.9	21.5	23.5	23.9	24	24.9	22.2	17.3	9.1

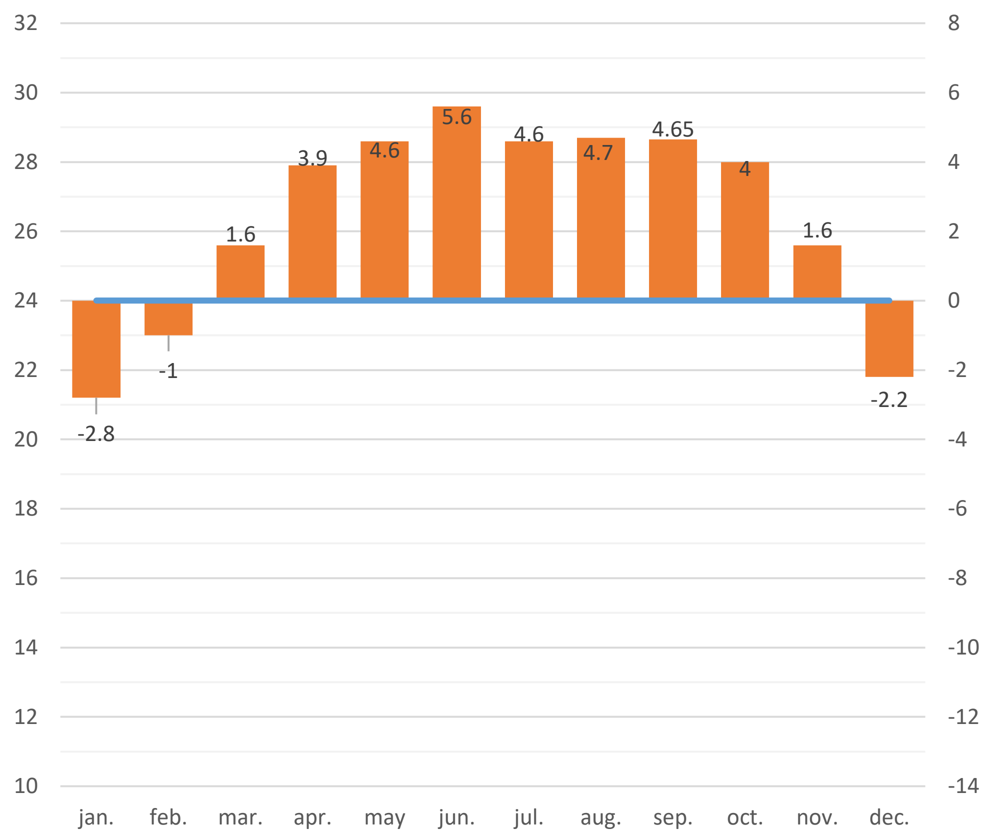


Figure 2.23 Monthly maximum Effective temperature deviation from comfort temperature (24 deg C).

Table 2.4 Discomfort index calculation

Season	Month	Discomfort level deg C	Duration (month)	Index	Percentage
Hot dry	March	1.6	1	1.6	
	April	3.9	1	3.9	
	May	4.6	1	4.6	
				10.1	24.5
Hot wet	June	5.6	1	5.6	
	July	4.6	1	4.6	
	August	4.7	1	4.7	
	September	4.65	1	4.65	
	October	4	1	4	
	November	1.6	1	1.6	
				25.15	61
Cold dry	December	-2.2	1	2.2	
	January	-2.8	1	2.8	
	February	-1	1	1	
				6	14.5
				41.25	100
Total hot season	(Hot dry+ hot wet)				85.5
Total wet season	(Hot wet)				61

The result shows that the hot season and humid season outweigh the cold dry season.

2.5 Passive cooling

One of the many functions of building is to provide comfort to its occupant. These comfort condition are achieved in the field of thermal, visual or acoustical environments. Invention and technological advancement enable us to achieve this comfort with ease in exchange of energy expenditure. Careful planning and design decision from the inception of the building can significantly reduce energy expenditure and can also provide comfort condition.

In case of thermal and visual environment the design of heating, cooling and lighting of buildings is accomplished in three tiers. The first tier is the architectural design of the building itself to minimize heat loss in the winter, to minimize heat gain in the summer, and to use light efficiently. The second tier involves the use of natural sources such as passive heating, cooling and day lighting systems. Tiers one and two can be accomplished by the architectural design of the building. Tier three involves using mechanical and electrical equipment which uses mostly nonrenewable sources to handle the remaining loads after tiers one and two (Figure 2.24) (Lenchner, 2001). Table 2.5 presents the design considerations at each of the three tiers.

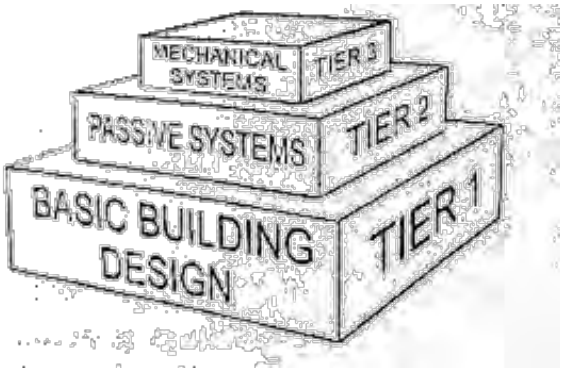


Figure 2.24 The three tier approach to the design of heating, cooling, and lighting systems produces comfortable, energy efficient, economical and sustainable buildings. Source: (Lenchner, 2001)

Table 2.5 The Three Tier Design Approach. Source: (Lenchner, 2001)

	Heating	Cooling	Lighting
Tier 1 Basic Building Design	**Conservation** 1. Surface to volume ratio 2. Insulation 3. Infiltration	**Heat avoidance** 1. Shading 2. Exterior colors 3. Insulation	**Daylight** 1. Windows 2. Glazing type 3. Interior finishes
Tier 2 Natural Energies and Passive Techniques	**Passive Solar** 1. Direct gain 2. Trombe wall 3. Sun Space	**Passive cooling** 1. Evaporative cooling 2. Convective cooling 3. Radiant cooling	**Day lighting** 1. Skylights 2. Clerestories 3. Light shelves
Tier 3 Mechanical and Electrical Equipment	**Heating equipment** 1. Furnace 2. Ducts 3. Fuels	**Cooling equipment** 1. Refrigeration machine 2. Ducts 3. Diffusers	**Electric light** 1. Lamps 2. Fixtures 3. Location of fixtures

Passive cooling can utilize the same general principle of three tiers approach mentioned in above section (Figure 2.25).

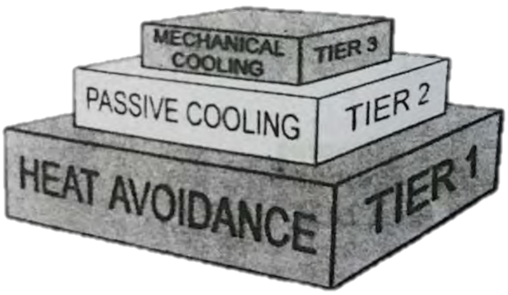


Figure 2.25 Cooling need of buildings are best and most sustainably achieved by the three tier design approach. Source: (Lenchner, 2001)

Furthermore, passive cooling of buildings can fall under three broad division based on thermal energy: heat prevention/reduction, (reduce heat gains): thermal moderation (modify heat gains); and heat dissipation (remove internal heat). These three broad categories are then further subdivided into other categories which shows the means by which these broad categories are adopted. The detail of these categories and sub categories are boiled down in detail diagram which are shown in Figure 2.26 (Geetha and Velraj, 2012).

2.5.1 Solar and heat protection techniques (*Reduce heat gains)*

A building is part of an environment and thus must be designed to assimilate to its climate of the region in which it resides. A building itself sustains a climate (microclimate) of its own. Therefore, adequate measurements must be taken such as "minimization of internal heat gain" for consideration in order to maximize the effectiveness of the passive cooling technique.

In addition, a site design is also heavily influenced by other external factors such as economic concern, zoning rules and regulations, and contiguous developments, which can contribute considerably towards designing a building. To improve microclimate of a construction, available wind and artificial greenery could be a very useful method for reducing incident solar radiation and thus serves both aesthetic and functional (reduce the cooling load) aspect of the design.

Solar control is the best measure against heat gain protection. Implementation of different shading devices is used to mitigate incident solar radiation. The components of the three major divisions are enumerated in the following paragraphs (Geetha and Velraj, 2012; Wikipedia, 2017).

Microclimate: Climate is the average atmospheric condition of an entire region over an extended period of time as opposed to microclimate which consists of certain aspects, such as topographical influences (Figure 2.27), soil content, and urban structure. Climate of urban area varies considerably from that of a rural area, due to human modification of nature. This modification effect can be attenuate significantly by different strategies, such as, landscaping, vegetation, and water management. (Geetha and Velraj, 2012)

Solar control: Impact of solar radiation on structure typically rely on but not limited to climate, region, geographic position, and sea level, time of year and day, and surface angle. Excessive radiation inside interior space is unfavorable for thermal comfort and thus is of pivotal importance of consideration while designing a structure. Aperture, a means for passive cooling, with optimal combination of orientation, size and tilt of the openings can maximize solar radiation in winter and minimize solar radiation in summer (Mazria, 1979). Glazing can also contribute to solar radiation. Insulation, selective coating with optical properties, absorbing and reflecting surface (Figure 2.29) can be used to obtain desirable effect (Seeboth, Schneider and Patzak, 2000; Kaushika and Sumathy, 2003; Gugliermetti and Bisegna, 2003) . Shading can affect the radiation on a structure by preventing partial to complete penetration of sunbeam (Figure 2.28). Heat transmission through envelop (wall, roof, floor) can also add to heat gain. Thermal insulation can be used to reduce heat transmission. However, this methods requires extensive and integrated analysis to implement since critical decisions could lead to synergy or rise in cost. (Geetha and Velraj, 2012)

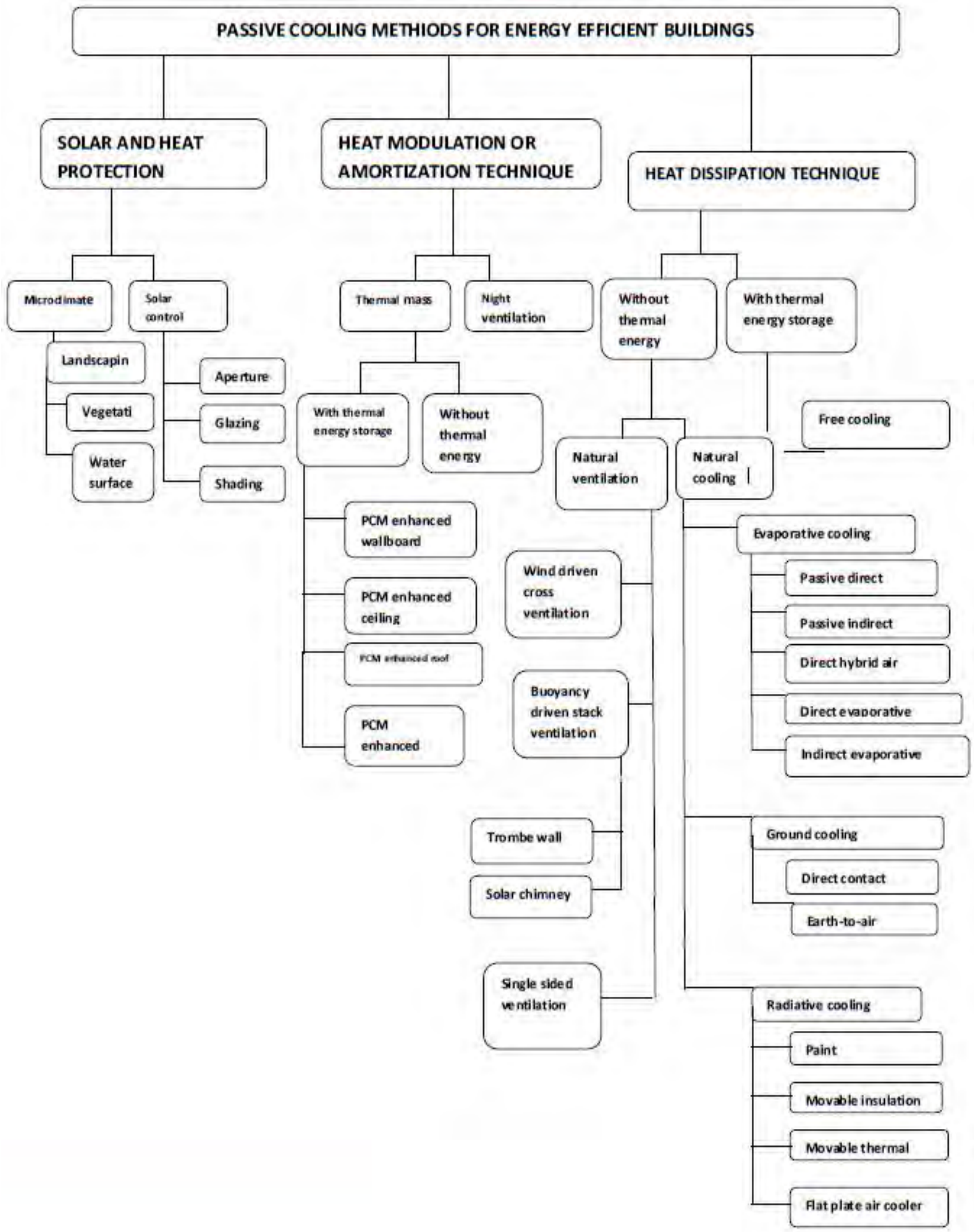


Figure 2.26 Passive cooling methods for energy efficient building. Source: (Geetha and Velraj, 2012)

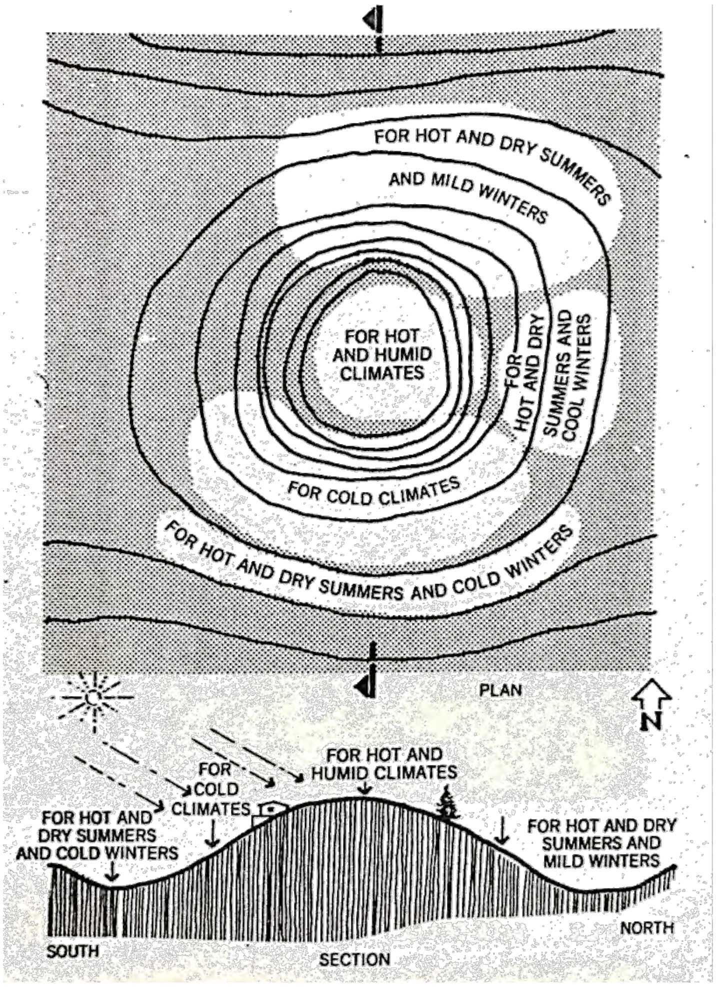


Figure 2.27 Preferred building sites around a hill in response to microclimate for envelop dominated building. Source: (Lenchner, 2001)

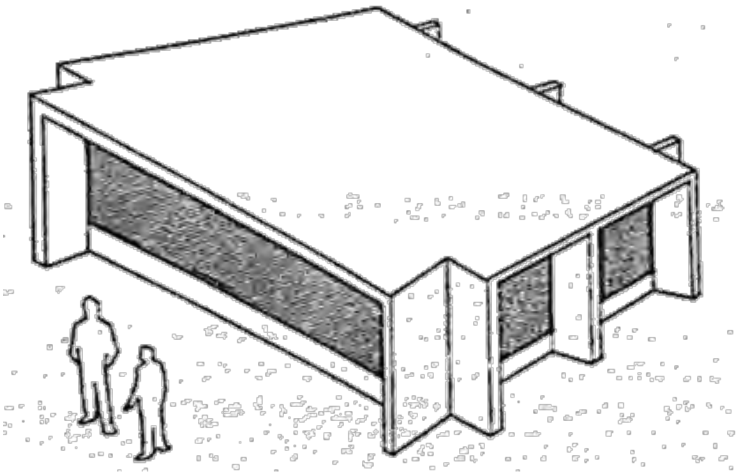


Figure 2.28 Well designed shading devices often combined vertical and horizontal elements and can protect against solar radiation. Source: (Lenchner, 2001)

	a				b		
Reflected	9%	Transmitted	75%	Reflected	7%	Transmitted	43%
Reradiated	8%	Reradiated	8%	Reradiated	25%	Reradiated	25%
Excluded	17%	Gain	83%	Excluded	32%	Gain	68%

Figure 2.29 Performance comparison of (a) ordinary glass and (b) heat absorbing glass (right). Source: (Koenigsberger et al., 2003)

2.5.2 Heat modulation or amortization technique (Modify heat gains)

The thermal management can be obtained by the following two techniques.

Thermal Mass: One of them; "thermal mass of a building" (constructing walls, floors, partitions using materials with high heat capacity) used with the aim of absorbing radiation during day time and controlling the indoor temperature swings. The purpose is to reduce peak cooling load and disseminate remaining heat to the surroundings. Desired outcome could be achieved by either using of heavy construction material or by using Phase Change Material (PCM) with high thermal inertia in various surfaces on a structure (i.e. PCM in wallboard, roof and ceiling) in the construction process (Pasupathy, Velraj and Seeniraj, 2008).

Night Ventilation or night flush cooling: The second method calls for storing low temperature during night by night ventilation, and this 'in-stored coolness' is in turn used as a means to bar the temperature from rising during day time, resulting in substantial reduction of energy consumption for cooling. Night ventilation performs better in hot and dry climates with a daily temperature range above 17°C, but it can be used in moderately humid region with diurnal range of 11°C. It works in two stages. At night natural ventilation or fan brings in cool outside air inside the building, consequently cools it. In the following day openings of the building are closed to prevent hot outside air entering into the building, thereby avoiding heating of the building (Figure 2.30) (Lenchner, 2001). Physical parameters of the building and ambient climatic condition of the region are crucial in the performance of night ventilation.

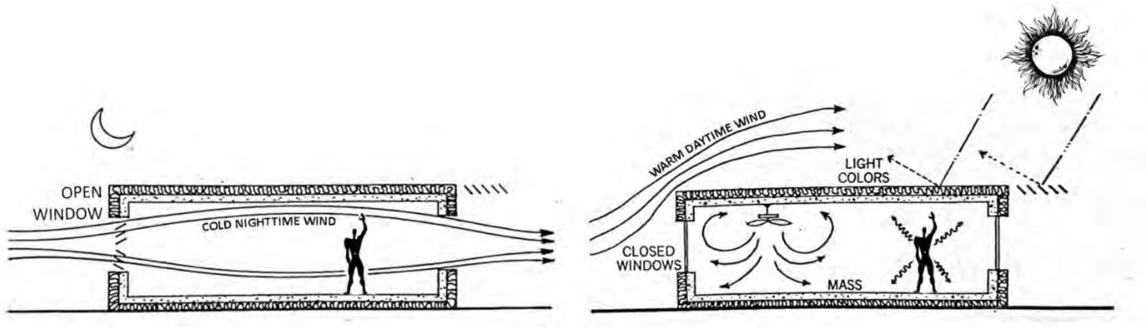


Figure 2.30 Night cooling uses cool air of the night to flush out the heat from the building and thereby the building act as a heat sink during day. The building must have to be sealed from hot outside air during day to effectively use night flush cooling. Source: (Lenchner, 2001)

2.5.3 Heat dissipation technique (removing internal heat)

Sometimes the two abovementioned techniques do not suffice in obtaining desired outcome, hence a more advanced cooling strategy is required. "Natural ventilation" a term denoting the use of natural heat sinks in-order to disseminate excess interior heat to ambient is used. It is in fact de facto important passive cooling technique, which modern architecture mostly overlook due to an attempt to reduce daytime infiltration of radiation by constructing large glass structures. Effective use of natural ventilation requires an in-depth knowledge of air flow pattern around the structure, with a view to ventilate largest possible indoor space. Some of these techniques are following.

Natural Ventilation: One way to achieve natural ventilation is to use "Wind-driven cross ventilation". It basically deploys ventilation opening on opposite sides of an enclosed space (Figure 2.31). Buoyancy-driven stack ventilation or displacement ventilation (DV) as it is sometimes coined, uses density difference of air to draw cool, fresh air from outside through exhaust and small openings. This type of strategy requires a chimney to create adequate elevation to achieve the required flow. Single-sided ventilation, as the name recommend, uses opening on one side in a single room, thus used for localized ventilation solution.

Natural Cooling: Another method of passive cooling is natural cooling that uses evaporative cooling, ground cooling, radiative cooling, or a combination of these three.

Evaporative cooling uses an element (i.e. water) with high latent heat to absorb an interior ambient heat to change its phase thus maintaining a comfortable and tolerable heat level (Figure 2.32). Passive direct systems include the use of vegetation for evaporation, the use of fountains, sprays, pools and ponds as well as the use of porous material saturated with water. Evaporative cooling can be direct or indirect. In the case of direct evaporative cooling, evaporation takes place in indoor air then the temperature drops at the same time the humidity rises. This is desirable in hot and dry climates but not applicable for humid climates as the humidity is already too high. Indirect evaporative cooling works in a similar principle except the evaporation takes place outside of the space to be cooled, thereby avoiding humidifying the inside air.

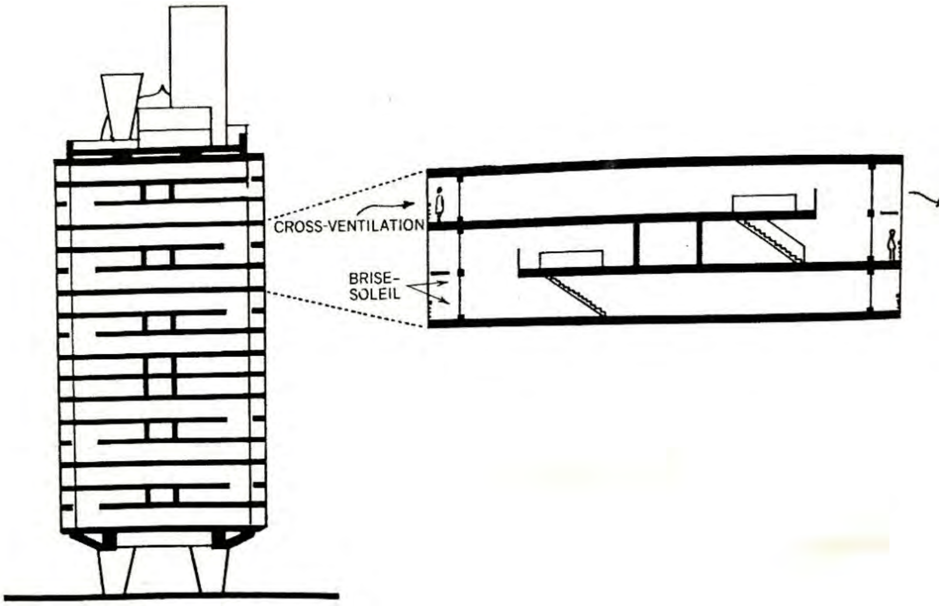


Figure 2.31 Le Corbusier designed Unite d'Habitation to provide cross-ventilation for each apartments. The apartments are designed as duplexes and corridors are provided only every third floor to ensure cross ventilation in each apartment. Source: (Lenchner, 2001)

Ground cooling rely heat dissemination from a structure to the ground. This is useful method during the hot days because ground temperature differs considerably than the indoor ambient heat. This is achieved by either putting large section of envelope of the structure directly in contact with the ground or by circulating cool underground air (Figure 2.33). The temperature of the ground must be taken into consideration for ground cooling. The surface of the ground fluctuates with air temperature. But the fluctuations decreases with depth of the ground. At about 20 feet depth, annual temperature fluctuations almost disappear and a steady state temperature exists year round (Figure 2.34). This steady state temperature is equal to the annual air temperature (Lenchner, 2001).

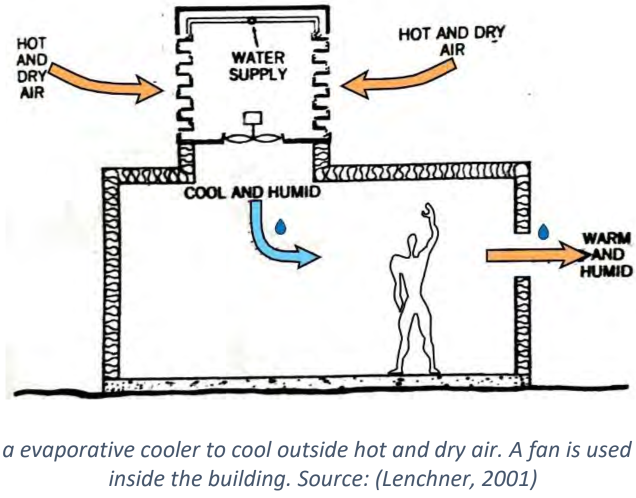


Figure 2.32 Water used in a evaporative cooler to cool outside hot and dry air. A fan is used to draw cool and humid air inside the building. Source: (Lenchner, 2001)

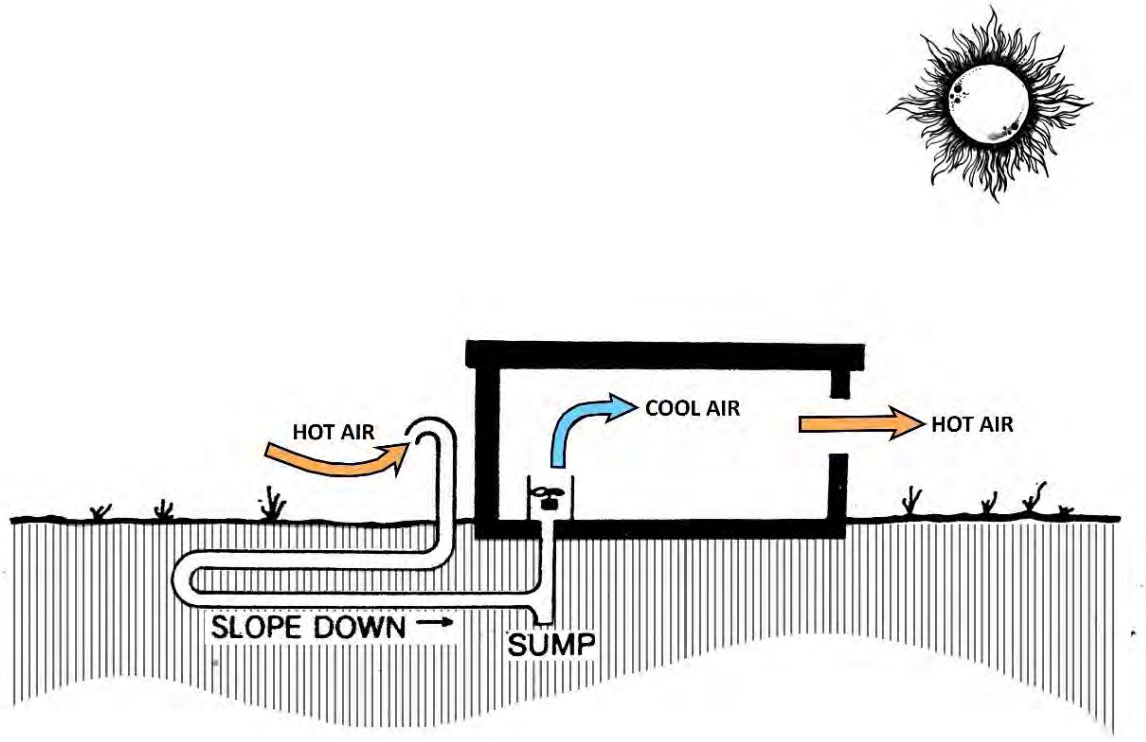


Figure 2.33 In indirect earth cooling with an open loop system a tube is buried in the ground to cool the hot outside air. The air passes through the tube and enters into the building. Source: (Lenchner, 2001)

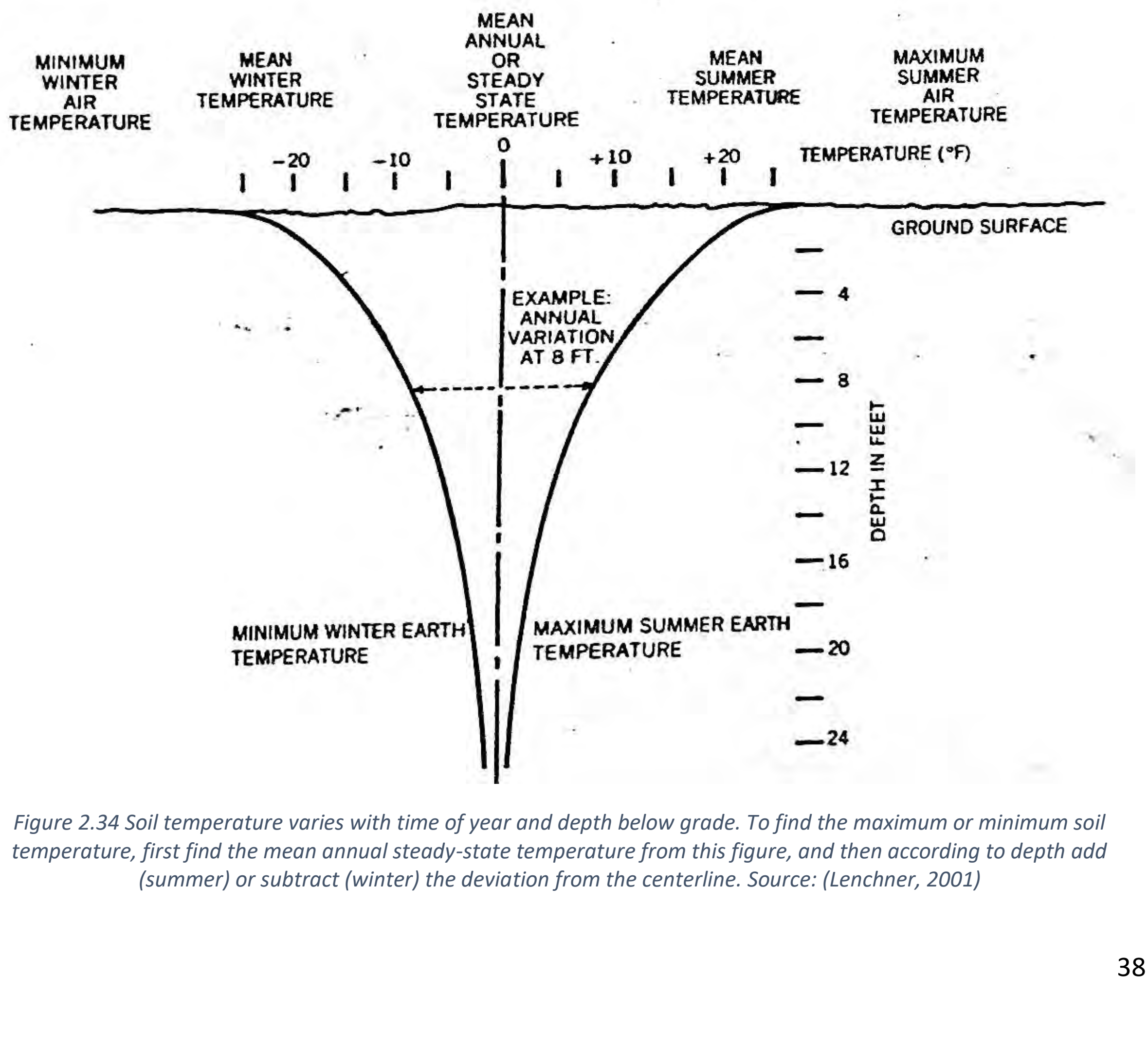


Figure 2.34 Soil temperature varies with time of year and depth below grade. To find the maximum or minimum soil temperature, first find the mean annual steady-state temperature from this figure, and then according to depth add (summer) or subtract (winter) the deviation from the centerline. Source: (Lenchner, 2001)

Radiative cooling uses properties of heat itself to lead to heat sink. Heat tends to be emitted from higher temperature objects towards lower temperature objects. In this scenario, the structure is the heated objects and the sky functions as a heat sink. These are of two kinds: direct or passive radiative cooling; and hybrid radiative cooling.

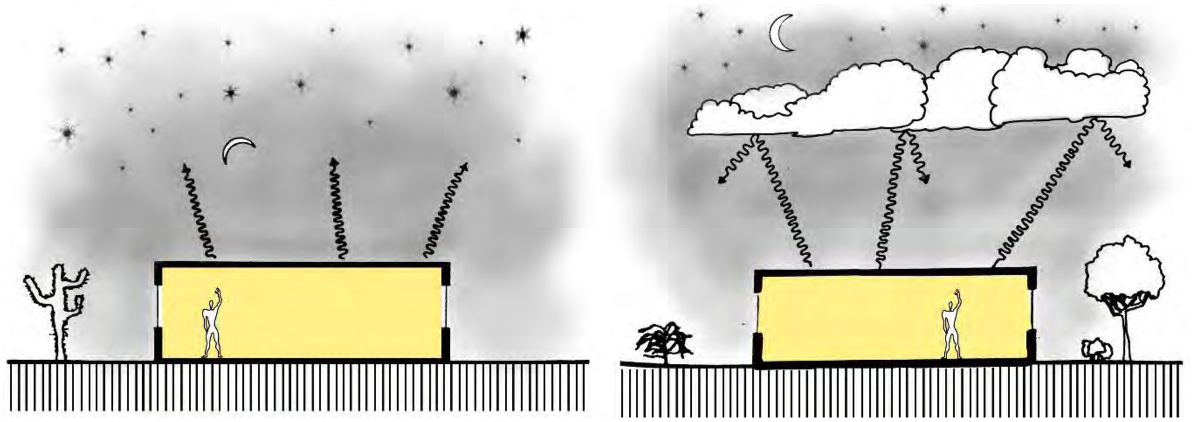


Figure 2.35 The night sky act as a heat sink the roof radiates heat to the night sky. Any obstruction (e.g. Cloud, dust or humidity) reduces efficiency of the radiative cooling. Source: (Lenchner, 2001)

Direct radiative cooling uses the surface of the structure or "the envelope of the structure" as it most of the time called, emits towards the sky and thus become cooler. Since the roof has the maximum exposure to the sky, it can be used as an effective radiator. The roof must then be protected from outside heat sources at day by means of insulation and this insulation must be moved at night for effective radiative cooling. High humidity can reduce the efficiency of the radiative cooling and overcast sky can stop radiative cooling (Figure 2.35). Some notable direct radiative cooling system are shown in the following figures (Figure 2.37 - Figure 2.38).

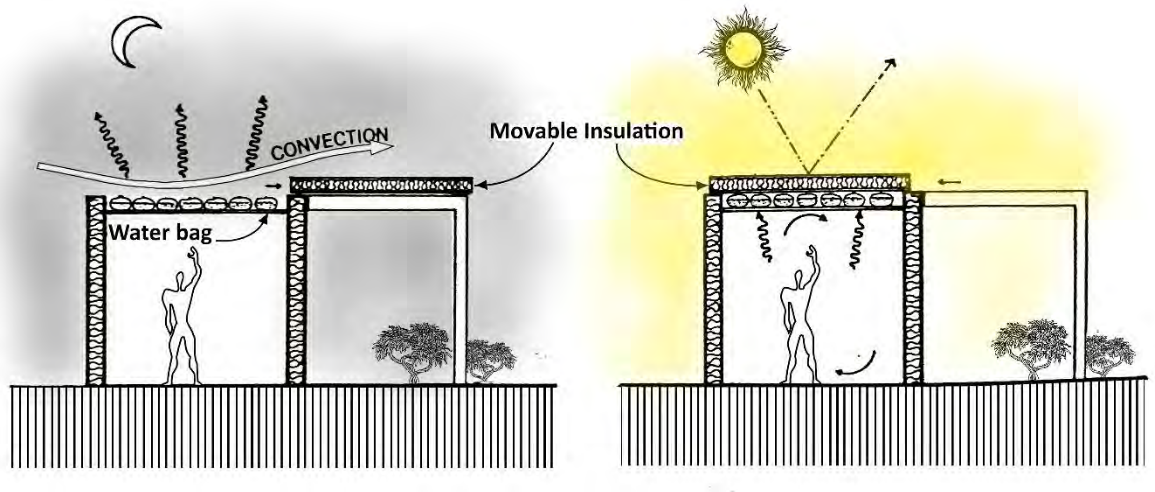


Figure 2.36 Water bag can be used as a radiating roof with movable insulator. The insulation prevent heating the water bag during the day.

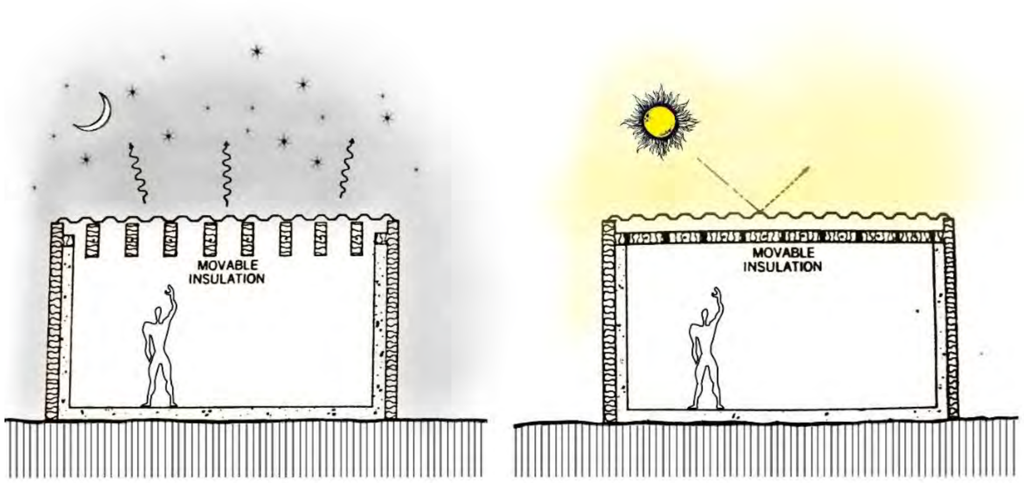


Figure 2.37 Operable insulation can also be used in direct radiative cooling to insulate the building during daytime.

In case of *Indirect radiative cooling* the radiator is a metal plate rather than the envelope itself and this metal plate radiator cools outside air which is then blown into the building by fan (Figure 2.38) (Geetha and Velraj, 2012; Lenchner, 2001).

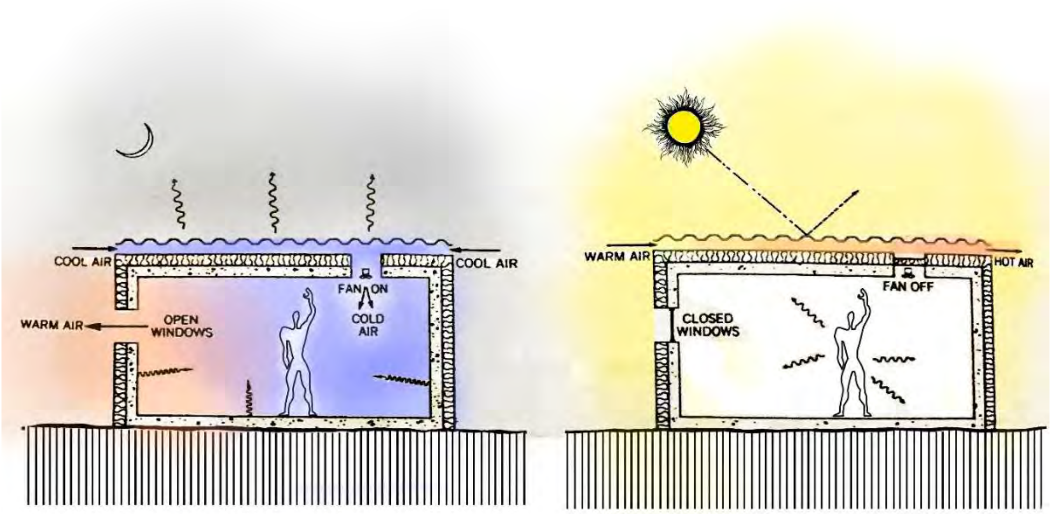


Figure 2.38 Indirect radiative cooling uses specialized radiator to cool air, which is then blown into the building to cool the mass.

2.6 Codes and standards

Bangladesh National Building Code (BNBC, 2006) provide minimum standards for regulating and controlling the design, construction, installation, quality of materials, location, operation, maintenance and use of air-conditioning, heating and ventilation systems to ensure public health, safety and welfare.

According to BNBC (2006) Air-conditioning, heating and ventilation system shall be designed, constructed and installed in accordance with good engineering practice such as described in the

ASHRAE (American Society of Heating, Refrigerating and Air-conditioning Engineers) Handbooks, HRA (Heating, Refrigerating and Air-conditioning Institute of Canada) digest, HI (Hydraulic Institute of USA) manuals and IHVE (Institute of Heating and Ventilating Engineers, UK) Guide (HBRI and BSTI, 2006).

Although there is no specific guideline, it is mentioned in BNBC (2006) that through building planning e.g. orientation of building, building design and use of material, glazing design, insulation material energy consumption should be optimized. For inside design condition the following guidelines are provided in BNBC (Table 2.6 and Table 2.7).

In section 3.3.2.1 (a), it is stated that to avoid thermal shock, the difference between the dry bulb temperatures of outdoor air and indoor air shall not exceed 11 deg C. If it is absolutely necessary to have a difference more than l1 deg C, there shall have adequate provision for ante-room to reduce the effect of thermal shock.

Velocity of air is described in section 3.3.2.1 (d). In an air-conditioned space, in the zone between the floor level and the 1.5 m level, shall be within 0.12 m/s and 0.25 m/s for comfort applications for commercial buildings, and for other applications it shall not exceed 0.5 m/s.

Table 2.6 Inside design condition for summer. Source: BNBC (2006)

Type of Application	**Normal Practice**			**Special Practice**	
	Dry Bulb deg C	Relative Humidity %	Temperature Swing deg C	Dry Bulb deg C	Relative Humidity %
GENERAL COMFORT **Apartment, House, Hotel, Office, Hospital, School etc.**	24.5~26	50~55	1~2	23.5~24.5	50

Table 2.7 Required Mechanical Ventilation Air. Source: BNBC (2006)

Occupancy Classification	**Required Ventilation Air (ACH)**
Hospitals, nursing and convalescent homes	
Autopsy room	12
Delivery rooms, Trauma rooms	15
Laboratories	6
Operating rooms	20
Patient rooms	2
Pharmacy, medication rooms	4
Physical therapy areas and treatment rooms	6
Recovery and intensive care rooms	6
Soiled utility rooms, janitor closets	10

For outside design conditions and outdoor air requirements BNBC provide following guideline shown Table 2.8 and Table 2.9 for HVAC designing.

Table 2.8 Outside design condition for major cities

Column-1	Column-2						Column -3	Column-4		
Name of City	**Design Dry Bulb and Mean Coincident Wet Bulb Temperature (deg C)**						**Mean daily range (deg C)**	**Design Wet Bulb Temperature (deg C)**		
	1%		**2.5%**		**5%**			**1%**	**2.5%**	**5%**
	Dry bulb temp.	**Wet bulb temp.**	**Dry bulb temp.**	**Wet bulb temp.**	**Dry bulb temp.**	**Wet bulb temp.**				
Dhaka	36	27.5	35	27.5	34	28	7.5	29.5	29	28.5
Chittagong	33.5	27.5	33	27.5	32.5	27.5	7.0	28.5	28	27.5
Khulna	36.5	29	35.5	29	34.5	29	8.0	30	29.5	29
Rajshahi	39.5	24	38	24.5	36	25	9.5	29.5	29	29

Table 2.9 Outdoor air requirements

Occupancy Classification	Outdoor Air Quantity (l/s per Person Unless Otherwise Indicated)	
	Recommended	Minimum
Hospitals, nursing and convalescent homes		
Autopsy room	20-25	15
Delivery rooms, Trauma rooms	-	10
Laboratories	10-12.5	7.5
Operating rooms	-	10
Patient rooms	7.5-10	5
Pharmacy, medication rooms	10-12.5	7.5
Physical therapy areas and treatment rooms	10-12.5	7.5
Recovery and intensive care rooms	-	7.5
Soiled utility rooms, janitor closets	3.5-5	2.5

Considerable amount of literature on comfort standard for hospitals and other healthcare buildings are available at present (Khodakarami and Nasrollahi, 2012). Some of the studies are focused on the environment parameters such as indoor temperature, humidity and air movement; some are concentrated on thermal discomfort and thermal sensation of patients and hospital staffs. Investigation also carried out to determine the effect of temperature and humidity variation on infections, bacterial growth, and air borne diseases, indoor air quality and hygiene (Khodakarami and Nasrollahi, 2012). At present, two different approaches for the definition of thermal comfort coexist, each one with its potentialities and limits: the rational or heat-balance approach and the adaptive approach. The rational approach uses data from climate chamber studies to support its theory, best characterized by the works of Fanger while the adaptive approach uses data from field studies of people in building (Djongyang, Tchinda and Njomo, 2010; Doherty and Arens, 1988).

2.6.1 Rational or heat balance thermal comfort model

Codes and guidelines in ASHRAE (2003) application handbook are influenced by the measure of infection control as well as comfort. Table 2.10 briefly describes the indoor environmental parameters recommended by ASHRAE (2003). Guidelines for hospitals are usually provided as a measure for infection control. Air temperature and relative humidity can inhibit or promote the growth of bacteria and activate or deactivate viruses. High temperature can cause out-gassing of toxins from building materials and low temperature can cause discomfort and delay recovery. Low humidity affects also comfort and health such as drying nose, throat, eyes and skin. It also increases susceptibility to respiratory disease. Air velocity of 0.1 m/s is sufficient in occupied areas of patient room (Kameel and Khalil, 2003).

Table 2.10 Factors of indoor air quality recommended by ASHRAE (2003)

Function space	Pressure relationship to adjacent area	Minimum air changes of outside air per hour	Minimum total air changes per hour	All air exhausted directly to outside	Air recirculated within room units	Relative humidity %	Design temperature, ◦ C
Patient room	a	2	6[b]	–	–	30(W), 50(S)	24 ± 1
Newborn nursery suite	a	2	6	–	No	30–60	22–26
Labor/delivery/recovery	a	2	6[b]	–	–	30(W), 50(S)	24 ± 1
Patient corridor	a	2	4	–	–	–	–
General inpatient area not covered in ASHRAE Application handbook [1]	a	2	4	–	–	30–60	≤24

a Continuous directional control not required.
b Total air changes per room may be reduced to four when using supplemental heating and/or cooling systems (radiant heating and cooling, baseboard heating, etc.).
W=Winter
S=Summer

To satisfy patient comfort, in patient rooms required a minimum of 6 ACH (air changes per hour) in inpatient rooms, but in rooms with supplemental heating and/or cooling this rate may be reduced to 4 ACH (Ninomura and Bartley, 2001). The World Health Organization (WHO) on the other hand has documented a specific guideline for natural ventilation of hospitals, in which it strongly recommends the rate of 60 l/s/patient (Atkinson J, 2009).

Regarding to other study by Guyton, Melhado et al. in 2006 have addressed that outside the normal body temperature, which is about 37 ◦ C (36.1–37.2 ◦ C), a person is considered to be sick; however, he/she can survive at a range of 32–42 ◦ C. (Melhado, Hensen and Loomans, 2006). They also discussed that, to prevent patient thermal risk, the temperature must not drop below 21 ◦ C referred to Johnston and Hunter. Moreover, referred to other studies done by Leslie and Sessler and Wildt (2003) they discussed that a temperature between 24◦C and 26◦C is suitable for thermal comfort in general (Guyton, 1998; Leslie and Sessler, 2003; Wildt, 1996).

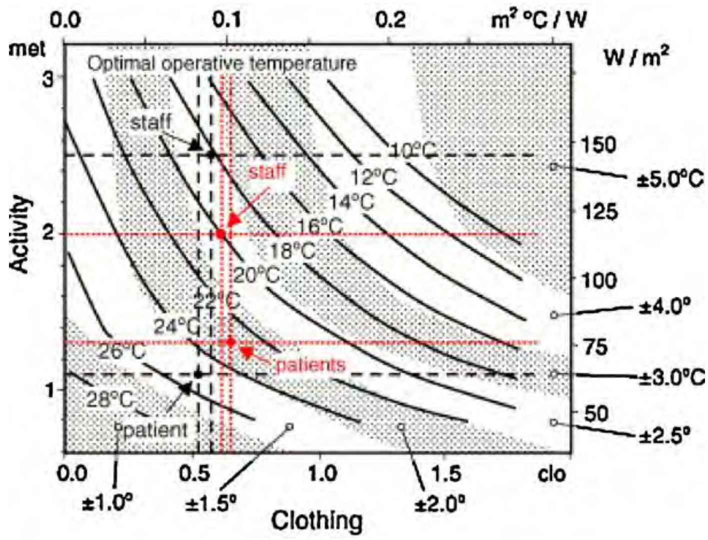


Figure 2.39 Optimum operative temperature in sumer and winter. Source: (Skoog, 2006)

Figure 2.39 presents the difference in optimal operative temperature for patients and staff for both summer and winter. The hospital, subject of this study, is located in southern Sweden. This analysis showed that it is wrong to treat the patients and staff as one coherent group of users with the same needs and performances.

Table 2.11 Thermal comfort ranges in some standards and guidelines

Standard/Guideline	**RH [%]**	**Design temperature [o C]**	**Maximum air velocity [m/s]**	
ASHRAE; 2008	Max. 60	21-24	-	Inpatient nursing: patient room
ASHRAE; 2007	30 (W)-50 (S)	21-24	-	Hospital and outpatient facilities: nursing: patient room
ISIAQ; 2003	<60%, preferable <50%	-	-	Healthcare: patient rooms
College Bouw ziekenhuis-voorzieningen; 2002	-	22.5-25.5	-	Uses -0.5 < PMV < 0.5 for acceptable comfort range
VIPA; 2002	40-65 30-70 30-70	23.5-25.5/21-23 23-26/20-24 22-27/19-25	0.18/0.15 0.22/0.18 0.25/0.21	Optimal (summer/winter) Normal (summer/winter) Minimal (summer/winter)

However, the questionnaire analysis show that both patients and staff are satisfied with the indoor air temperature in both summer and winter seasons. The author discussed that this conflicting results may be yielded from different activity levels and clothing levels of both types of occupants (Skoog, 2006). Some recommendations and guidelines of thermal comfort ranges for design of patient rooms for healthcare inpatient nursing are summarized in Table 2.11

2.6.2 Adaptive thermal comfort model

The requirement for assessing the overheating criteria of building grew out when in late 1980s, dynamic model were capable of predicting the internal temperatures in buildings. This was predominantly necessary for buildings that are free running. In the CIBSE Guide this type of buildings are defined as a building that does not consume energy for heating or cooling. ASHRAE Standard 55 defined same type of building as ‘naturally conditioned’ (Lomas and Giridharan, 2012; ANSI/ASHRAE 55-2004, 2004).

In the late 80s, field work by Humphreys showed that, in free-running buildings, internal temperature preferences increased with ambient temperature (CIBSE, 1986; CIBSE, 1999). While there were various criteria, they were broadly consistent in placing an upper threshold value of 27/28^{o}C and permitting a small number (or percentage) of occupied hours to exceed this. The design criterion used most often today in the UK is that stated in the CIBSE Guide A that “during warm summer weather 25^{o}C is an acceptable temperature” and for offices, schools and the living areas of dwellings, the overheating criterion is “1% annual occupied hours over operative temperature of 28^{o}C”. The Guide notes that local fans that increase air speed can be equivalent to reducing the OT by 2K (Lomas and Giridharan, 2012).

In UK Department of Health published Health Technical Memorandum HTM03-01, which gives the range of internal temperatures for hospitals as 18-28^{o}C for single and general wards with supply-only ventilation. The memorandum notes that mechanical ‘cooling is very expensive’ and so ‘calculations and thermal modelling should be undertaken to ensure that, during summertime, internal temperatures in patient areas do not exceed 28^{o}C (dry-bulb) for more than 50h per year; which equates to about 0.6% of occupied hours as wards are virtually permanently occupied. (Department of Health UK, 2007)

Nighttime thermal comfort also is an important factor in a hospital context. A brief literature review revealed the complexity of providing a criterion, because the way thermal comfort expressed is inapplicable whilst sleeping (Lomas and Giridharan, 2012). Sleep studies thus rely on measurements of rates of heat loss, skin temperature, sleep patterns and nighttime awakening, rather than satisfaction surveys. For homes, the CIBSE Guide notes that “thermal comfort and quality of sleep begins to decrease if bedroom temperatures rise much above 24^{o}C and that “bedroom temperatures at night should not exceed 26^{o}C unless ceiling fans are available” (Lomas et al., 2012; CIBSE, 2006).

Extensive field measurement has been conducted which supported the concept of thermal adaptation (de Dear, 1998). These have led to the development of adaptive thermal comfort standards in which the threshold of acceptable indoor temperature increases as the external ambient temperature increases. The adaptive standards are based on field surveys that inherently account for the various factors that influence thermal comfort.

As data is drawn from across the globe, the adaptive standards are inherently applicable to a very wide range of places and years. Further, being based on measured data, the standards derived are inherently applicable to buildings' performance assessment as well. All this is in stark contrast to the simple criteria described in section 2.7.1. Thus for the occupants of free-running buildings, it seems entirely sensible to use adaptive comfort criteria, rather than the simple, static, non-climate sensitive criteria.

The ASHRAE 55 standard (ANSI/ASHRAE 55-2005, 2010; de Dear and Brager, 1998) provided an 'optional method' for 'naturally conditioned' spaces, i.e. those that are not mechanically cooled, i.e. free-running (ANSI/ASHRAE 55-2004, 2004). Mechanical ventilation with unconditioned air is permissible but spaces must be primarily regulated by occupants' opening and closing of windows. The method applies when occupants are engaged in near-sedentary activity and free to adapt their clothing. The method provides an allowable indoor operation temperature (OT) with upper and lower bounds that increase with the mean monthly ambient air temperature (T_{mm}) at a rate of 0.31 K per K; this is applicable when $10\,^{\circ}C < T_{mm} < 33.5\,^{\circ}C$.

The CIBSE Guide A (CIBSE, 2006), presents an envelope of acceptable indoor OT, which increases with the daily mean ambient air temperature (T_{rm}) at a rate of 0.33 K per K. This is applicable between limits of $8\,^{\circ}C < T_{rm} < 25\,^{\circ}C$. The use of T_{rm}, rather than T_{mm} as in the ASHRAE method, recognizes that adaption takes place over a time scale of days and not months. The guide is applicable to free-running buildings, in which occupants may exercise environmental control, e.g. via operable windows, the use of fans, or by changes to clothing, and it is implicit, but not stated, that the envelope is relevant to normal healthy individuals.

The new European Standard BSEN15251 (BSEN15251, 2008) offers a more holistic approach than the ASHRAE method and, as a national and EU standard has precedence over the CIBSE method. As the standard's title indicates, it is explicitly applicable to both 'design and assessment of thermal environment'. BSEN15251 provides an envelope for acceptable OT that increase with T_{rm}, in this case at a rate of 0.33 K per K over the range $10 < T_{rm} < 30^{o}C$and $15 < T_{rm} < 30^{o}C$ for upper and lower bounds respectively; where T_{rm} is defined identically to the CIBSE method. Importantly, the standard's scope includes 'hospitals', and 'methods for long term evaluation of the indoor environment', and the envelope width depends on the 'Category' of the space under consideration.

The most stringent is Cat I: 'High level of expectation [which] is recommended for spaces occupied by very sensitive and fragile persons with special requirements like, handicapped, sick, very young children and elderly persons'. This category has the narrowest envelope (which is identical to the CIBSE envelope) and will yield less that 6% of normal health persons dissatisfied. Cat II is the 'normal level of expectation and should be used for new buildings and renovations', less than 10% dissatisfied, and

Category III: 'acceptable, moderate level of expectation and should be used for existing buildings', 15% dissatisfied. Here it is suggested that Cat I might apply to hospital wards, Cat II to staff areas, consultation and administrative offices and Cat III to public and circulation spaces. The standard does not place strict limits on the frequency at which the Category limits may be exceeded, although exceed of 3-5% of hours are suggested.

Figure 2.40 compares the aforementioned adaptive comfort standards and their equation, ranges and applicability.

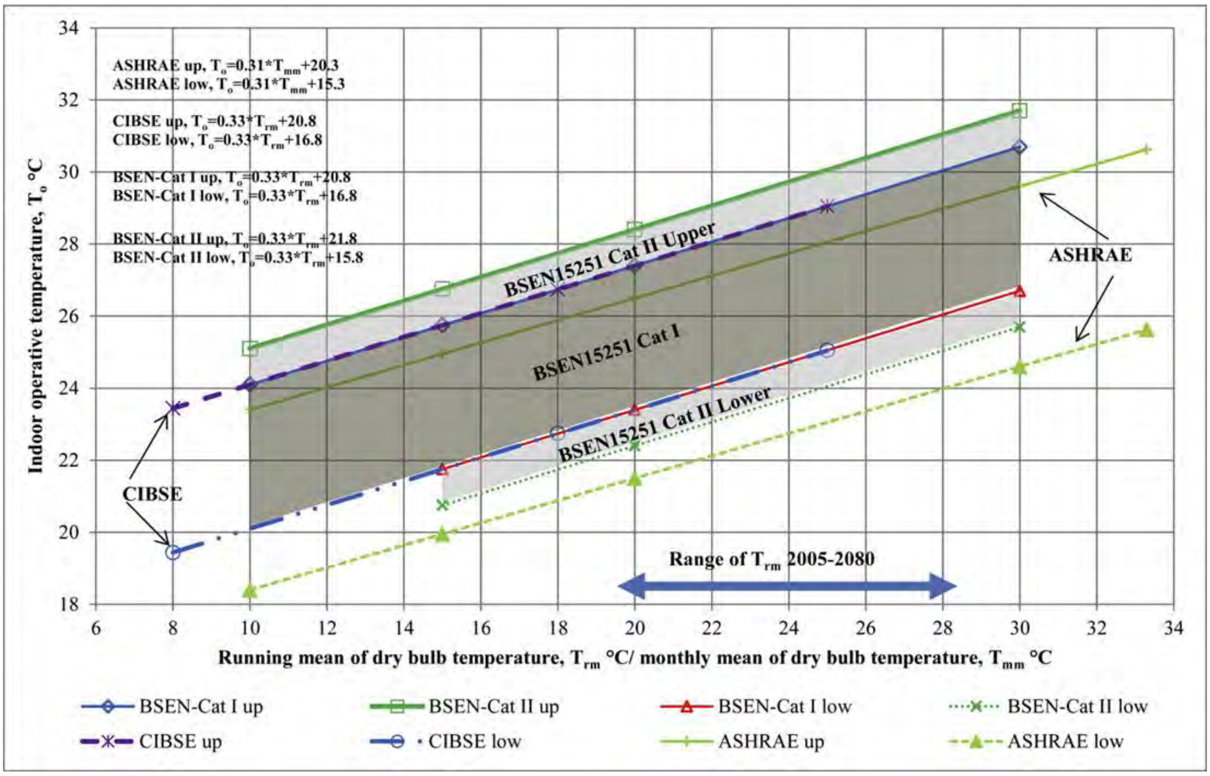


Figure 2.40 Comparison of adaptive thermal comfort standards: equations, envelopes, boundaries and limits of applicability. Source: (Lomas and Giridharan, 2012)

Table 2.12 presents operative temperature calculated from ASHRAE, CIBSE and BSEN15251 comfort standards based on outdoor temperature i.e. mean monthly ambient air temperature (T_{mm}) and daily mean ambient air temperature (T_{rm}) of Rajshahi. BSEN15251 offers wide range of operative temperature in three categories that also include hospitals unlike other standards. Therefore in this study BSEN15251 is used for thermal comfort standard to facilitate passive cooling inside inpatient rooms in the context of Rajshahi.

2.7 Hospitals in Bangladesh

The health system of a country is the societal response to the determinants of health. The health care institutions provide treatment for patient with a wide range of acute and chronic conditions. Hospitals vary in type of specialisms they support, in their provision of specialist curative medicine, preventive medicine and aftercare (rehabilitation), examination (diagnostics) and treatment (therapy); in the intensity of care, the standard of accommodation and level of welfare, psychiatric care, and training and research activities.

Table 2.12 Operative temperature derived from ASHRAE, CIBSE and BSEN

		Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
		Winter			**Pre monsoon**			**Monsoon**				**Post Monsoon**	
ASHRAE	Indoor operative temp low: deg C	21.3	20.8	21.6	23.2	24.4	24.4	24.5	24.3	24.4	24.3	23.8	22.6
	Indoor operative temp up: deg C	26.3	25.8	26.6	28.2	29.4	29.4	29.5	29.3	29.4	29.3	28.8	27.6
CIBSE	Indoor operative temp low: deg C	23.1	22.7	23.5	25.2	26.4	26.5	26.6	26.4	26.4	26.3	25.9	24.6
	Indoor operative temp up: deg C	27.1	26.7	27.5	29.2	30.4	30.5	30.6	30.4	30.4	30.3	29.9	28.6
BSEN cat I	Indoor operative temp low: deg C	23.1	22.7	23.5	25.2	26.4	26.5	26.6	26.4	26.4	26.3	25.9	24.6
	Indoor operative temp up: deg C	27.1	26.7	27.5	29.2	30.4	30.5	30.6	30.4	30.4	30.3	29.9	28.6
BSEN cat II	Indoor operative temp low: deg C	22.1	21.7	22.5	24.2	25.4	25.5	25.6	25.4	25.4	25.3	24.9	23.6
	Indoor operative temp up: deg C	28.1	27.7	28.5	30.2	31.4	31.5	31.6	31.4	31.4	31.3	30.9	29.6

While early hospitals were consciously planned as medico-surgical institution, nowadays a shift can be observed towards increasing humanization of the facilities. Modern hospital tends to provide residential atmosphere which is more important than the uncompromising sanitary design of their predecessors. The length of stay of patients is getting progressively shorter. The general hospital is divided into operational areas of care provision, examination and treatment, supply and disposal, administration and technology. In addition, some facilities support residential areas and possibly areas for teaching and research (Neufert and Neufert, 2000).

The form of the hospital building is strongly influenced by the choice of access and circulation routes. Major types of hospitals forms are spine form with branching sections (individual departments) or central core with radial outward circulations.

There should be provision for future expansion and self-contained circulation route must be avoided as it will impede future expansion. The vertical arrangement and circulation should ensure most efficient connection and circulation between the functional areas – care, treatment, supply and disposal, access for bedridden patients, service yard, underground garage, stores, administration and medical services (Neufert and Neufert, 2000).

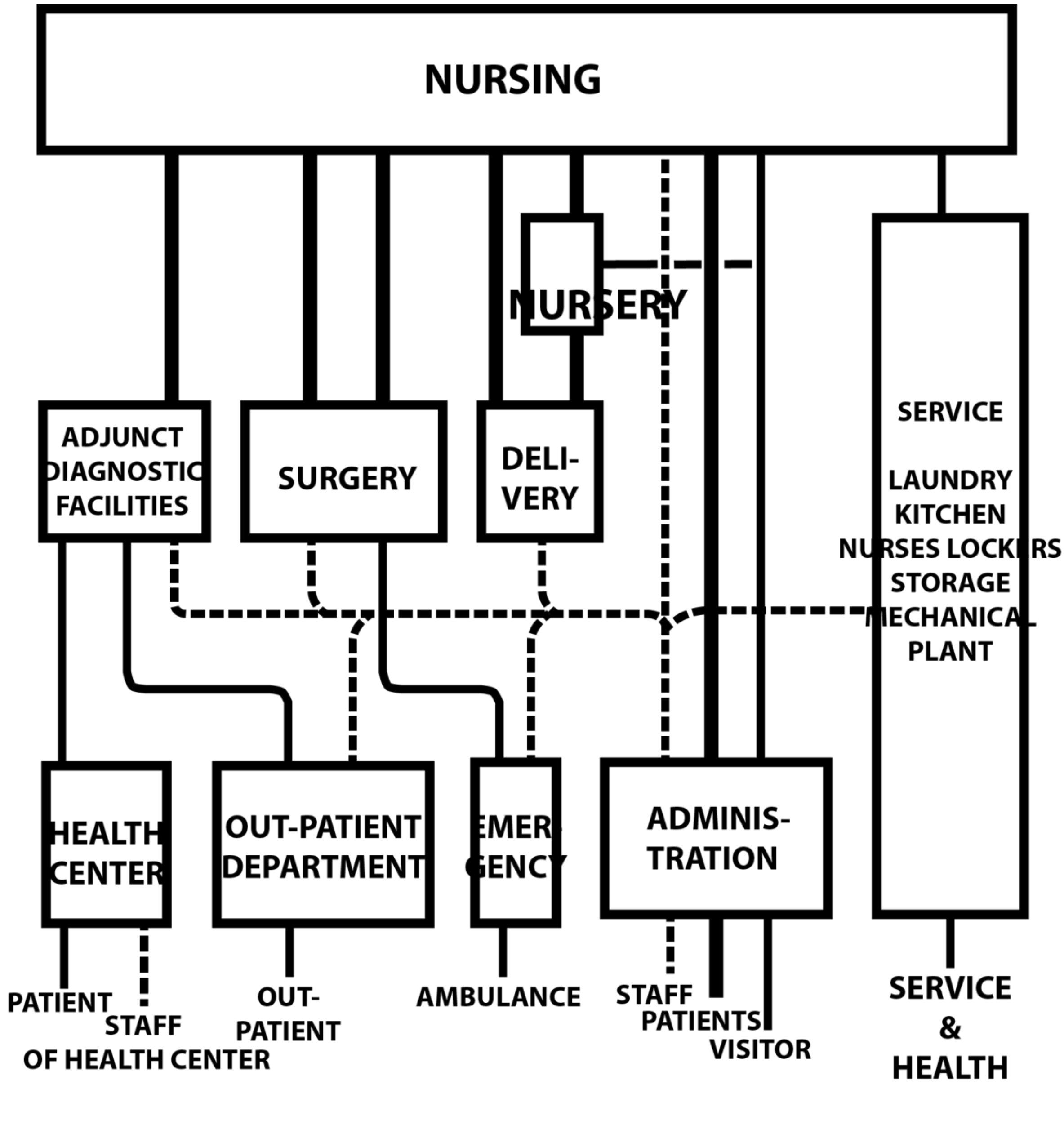


Figure 2.41 Functional Flow chart of a General hospital. Source: (Chiara and Crosbie, 1983)

The Government of Bangladesh is constitutionally committed to "supply the basic medical requirements to all segments of the people in the society" and the "improvement of the nutritional and the public health status of the people". Bangladesh has a well-structured health system with three tiers of primary health care – Upazila Health Complexes (UHC) at the sub-district level, Union Health and Family Welfare Centers (UHFWC) at the Union (collection of few villages) level, and Community Clinics (CC) at the village level. These are backed by the District Hospitals providing secondary level care and the tertiary hospitals of various kind in large urban centers. A total of 536 public hospitals with 37,387 beds provide inpatient care services in Bangladesh for a population of 160 million. District hospitals are usually termed secondary care hospitals since unlike the medical college hospitals these have fewer specialty care facilities. The medical college hospitals are located in the regional urban hubs covering several districts, and provide specialty care in a wide range of disciplines. These hospitals provide tertiary care services (Islam and Biswas, 2014). Large corporate groups, NGOs and charitable organizations are investing in health infrastructure, modern medical equipment and technologies leading to the availabilities of specialty hospitals across the country, especially in large major districts. Following table (Table 2.13) presents the current health care situation in Bangladesh.

Hospitals are complex buildings with a broad range of services and functions. The indoor condition should serve in a way that will ensure thermal comfort, air quality and visual comfort so that patient recovery time is reduced. Also hospitals are required to maintain hygienic conditions. These requirements lead to the fact that the energy demand of hospitals is among the highest of non-residential buildings. Increased energy cost, budget constraints and growing sustainability concerns have changed this approach (Boemi, Irulegi and Santamouris, 2016).

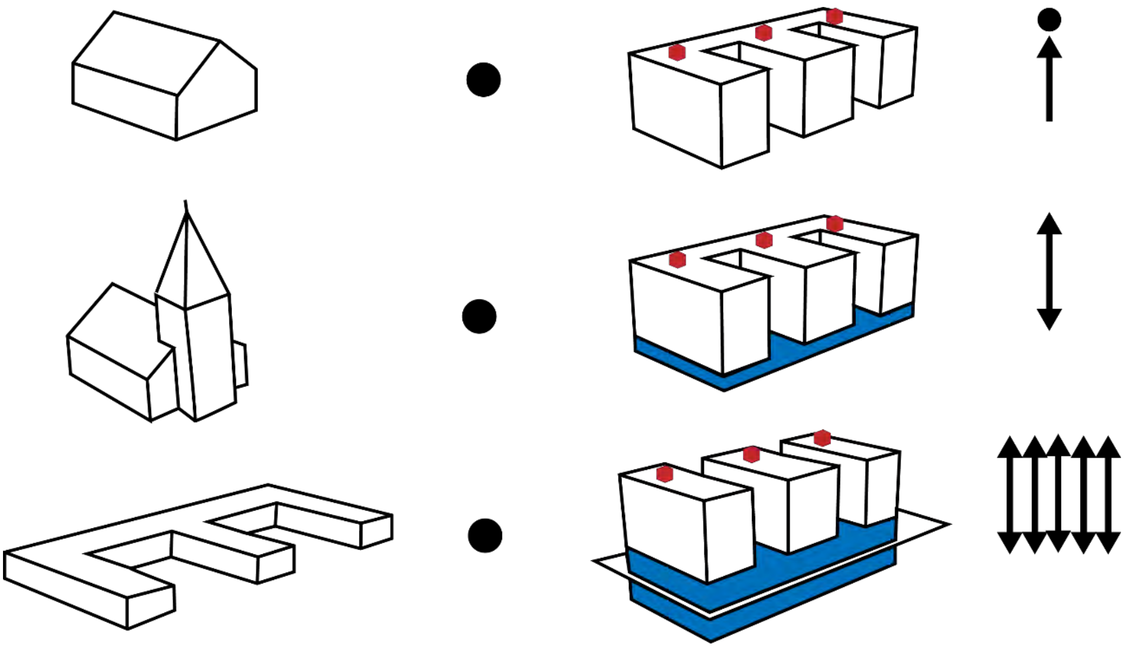


Figure 2.42 Evolution of health care, from "hope" to "podium on platform" type buildings. (Burpee et al., 2009)

The simple form of primitive nursing center transformed into a complex form of “comb” or “rack” design, i.e. pavilion connected by gallery, to accommodate and serve a greater number of people. As technology and specialized services evolved with even more demand for health care services, the form of the hospital extended vertically along with horizontal expansion. Finally the form evolved to a building complex with podium as a base and multiple towers connected horizontally and vertically on top of that base (Figure 2.42).

Table 2.13: Heath care infrastructure and Socio-demographic indicators of Bangladesh. Source: (Islam and Biswas, 2014)

Subject	Indicators	Value
Population	Total Population in million	156.6
	Density (population/km2)	1015
	Crude death rate per 1000 population	6
Life expectancy(years)	Male	66.6
	Female	68.8
	Persons per hospital bed	1860
	No. of doctors per 10,000 population	7.7
Economic indicators	GNI per capita—US$	$640
	PPP GNI per capita	$1620
	Annual growth rate (percent)	6.3
Health Facilities/Hospitals	Sub-district hospitals	413
	Secondary & tertiary hospitals	117
	Medical Colleges	17
	Infectious Disease Control Centers	5
	Chest Hospitals	12
	Community Clinics	10723
Health Workforce in public facilities	Physicians	11,300
	Nurses	13483
	Medical technologists	4,658
	Medical assistants	3,694
	Domiciliary staff	23,285
	Non-medical	218
Health services	Persons per hospital bed	1,860
	No. of doctors per 10,000 population	7.7
Health Financing	GDP spent on healthcare	3%
	Health expenditure as a % government budget	7.4
	Out-of-pocket expenditure for health	65.9 %
	Per capita total expenditure on health (U.S.$)	23
	Per cent coming from development aid/partners	8

The benefits of high indoor environmental quality in hospital was perceived during King Louis XV of France at the end of the eighteenth century. A committee detailed two main types of hospital buildings— the radial and the pavilion. In particular, the latter enabled a significant improvement in ventilation and natural lighting, which became very popular (Figure 2.43). But later the technological developments in health care sector led to a "Technological" and "Industrial" approach, to the provision of integrated services. This "all in one" efficient process, supported by frame structure and rapid development of air conditioning technology, promoted single-block deep plan arrangements. As a result this new type of building has a very limited exposure to natural ventilation and light. Since the 1990s, feasibility of mega block hospitals came under scrutiny because of the concerns for patients and staffs wellbeing as well as long term cost of the buildings' operation. The deep plan, block type hospitals require lower capital investment but eventually their life cycle cost become higher, due to higher operational expenses compared to narrower types of buildings (Glanville R, 2009; Boemi, Irulegi and Santamouris, 2016).

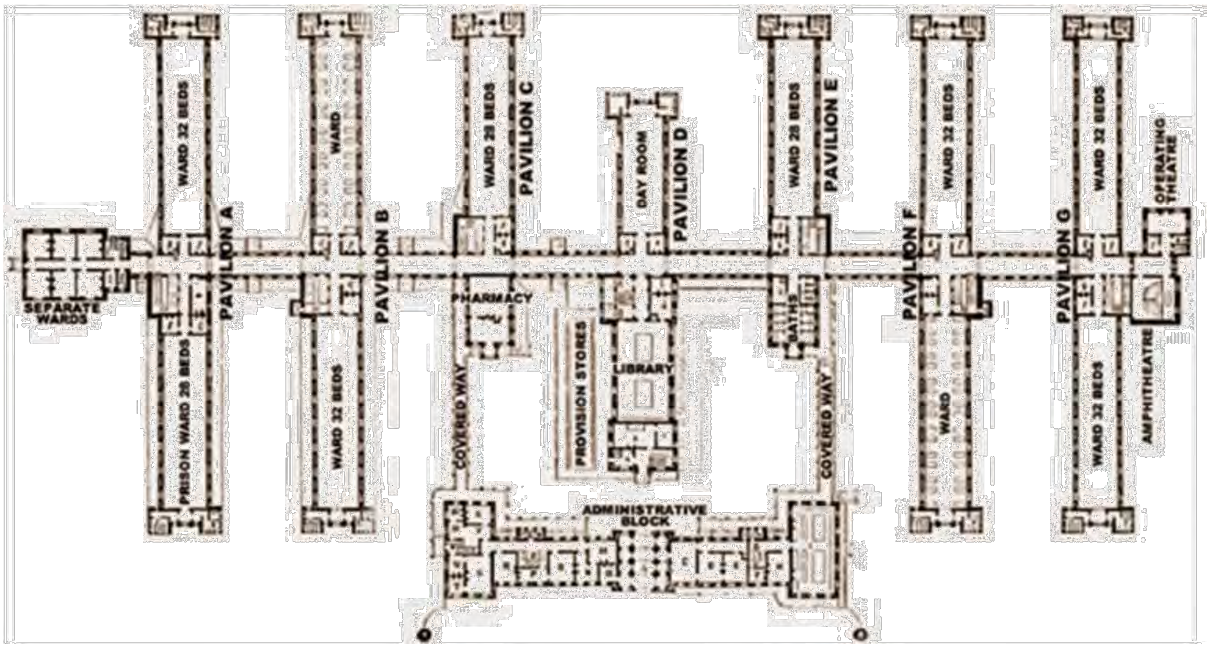


Figure 2.43 Plan of the Royal Herbert Hospital in Woolwich (London) Source: http://www.royalherbert.co.uk/history.php

2.7.1 Hospitals and energy usage

Energy usage in the sense of energy efficiency is the major consideration of sustainability. From many studies carried out in Europe over the last 30 years, it has been established that hospitals are among the biggest energy consumers of all non-residential building types, together with hotels and restaurants (Figure 2.44). In hospital building energy demand are continuous throughout 24 hours a day, all year round, therefore the benefits of energy saving are even greater than an office or commercial center, where energy demand is intermittent. Depending on the hospital type, its size, function, location and the type of its building envelope and HVAC systems specific energy consumption values vary between 250 and 600 kWh/m^2 (Santamouris and Asimakopoulos, 1996).

There are a few reasons for rising energy demand by the hospitals: upsurge of medical equipment use, e.g. medical imaging equipment; trend towards single patient rooms; and requirements for indoor air quality, visual and thermal comfort.

Fast growth in private health care sector also led to higher energy consumption. Many modern hospitals may consume ten to fifteen times more energy per bed as compared to a typical government hospital (Kapoor and Kumar, 2011). The major obstacles have been less awareness among the management of the hospitals and lack of expertise to identify and implement energy saving measures e.g. passive cooling techniques.

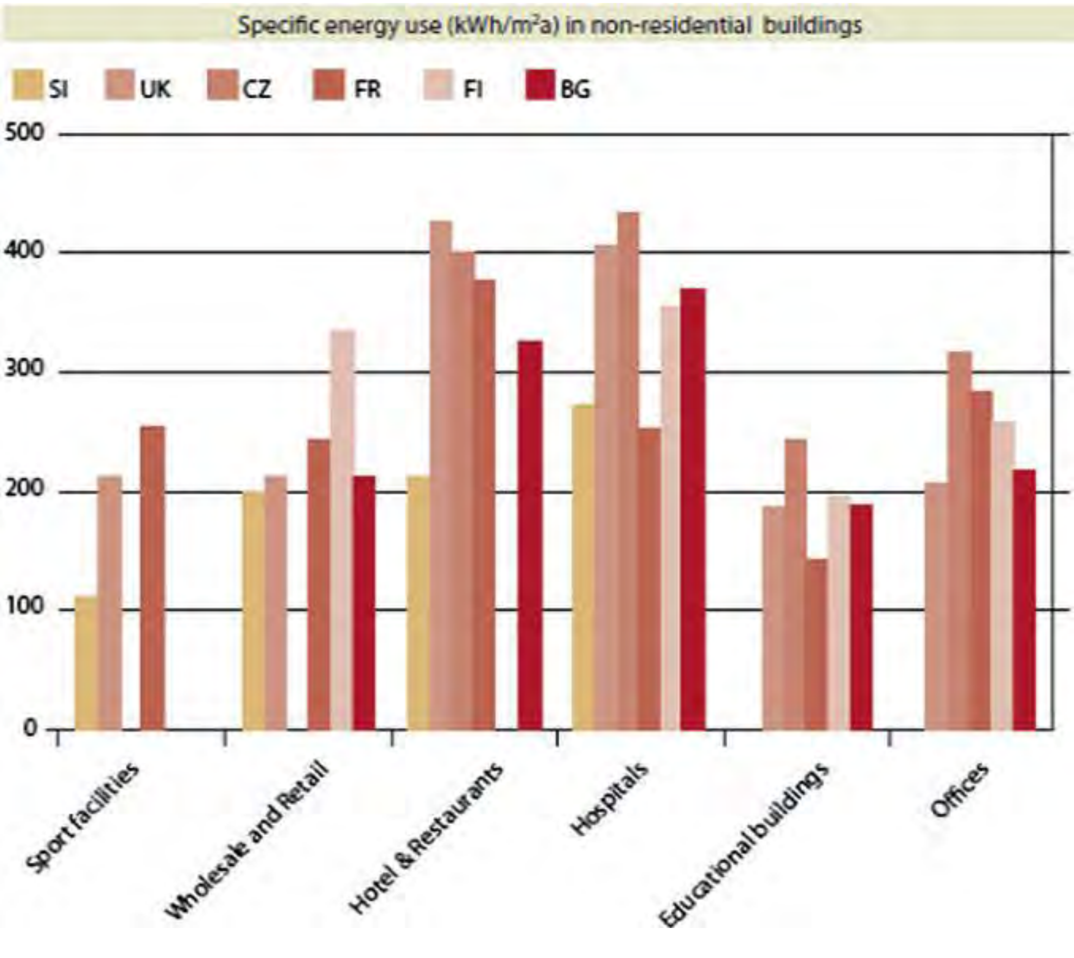


Figure 2.44 Specific energy use in hotels, as compared to other non-residential buildings for specific European country. (Burpee et al., 2009)

A survey in India under USAID ECO III projects made an estimation of electricity consumption and electricity cost estimates. The results are shown in Table 2.14. Government hospitals in the rural area consumes lowest electricity in terms of kWh/Bed/year. On the contrary governmental hospital in urban area yielded higher rate of electricity consumption in kWh/Bed/year. Highest energy consumption are found in private health care sector.

Table 2.14 Estimated electricity consumption in hospitals and nursing home in India, 2009. Source: USAID ECO III Projects, 2010, Center Bureau of Health Intelligence, National health profile, 2009

Hospital type	No of hospital	No of bed	Estimated kWh/Bed/year
Government Hospitals – Urban	3,115	3,69,351	1,000-2,000
Government Hospitals – Rural	6,281	1,43,069	200-400
Private/NGO hospitals	22,000	1,60,000	8,000-25,000
Private Nursing home		4,00,000	3,000-5,000

ECO III also carried out energy audit sample survey to measure Energy Performance Indices in terms of Annual electricity consumption per square meter of the hospital's built up area (kWh/sqm/year) and annual energy consumption per bed (kWh/Bed/year).

Table 2.15 presents EPI trends seen in eleven government hospitals and seven multi-specialty private hospitals.

Table 2.15 Energy Bench marks in selected hospitals in India. Source: USAID ECO III Projects

Sl. No	Type	Category	Climate	No. of Beds	kWh/sqm/year	kWh/bed/year
1	Private	Multi-specialty	Hot & Dry	600	1518	5415
2	Private	Multi-specialty	Composite	130	274	18331
3	Government	City/municipal	Warm & Humid	100	20	608
4	Government	City/municipal	Warm & Humid	330	45	321
5	Private	Multi-specialty	Composite	937	197	9782
6	Private	Multi-specialty	Composite	500	2610	17762
7	Private	Multi-specialty	Composite	500	235	15774
8	Private	Multi-specialty	Warm & Humid	224	239	25781
9	Government	City/municipal	Hot & Dry	1513	93	1194
10	Government	City/municipal	Warm & Humid	1394	33	749
11	Government	City/municipal	Warm & Humid	850	25	1330
12	Government	City/municipal	Hot & Dry	1050	47	1658
13	Government	City/municipal	Hot & Dry	720	23	1886
14	Government	City/municipal	Composite	272	77	6091
15	Government	City/municipal	Composite	200	199	2500
16	Government	City/municipal	Composite	1100	161	4364
17	Government	City/municipal	Hot & Dry	638	269	8026
18	Private	Multi-specialty	Composite	1402	84	15181

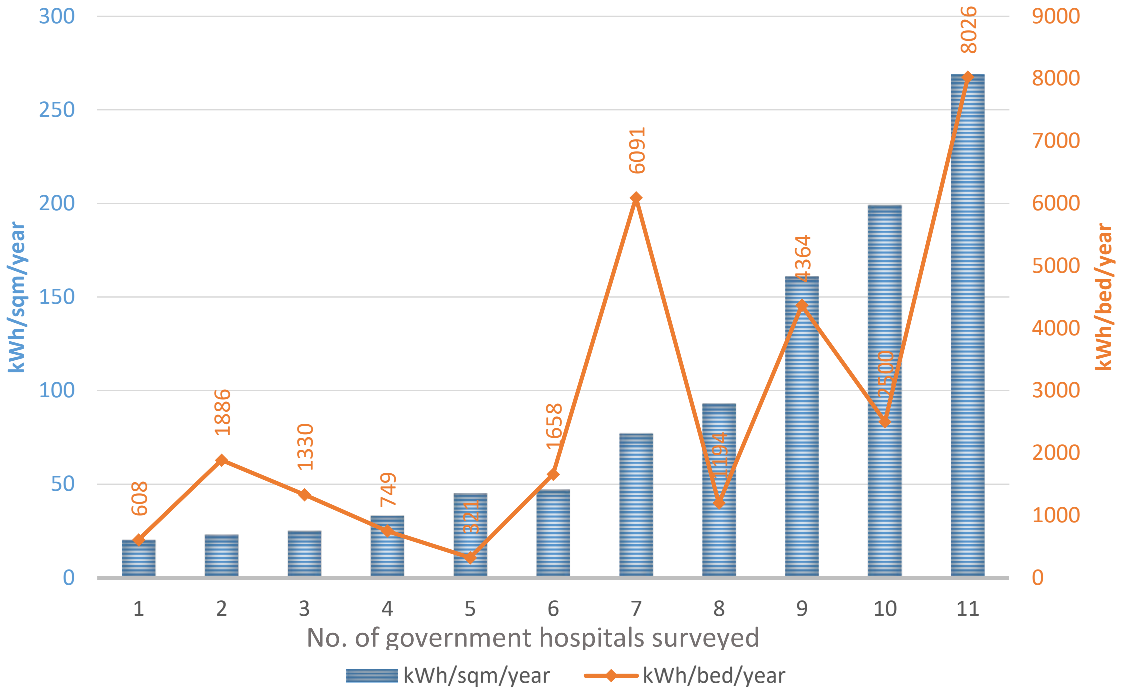


Figure 2.45 Energy Performance-Government Hospital

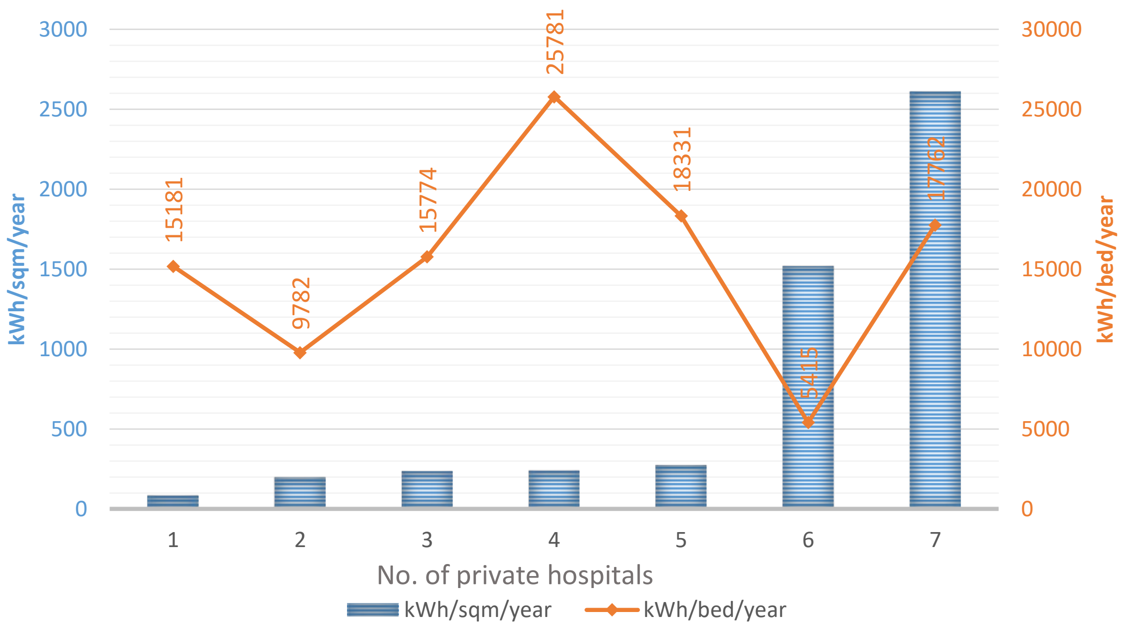


Figure 2.46 Energy Performance - Private hospital

Figure 2.45 and Figure 2.46 show the differences of energy performance of 11 government and 7 private hospitals. Both indices of energy performance kWh/sqm/year and kWh/bed/year show that in private hospitals energy consumption is significantly higher than governmental hospitals. Policy differences to deliver health care services to the patients may conceivably contributed to this fact. Government hospitals are focused on extending its health care services to the mass people economically. Private hospitals are energy intensive due to the nature of specialty health care services and extensive equipment dependency for diagnosis, preference for single room, central heating and air conditioning, compact multistoried building and strict environment control. These findings help to establish energy benchmarking for hospital (government and private hospital) across India with different climatic zone. As a result an online tool 'ECObench' (http://eetools.in/) for commercial building including hospital has been developed. Hospital authority can use this tool to evaluate its building performance by comparing energy performance of similar building that is available in its database. In context of Bangladesh similar program can be launched to create energy benchmark for hospitals which will help to analyze energy performance of the hospitals, optimize energy performance and monitor energy efficiency.

Breakdown of the energy consumption of two comparable in size, large university hospitals, in Thessaloniki, Greece, and in Oslo, Norway (Figure 2.47) indicate that energy consumption are similar in the sector of lighting, cooking, equipment and other building related consumption except the heating and cooling loads due to their dependency on the climatic conditions. The energy usage data also demonstrate that energy usage for thermal comfort alone accounts for almost half of the total energy spending. Similar trend of energy usage (Figure 4.2) in thermal comfort sector can be observed from the field survey of hospital in the context of Rajshahi.

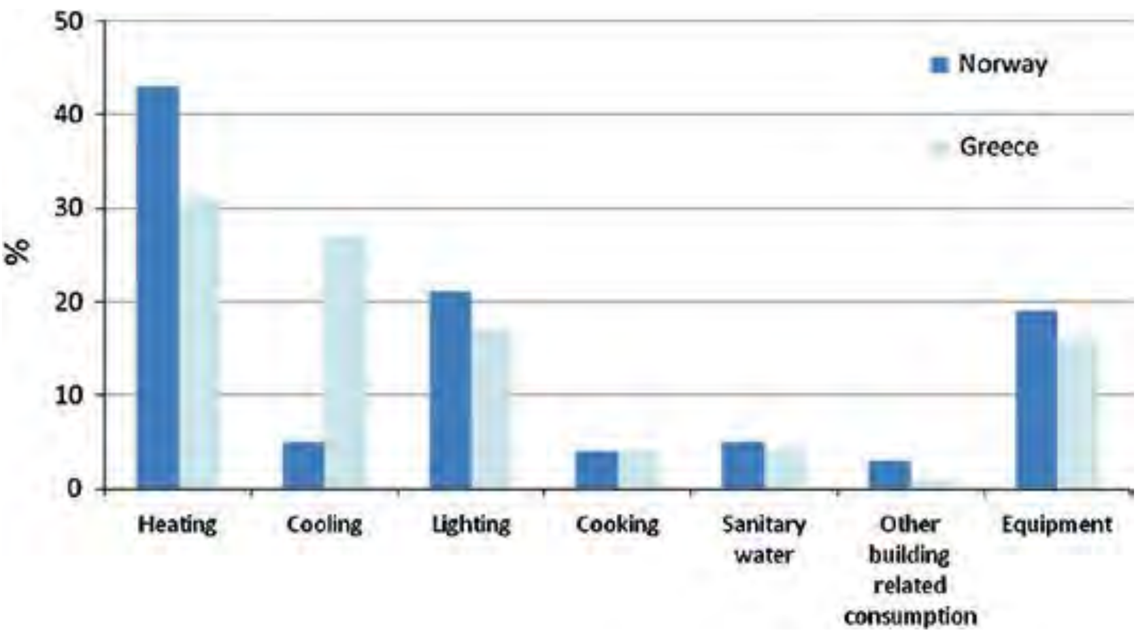


Figure 2.47 Energy consumption breakdown for comparable hospitals in Norway and Greece

To improve the energy efficiency of hospitals which is similar to any other type of buildings, it is paramount to adopt action plan comprising of monitoring, analyzing, and optimizing sequence (Figure 2.48) of actions, as described in the following paragraph (Boemi, Irulegi and Santamouris, 2016).

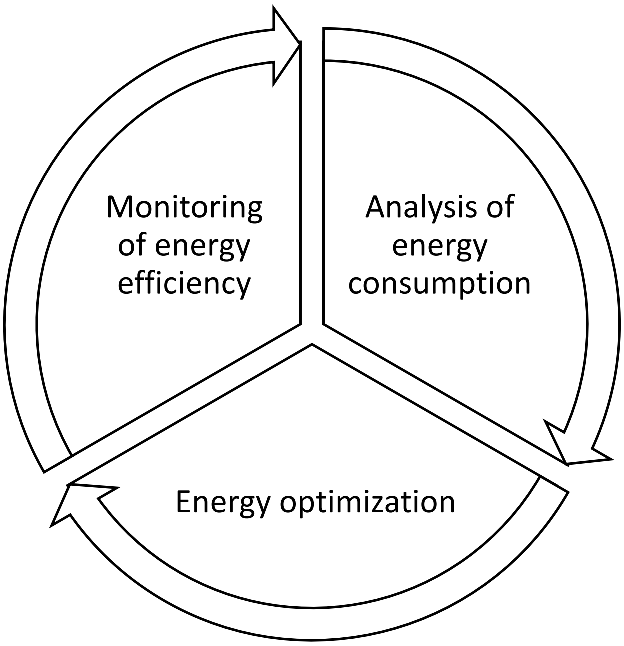


Figure 2.48 Methodological approach for the improvement of energy efficiency. Source: (Boemi, Irulegi and Santamouris, 2016)

Monitoring of energy efficiency: Consumption first has to be measured in order to be able to reduce energy consumption in a hospital. In old hospitals without building management this may prove a daunting and tedious task. The measured data has to be validated and consolidated, so that it can provide meaning values. During the data collection following things must be considered: the weather conditions for the time period of the measurements; the operational patterns; and conditions of the hospital, as well as the indoor environmental quality conditions that have prevailed for the same time period.

Analysis of Energy Consumption: The analysis must be performed in a detailed and meaningful manner so as to be able to compare values to generate benchmarks and use those values as the foundation for optimization. It is paramount to being able to determine the energy breakdown with respect to its use, especially considering electrical loads, as they are more difficult to monitor. Very recent EN 16247-2 standard with analytical energy audits provide the necessary detailed data (Boemi, Irulegi and Santamouris, 2016).

Energy optimization: Energy optimization is the outcome of the process, based on the results of the energy audit and subsequent analysis consisting of proposed actions on three different levels: small-scale improvements as part of the operation and maintenance procedure, expected to reduce energy consumption by perhaps up to 5 %and reduce energy costs due to smarter energy source and tariff choices; standard energy conservation and renewable energy sources utilization measures, expected to achieve energy savings ranging between 20 and 30 %; and energy refurbishment measures as part of an extensive renovation of the hospital, expected to reduce the building's consumption drastically—and to yield an almost new building (Boemi, Irulegi and Santamouris, 2016).

To improve the hospital's energy efficiency an integrated strategy that will consider technical and non-technical parameters is required, in order to meet the overall optimization goals. One possible form of this strategy is shown in Figure 2.49.

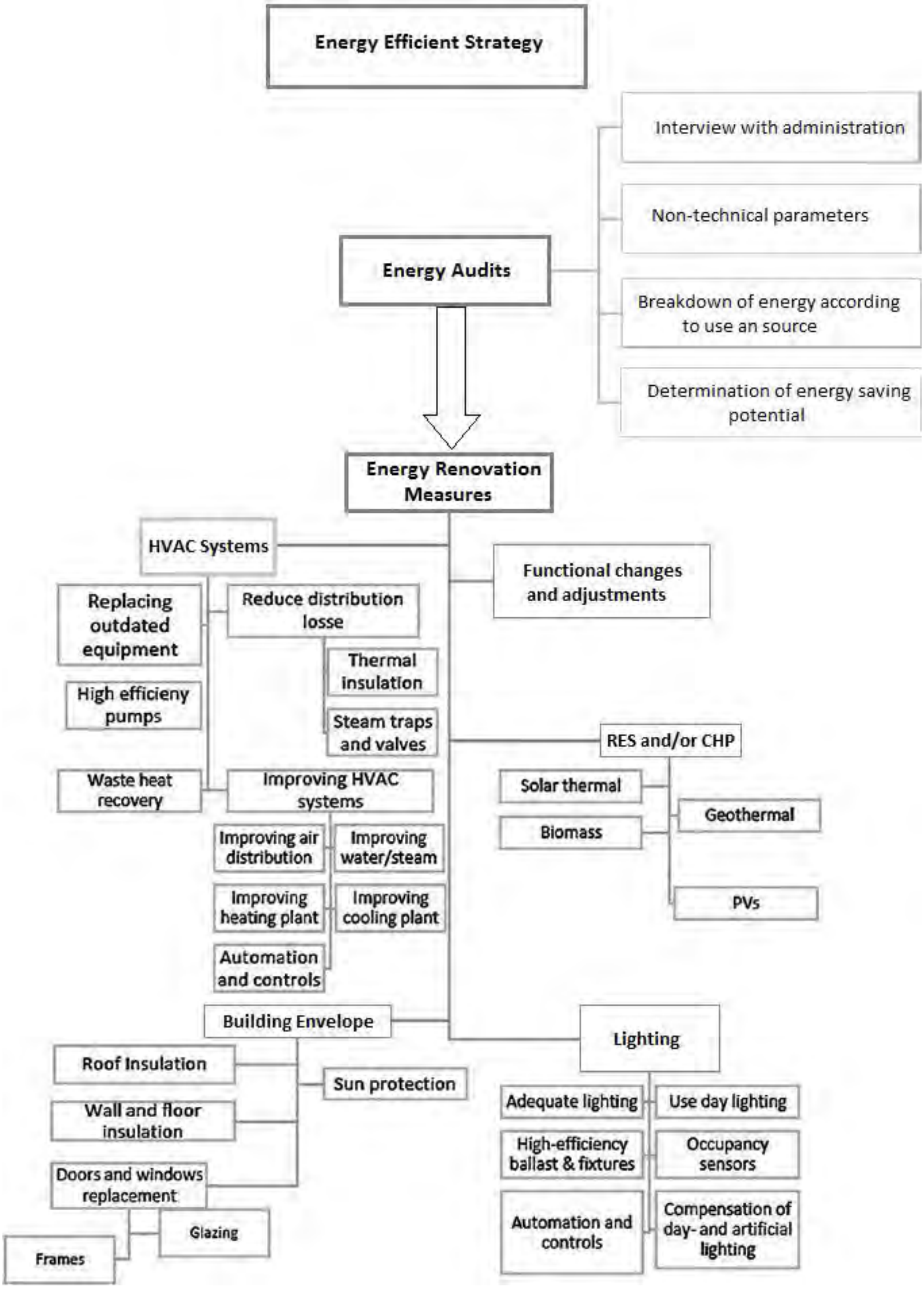


Figure 2.49 A strategy for promoting energy efficiency in hospitals. Source: (Boemi, Irulegi and Santamouris, 2016)

2.7.2 Thermal Comfort, Indoor Air Quality, and Hygiene in Hospitals

Indoor environment issues are getting priorities as there has been a better understanding of the effect on patients' healing and medical staff's well-being. Thermal comfort and indoor air quality are strongly linked because of their relationship with ventilation. A number of studies has been conducted since the late 1980s on thermal comfort in hospitals. These studies focuses on environmental parameters determining thermal comfort which is based on (PMV) method. These parameters are indoor air temperature, relative humidity, and air velocity. However, in the last two decades, research has also focused on the thermal comfort of patients and hospital staff based on the latest ASHRAE 55 and the EN 7730 standards that adopt the adaptive thermal approach. The ASHRAE 55 adaptive comfort standard applies only to naturally cooled buildings and therefore cannot be used in hospitals that feature central HVAC system (Boemi, Irulegi and Santamouris, 2016; Ferraro et al., 2015; Azizpour et al., 2013; Croitorua et al., 2015) .

These standards apply for healthy people. Normally, patients require higher air temperatures, as they have lower metabolic rates, due to both medication and lack of physical activity. Medical staff, especially in surgery and examination rooms, need lower air temperatures, due to the intensity of their activities (Ferraro et al., 2015; Skoog, Fransson and Jagemar, 2005). Therefore this contradiction of comfort requirements need to be addressed and this can be done by compromising with air temperature requirement, ventilation requirement and balancing them accordingly. One of the characteristic features of hospital buildings is that they support a wide range of function and services such as medical care areas, for the diagnostic and treatment units, including clinical laboratories, imaging, emergency rooms, operating rooms, hospitality functions (food services and housekeeping units), and administrative part of the buildings with offices, archives, and supply stores (Khodakarami and Nasrollahi, 2012).

The inpatient care or bed-related functions probably account for the biggest surface percentage of the building and also for energy consumption (Papadopoulos, 2016). To ensure thermal comfort and indoor air quality with least possible energy consumption is probably the key objective of any energy design and energy conservation measure in the field.

2.7.3 Inpatient room in hospitals

Inpatient rooms are dedicated to the care of patient whose condition requires admission to hospitals. In modern health care services, patients are only admitted in inpatient care when they are extremely ill or have severe physical trauma. This is due to advancement in modern medicine and comprehensive outpatient service. Normally patients enter inpatient care from referral from a doctor or emergency department and is ended by writing a discharge note by the doctor when the patient recovers from the illness (Wikipedia, 2017).

The history of inpatient care goes back to 230 BC in India where Ashoka founded 18 hospitals . The Romans also built specialized temple for sick patient in 291 AD. Florence Nightingale was famous for her nursing and contribution to improve medical care in the mid-19th century. She changed the course of inpatient care by focusing on improving sanitary conditions and better living conditions within the hospital. The original model for inpatient care required a family physician to admit a patient and manage the patient's care afterwards, which is no longer the case. It is replaced by 'hospitalist medicine' a term refer to around the clock inpatient care from physician whose sole practice is in the hospital. Today this model is adopted by hospitals around the world for inpatient care (Wikipedia, 2017; Wachter and Goldman, 1996).

Each inpatient care department is attached to specific medical faculties (e.g. surgery, medical, accident and emergency). To maintain an adequate level of supervision no inpatient care area should exceeds 16-24 beds. For economical use of staff, two nurse workstations are often connected together. Based on the class, type and seriousness of the illness, three types of inpatient room can be distinguished: normal nursing area, intensive care area and special care area. There are fewer beds (6-12 beds) in the inpatient room with intensive care and special care areas. 'Normal care units' are used for general inpatient care for short term and acute illness. 'Intensive care units' are for patient under constant observation and usually larger than normal inpatient room with strict environmental control. 'Special care units' are for patients with special need such as newborn babies, people with infectious diseases, the chronically ill, rehabilitation patients, neurotics and hypochondriancs. The length of the stay of these patients is generally longer than average (Neufert and Neufert, 2000).

Medical rooms and washrooms should be accessed from the main station corridor and must be easily supervised from nurses' stations. Each inpatient room must have at least one assistant doctor room and two doctor rooms to facilitate minor examination and treatment. The necessary supply and disposal rooms for medicines, linen, refuse, food and other goods should also be located around the nurse's station. Each inpatient room (18-24) is served by an independent nursing team.

The patient bed must be accessible from three sides. The smallest size for one bed room is 10 sqm. For a two and three bed room, a minimum of 8 sqm per bed should be allowed.

In recent time health care industry especially in private sector experiences a trend toward single patient room (Figure 2.50). Despite the fact of increasing construction cost due to single patient room, the gradual move away from the semi-private, or shared, patient room is fueled by the greater control of infection in a private room, the increased popularity and enhancement of reputation hospitals have received, opportunities and space to socialize with friends and family, and the reported decrease in staff errors. However, the increasing cost of construction, limitation due to layout and circulation efficiency, rising energy cost and social isolation compelling to reconsider the single room policy in the healthcare industry (Cullinan and Wolf, 2010).

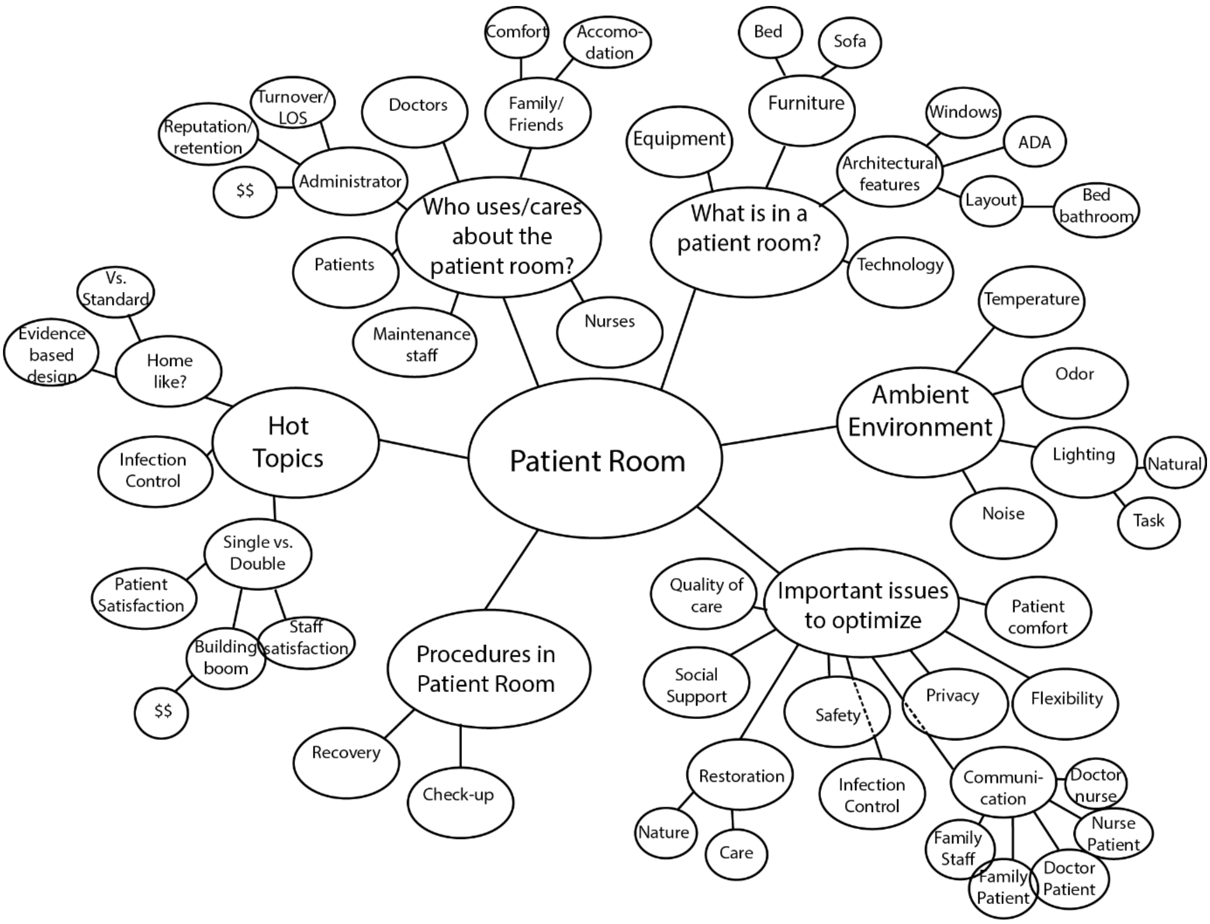


Figure 2.50 Issues related with patient room in a hospital. Source: (Cullinan and Wolf, 2010)

2.8 Building Envelope

Building can be considered as a defined unit and its heat exchange processes with the out-door environment can be calculated. Conduction of heat may occur either inwards or outwards through envelope, the rate of which depends on the material properties, surface area and temperature difference. Convection heat flow between the interior of the building and the open air, depends on the rate of the ventilation. This can be calculated from ventilation rate and temperature difference. Radiation heat gain through the opening in envelope can be calculated from the area of the opening, radiation intensity and solar gain factor of the transparent materials (Koenigsberger et al., 2003).

An efficient thermal envelope not only minimizes heat gain in the summer but also prevents heat loss in the winter. The design of an efficient thermal envelope is the first tier of the three-tier design approach (Lenchner, 2001).

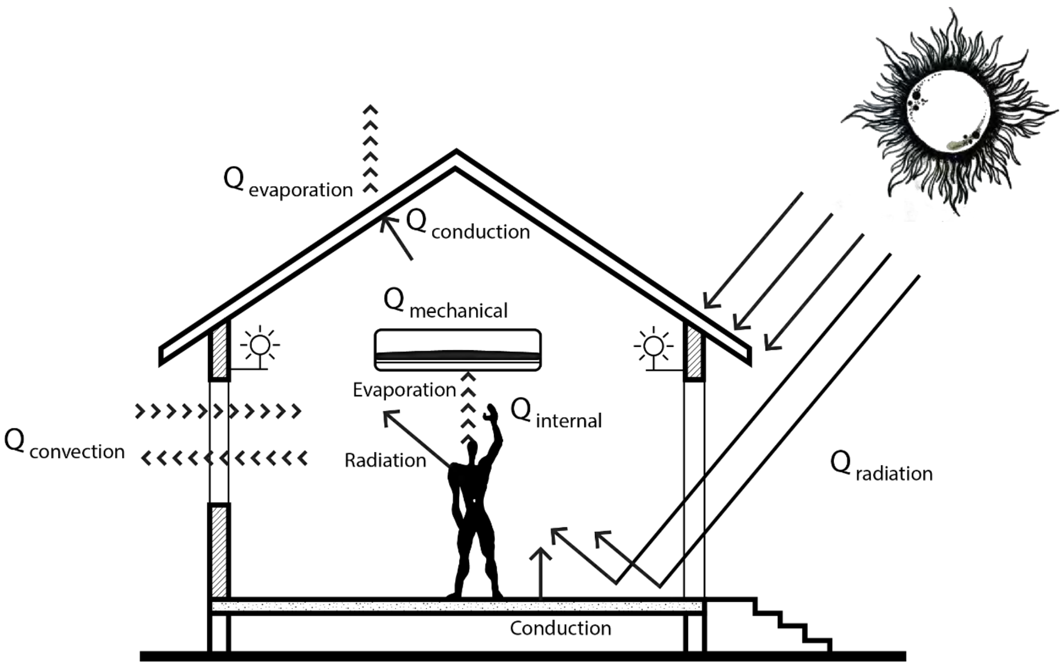


Figure 2.51: Heat exchange processes between a building and the external environment. Source: Givoni 1998

The building envelope works as a filter between the indoor and outdoor environments of a building (Figure 2.51). Different elements of the building envelope e.g. walls, fenestration, roof, foundation, thermal insulation, thermal mass, external shading devices are the important parts of any building. Therefore, the construction and materials of the building envelope are very important to achieve thermal insulation to minimize heat gain in summer and heat loss in winter. Energy savings of 31.4% and peak load savings of 36.8% from the base case were recorded for high-rise apartments in the hot and humid climate of Hong Kong by implementing passive energy efficient strategies. The strategies include adding extruded polystyrene (EPS) thermal insulation in walls, white washing external walls, reflective coated glass window glazing, 1.5m overhangs and wing wall to all windows (Cheung, Fuller and Luther, 2005; Balaras et al., 2000). An energy efficient building envelope design saved as much as 35% and 47% of total and peak cooling demands respectively (Chan and Chow, 1998).

The building envelope usually consists of multiple layers. This individual layer is responsible for resisting the heat flow in or out of the building. Each layer varies in material, thickness, color hence their thermal properties also changes (Price and Smith, 1995). To find out the overall transmittance or the U value of the wall construction, first resistance of individual layer has to be calculated then reciprocal of the total resistance would return the transmittance value of the composite wall (Koenigsberger et al., 2003).

Table 2.16 shows code standard of U-values for UK buildings which progressively decreases over the years. Similar standard can be adopted in BNBC for building envelop to increase thermal efficiency of the building envelop as technology is available.

Table 2.16 Code standard U-values (W/m²K) for UK buildings. Source: (John G, 2005).

Envelope element	1995 standard U-values (W/m²k)	2000 standard U-values (W/m²k)	Percentage reduction in U-value (%)
Walls	0.45	0.35	22
Roofs	0.25	0.16	36
Floors	0.45	0.25	44
Windows	3.3	2.2	33

2.8.1 Wall

Walls are a predominant fraction of a building envelope and are expected to provide thermal and acoustic comfort within a building, without compromising the aesthetics of the building. The thermal resistance (R-value) of the wall is crucial as it influences the building energy consumption heavily. (Christian and Kosny, 2006)

Conventionally, based on the materials used in construction, walls can be classified as wood-based walls, metal-based walls and masonry-based walls (Sadineni, Madala and Boehm, 2011).There are other types of advanced material and wall construction e.g. Fiber-reinforced plastic (FRP), unfired clay bricks, a straw–clay mixture, straw bales, lightweight concrete wall, ventilated or double skin wall, wall with latent heat storage (Goodhew and Griffiths, 2005) that are applied to improve the energy efficiency and comfort levels in buildings. The following sections describe such advanced wall technologies.

Lightweight concrete (LWC) walls: Lightweight concrete (LWC) refers to any concrete produced with a density of less than 2000 kg/m^3. Mixing with other material with low conductivity can improve the thermal resistance of LWC. This material can be natural (such as pumice, diatomite, expanded clay or expanded shale, etc.), processed by-products (such as foamed slag, sintered pulverized fuel ash) or unprocessed materials. In recent year aggregates with low-conductivity such as polystyrene beads, vermiculite and leca gaining interest in research field (Al-Jabri et al., 2005). Another type of LWC is Autoclaved aerated concrete (AAC) which uses aluminum powder to create miniscule air bubble to produce thermal resistance. All kinds of LWC walls are particularly useful in countries where concrete construction is predominant and the use of insulation in walls is not a common practice. (Sadineni, Madala and Boehm, 2011)

Ventilated or double skin walls: An air gap between two layers of masonry wall braced with metal ties constitutes a ventilated or double skin wall. They are also called cavity walls. There are two basic kinds of ventilated walls, one with forced ventilation in the cavity, and the other with natural ventilation (stack effect). Most commonly, ventilated walls are used to enhance the passive cooling of buildings. Although, energy savings for all the wall designs increase with the increase in width of the air gap, however, further increase over 0.15m yielded only diminishing returns (ASHRAE, 2013). A typical summer cooling energy savings of 40% can be achieved with a carefully designed ventilated wall (Ciampi, Leccese and Tuoni, 2003; Sadineni, Madala and Boehm, 2011).

Walls with latent heat storage: The phase change material (PCM) is incorporated in light weight wall structures to enhance the thermal storage capacity. PCM material is impregnated commonly in gypsum or concrete walls (Athienitis et al., 1997; Kuznik and Virgone, 2009; Sadineni, Madala and Boehm, 2011) .

2.8.2 Fenestration

Fenestration refers to openings in a building envelope that are primarily windows and doors. The fenestration plays a vital role in providing thermal comfort and optimum illumination levels in a building. They are also important from an architectural standpoint in adding aesthetics to the building design. In recent years glazing technologies have been improved significantly. Some of the technologies that showed promises are solar control glasses, insulating glass units, low emissivity (low-e) coatings, evacuated glazing, aerogels, and gas cavity fills (Robinson and Hutchins, 1994). Study carried out to evaluate the performance of the glazing system in India (Singh and Garg, 2009).

Different types of glazing materials and technologies that are aimed at providing high performance insulation (HPI) or solar gain control (SC) or day lighting (DL) solutions or a combination are presented in the following section.

Aerogel glazing: Aerogels are open celled mesoporous solids with a volume porosity of greater than 50%.They are typically 90–99.8% air by volume. Their high performance, low density and outstanding light diffusing properties make them an appropriate choice for roof-light applications (Bahaj, James and Jentsch, 2008).

Vacuum glazing: Vacuum space is created between two glass panes to eliminate the conductive and convective heat transfers between the glass panes reducing the center-of-glass U-value to as low as $1W/m^2$. Most often, low-e coating is applied on one or both of the glass panes to reduce the re-radiation into the indoor space (Sullivan et al., 1996). Study of performance of vacuum and argon filled double glazing, triple glazing conducted. Although, the technology faces some challenges in maintaining vacuum for longer periods, it is still a widely used energy efficient glazing option (Bahaj, James and Jentsch, 2008; Sadineni, Madala and Boehm, 2011).

Switchable reflective glazing: Switchable reflective glazing is essentially a variable tint glazing and is typically suitable for cooling load dominant buildings with large solar gain (Sullivan et al., 1996). In some types, the optical properties change with incident solar radiation. In other types light guiding elements reflect solar radiation (Bahaj, James and Jentsch, 2008; Sadineni, Madala and Boehm, 2011).

Frames: The edge components (frame and spacer) of advanced fenestrations should minimize thermal bridging and infiltration losses (Robinson and Hutchins, 1994; Gustavsen et al., 2008).

2.8.3 Roofs

Roofs are a critical part of the building envelopes that are highly susceptible to solar radiation and other environmental changes. Roofs account for large amounts of heat gain/loss, especially, in buildings with large roof area. In UK the U value for roof was progressively reduced by building regulation as technology is available over the years (Gaffin et al., 2005). Some passive cooling techniques could be implemented in tropical climates as result of modification in roof architecture. This usually contribute to a 6ºC drop in the indoor temperature (Sanjay and Chand, 2008). Roofs can be classified into different categories based on the type of construction. The following paragraphs present some of the commonly used roofing structures along with recent developments.

Masonry roofs: In the developing countries of South Asia and the Middle East, masonry houses with reinforced cement concrete (RCC) roofs are popular owing to their pest resistance, natural calamity resistance, availability and cost effectiveness of concrete ingredients (Halwatura and Jayasinghe, 2008). During tropical summers, they retain heat for a longer period. The indoor temperatures exceed 40ºC due to high roof temperatures. This problem of high roof temperatures can be mitigated by employing roof shading, cool roof coatings or compound roof systems - a combination of radiation reflectors and thermal insulation (Sanjay and Chand, 2008; Alvarado, Terrell and Johnson, 2009; Ahmad, 2010) .

Light weight roofs: Lightweight aluminum standing seam roofing systems (LASRS) are popularly used on commercial and government buildings in developed countries. It has unfavorable thermal properties which can be improved by adding thermal insulation and light color (Han, Lu and Yang, 2009).

Ventilated and micro-ventilated roofs: The ventilated roof systems are essentially two slabs delimiting a duct through which air flows. This air gap/air flow diminishes the heat transfer across the roof into the building. Unlike non-ventilated roof, according to a detailed energy analysis a ventilated roof can save energy up to 30%, during Italian summer (Ciampi, Leccese and Tuoni, 2005).

Vaulted and domed roofs: Vaulted and domed roofs are quite popular in the vernacular architecture of the Middle East where the climatic conditions are hot and arid. They are only suitable for hot and dry climates, due to the presence of larger beam component of the solar radiation which is effectively reflected by the curved roof surface, and not so much for hot and humid climates (Tang, Meir and Wu, 2006).

Solar-reflective/cool roofs: Solar-reflective roofs or cool roofs are high solar reflectance and high infrared emittance roofs. They maintain lower roof surface temperature and inhibit the heat conduction into the building. An experiment was carried out to find out the effect of solar reflective roof of six case study in California. It was observed that the temperature was lowered by 33-42K (Liu, 2006; Akbari, Levinson and Rainer, 2005). Table 2.17 presents solar reflectance and infrared emittance properties of some typical roof materials and temperature rise behavior.

Table 2.17 Solar reflectance and infrared emittance properties of typical roof types along with temperature rise. Source: (Tang, Meir and Wu, 2006)

Roof surface type	Solar reflectance	Infrared emittance	Roof surface temperature rise (°C)
Ethylene propylene diene monomer (EPDM)–black	0.06	0.86	46.1
EPDM–white	0.69	0.87	13.9
Thermoplastic polyolefin (TPO)–white	0.83	0.92	6.11
Bitumen–smooth surface	0.06	0.86	46.1
Bitumen–white granules	0.26	0.92	35
Built-up roof (BUR)–dark gravel	0.12	0.90	42.2
BUR–light gravel	0.34	0.90	31.7
Asphalt shingles–generic black granules	0.05	0.91	45.6
Asphalt shingles–generic white granules	0.25	0.91	35.6
Shingles–white elastomeric coating	0.71	0.91	12.2
Shingles–aluminum coating	0.54	0.42	28.3
Steel–new, bare, galvanized	0.61	0.04	30.6
Aluminum	0.61	0.25	26.7
Siliconized polyester–white	0.59	0.85	20.6

Green roofs: A building roof that is either fully or partly covered with a layer of vegetation is called a green roof. It is a layered composite system consisting of a waterproofing membrane, growing medium and the vegetation layer itself. Sometimes, it contains additional layer for root barrier, drainage system and irrigation system. Two types of green roof are available based on rooting type – intensive (shrubs and trees with deeper substrate layer) and extensive (lawn and sedum with thinner substrate layer). Extensive type is used widely as it can be planted with little modification of the existing roof and require least maintenance (Sadineni, Madala and Boehm, 2011). Approximately 120-150 kg/m^2 load is added for extensive green roof (Castleton et al., 2010). It is effectively used with poorly insulated roof rather than well-insulated roof. Simulation showed that green roof on non-insulated roof saved 10.5% compared to insulated roof which saved only 0.6%. Dry clay soil is better insulator than moist clay soil (Wong et al., 2003; Eumorfopoulou and Aravantinos, 1998). The wet clay soil performs better in hot dry weather as it acts as a passive cooler which removes heat through evapotranspiration at a double rate of dry clay soil (Lazzarin, Castellotti and Busato, 2005). Figure 2.52 compare the energy exchange performance of dry or wet green roof with traditional roof. Study of green roof in UK and Singapore, reported better thermal performance compared to typical thermal insulation (Balaras, 1996; Wong et al., 2003). 70-90% heat gain reduction and 10-30% heat loss reduction is reported when using green roof in Toronto, Canada (Liu and Minor, 2005). The green roof has an equivalent albedo of about 0.7–0.85 as against an albedo of 0.1–0.2 for bitumen/tar/gravel roof (Gaffin et al., 2005).

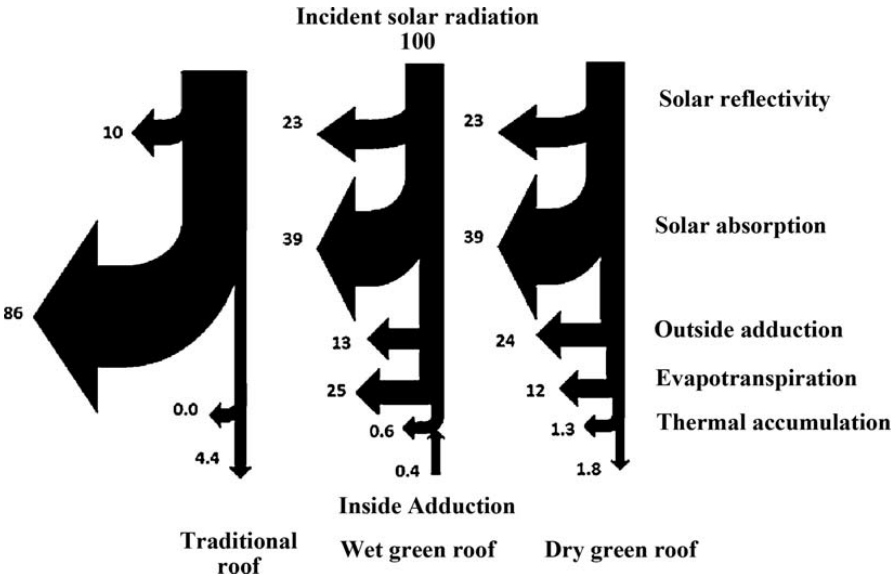


Figure 2.52 Comparison of the energy exchanges of the dry or wet green roof with a traditional roof, summer season. Source: (Lazzarin, Castellotti and Busato, 2005)

Photovoltaic roofs: There have been significant efforts in recent years in integrating photovoltaic (PV) into building envelope. Especially, in countries where land-use is an important constraint, building integrated PV (BIPV) offer an effective solution by the use of building surface area while facilitating energy production and building envelope weather protection. Some sandwich PV roofing provide multi-functionality such as electricity generation as well as thermal insulation (Bahaj, 2003).

2.9 Key findings from literature review

Key findings from literature review are enumerated as following.

Comparative climatic analysis of Bangladesh showed the overall pattern of temperature, rainfall, humidity and wind distribution throughout different zones and from this analysis it is clear that Rajshahi is comparatively hotter and drier than other regions with higher extreme temperature and lower rainfall. Therefore, this region requires special attention to the building envelope to provide passive comfort cooling.

Weighting of the season using SET which combined the effect of temperature and humidity (Section 2.4) helped to formulate the appropriate strategy to facilitate passive cooling techniques into inpatient room of hospital building envelope.

The detailed study of passive cooling techniques, example cases and climatic analysis narrowed down the available passive cooling strategy that can be installed into building envelope with minimum intervention. Such strategies include sun protection, wall and floor insulation, doors and windows replacement and roof insulation.

The history of hospital building, trend of energy uses and the critical issues regarding thermal comfort was discussed and the understanding helped to device different methods that can be applied to building envelope to improve the energy performance and thermal condition of the patient. The number of patient should not exceed 16-24 beds to maintain adequate level of supervision. Also there is a trend toward single patient room, especially in the private health care sector owing to the popular demand, competition among rival hospitals, better medical care provision and better infection control. However, the exponential rise of cost of providing single room in terms of space and construction, increases energy consumption and social isolation forcing to rethink the single room inclination in the healthcare industry. A combination of single and multiple patient rooms can be a better way to optimize resource usage.

No data or published record could be found on hospital energy usage in Bangladesh. Therefore energy audit is necessary to investigate the current state of energy consumption in Hospital buildings. To improve the energy efficiency of the hospital a comprehensive measures encompassing monitoring, analysis and optimization of energy usage has to be taken to set standard in the context of Bangladesh.

Although limited in scope BNBC provide guideline for air conditioned space, which mentioned the following conditions: temperatures difference of outside and inside air should not exceed 11 deg C; air velocity of 0.12 m/s to 0.25 m/s at 1.5 m level; a dry bulb temperature of 24.5–26 deg C; a relative humidity range of 50-55%; depending on the occupancy and functional requirement a ventilation rate of 2-20 ACH. It also states outside design condition for major cities. Design dry bulb and mean coincident wet bulb temperature of 1%, 2.5% and 5% and mean daily range are given in Table 2.8 and air requirement of different functional area of the hospital are given in Table 2.9. The value of outside design condition in Rajshahi can be used for setting extreme condition for simulating inpatient room.

Literature review of current comfort models specify two different approaches; one the rational or heat balance model, other adaptive approach. From the study of these two models it is found that adaptive model best characterize free running or naturally ventilated building. ASHRAE 55 comfort standard in 2004 defined ‘optional method’ for ‘naturally conditioned’ spaces. However, the CIBSE guide A

(CIBSE, 1986; CIBSE, 1999) presents a boundary condition which changes with daily mean ambient temperature hence account for the adaptation that takes place daily unlike ASHRAE (ANSI/ASHRAE 55-2005, 2010) which uses monthly mean. New European standard BSEN 15251 (BSEN15251, 2008) offers a more holistic approach and includes hospitals and has three categories based on thermal comfort requirement.

2.10 Conclusion

This chapter has achieved the first objective by laying out the framework of facilitating passive cooling inside inpatient room of hospital building.

According to the scope of this thesis, climatic analysis from meteorological data establishes the basis of applying passive cooling techniques. Then study of passive cooling techniques from previous research and case studies provide the understanding that is necessary to select appropriate techniques to facilitate passive cooling in the context of Rajshahi. The code and standard and different envelope configurations have been discussed in this chapter, which is based on previous research and published sources. The information and data of this chapter helped to focus the issue on which field survey and detail steps of simulation study has been developed in next chapters.

3 CHAPTER THREE: METHODOLOGY

Introduction

Methodology

Selection of hospital

Selection of inpatient room

Field survey and data collection

Simulation tools selection

Defining Simulation Parameters

Simulation Output Variables

Conversion of simulation results into performance measure

Conclusion

3.1 Introduction

Chapter 2 discusses the outcomes of the literature review to describe the basic information required to identify the parameters on which the simulation could be conducted. This chapter contains detail steps of the methodology of field study and simulation. Field survey was conducted to understand the relationship of indoor environment, energy consumption and comfort condition of inpatient room. Moreover the purpose of field work are to understand the thermal performance of existing envelopes of hospital building constructed by local available building materials; to calculate and compare the energy consumption of different inpatient rooms with single and multiple bed occupancy; and to evaluate the indoor environmental condition in terms of indoor comfort requirements to assess the performance of building envelope for the inpatient room. By using dynamic building energy performance simulation tool i.e. EnergyPlus, the amount of heat transfer through building envelope from the outdoor environment can be calculated. Then the performances of different envelope construction assemblies can be evaluated to facilitate passive cooling inside inpatient room.

The findings of this chapter helps to evaluate the performance of envelop conditions of inpatient room and to perform experimental parametric exercises. This chapter includes the method of field survey and simulation which includes selection of hospital building, selection of inpatient room, field survey and data collection, simulation tools selection, definition of simulation parameters, simulation output variables and conversion of simulation results into performance measures. The next chapter will present results of field survey and will also compare and analyze the simulation results in terms of thermal parameters (e.g. mean air temperature, mean radiant temperature, mean operative temperature, air relative humidity, surface inside and outside temperature) based on the recommended methodology developed in this chapter.

3.2 Methodology

The methodology is envisaged in the following stages (Lomas and Giridharan, 2012).

- The geometry, construction and environmental control of the spaces are determined first. This is accomplished by field measurement, observation, and interviews with administration and staff.
- Temperatures, air velocity, humidity, electricity usage, window and door opening behavior are observed and recorded in and outside of the inpatient rooms.
- These data are compared with the appropriate thermal comfort standard to assess the thermal environment and to find out whether the spaces satisfy the comfort standard inside inpatient room during the monitoring period.

- Measurements obtained from field survey are used to generate 3D model of the case inpatient room using suitable 3D generating application for simulation.
- The 3D model is converted and imported to a simulation program that is capable of assessing thermal performance for different envelop conditions.
- Then the field data is used to calibrate the 3D model of the inpatient room which will be assessed within a dynamic thermal environmental model.
- Finally this model is used to assess the performance of internal environmental condition for different envelope construction to facilitate passive cooling inside inpatient rooms.

Figure 3.1 shows the flow diagram of the methodology for the field survey and subsequent simulation process of this research.

3.2.1 Selection of hospital

There are many health care institutions in Rajshahi. These health care institutions include nursing home, diagnostic centers, specialized hospital, private and government owned primary, secondary and tertiary level health care facilities. Most of these facilities are developed around the area Laximpur, due to the location of Rajshahi medical college and hospital. Based on literature review and pilot survey following criteria has been set for the selection of hospital building.

- The hospital has to be located in Rajshahi region.
- The hospital building must be built for health care service and conform with the building construction regulation of the concerned authority.
- To incorporate passive cooling techniques effectively into the envelop of the inpatient room, the hospital building need to conform 1st tier techniques (solar and heat protection) from 3 tiers strategy of passive cooling.
- The prospective hospital building should include design consideration of the local climatic factors (building orientation, building form, shading devices, thermal mass, insulation) thus reducing solar heat gain and allowing natural ventilation.

The scale and volume of the building should be convenient to handle within the time limit of this study.

- For collection and comparison of data on the thermal environment and energy performance of the inpatient rooms, the prospective hospital should have different types of inpatient room e.g. single bed and multiple bed inpatient room.
- Access to hospital premise for field survey is permitted.
- Access to inpatient room for data collection for the study is permitted.

Figure 3.1 Flow diagram of the simulation process of this research

Based on the aforementioned criteria Rajshahi medical college hospital was taken as the case hospital building to study envelop characteristics to facilitate passive cooling inside inpatient room. During preliminary survey for selection of the hospital following features were observed in Rajshahi medical college hospital.

- Due to its pavilion style layout i.e. H shaped planning, it has naturally ventilated inpatient medical units.
- It has multiple type inpatient rooms i.e. single room, and 10 bed and 25 bed inpatient room.
- Unlike many other private health care institutes in Rajshahi, it was planned and designed as a hospital.
- Accessibility to patient within the inpatient room was accepted.
- Accessibility to hospital staff for interviews was accepted.
- Government hospitals are planned and designed as health care institutes hence they represents architectural trends, social attitudes and political approaches for providing health care services to the mass people.

Rajshahi medical college hospital is a tertiary level hospital with 27 departments and 57 wards. It has a capacity of 1200 beds.

3.2.2 Selection of inpatient room

Rajshahi medical college hospital has different types of inpatient rooms. Three types of inpatient rooms were found in the field survey based on their bed capacity. They are single bed inpatient room, medium size inpatient room with a capacity of 8 to 10 beds and large inpatient room with a capacity of 30 to 50 beds. Depending on the patient condition, thermal comfort and ventilation requirement some of these inpatient rooms are air conditioned and some are naturally ventilated. Based on these findings four inpatient rooms were selected for the field survey to get an overall picture of the envelop condition of these inpatient rooms. Inpatient room for surgery patient (Inpatient room no 05) and Inpatient room for Neurosurgery patient (Inpatient room no 08) are naturally ventilated with 47 and 33 beds respectively, Inpatient room for cardiology patient (Inpatient room no 32) is newly constructed 8 bed air conditioned room and Inpatient room with single bed is naturally ventilated room.

Surgery and neurosurgery inpatient rooms are identical in volume, size and shape. Both rooms are north south oriented and has corridor on south side. This corridor is then connected with the main circulation corridor (Figure 3.2(a) and Figure 3.3). Cardiology inpatient room is located in the newly constructed four storied square block with a central courtyard which is connected by corridor (Figure 3.2(b) and

Figure 3.3). This inpatient room is not naturally ventilated. Temperature is regulated by split type air conditioner. VIP inpatient room is a single bed room with toilet on corridor side and verandah on south side.

For the purpose of simulation study and parametric analysis the criteria for selection of the inpatient room are set as following

- Inpatient room should have multiple bed to account for thermal load from occupant.
- To facilitate passive cooling the inpatient room should be naturally ventilated, so the windows and doors have to be operable.
- The building containing inpatient room should be regular in shape and simple in geometric configuration to avoid complexity in simulation.
- Access to inpatient room for data collection (e.g. environmental data, physical data, thermal comfort data, energy consumption data) for the research is permitted.
- Patients can be observable for longer period of time to observe their behavioral adjustment to achieve thermal comfort.

Both surgery and neurosurgery inpatient room can be used for simulation study according to the above criteria. In this study surgery inpatient room are taken for simulation analysis.

3.2.3 Field survey and data collection

To conduct the simulation analysis of the building envelope of the hospitals; environmental aspects, building features, comfort conditions, occupancy pattern of the patients, doctors, nurses and visitors, and electrical load e.g. lights, ceiling fans, medical equipment were monitored and recorded from 22 February to 24 February in the inpatient rooms.

(a) *(b)* *(c)* *(d)*

Figure 3.2 Envelope of Hospital building from field survey, (a) surgery inpatient room (b) cardiology inpatient room (c) neurosurgery inpatient room (d) corridor of surgery inpatient room - Rajshahi Medical College, Rajshahi.

Measurements of the inpatient rooms were taken, construction method and material of construction was observed and recorded for building simulation model. Interview and thermal comfort survey was conducted for the patients, doctors, nurses, and visitors.

a) Environmental data collection

Digital thermo anemometer and hygro-thermometer were used (Table A.1) to take instantaneous measurement of temperature, air velocity, relative humidity at two hour intervals inside of the inpatient room and at the corridor throughout the day for a period of three days to study the indoor environment condition as well as corresponding outdoor environmental condition. Data was collected at three different heights, firstly at 100 mm which is the floor level and secondly at 460 mm which is at bed level and finally at 1600 mm which is at head level. Environment data found in the survey is presented in (Table 4.2) in tabular form.

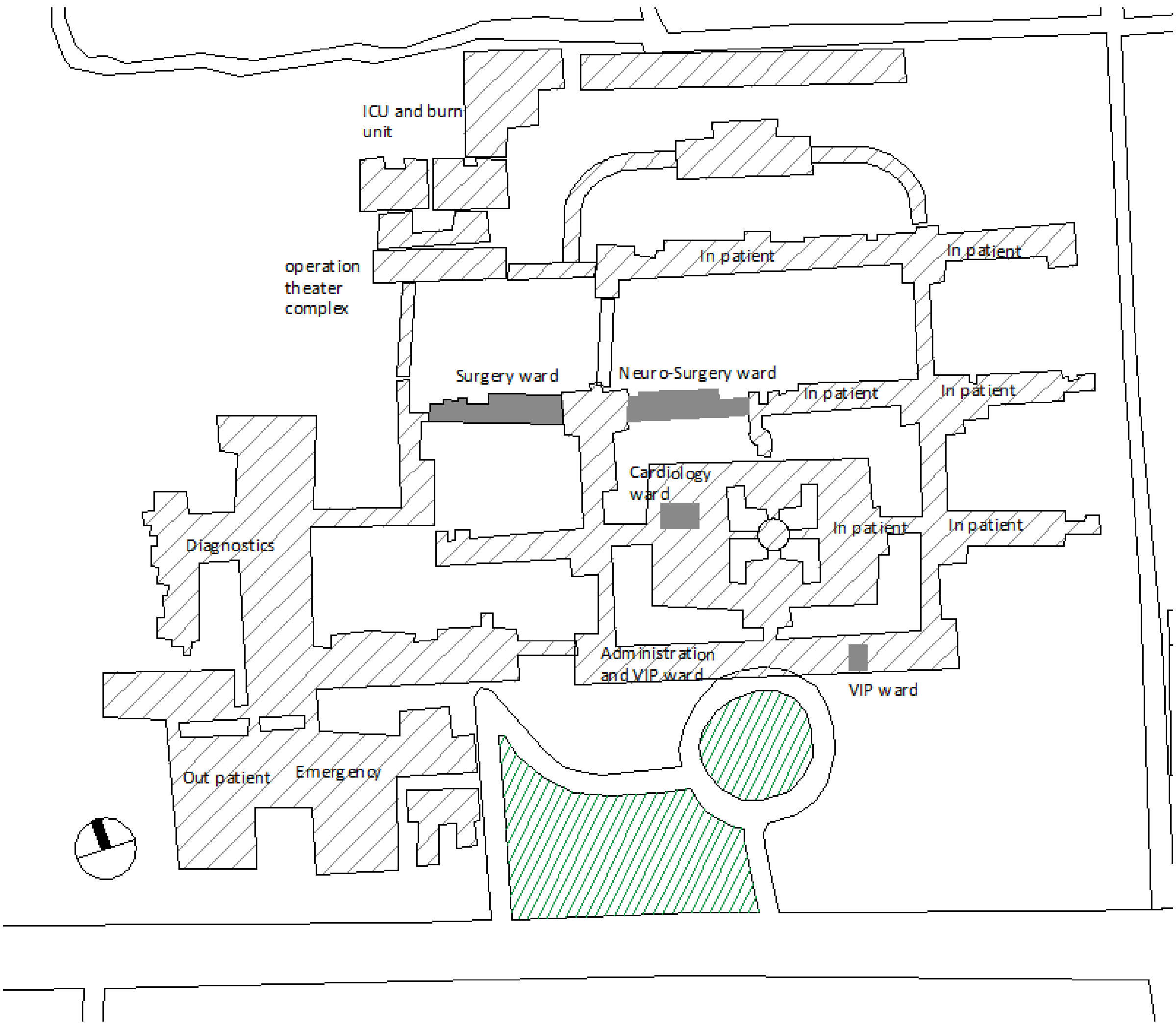


Figure 3.3 Rajshahi medical college hospital plan and surveyed inpatient rooms. (Inpatient rooms are shown in gray color)

b) Electrical equipment and energy consumption

Interview of administrative staff was conducted to obtain overall energy consumption data of the hospital. Electrical load of the inpatient room was calculated from the number of electrical fixtures and medical instruments and their rated input power. This data was later used as input in OpenStudio to calculate the energy consumption and heat dissipation from the equipment in the inpatient room. Summary of the data was presented in Table 4.3.

c) Thermal comfort survey

The procedure of comfort survey included interviewing the subject (subjective measurement) using questionnaire while at the same time evaluating the environmental parameters around the subject (Objective measurement). Due to the medical condition and types of subjects, not all of the occupants were able to participate in the survey.

3.2.4 Simulation tools selection

Before the arrival of computer-aided building simulation, manual calculation, 'rule of thumb' method and assumption is used by architects and engineer in conventional design concepts to assess the internal environmental condition of the building. This approach often led to either overestimation or underestimation of real life situation consequently poor performance of the building. For complex building it would be impractical to achieve energy efficient, comfortable environment without resorting to computer-aided detailed building simulation program (Hong, Chou and Bong, 2000). A wide variety of building simulation program is available and used by building energy community. Some major energy programs e.g. BLAST, BSim, DeST, DOE-2.1E, ECOTECT, Ener-Win, Energy Express, Energy-10, EnergyPlus, eQUEST, ESP-r, IDA ICE, IES/VES, HAP, HEED, PowerDomus, SUNREL, Tas, TRACE and TRNSYS which were developed during the last 50 years providing professionals with key performance analysis of the built environment (Crawley et al., 2008).

Criteria for selecting simulation tools are as follows:

- Climatic data from nearby station can be modelled and given as input to simulate the local climate.
- Thermal properties of materials can be modified and customized that are based on data found in laboratory test and different standards to simulate thermal behavior of material.
- 3D model of the case inpatient room can be modeled using popular 3D software such as SketchUp, AutoCAD.
- It should have high precision prediction capability for dynamic indoor thermal condition based on the input of outdoor climatic condition.

- It can produce thermal output metrics for indoor thermal environment assessment such as mean air temperature, mean radiant temperature, mean operative temperature, surface temperature, humidity, and wind speed.

In this study EnergyPlus in conjunction with OpenStudio plug-in integrated with Trimble SketchUp are used for simulation.

a) EnergyPlus

EnergyPlus is a modular, structured building energy analysis and thermal load simulation program (Figure 3.4) which is based on the most popular features and capabilities of BLAST and DOE-2. It was developed to optimize energy performance of building which was driven by the energy crisis of the early 1970s and realization that building energy consumption is a major component of the American energy usage statistic. It uses text file for input and output as well as its native idf file format. User can specify time step (15-min default) which is used to calculate load by the heat balance engine. EnergyPlus will calculate the heating and cooling loads necessary to maintain thermal control set points, conditions throughout a secondary HVAC system and coil loads, and the energy consumption of primary plant equipment as well as many other simulation details that are necessary to verify that the simulation is performing as the actual building would. This comprehensive program can yield precise space temperature profile which is essential for system and plant sizing and energy consumption. This software is also capable of evaluating realistic system control, moisture absorption and desorption in building elements, radiant heating and cooling systems, and inter zone air flow (Crawley et al., 2008; Laboratory, 2017; Ahmed, 1995; ANSI/ASHRAE 55-2005, 2010).

Below is list of some of the features of the first release of EnergyPlus. While this list is not exhaustive, it is intended to give the reader an idea of the rigor and applicability of EnergyPlus to various simulation situations.

Integrated, simultaneous solution where the building response and the primary and secondary systems are tightly coupled (iteration performed when necessary)

Sub-hourly, user-definable time steps for the interaction between the thermal zones and the environment; variable time steps for interactions between the thermal zones and the HVAC systems (automatically varied to ensure solution stability)

ASCII text based weather, input, and output files that include hourly or sub-hourly environmental conditions, and standard and user definable reports, respectively

Heat balance based solution technique for building thermal loads that allows for simultaneous calculation of radiant and convective effects at both in the interior and exterior surface during each time step

Transient heat conduction through building elements such as walls, roofs, floors, etc. using conduction transfer functions

Improved ground heat transfer modeling through links to three-dimensional finite difference ground models and simplified analytical techniques.

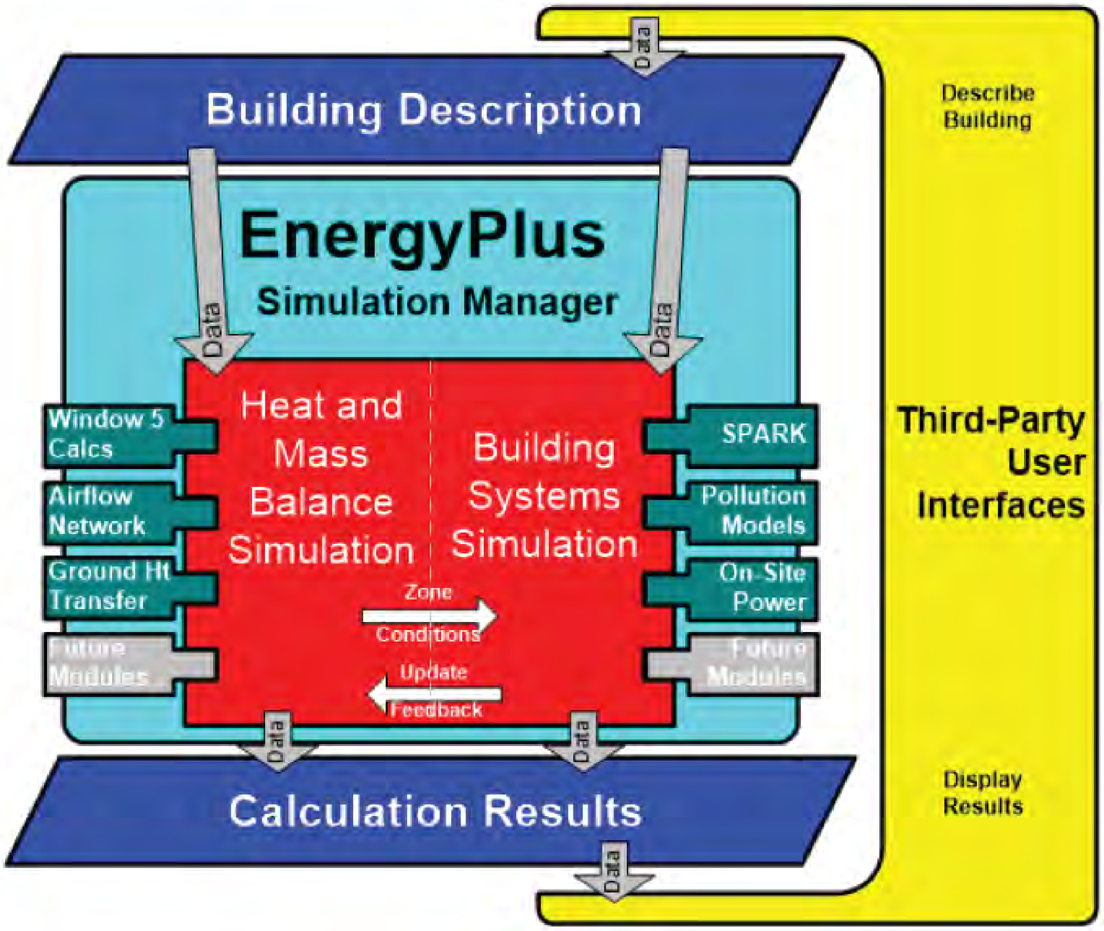


Figure 3.4 Structure of EnergyPlus. Source: (Laboratory, 2017)

b) OpenStudio plug in for Sketch Up

OpenStudio is a collection of software tools to support whole building energy modeling using EnergyPlus and advanced daylight analysis using Radiance. OpenStudio is an open source project to facilitate community development, extension, and private sector adoption. OpenStudio includes graphical interfaces along with a Software Development Kit (SDK).

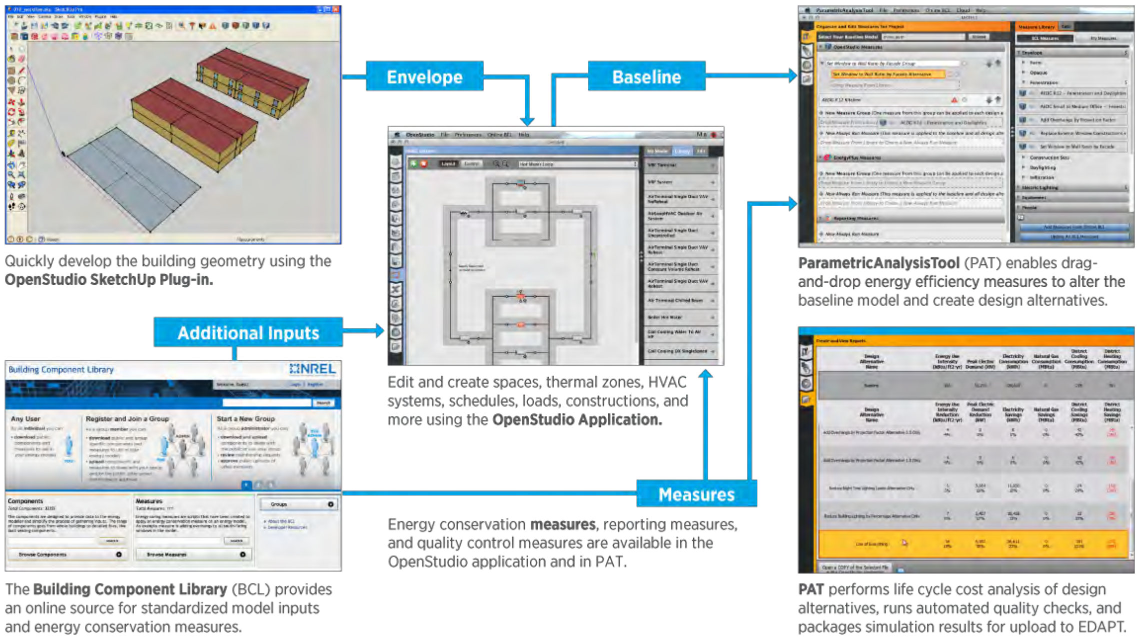


Figure 3.5 Workflow overview of OpenStudio. Source: http://nrel.github.io/OpenStudio-user-documentation/img/workflow_diagram.png

The graphical applications include the OpenStudio SketchUp Plug-in, OpenStudio Application, ResultsViewer and the Parametric Analysis Tool (Figure 3.5). The OpenStudio SketchUp Plug-in is an extension to Trimble's popular SketchUp 3D modeling tool that allows users to quickly create geometry needed for EnergyPlus. Additionally, OpenStudio supports import of gbXML and IFC for geometry creation. The OpenStudio Application is a fully featured graphical interface to OpenStudio models including envelope, loads, schedules, and HVAC results. Viewer enables browsing, plotting, and comparing simulation output data, especially time series. The Parametric Analysis Tool enables studying the impact of applying multiple combinations of OpenStudio Measures to a base model as well as export of the analysis results for EDAPT submission.

In addition to the graphical interface, OpenStudio allows building researchers and software developers to quickly get started through its multiple entry levels, including access through C++, Ruby, and C#. Users can leverage the Ruby interface to create OpenStudio Measures that can be easily shared and applied to OpenStudio Models.

3.2.5 Defining Simulation Parameters

Field data is used to build 3D model using SketchUp in combination with open studio plug in. The inbuilt functionality of open studio plug in automatically categorizes different envelope type into wall floor and roof as surfaces while modeling. It also define opening such as window and door into sub surfaces. Shedding surfaces and interior partition was modeled in SketchUp with open studio plug in. All necessary variables and inputs have been assigned using OpenStudio application to complete the modeling of the case inpatient room. This was done step by step using OpenStudio work flow. The parameters are as following.

- Climate and location
- Building operation, activity behavior and schedule
- Internal condition and thermal load
- Construction assemblies and building material data base
- Space type and thermal zone
- Simulation output variables

a) Climate and location

The weather data used in energy plus is a text based format. Data is available from a wide variety of sources and formats. It can be from locally recorded weather data representing single year or statistically produced synthetic year representing long term weather patterns. EnergyPlus websites has a rich database of weather data from all around the world. Under its Asia WMO Region 2, it contains 8 region's weather data of Bangladesh but no data is available on Rajshahi. The closest region on which the data is readily available and which represent Rajshahi is Iswardi which is 60 Km away from Rajshahi. Although a time series weather data from March 2016 is available from Bangladesh Metrological department's website and obtainable in spread sheet format, but is not suitable to use as a simulation data due to the fact that this data only represent Test Reference Year-type (TRY) weather data; meaning these data does not truly represent an empirical data rather this data represents a typical data. "Elements" an open sources software can be used to create a weather data profile or even modify an existing weather data profile to use in EnergyPlus software for any location. Another option is to use "Meteonorm" commercial software which can generate typical meteorological years for any place by interpolating data from nearby weather stations.

Table 3.1 Simulation parameters for climate and location.

Parameters	Specification
Location	Rajshahi, Bangladesh
Longitude	24.37
Latitude	88.6
Time zone	+6 GMT
Run period	January 2016 to December 2016
Units	SI (Kg, m, sec, etc.)
Elevation	14m
Orientation	Front elevation facing south
Building shape	Rectangular

If simulation for other region is required to be performed, where no data is available in close proximity, then either of this two software can generate necessary weather data for the simulation in EnergyPlus. Table 3.1 presents the sets of parameters used to set climate and location related information in the simulation.

b) Building operation, activity behavior and schedule

One of the processes used by "OpenStudio" is quantifying patterns about occupancy, activity, electrical equipment, other equipment, and infiltration. These inputs can be given using parameter such as times, days, weeks, and seasonal variation. Most of these schedules are prepared by modifying default schedules provided by the software according to the field study. Table 3.2 presents a list of schedule set used in the simulation.

Table 3.2 Schedule set used in the simulation

Sl. No.	Schedule name	Variable	Time Span
1	Hospital activity schedule	W/person	January to December
2	Hospital building occupancy schedule	Fraction of 1 for daily limit	January to December
3	Hospital light schedule	Fraction of 1 for daily limit	January to December
4	Hospital equipment schedule	Fraction of 1 for daily limit	January to December
5	Hospital infiltration schedule	Fraction of 1 for daily limit	January to December

c) Internal condition and thermal load

Heat gain from internal loads such as people, light, equipment, can be significant source of thermal load especially for large structure. These inputs can be set as energy density per unit area which is calculated from data obtained in field survey and presented in Table 4.1, Table 4.2 and Table 4.3. Table 3.3 summarizes internal condition and thermal load from different sources used in OpenStudio to simulate internal heat gain.

Table 3.3 Internal thermal load from field survey

Type of load	Value	Unit	Space type
Occupant load	0.350371	People/m^2	Inpatient room, patient room corridor, Office
Light	2.267106	W/m^2	Inpatient room, patient room corridor, Office
Electrical Equipment	6.470849	W/m^2	Inpatient room, Office

d) Construction assemblies and building material data base

Data on envelope material observed in field survey are categorized into three types in OpenStudio; surface construction (wall, floor and ceiling), sub surface construction (window and door) and space shading constructions. Surface construction material comprise of two layers namely core material and finish material. Thickness and thermal properties of core and finish material of surface construction are obtained from field observation and previous research and published standard (Chowdhury, 2014; ASHRAE, 2013). Same is true for shading construction; the only exception is the subsurface construction which only comprises of one layer.

To describe the thermal properties of surface materials following variables (Table 3.4) are necessary to be defined for simulation:

Table 3.4 Parameters for surface (wall, floor, slab) material properties

Parameter	Unit
Roughness	Very Rough/ Rough / Medium Rough/ Medium Smooth/ Smooth/ Very Smooth
Thickness	m
Conductivity	W/m.K
Density	kg/m^3
Specific Heat	J/kg.K
Thermal Absorptance	Fraction of 1
Solar Absorptance	Fraction of 1
Visible Absorptance	Fraction of 1

For window materials (sub-surface) following variables (Table 3.5) are used for simulation

Table 3.5 Parameters for window material properties

Parameter	Unit
Optical Data type	Spectral Average / Spectral
Thickness	Fraction of 1
Solar Transmittance At Normal Incidence	Fraction of 1
Front Side Solar Reflectance At Normal Incidence	Fraction of 1
Back Side Solar Reflectance At Normal Incidence	Fraction of 1
Visible Transmittance At Normal Incidence	Fraction of 1
Front Side Visible Reflectance Transmittance At Normal Incidence	Fraction of 1
Back Side Visible Reflectance Transmittance At Normal Incidence	Fraction of 1
Infrared Transmittance At Normal Incidence	Fraction of 1
Front Side Infrared Hemispherical Emissivity	Fraction of 1
Back Side Infrared Hemispherical Emissivity	Fraction of 1
Conductivity	W/m.K
Dirt Correction Factor For Solar And Visible Transmittance	Fraction of 1

Solar transmittance, solar reflectance, emissivity are expressed as a fraction of 1 and depends on material properties.

After defining individual material properties composite material are then prepared for defining envelope properties in order to conduct parametric study to compare their performance for facilitating passive cooling.

Four configurations of wall construction are considered which are locally available. They are shown in Table 3.6.

Table 3.6 Composite wall surface construction for parametric simulation

Material	10” (254 mm) brick Construction	5” (127 mm) brick Construction	11.5” (292 mm) Cavity brick wall Construction	4” (100 mm) Hollow concrete wall construction
Layer/Material ID	WB10	WB05	WB11	WC04
Outside to Inside	8.5 mm Local Tiles	8.5 mm Local Tiles	8.5 mm Local Tiles	8.5 mm Local Tiles
	12.7 mm plaster	12.7 mm plaster	12.7 mm plaster	12.7 mm plaster
	254 mm brick	127 mm brick	127 mm brick	100 mm Hollow concrete block
	12.7 mm plaster	12.7 mm plaster	38 mm Air gap	12.7 mm plaster
	8.5 mm Local Tiles	8.5 mm Local Tiles	127 mm brick	8.5 mm Local Tiles
			12.7 mm plaster	
			8.5 mm Local Tiles	
U value	1.505 W/m^{2}K	2.3074 W/m^{2}K	1.1609 W/m^{2}K	2.5504 W/m^{2}K

3.2.6 Simulation Output Variables

Annual time series thermal condition inside a space can provide insights of thermal comfort and consequently energy consumption due to cooling load. Simulation can be used to produce a time series data year round or for critical period inside a space to assess the performance of the envelope condition.

The proposed simulation examines four different envelope conditions and their performance in terms of heat flow from external sources as well as from internal sources. External sources can be categorized as direct and indirect solar radiation, heat gain from convection and conduction due to temperature difference. Internal sources include occupants, light and other electrical equipment. For the simulation study, the following output variables have been considered:

- Surface Inside Face Temperature
- Surface Outside Face Temperature
- Zone Air Relative Humidity
- Zone Air Temperature
- Zone Mean Air Temperature
- Zone Mean Radiant Temperature

- Zone Operative Temperature
- Zone Outdoor Air Dry Bulb Temperature
- Zone Outdoor Air Wet Bulb Temperature
- Zone Outdoor Air Wind Speed

There are other variables that can be used to generate information from the simulation about other thermal quantities, to name a few - people air temperature, people total heating energy, zone air heat balance inter-zone air transfer rate, zone air heat balance outdoor air transfer rate, zone air humidity ratio, zone electrical equipment electric energy, zone lights electrical energy, zone mean air humidity ratio, zone infiltration air change rate etc.

3.2.7 Conversion of the simulation results into performance measure

Google SketchUp with OpenStudio plugin was used to model, visualize and edit the building geometry which was the most popular user interface program for EnergyPlus.

OpenStudio plugin was used to launch energy plus simulation after assigning some attributes of weather data, schedule, construction assemblies, and thermal load, space and zone settings. OpenStudio application itself can perform basic simulation. For more detailed output IDF editor of EnergyPlus can be used to edit the exported IDF file from OpenStudio and then it can be used to get desired output from directly using EnergyPlus simulation engine.

Once output variables has been set and calculated using simulation engine for the thermal zones, the result can be presented through graphical representation by using “ResultViewer” which can produce line plot, stack plot and color maps. Such graphical presentation sheds light on valuable insights on the thermal condition of the zone and enables comparison of the envelope performance.

3.3 Conclusion

This chapter describes the detailed methodology of field study of Rajshahi Medical College Hospital about envelope conditions of four in–patient rooms i.e. surgery, neurosurgery, cardiology, and VIP to have insights on the prospect of facilitating passive cooling through building envelope. It also focuses the findings of the existing comfort condition, occupancy type and behavior, energy consumption pattern of different inpatient rooms and of different electrical equipment and schedule of their use. This chapter also describes modeling the case inpatient room in OpenStudio SketchUp plugin and data input of different variable to prepare the model for thermal simulation of its existing envelope as well as proposed envelope in order to compare the performance. It is neither possible in the given scope and time, nor pragmatic to take in consideration of all inpatient rooms for case study and year round data of climatic conditions. The results of the field study and detail simulation analysis of case inpatient room for four envelope conditions have been presented in the next chapter.

4 CHAPTER FOUR: FIELD SURVEY AND SIMULATION RESULTS

Introduction

Existing outdoor and indoor environment of the inpatient room

Thermal Comfort Survey

Building features and envelop condition

3D model of the case inpatient room for simulation

Space types and thermal zones

Simulation analysis

Results analysis

Comparison

Conclusion

4.1 Introduction

Methodology that is described in chapter 3 is formulated from literature review. This chapter contains the descriptions of the field results and analysis of the simulation output based on the outcomes of the previous two chapters. This chapter is structured into two major sections. The first section summarizes the results of field study. In the second section the simulation outputs are summarized as in the form of descriptive statistics. The detailed output in graphical format (line plot) of the four envelope types which consist of extreme design conditions as well as thermal conditions for a span of 6 months (Pre monsoon to monsoon) are presented in Appendix C. This will provide insights on the performance of each four envelope types. It also analyzes the results and compare the performance of the four envelopes using output variables set in chapter 4 and plotting them in line graph. The comparison and analysis based on the activities of this chapter have been discussed in end of this chapter and recommendations have been presented in concluding Chapter 5.

4.2 Existing outdoor and indoor environment of the inpatient room

Four inpatient rooms of surgery, neurosurgery, cardiology, and VIP were surveyed. Features and physical dimensions of these inpatient rooms are presented in Table 4.1.

Table 4.1 List of selected inpatient rooms for field survey

Inpatient room	No. of Bed	Length	Width	Height	Floor level	Floor area (sft)	Volume (cft)	No. of patient	No. of Medical staff	No. of visitor
Inpatient room - Surgery (Ward no 05)	47	194’	33’6	12’	1st	6264	75168	84	40	80
Inpatient room - Neurosurgery (Ward no 08)	33	194’	33’6	12’	1st	6264	75168	50	18	100
Inpatient room - Cardiology (Ward no 32)	10	28’	23’	12’	1st	644	7728	14	6	8
Inpatient room - VIP (Ward no 04)	1	31’	14’	11’	2nd	434	4774	1	5	3

Environmental data of air temperature, humidity and air velocity recorded inside and outside of the inpatient room during field investigation are presented in Table 4.2. Air Temperature in the outdoor were found to be within the range of 25 to 32.1 deg C. Outdoor temperature in inpatient room of cardiology and VIP were lower than the other two inpatient rooms. This was perhaps due to the shade and orientation of the corridor. Indoor temperature range was 23 to 31.1 deg C. Indoor temperature in inpatient room of cardiology, neurology and VIP closely resembled the outdoor temperature. Because these inpatient rooms are naturally ventilated. However, temperature in inpatient room of cardiology is controlled by air conditioning and kept within 22 to 23 deg C range. Relative humidity was found to be low inside and outside of the inpatient room throughout the field survey and recorded as 20% to 35%. Air speed was low. It varied from 0.2 to 1.2 m/s inside three of the naturally ventilated inpatient rooms. Maximum air speed of 2.4 m/s was recorded outside of the inpatient room during the survey.

The findings are described below in Table 4.2.

Table 4.2 Environmental data recoded in field survey

	Indoor						**Outdoor**					
	Air temperature deg C		Relative humidity%		Air speed		Air temperature		Humidity		Air speed	
Inpatient room	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Inpatient room - Surgery (Ward no 05)	31.1	28.7	35	20	0.5	0.1	32.1	26.1	35	20	1.2	0.2
Inpatient room - Neurosurgery (Ward no 08)	31.2	26	33	21	2.4	0.1	31.1	25	29	22	1.6	0
Inpatient room - Cardiology (Ward no 32)	23	22	25	24	0	0	28.8	25.3	24	21	0.2	0
Inpatient room -VIP (Ward no 04)	25	24.2	28	23	2.4	2	27.5	25	28	23	0.1	0.6

Three types of electrical equipment were found in the inpatient rooms. Incandescent light bulbs, CFL light bulbs and tube lights are used for artificial illumination. Ceiling fans and Split type air conditioners are used for achieving thermal comfort in different inpatient rooms. Medical instruments are used to support and monitor the patients. Electrical load were calculated from the lighting equipment, cooling equipment and medical instruments found in the survey for the four inpatient rooms. Figure 4.1 shows the electricity consumption of the four inpatient room in these three category. Surgery and neurosurgery inpatient rooms consume 17707 kWh/year and 18631 kWh/year respectively. In spite of smaller bed capacity and volume cardiology inpatient room consume 88422 kWh/year electricity. Use of air conditioners for cooling purpose contributed much higher amount of electricity consumption. VIP inpatient room uses lowest amount of energy compared to others. For energy performance comparison kWh/sqm/year and kWh/bed/year metric are useful indicator. Energy performance comparison of the four inpatient rooms are shown in Figure 4.1 and Figure 4.2.

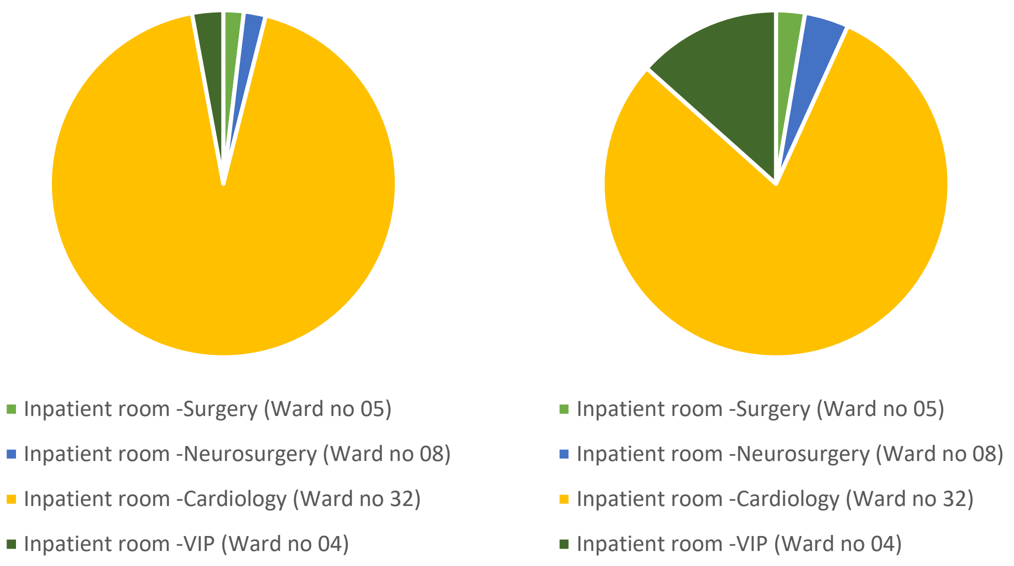


Figure 4.1 Energy consumption comparison of 4 inpatient rooms. (a) kWh/sqm/year (b) kWh/bed/year.

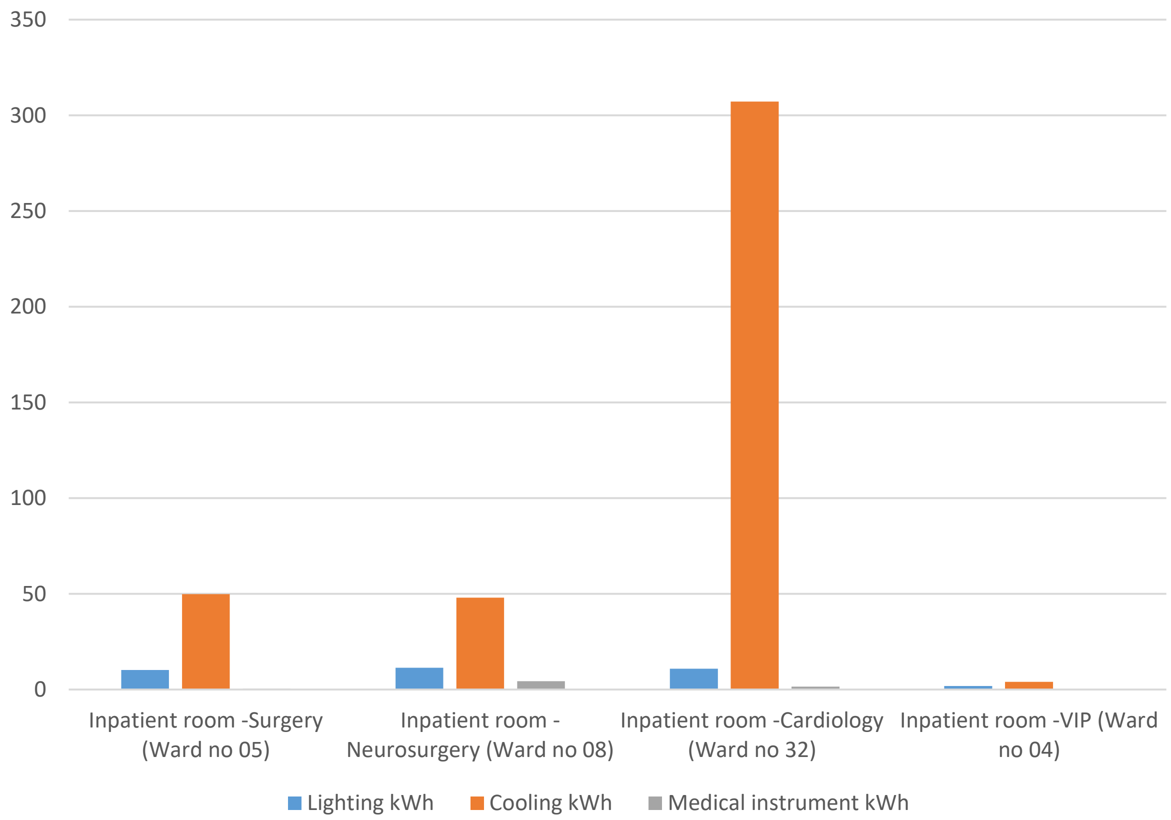


Figure 4.2 Energy consumption comparison of lighting, cooling and medical instruments of 4 inpatient rooms.

Electrical equipment and electrical load are calculated from the survey and summarized in Table 4.3. Electricity is used for lighting, cooling and medical instruments. Ceiling fans are used for cooling effect in the inpatient rooms except cardiology. Cardiology inpatient room uses air conditioning for cooling. As a result both KWh per bed and KWh per sqm was higher in cardiology inpatient room than other three inpatient rooms.

Table 4.3 Electrical equipment and electrical load

Inpatients room/ electrical equipment	Incandescent bulb	Energy saving bulb	Tube light	Ceiling fan	Table fan	Medical instrument	Air conditioner	others	Total (kW and kWh/year)	Area and no. of bed	kWh/ sqm/ year and KWh/ bed/ year
Inpatient room - Surgery (Ward no 05)	-	2 nos. x 32 w = 64 w	9 nos. x 40w = 360 w	26 nos. x 80 w = 2080 w	-	2 nos. x 10 w =20 w	-	-	2.52 kW 17707 kWh/ year	582.24 47	30.41 376.74
Inpatient room - Neurosurgery (Ward no 08)	-	6 nos. x 32 w = 192 w	7 nos. x 40 w = 280 w	25 nos. x 80 w = 2000 w	-	14 nos. x 10 w + 2 nos. x 20 w = 180 w	-	-	2.62 kW 18631 kWh/ year	582.24 33	31.99 564.58
Inpatient room - Cardiology (Ward no 32)	3 nos. x 60 w = 180 w	1 nos. x 32 w = 32 w	6 nos. x 40 w = 240 w	-	-	6 nos. x 10 w =60 w	2 nos. x 6400 w = 12800 w	-	13.25 kW 88422 kWh/ year	59.9 8	1476.1 11053
Inpatient room - VIP (Ward no 04)	-	-	2 nos. x 40 w = 80 w	2 nos. x 80 w = 160 w	1 nos. x 10 w =10 w	1 nos. x 5 w =5 w	-	-	0.26 kW 1932 kWh/ year	40.3 1	47.94 1932

4.3 Thermal Comfort Survey

33 patients participated in the thermal comfort survey. Personal parameters (metabolic rate, activity level, clothing) was determined by observing the subjects during the questionnaire session. Environmental data were collected at the same time by measuring air temperature, humidity and air velocity. Time constraint became a major bar for conducting proper and comprehensive comfort survey. This survey only intend to highlight the thermal comfort condition during the survey period of the inpatient room. The results of the thermal comfort survey are summarized in Table 4.4

Table 4.4 Patients Thermal sensation Vote

ASHRAE thermal sensation scale	Vote	Percentage of Vote
Cold	0	0%
Cool	0	0%
Slightly cool	0	0%
Neutral	21	63.64%
Slightly warm	6	18.18%
Warm	3	9.09%
Hot	3	9.09%

Out of 33 patients interviewed 21 patients reported neutral thermal sensation of the perceived environment. 6 patients reported slightly warm and 6 patients felt warm to hot. Air temperature during this interview was recorded as 28-30 deg C. Humidity level was 25-30%. Ceiling fan was turned off during the whole period.

Table 4.5 shows number of subjects were present during the survey. It was found in the survey that surgery and neurosurgery inpatient rooms has more patients than its intended capacity. On the contrary cardiology and VIP inpatient rooms has patients as per its capacity.

Table 4.5 Wards and total number of subjects present during the survey.

Inpatient room	Patients			Medical staff			Visitors		
	Male	Female	Total	Male	Female	Total	Male	Female	Total
Inpatient room - Surgery (Ward no 05)	84	0	84	23	17	40	30	50	80
Inpatient room - Neurosurgery (Ward no 08)	50	0	50	18	0	18	40	60	100
Inpatient room - Cardiology (Ward no 32)	12	2	14	6	0	6	6	2	8
Inpatient room - VIP (Ward no 04)	1	0	1	4	1	5	2	1	3

4.4 Building features and envelop condition

Inpatient room - Surgery is located on the first floor of the 3rd block from the entry in the North West corner of the hospital. Toilet block is located at the west end and doctor and nurse chambers are located at the east end. A corridor on south side is connecting the ward with the main circulation corridor (Figure 4.3 and Figure 4.5(b)). This inpatient room is constructed in 1965 and is naturally ventilated. Envelope details of the inpatient room are shown in Figure 4.4 and in Table 4.6.

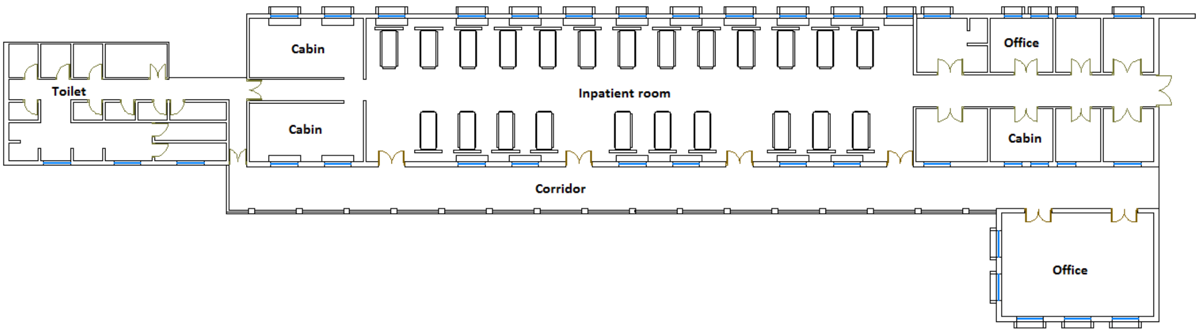


Figure 4.3 Inpatient room of Surgery plan.

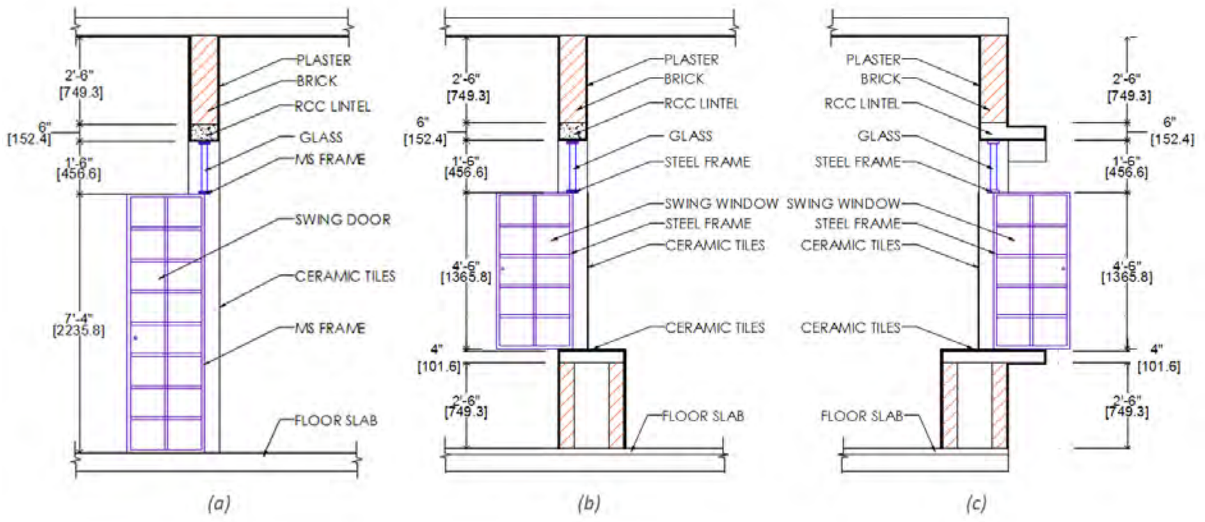


Figure 4.4 Inpatient room of Surgery envelope section. (a) Door section on corridor side (b) window section on corridor side (c) window section on exterior wall.

(a) (b)

Figure 4.5 Inpatient room (a) Surgery exterior photo (b) corridor side wall photo.

Table 4.6 Existing Envelope detail of Inpatient room of surgery (Ward no 05).

Inpatient room of Surgery (Ward no 05)	North wall (Exterior)	South wall (Exterior)	East wall (Exterior)	West wall (Exterior)	Internal wall	Ceiling	Floor
Wall thickness	10" (254 mm)	10" (254 mm)	10" (254 mm)	10" (254 mm)	5" (127 mm)	6"(15.2 mm)	6"(15.2 mm)
Construction material (Outside to inside)	White paint	1/3" (8 mm) white ceramic tiles	1/3" (8 mm) white ceramic tiles	White paint	1/3" (8 mm) white ceramic tiles	-	-
	1/2" (12 mm) plaster	1/2" (12 mm) plaster	1/2" (12 mm) plaster	1/2" (12 mm) plaster	1/2" (12 mm) plaster	1/4" (6.35 mm) mosaic finish	1/4" (6.35 mm) plaster
	10" (254 mm) brick	10" (254 mm) brick	10" (254 mm) brick	10" (254 mm) brick	5" (127 mm) brick	6" (152 mm) RCC	6" (152 mm) RCC
	1/2" (12 mm) plaster	1/2" (12 mm) plaster	1/2" (12 mm) plaster	1/2" (12 mm) plaster	1/2" (12 mm) plaster	1/4" (6.35 mm) plaster	1/4" (6.35 mm) mosaic finish
	1/3" (8 mm) white ceramic tiles	1/3" (8 mm) white ceramic tiles	1/3" (8 mm) white ceramic tiles	1/3" (8 mm) white ceramic tiles	1/3" (8 mm) white ceramic tiles	-	-
No. of Door, type and Material	0	4	1	0	22	-	-
	-	7' Swing door with 1'6" awning ventilator	7' Swing door with 1'6" awning ventilator	-	7' Swing door with 1'6" awning ventilator	-	-
	-	MS sheet and glass pane with MS angle.	MS sheet and glass pane with MS angle.	-	MS sheet and glass pane with MS angle.	-	-
No. of window, type and material	17	18	0	0	0	-	-
	4' 6" Swing window with 1'6" awning type ventilator	4' 6" Swing window with 1'6" awning type ventilator	-	-	-	-	-
	MS sheet and glass pane with MS angle.	MS sheet and glass pane with MS angle.	-	-	-	-	-

Inpatient room of Neurosurgery is located on the 1st floor at the central section of the 3rd block from the entry of the hospital. Toilet block is located at the east end and doctor and nurse chambers are located at the west end. A corridor on south side is connecting the ward with the main circulation corridor

(Figure 4.6 and Figure 4.8). This inpatient room is constructed in 1965 and is naturally ventilated. Envelope details of the inpatient room are shown in Figure 4.7 and in Table 4.7.

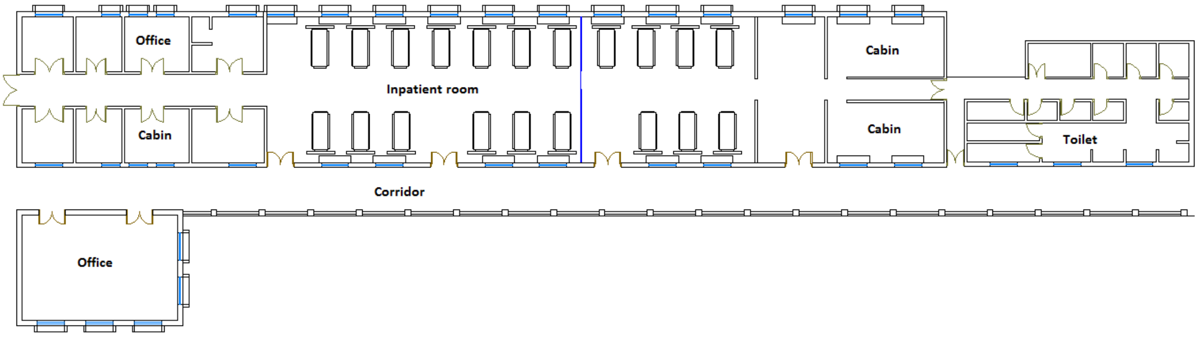


Figure 4.6 Inpatient room of Neurosurgery plan.

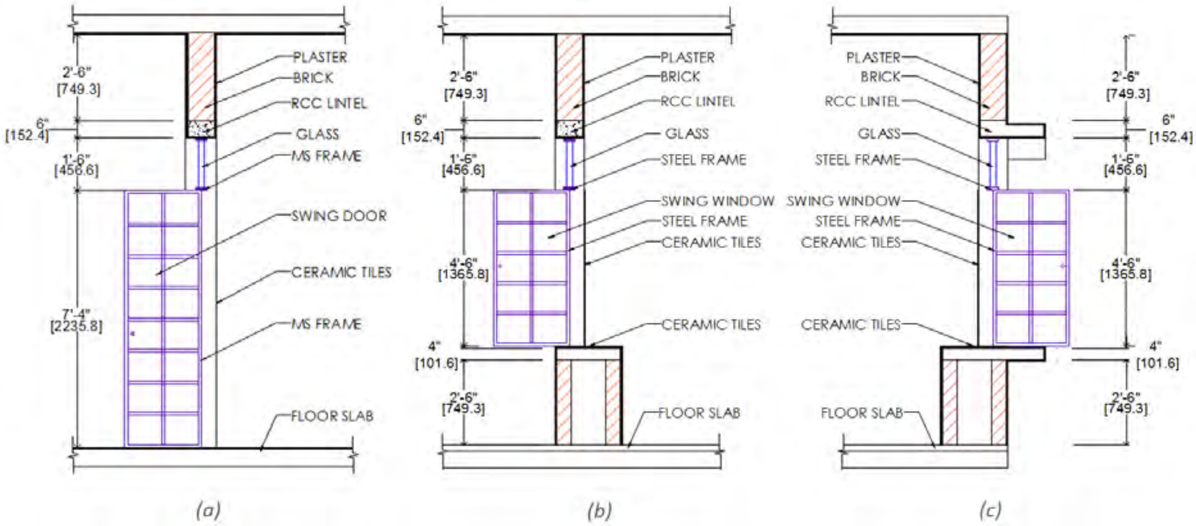


Figure 4.7 Inpatient room of Neurosurgery envelope section. (a) Door section on corridor side (b) window section on corridor side (c) window section on exterior wall.

Figure 4.8 Interior of Inpatient room of Neurosurgery: Source: Field survey photo

Table 4.7 Existing Envelope detail of Inpatient room of Neurosurgery (Ward no 08).

Inpatient room of Neurosurgery (Ward no 08)	North wall (Exterior)	South wall (Exterior)	East wall (Exterior)	West wall (Exterior)	Internal wall	Ceiling	Floor
Wall thickness	10" (254 mm)	10" (254 mm)	10" (254 mm)	10" (254 mm)	5" (127 mm)	6"(15.2 mm)	6"(15.2 mm)
Construction material (Outside to inside)	White paint	1/3" (8 mm) white ceramic tiles	White paint	1/3" (8 mm) white ceramic tiles	1/3" (8 mm) white ceramic tiles	-	-
	1/2" (12 mm) plaster	1/2" (12 mm) plaster	1/2" (12 mm) plaster	1/2" (12 mm) plaster	1/2" (12 mm) plaster	1/4" (6.35 mm) mosaic finish	1/4" (6.35 mm) plaster
	10" (254 mm) brick	10" (254 mm) brick	10" (254 mm) brick	10" (254 mm) brick	5" (127 mm) brick	6" (152 mm) RCC	6" (152 mm) RCC
	1/2" (12 mm) plaster	1/2" (12 mm) plaster	1/2" (12 mm) plaster	1/2" (12 mm) plaster	1/2" (12 mm) plaster	1/4" (6.35 mm) plaster	1/4" (6.35 mm) mosaic finish
	1/3" (8 mm) white ceramic tiles	1/3" (8 mm) white ceramic tiles	1/3" (8 mm) white ceramic tiles	1/3" (8 mm) white ceramic tiles	1/3" (8 mm) white ceramic tiles	-	-
No. of Door, type and Material	0	4	0	1	22	-	-
	-	7' Swing door with 1'6" awning ventilator	-	7' Swing door with 1'6" awning ventilator	7' Swing door with 1'6" awning ventilator	-	-
	-	MS sheet and glass pane with MS angle.	-	MS sheet and glass pane with MS angle.	MS sheet and glass pane with MS angle.	-	-
No. of window, type and material	17	18	0	0	0	-	-
	4' 6" Swing window with 1'6" awning type ventilator	4' 6" Swing window with 1'6" awning type ventilator	-	-	-	-	-
	MS sheet and glass pane with MS angle.	MS sheet and glass pane with MS angle.	-	-	-	-	-

Inpatient room of Cardiology is located on the first floor of the new building constructed in 2012 in the center of the main building. Doctor and nurse chambers are located at the corridor and opposite of the corridor respectively (Figure 4.9 and Figure 4.11). This building has a deep plan compact layout unlike the older part of the hospital and it is mechanically ventilated. Envelope details of the inpatient room are shown in Figure 4.10 and in Table 4.8.

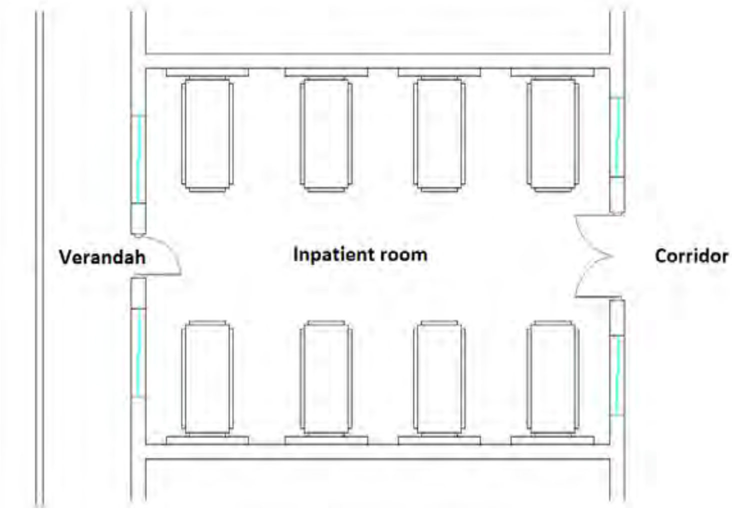
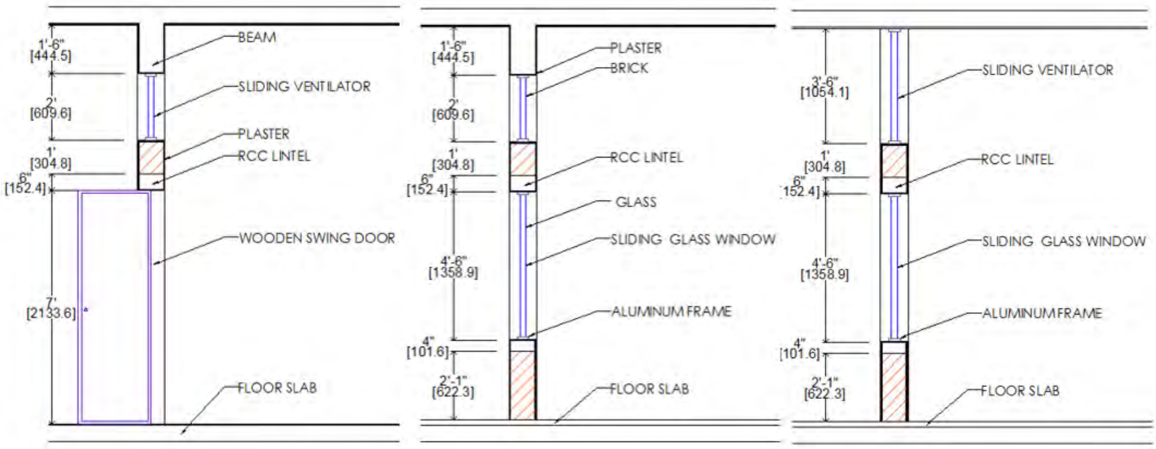


Figure 4.9 Inpatient room of Cardiology plan.



(a) *(b)* *(c)*

Figure 4.10 Existing envelope detail of Inpatient room of Cardiology (Ward no 32). (a) Door section on corridor side (b) window section on corridor side (c) window section on exterior wall.

(a) *(b)*

Figure 4.11 Inpatient room of (a) Cardiology exterior view and (b) interior view.

Table 4.8 Existing Envelope detail of Inpatient room of Cardiology (Ward no 32).

Inpatient room of Cardiology (Ward no 32)	**North wall (Exterior)**	**South wall (Exterior)**	**East wall (Exterior)**	**West wall (Exterior)**	**Internal wall**	**Ceiling**	**Floor**
Wall thickness	10" (254 mm)	10" (254 mm)	10" (254 mm)	10" (254 mm)	-	6"(15.2 mm)	6"(15.2 mm)
Construction material (Outside to inside)	White paint	1/3" (8 mm) white ceramic tiles	1/3" (8 mm) white ceramic tiles	White paint	-	-	-
	1/2" (12 mm) plaster	1/2" (12 mm) plaster	1/2" (12 mm) plaster	1/2" (12 mm) plaster	-	1/4" (6.35 mm) mosaic finish	1/4" (6.35 mm) plaster
	10" (254 mm) brick	10" (254 mm) brick	10" (254 mm) brick	10" (254 mm) brick	-	6" (152 mm) RCC	6" (152 mm) RCC
	1/2" (12 mm) plaster	1/2" (12 mm) plaster	1/2" (12 mm) plaster	1/2" (12 mm) plaster	-	1/4" (6.35 mm) plaster	1/4" (6.35 mm) mosaic finish
	1/3" (8 mm) white ceramic tiles	1/3" (8 mm) white ceramic tiles	1/3" (8 mm) white ceramic tiles	1/3" (8 mm) white ceramic tiles	-	-	-
No. of Door, type and Material	0	0	1	1	0	-	-
	-	-	7' Swing door with 1'6" sliding ventilator	7' Swing door with 1'6" sliding ventilator	-	-	-
	-	-	Wood	Wood	-	-	-
No. of window, type and material	0	0	2	2	0	-	-
	-	-	4'6 sliding window with 2' sliding ventilator	4'6 sliding window with 3'6" sliding ventilator	-	-	-
	-	-	Aluminum frame with glass pane	Aluminum frame with glass pane	-	-	-

Inpatient room of VIP is located on the second floor of the 1st block from the entry in the southeast part of the hospital. A corridor on north side is connecting the ward with the main circulation corridor. It has verandah on south side and has toilet on north side (Figure 4.12 and Figure 4.14). It is naturally ventilated. Envelope details of the inpatient room are shown in Figure 4.13 and in Table 4.9.

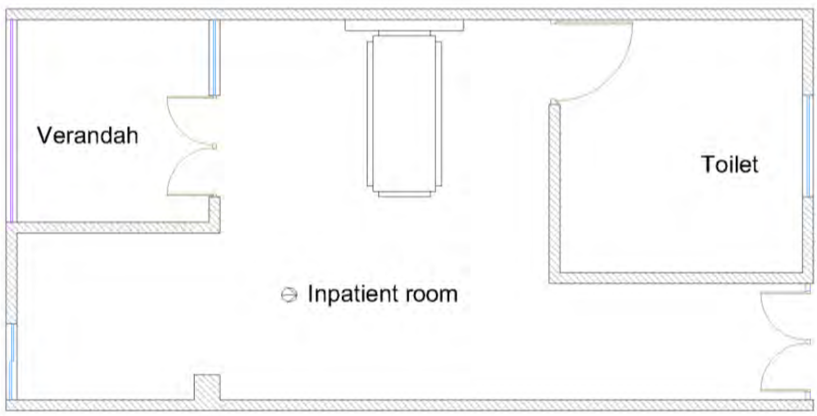


Figure 4.12 Inpatient room of VIP plan.

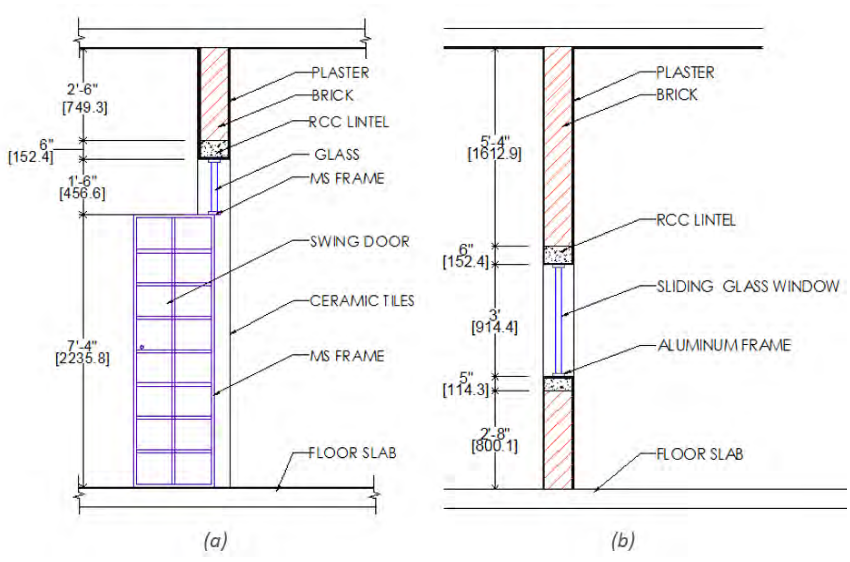


Figure 4.13 Existing envelope detail of Inpatient room of VIP (Ward no 04). (a) Door section on corridor side (b) window section.

Figure 4.14 Interior of Inpatient room of VIP.

Table 4.9 Existing envelope detail of Inpatient room of VIP (Ward no 04).

Inpatient room of VIP (Ward no 04)	North wall (Exterior)	South wall (Exterior)	East wall (Exterior)	West wall (Exterior)	Internal wall	Ceiling	Floor
Wall thickness	5” (127 mm)	5” (127 mm)	5” (127 mm)	5” (127 mm)	-	6”(15.2 mm)	6”(15.2 mm)
Construction material (Outside to inside)	White paint	White paint	White paint	White paint	White paint	-	-
	1/2” (12 mm) plaster	1/2” (12 mm) plaster	1/2” (12 mm) plaster	1/2” (12 mm) plaster	1/2” (12 mm) plaster	1/4” (6.35 mm) mosaic finish	1/4” (6.35 mm) plaster
	5” (127 mm) brick	5” (127 mm) brick	5” (127 mm) brick	5” (127 mm) brick	5” (127 mm) brick	6” (152 mm) RCC	6” (152 mm) RCC
	1/2” (12 mm) plaster	1/2” (12 mm) plaster	1/2” (12 mm) plaster	1/2” (12 mm) plaster	1/2” (12 mm) plaster	1/4” (6.35 mm) plaster	1/4” (6.35 mm) mosaic finish
	White paint	White paint	White paint	White paint	White paint	-	-
No. of Door, type and Material	1	0	0	0	1	-	-
	7’ Swing door with 1’6” fixed panel in upper portion	-	-	-	7’ Swing door	-	-
	Glass pane with MS angle.	-	-	-	Wood	-	-
No. of window, type and material	0	1	0	0	0	-	-
	-	4’6 sliding window	-	-	-	-	-
	-	Aluminum frame with glass pane	-	-	-	-	-

The envelop conditions of four inpatient rooms are summarized in tabular form in Table 4.6 to Table 4.9. Exterior wall are constructed as 254 mm brick construction in three of the inpatient rooms except VIP inpatient room. Inside of the walls are finished with glossy white tiles for ease of cleaning. Outside of the wall are plastered and painted with white paint. All of the walls of the VIP inpatient room are constructed as 127 mm brick construction with plastered finish on both side. Doors and windows are constructed of metal and glass panel with MS angle. All exterior windows has 460 mm projected sun shade.

As these envelops of the inpatient room are comprised of multiple layers, construction material with different thermal properties can be used as parameters to simulate the overall thermal condition and minimize heat gain through envelop to facilitate passive cooling inside inpatient room.

4.5 3D model of the case inpatient room for simulation

Surgery ward (ward No. 05) described in section 4.4 was taken as case space for simulation study. The inpatient room has a floor area of 582.24 m^2 (60 meter x 10.2 meter) and its clear height 3.45 meter. The block is east-west elongated and north –south oriented. It has a capacity for 47 beds. The whole ward is naturally ventilated with 17 operable windows on north side and 13 operable window and 4 doors on south side. All windows and doors have in addition awning ventilators.

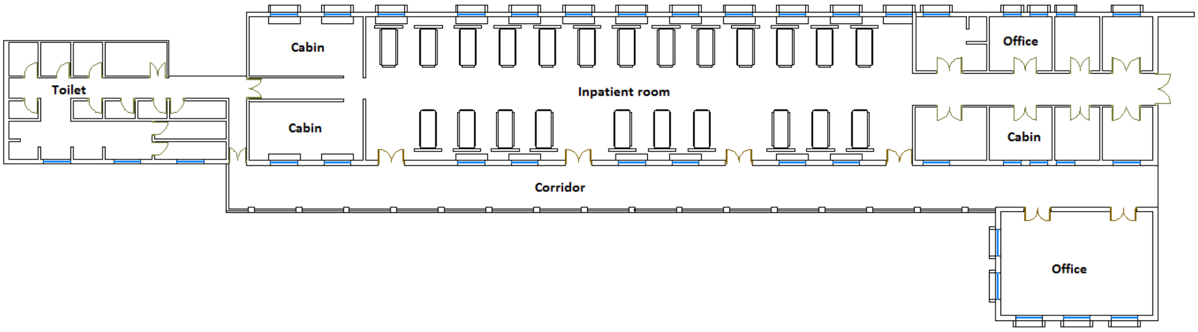


Figure 4.15 Inpatient room of Surgery plan

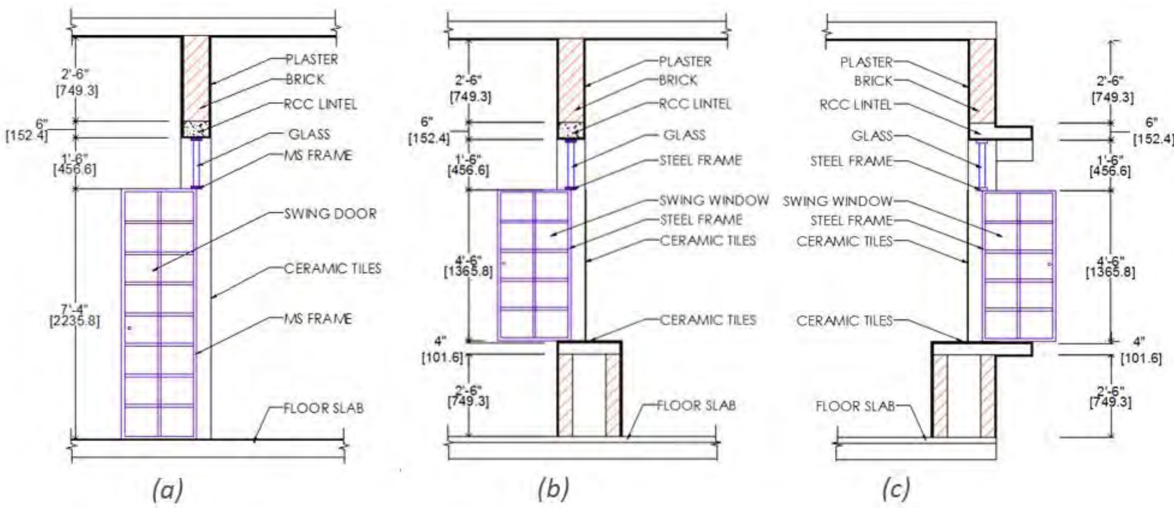


Figure 4.16 Existing envelope detail of Inpatient room of Surgery (Ward no 05). (a) Door section on corridor side (b) window section on corridor side (c) window section on exterior wall.

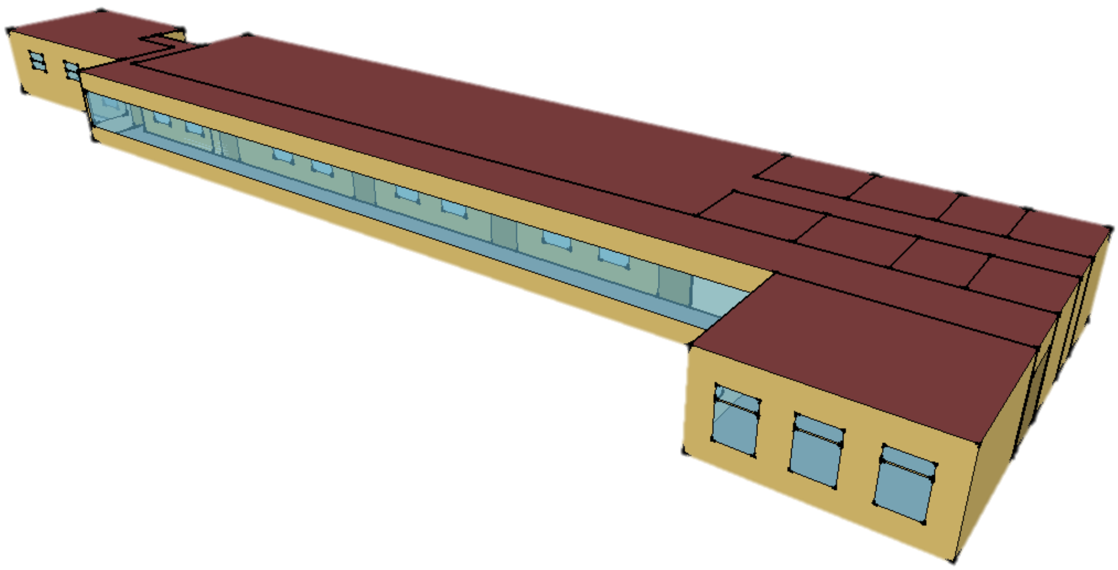


Figure 4.17 3D model generated using SketchUp 2016 with OpenStudio plugin

The parameters of existing condition for the 3D model are set in Table 4.10 as found in the field survey of the case inpatient room.

Table 4.10 Parameters for 3D modeling from field survey.

Sl. No.	Parameter	Specification
1	Inpatient floor dimension	60 meter x 10.2 meter
2	Total floor area	582.24 m^2
3	Window size	1.37m x 1.37m
4	Number of windows	30
5	Window lintel level	850 mm
6	Window sill level	2690 mm
7	Window material	Glass, metal sheet and metal angle
8	Door size	2.235 m x 1.37 m
9	Number of doors	4
10	Door material	Glass, metal sheet and metal angle
11	Ceiling height	11.33 m
12	Floor slab core material	RCC concrete
13	Floor slab finish material	Plaster, terrazzo
14	Roof slab core material	RCC concrete
15	Roof slab finish material	Plaster
16	Wall construction material	Brick, plaster, local tiles

4.6 Space types and thermal zones

At this stage different space types that are found in field survey are assigned in OpenStudio for simulation purpose.

Then each space is associated with their respective schedule set - occupancy, light, other electrical equipment, infiltration, and activity; Air Flow - Ventilation (calculated from field data); infiltration rate (default value); Load - electrical load, people thermal load.

Spaces with similar thermal load and characteristics are grouped into thermal zone. Three thermal zones are defined in this simulation study.

Surface and subsurface of each space are assigned with properties of surface type, construction, outside boundary condition, exposure to sun and wind, interior partition construction, shading surface construction.

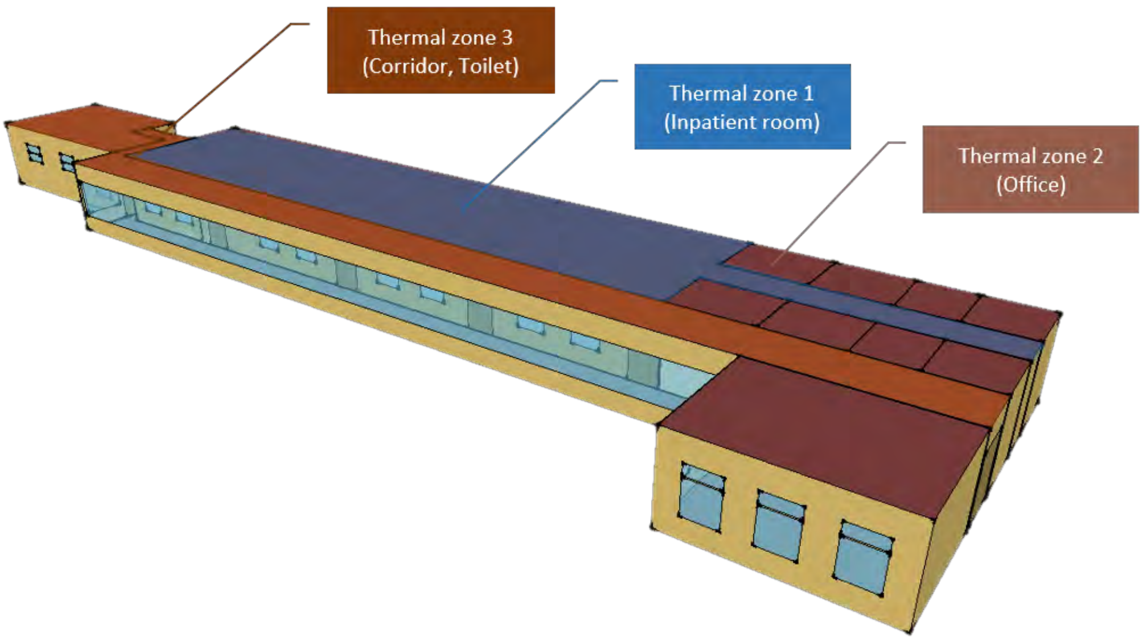


Figure 4.18 Spaces grouped into Thermal zone.

4.7 Simulation Analysis

Temperature and humidity conditions are based on annual percentiles of 1.0%. The use of annual percentiles to define design conditions ensures that they represent the same probability of occurrence in any climate, regardless of the seasonal distribution of extreme temperature and humidity. First results of the simulation are compared for output variables of mean air temperature, mean radiant temperature, mean operative temperature, relative humidity, surface inside and outside temperature as 1.0 percentile of cooling (hot), and dehumidification (humid) design condition for each zones. Then results are compared for output variables presented in section 3.2.6 for a duration of six months from March to August (Pre monsoon to Monsoon period) representative of each zones. The detail output of the simulation are shown in Appendix C. The results for four envelope conditions from simulation are summarized in the following sections:

4.7.1 Annual Cooling Condition for 1.0 percentile: Wall Type WB10

Annual cooling condition for 1.0 percentile represent the hot day of a typical meteorological year with a probability of 1% occurrence. Here wall type WB10 denotes the envelope condition with 10” brick in core with plastered and tiled finish on outside. The simulation results from EnergyPlus are summarized in the form of descriptive statistics in Table 4.11. The detailed value for each output variable are shown in graph as line plot in the figure from C.1 to C.6.

Three temperature indices are used (Mean Air Temperature, Mean Radiant Temperature, and Mean Operative temperature) to discern the variation of thermal performance of WB10 for three thermal zones. The simulation results indicates that in all of the cases of thermal indices, zone 3 (corridor and toilets) matches with outside conditions as it has the maximum exposure to the outdoor.

Mean Air Temperature:

From standard deviation it is apparent that zone 2’s (office) diurnal variation (5.79 deg C) is the least and zone 3’s (corridor) is the highest (8.71 deg C). Zone 1 (inpatient room) (6.75 deg C) moderately fluctuate with outdoor air temperature.

The mean max air temperature for all three zones converges at about 37 deg C whereas lowest temperature vary from 28.5 deg C to 31.24 deg C (Figure C.2).

Mean Radiant Temperature:

Same as aforementioned mean air temperature, zone 3 has the highest diurnal range (4.63 deg C) of Mean Radiant Temperature. Although from standard deviation it is apparent that zone 1 (inpatient room) and zone 2 (office) has a similar pattern, zone 2 shows higher mean radiant temperature than zone 1 (Figure C.3). Close proximity of the surfaces and lesser volume of zone 2 may be contributing to this thermal characteristics.

Mean Operative Temperature:

Mean Operative Temperature demonstrate similar pattern as it represents the combined effect of air temperature and radiant temperature (Figure C.4).

Relative humidity:

Since Relative humidity is inversely correlated with air temperature, its highest value coincides with lowest air temperature and vice versa. For zone 1, zone 2, and zone 3 the lowest relative humidity of 48.44%, 31.24%, and 48.16% respectively occurs at 2 p.m. in the afternoon (Figure C.5).

Surface Inside and Outside temperature:

Four walls types and their corresponding outside and inside surface temperature of the of inpatient room for envelope type WB10 are shown in Figure C.6. Higher time lag and decrement factor can be observed for north and west wall which is exposed to outdoor. On the contrary south and east wall demonstrate almost no time lag and relatively lower decrement factor compared to other two walls. This is may be due to the fact that both of them are in shaded region of the case inpatient room.

Table 4.11 Summary of the statistical value of Annual Cooling Condition for 1.0 percentile: Wall Type WB10

	Mean Value	**Max. Value**	**Min. Value**	**Range**	**Standard deviation**
Outdoor Air DBT	32.32	37.20	28.10	9.10	0.81
Outdoor Air WBT	25.60	26.80	24.54	2.26	0.81
Mean Air Temperature: Zone 1	33.24	36.85	30.09	6.75	2.43
Mean Air Temperature: Zone 2	33.89	37.02	31.24	5.79	2.06
Mean Air Temperature: Zone 3	32.54	37.21	28.50	8.71	3.11
Mean Radiant Temperature: Zone 1	33.91	34.64	33.06	1.58	0.54
Mean Radiant Temperature: Zone 2	34.96	35.83	34.09	1.73	0.57
Mean Radiant Temperature: Zone 3	35.03	37.45	32.82	4.63	1.54
Mean Operative Temperature: Zone 1	33.57	35.66	31.62	4.04	1.41
Mean Operative Temperature: Zone 2	34.42	36.31	32.70	3.61	1.25
Mean Operative Temperature: Zone 3	33.79	37.18	30.73	6.45	2.22
Mean Humidity: Zone 1	58.03	67.36	48.44	18.92	6.64
Mean Humidity: Zone 2	55.96	63.17	48.16	15.00	5.18
Mean Humidity: Zone 3	59.28	73.31	45.20	28.11	10.03

4.7.2 Annual dehumidification Condition for 1.0 percentile: Wall Type WB10

Annual dehumidification condition for 1.0 percentile represent the humid day of a typical meteorological year with a probability of 1% occurrence. Here wall type WB10 denotes the envelope condition with 10” brick in core with plastered and tiled finish on outside. The simulation results from

EnergyPlus are summarized in the form of descriptive statistics in Table 4.12. The detailed value for each output variable are shown in graph as line plot in the figure from C.7 to C.12.

Three temperature indices are used (Mean Air Temperature, Mean Radiant Temperature, and Mean Operative temperature) to discern the variation of thermal performance of WB10 for three thermal zones. The simulation results indicates that in all of the cases of thermal indices, zone 3 (corridor and toilets) varies significantly with outside conditions as it has the maximum exposure to the outdoor.

Mean Air Temperature:

From standard deviation it is apparent that zone 2's (office) diurnal variation (5.95 deg C) is the least and zone 3's (corridor) (8.73 deg C) is the highest. Zone 1 (inpatient room) moderately (6.98 deg C) fluctuate with outdoor air temperature.

The mean max air temperature for all three zones converges whereas lowest temperature vary 23.3 deg C to 26.3 deg C (Figure C.8).

Table 4.12 Summary of the statistical value of Annual Dehumidification Condition for 1.0 percentile: Wall Type WB10

	Mean Value	Max. Value	Min. Value	Range	Standard deviation
Outdoor Air DBT	27.12	32.00	22.90	9.10	2.38
Outdoor Air WBT	26.40	29.11	22.90	6.22	2.38
Mean Air Temperature: Zone 1	28.41	32.12	25.14	6.98	2.54
Mean Air Temperature: Zone 2	29.06	32.26	26.30	5.95	2.15
Mean Air Temperature: Zone 3	27.40	32.07	23.34	8.73	3.12
Mean Radiant Temperature: Zone 1	29.36	30.14	28.44	1.69	0.58
Mean Radiant Temperature: Zone 2	30.27	31.17	29.36	1.81	0.60
Mean Radiant Temperature: Zone 3	30.24	32.72	27.97	4.75	1.58
Mean Operative Temperature: Zone 1	28.88	31.04	26.83	4.21	1.48
Mean Operative Temperature: Zone 2	29.66	31.60	27.87	3.74	1.30
Mean Operative Temperature: Zone 3	28.82	32.24	25.73	6.52	2.25
Mean Humidity: Zone 1	89.41	95.20	83.01	12.19	3.52
Mean Humidity: Zone 2	86.22	93.29	82.16	11.14	3.54
Mean Humidity: Zone 3	93.65	98.89	80.87	18.02	6.39

Mean Radiant Temperature:

As mentioned in the previous passage, zone 3 has the highest diurnal range (4.75 deg C) of Mean Radiant Temperature. Although from standard deviation it is apparent that zone 1 (inpatient room) and zone 2 (office) has a similar pattern, zone 2 shows higher mean radiant temperature than zone 1 (Figure C.9). Close proximity of the surfaces and lesser volume of zone 2 may be contributing to this thermal characteristics.

Mean Operative Temperature:

Mean Operative Temperature demonstrate similar pattern as it represents the combined effect of air temperature and radiant temperature (Figure C.10).

Relative humidity:

Since Relative humidity is inversely correlated with air temperature, its highest value coincide with lowest air temperature and vice versa. For zone 1, zone 2, and zone 3 the lowest relative humidity of 83.01%, 82.16%, and 80.87% respectively occurs at 2 p.m. in the afternoon (Figure C.11).

Surface Inside and Outside temperature:

Four walls types and their corresponding outside and inside surface temperature of the of inpatient room for envelope type WB10 are shown in Figure C.12. Higher time lag and decrement factor can be observed for north and west wall which is exposed to outdoor. On the contrary south and east wall demonstrate almost no time lag and relatively lower decrement factor compared to other two walls. This is may be due to the fact that both of them are in shaded region of the case inpatient room.

4.7.3 Thermal Condition of Zones from March to August: Wall Type WB10

In this section thermal condition from March to August (Pre monsoon to monsoon period) are presented for the three zones. Wall type WB10 denotes the envelope condition with 10” brick in core with plastered and tiled finish on outside. The simulation results from EnergyPlus are summarized in the form of descriptive statistics in Table 4.13. The detailed value for each output variable are shown in graph as line plot in the figure from C.13 to C.27.

Three temperature indices are used (Mean Air Temperature, Mean Radiant Temperature, and Mean Operative temperature) to discern the variation of thermal performance of WB10 for three thermal zones. The simulation results indicates that in all of the cases of thermal indices, zone 3 (corridor and toilets) varies significantly with outside conditions as it has the maximum exposure to the outdoor.

Mean Air Temperature:

All three zone show the trend of greater variation during pre-monsoon period compared to monsoon period (Figures C.14 to C.16).

From standard deviation it is apparent that zone 2's (office) variation is the least (2.45) and zone 3's (corridor) (3.49) is the highest. Zone 1 (inpatient room) moderately (2.79) fluctuate with outdoor air temperature. Zone 1, Zone 2, and Zone 3 shows a negative skew of -0.45, -0.39 and -0.24 respectively (Table 4.13).

Mean Operative Temperature:

Mean Operative Temperature demonstrate similar pattern as it represents the combined effect of air temperature and radiant temperature (Figures C.17 to C.19).

Table 4.13 Summary of the statistical value of thermal Condition from March to August: Wall Type WB10

	Mean Value	Median	Mode	Standard deviation	Skewness	Kurtosis	Max. Value	Min. Value	Range
Outdoor Air DBT	27.92	25.48	26.17	3.63	-1.22	0.89	42.50	12.60	29.90
Outdoor Air WBT	24.36	25.48	26.17	3.09	-1.22	0.89	29.76	12.23	17.52
Mean Air Temperature: Zone 1	29.68	29.69	-	2.79	-0.45	1.27	40.07	17.86	22.21
Mean Air Temperature: Zone 2	30.37	30.43	-	2.45	-0.39	1.27	39.83	20.21	19.62
Mean Air Temperature: Zone 3	28.19	28.13	-	3.49	-0.24	1.27	42.18	13.47	28.71
Mean Radiant Temperature: Zone 1	30.78	31.14	-	1.97	-0.92	1.36	36.74	23.22	13.52
Mean Radiant Temperature: Zone 2	31.49	31.75	-	1.86	-0.62	1.13	37.56	24.74	12.82
Mean Radiant Temperature: Zone 3	31.15	31.22	-	2.26	-0.28	0.96	39.17	22.04	17.14
Mean Operative Temperature: Zone 1	30.23	30.45	-	2.24	-0.71	1.51	38.25	20.65	17.61
Mean Operative Temperature: Zone 2	30.93	31.12	-	2.06	-0.54	1.32	38.57	22.57	16.00
Mean Operative Temperature: Zone 3	29.67	29.68	-	2.76	-0.26	1.21	40.40	17.94	22.47
Mean Humidity: Zone 1	70.68	73.88	-	13.41	-1.24	1.27	93.10	18.67	74.43
Mean Humidity: Zone 2	68.10	71.11	-	12.91	-1.14	0.96	90.30	19.17	71.13
Mean Humidity: Zone 3	75.57	79.91	-	16.76	-1.20	1.04	99.00	14.48	84.52

Mean Radiant Temperature:

Pre-monsoon period show greater variation than monsoon period (Figures C.20 to C.22). From standard deviation it is apparent that zone 2's (office) variation is the least (1.86) and zone 3's (corridor) (2.26) is the highest. Zone 1 (inpatient room) moderately (1.97) fluctuate with outdoor air temperature. Zone 1, Zone 2, and Zone 3 shows a negative skew of -0.92, -0.62 and -0.28 respectively (Table 4.13).

Relative humidity:

A common trend of higher variation during the pre-monsoon period and lower variation during the monsoon period can be observed for all three zones (Figures C.23 to C.25). As like other thermal parameters zone 3 (corridor) shows a greater standard deviation of 16.67 compared to other two zones with value of 13.41 and 12.91 for zone 1 and zone 2 respectively (Table 4.13).

Surface Inside and Outside temperature:

Two walls types (North and South wall) and their corresponding outside and inside surface temperature of the of inpatient room for envelope type WB10 are shown in figures C.26 to C.27. Higher time lag and decrement factor can be observed for north wall which is exposed to outdoor. On the contrary south wall demonstrate relatively lower time lag and decrement factor which has a corridor adjacent with it.

4.7.4 Annual Cooling Condition for 1.0 percentile: Wall Type WB05

Annual cooling condition for 1.0 percentile represent the hot day of a typical meteorological year with a probability of 1% occurrence. Here wall type WB05 denotes the envelope condition with 5” brick in core with plastered and tiled finish on outside. The simulation results from EnergyPlus are summarized in the form of descriptive statistics in Table 4.14. The detailed value for each output variable are shown in graph as line plot in the figure from C.28 to C.32.

Three temperature indices are used (Mean Air Temperature, Mean Radiant Temperature, and Mean Operative temperature) to discern the variation of thermal performance of WB05 for three thermal zones. The simulation results indicates that in all of the cases of thermal indices, zone 3 (corridor and toilets) varies significantly with outside conditions as it has the maximum exposure to the outdoor.

Mean Air Temperature:

From standard deviation it is apparent that zone 2’s (office) diurnal variation (2.04) is the least and zone 3’s (corridor) is the highest (3.10). Zone 1 (inpatient room) (2.42) moderately fluctuate with outdoor air temperature.

The mean max air temperature for all three zones converges at about 37 deg C whereas lowest temperature vary from 28.5 deg C to 31.30 deg C (Figure C.29).

Mean Radiant Temperature:

Same as aforementioned mean air temperature, zone 3 has the highest diurnal range (4.86 deg C) of Mean Radiant Temperature. Although from standard deviation it is apparent that zone 1 (inpatient room) and zone 2 (office) has a similar pattern, zone 2 shows higher mean radiant temperature than zone 1

(Figure C.30). Close proximity of the surfaces and lesser volume of zone 2 may be contributing to this thermal characteristics.

Mean Operative Temperature:

Mean Operative Temperature demonstrate similar pattern as it represents the combined effect of air temperature and radiant temperature (Figure C.31).

Table 4.14 Summary of the statistical value of Annual Cooling Condition for 1.0 percentile: Wall Type WB05

	Mean Value	Max. Value	Min. Value	Range	Standard deviation
Outdoor Air DBT	32.32	37.20	28.10	9.10	0.81
Outdoor Air WBT	25.60	26.80	24.54	2.26	0.81
Mean Air Temperature: Zone 1	33.31	36.90	30.15	6.74	2.42
Mean Air Temperature: Zone 2	34.02	37.10	31.30	5.80	2.04
Mean Air Temperature: Zone 3	32.55	37.21	28.50	8.70	3.10
Mean Radiant Temperature: Zone 1	34.13	34.97	33.15	1.82	0.63
Mean Radiant Temperature: Zone 2	35.23	36.32	34.08	2.24	0.79
Mean Radiant Temperature: Zone 3	35.11	37.60	32.74	4.86	1.64
Mean Operative Temperature: Zone 1	33.72	35.78	31.71	4.08	1.41
Mean Operative Temperature: Zone 2	34.63	36.54	32.75	3.79	1.29
Mean Operative Temperature: Zone 3	33.83	37.21	30.71	6.51	2.23
Mean Humidity: Zone 1	57.79	67.12	48.30	18.82	6.57
Mean Humidity: Zone 2	55.56	63.02	47.95	15.07	5.15
Mean Humidity: Zone 3	59.25	100.00	45.21	54.79	10.02

Relative humidity:

Since Relative humidity is inversely correlated with air temperature, its highest value coincides with lowest air temperature and vice versa. For zone 1, zone 2, and zone 3 the lowest relative humidity of 48.30%, 47.95%, and 45.21% respectively occurs at 2 p.m. in the afternoon (Figure C.32).

Surface Inside and Outside temperature:

Four walls types and their corresponding outside and inside surface temperature of the of inpatient room for envelope type WB05 are shown in Figure C.33. Higher time lag and decrement factor can be observed for north and west wall which is exposed to outdoor. On the contrary south and east wall demonstrate almost no time lag and relatively lower decrement factor compared to other two walls. This is may be due to the fact that both of them are in shaded region of the case inpatient room.

4.7.5 Annual dehumidification Condition for 1.0 percentile: Wall Type WB05

Annual dehumidification condition for 1.0 percentile represent the humid day of a typical meteorological year with a probability of 1% occurrence. Here wall type WB05 denotes the envelope condition with 5” brick in core with plastered and tiled finish on outside. The simulation results from EnergyPlus are summarized in the form of descriptive statistics in Table 4.15. The detailed value for each output variable are shown in graph as line plot in the figure from C.34 to C.38.

Three temperature indices are used (Mean Air Temperature, Mean Radiant Temperature, and Mean Operative temperature) to discern the variation of thermal performance of WB05 for three thermal zones. The simulation results indicates that in all of the cases of thermal indices, zone 3 (corridor and toilets) varies significantly with outside conditions as it has the maximum exposure to the outdoor.

Mean Air Temperature:

From standard deviation it is apparent that zone 2’s (office) diurnal variation (2.13) is the least and zone 3’s (corridor) (3.12) is the highest. Zone 1 (inpatient room) (2.53) moderately fluctuate with outdoor air temperature.

The mean max air temperature for all three zones converges at about (32 deg C) whereas lowest temperature vary from 23.33 deg C to 26.33 deg C Figure C.35).

Mean Radiant Temperature:

As mentioned in the previous passage, zone 3 has the highest diurnal range (4.98 deg C) of Mean Radiant Temperature. Although from standard deviation it is apparent that zone 1 (inpatient room) and zone 2 (office) has a similar pattern, zone 2 shows higher mean radiant temperature than zone 1 (Figure C.36). Close proximity of the surfaces and lesser volume of zone 2 may be contributing to this thermal characteristics.

Mean Operative Temperature:

Mean Operative Temperature demonstrate similar pattern as it represents the combined effect of air temperature and radiant temperature (Figure C.37).

Relative humidity:

Since Relative humidity is inversely correlated with air temperature, its highest value coincide with lowest air temperature and vice versa. For zone 1, zone 2, and zone 3 the lowest relative humidity of 18.82%, 11.47%, and 19.13% respectively occurs at 2 p.m. in the afternoon (Figure C.38).

Surface Inside and Outside temperature:

Four walls types and their corresponding outside and inside surface temperature of the of inpatient room for envelope type WB05 are shown in Figure C.39. Higher time lag and decrement factor can be observed for north and west wall which is exposed to outdoor. On the contrary south and east wall demonstrate almost no time lag and relatively lower decrement factor compared to other two walls. This is may be due to the fact that both of them are in shaded region of the case inpatient room.

Table 4.15 Summary of the statistical value of Annual Dehumidification Condition for 1.0 percentile: Wall Type WB05

	Mean Value	Max. Value	Min. Value	Range	Standard deviation
Outdoor Air DBT	27.12	32.00	22.90	9.10	2.38
Outdoor Air WBT	26.40	29.11	22.90	6.22	2.38
Mean Air Temperature: Zone 1	28.45	32.15	25.16	6.98	2.53
Mean Air Temperature: Zone 2	29.15	32.32	26.33	6.00	2.13
Mean Air Temperature: Zone 3	27.40	32.07	23.33	8.74	3.12
Mean Radiant Temperature: Zone 1	29.48	30.38	28.42	1.97	0.68
Mean Radiant Temperature: Zone 2	30.47	31.60	29.27	2.33	0.82
Mean Radiant Temperature: Zone 3	30.27	32.82	27.84	4.98	1.68
Mean Operative Temperature: Zone 1	28.96	31.10	26.85	4.26	1.48
Mean Operative Temperature: Zone 2	29.81	31.78	27.85	3.93	1.34
Mean Operative Temperature: Zone 3	28.84	32.25	25.67	6.58	2.26
Mean Humidity: Zone 1	57.79	67.12	48.30	18.82	6.57
Mean Humidity: Zone 2	85.74	93.49	82.02	11.47	3.48
Mean Humidity: Zone 3	93.63	100.00	80.87	19.13	6.37

4.7.6 Thermal Condition for Zones from March to August: Wall Type WB05

In this section thermal condition from March to August (Pre monsoon to monsoon period) are presented for the three zones. Wall type WB05 denotes the envelope condition with 5" brick in core with plastered and tiled finish on outside. The simulation results from EnergyPlus are summarized in the form of descriptive statistics in Table 4.16. The detailed value for each output variable are shown in graph as line plot in the figure from C.40 to C.54.

Three temperature indices are used (Mean Air Temperature, Mean Radiant Temperature, and Mean Operative temperature) to discern the variation of thermal performance of WB05 for three thermal zones. The simulation results indicates that in all of the cases of thermal indices, zone 3 (corridor and toilets) varies significantly with outside conditions as it has the maximum exposure to the outdoor.

Mean Air Temperature:

All three zone show the trend of greater variation during pre-monsoon period compared to monsoon period (Figures from C.41 to C.43).

From standard deviation it is apparent that zone 2's (office) variation is the least (2.50) and zone 3's (corridor) (3.49) is the highest. Zone 1 (inpatient room) moderately (2.81) fluctuate with outdoor air temperature. Zone 1, Zone 2, and Zone 3 shows a negative skew of -0.43, -0.33 and -0.24 respectively (Table 4.16).

Mean Operative Temperature:

Mean Operative Temperature demonstrate similar pattern as it represents the combined effect of air temperature and radiant temperature (Figures from C.44 to C.46).

Mean Radiant Temperature:

Pre-monsoon period show greater variation than monsoon period (Figures from C.47 to C.49). From standard deviation it is apparent that zone 2's (office) variation is the least (1.99) and zone 3's (corridor) (2.38) is the highest. Zone 1 (inpatient room) moderately (2.06) fluctuate with outdoor air temperature. Zone 1, Zone 2, and Zone 3 shows a negative skew of -0.80, -0.45 and -0.25 respectively (Table 4.16).

Relative humidity:

A common trend of higher variation during the pre-monsoon period and lower variation during the monsoon period can be observed for all three zones (Figures from C.50 to C.52). . As like other thermal parameters zone 3 (corridor) shows a greater standard deviation of 16.78 compared to other two zones with value of 13.49 and 13.05 for zone 1 and zone 2 respectively (Table 4.16).

Surface Inside and Outside temperature:

Two walls types (North and South wall) and their corresponding outside and inside surface temperature of the of inpatient room for envelope type WB05 are shown in figures from C.53 to C.54. Higher time lag and decrement factor can be observed for north wall which is exposed to outdoor. On the contrary south wall demonstrate relatively lower time lag and decrement factor which has a corridor adjacent with it.

Table 4.16 Summary of the statistical value of thermal Condition from March to August: Wall Type WB05

	Mean Value	Median	Mode	Standard deviation	Skewness	Kurtosis	Max. Value	Min. Value	Range
Outdoor Air DBT	27.92	25.48	26.17	3.63	-1.22	0.89	42.50	12.60	29.90
Outdoor Air WBT	24.36	25.48	26.17	3.09	-1.22	0.89	29.76	12.23	17.52
Mean Air Temperature: Zone 1	29.70	29.72	-	2.81	-0.43	1.26	40.13	17.72	22.41
Mean Air Temperature: Zone 2	30.43	30.49	-	2.50	-0.33	1.20	39.97	20.02	19.96
Mean Air Temperature: Zone 3	28.19	28.13	-	3.49	-0.24	1.27	42.19	13.43	28.76
Mean Radiant Temperature: Zone 1	30.82	31.16	-	2.06	-0.80	1.26	37.10	22.90	14.21
Mean Radiant Temperature: Zone 2	31.58	31.80	-	1.99	-0.45	0.95	38.08	24.31	13.77
Mean Radiant Temperature: Zone 3	31.16	31.22	-	2.38	-0.25	0.87	39.33	21.67	17.66
Mean Operative Temperature: Zone 1	30.26	30.48	-	2.29	-0.64	1.42	38.39	20.44	17.95
Mean Operative Temperature: Zone 2	31.01	31.17	-	2.15	-0.41	1.16	38.80	22.33	16.47
Mean Operative Temperature: Zone 3	29.68	29.69	-	2.81	-0.25	1.17	40.42	17.76	22.66
Mean Humidity: Zone 1	70.63	73.82	-	13.49	-1.22	1.21	93.21	18.71	74.50
Mean Humidity: Zone 2	67.91	70.82	-	13.05	-1.10	0.86	90.44	19.27	71.17
Mean Humidity: Zone 3	75.57	79.90	-	16.78	-1.19	1.03	99.01	14.50	84.52

4.7.7 Annual Cooling Condition for 1.0 percentile: Wall Type WB11

Annual cooling condition for 1.0 percentile represent the hot day of a typical meteorological year with a probability of 1% occurrence. Here wall type WB11 denotes the envelope condition with 11.5" brick cavity wall (5" brick construction on either side with 1.5" cavity) with plastered and tiled finish on outside. The simulation results from EnergyPlus are summarized in the form of descriptive statistics in Table 4.17. The detailed value for each output variable are shown in graph as line plot in the figures from C.55 to C.60.

Three temperature indices are used (Mean Air Temperature, Mean Radiant Temperature, and Mean Operative temperature) to discern the variation of thermal performance of WB11 for three thermal zones. The simulation results indicates that in all of the cases of thermal indices, zone 3 (corridor and toilets) varies significantly with outside conditions as it has the maximum exposure to the outdoor.

Mean Air Temperature:

From standard deviation it is apparent that zone 2's (office) diurnal variation (5.82 deg C) is the least and zone 3's (corridor) is the highest (8.71 deg C). Zone 1 (inpatient room) (6.77 deg C) moderately fluctuate with outdoor air temperature.

The mean max air temperature for all three zones converges at about 37 deg C whereas lowest temperature vary from 28.51 deg C to 31.19 deg C (Figure C.56).

Mean Radiant Temperature:

Same as aforementioned mean air temperature, zone 3 has the highest diurnal range (4.67 deg C) of Mean Radiant Temperature. Although from standard deviation it is apparent that zone 1 (inpatient room) and zone 2 (office) has a similar pattern, zone 2 shows higher mean radiant temperature than zone 1 (Figure C.57). Close proximity of the surfaces and lesser volume of zone 2 may be contributing to this thermal characteristics.

Table 4.17 Summary of the statistical value of Annual Cooling Condition for 1.0 percentile: Wall Type WB11

	Mean Value	Max. Value	Min. Value	Range	Standard deviation
Outdoor Air DBT	32.32	37.20	28.10	9.10	0.81
Outdoor Air WBT	25.60	26.80	24.54	2.26	0.81
Mean Air Temperature: Zone 1	33.23	36.85	30.08	6.77	2.44
Mean Air Temperature: Zone 2	33.85	37.01	31.19	5.82	2.07
Mean Air Temperature: Zone 3	32.54	37.21	28.51	8.71	3.11
Mean Radiant Temperature: Zone 1	33.90	34.65	33.05	1.60	0.55
Mean Radiant Temperature: Zone 2	34.88	35.77	34.02	1.76	0.58
Mean Radiant Temperature: Zone 3	35.06	37.51	32.84	4.67	1.55
Mean Operative Temperature: Zone 1	33.57	35.67	31.61	4.07	1.42
Mean Operative Temperature: Zone 2	34.37	36.29	32.63	3.65	1.27
Mean Operative Temperature: Zone 3	33.80	37.21	30.74	6.47	2.23
Mean Humidity: Zone 1	58.04	67.40	48.41	18.99	6.67
Mean Humidity: Zone 2	56.07	63.34	48.20	15.14	5.23
Mean Humidity: Zone 3	59.28	73.31	45.19	28.12	10.03

Mean Operative Temperature:

Mean Operative Temperature demonstrate similar pattern as it represents the combined effect of air temperature and radiant temperature (Figure C.58).

Relative humidity:

Since Relative humidity is inversely correlated with air temperature, its highest value coincides with lowest air temperature and vice versa. For zone 1, zone 2, and zone 3 the lowest relative humidity of 48.41%, 48.20%, and 45.19% respectively occurs at 2 p.m. in the afternoon (Figure C.59).

Surface Inside and Outside temperature:

Four walls types and their corresponding outside and inside surface temperature of the of inpatient room for envelope type WB11 are shown in Figure C.60. Higher time lag and decrement factor can be observed for north and west wall which is exposed to outdoor. On the contrary south and east wall demonstrate almost no time lag and relatively lower decrement factor compared to other two walls. This is may be due to the fact that both of them are in shaded region of the case inpatient room.

4.7.8 Annual dehumidification Condition for 1.0 percentile: Wall Type WB11

Annual dehumidification condition for 1.0 percentile represent the humid day of a typical meteorological year with a probability of 1% occurrence. Here wall type WB11 denotes the envelope condition with 11.5" brick cavity wall (5" brick construction on either side with 1.5" cavity) with plastered and tiled finish on outside. The simulation results from EnergyPlus are summarized in the form of descriptive statistics in Table 4.18. The detailed value for each output variable are shown in graph as line plot in the figures from C.61 to C.65.

Three temperature indices are used (Mean Air Temperature, Mean Radiant Temperature, and Mean Operative temperature) to discern the variation of thermal performance of WB11 for three thermal zones. The simulation results indicates that in all of the cases of thermal indices, zone 3 (corridor and toilets) varies significantly with outside conditions as it has the maximum exposure to the outdoor.

Mean Air Temperature:

From standard deviation it is apparent that zone 2's (office) diurnal variation (5.98 deg C) is the least and zone 3's (corridor) (8.73 deg C) is the highest. Zone 1 (inpatient room) (6.99 deg C) moderately fluctuate with outdoor air temperature.

The mean max air temperature for all three zones converges at about 32 deg C whereas lowest temperature vary 23.34 deg C to 26.26 deg C (Figure C.62).

Mean Radiant Temperature:

As mentioned in the previous passage, zone 3 has the highest diurnal range (4.78 deg C) of Mean Radiant Temperature. Although from standard deviation it is apparent that zone 1 (inpatient room) and zone 2 (office) has a similar pattern, zone 2 shows higher mean radiant temperature than zone 1 (Figure C.63). Close proximity of the surfaces and lesser volume of zone 2 may be contributing to this thermal characteristics.

Mean Operative Temperature:

Mean Operative Temperature demonstrate similar pattern as it represents the combined effect of air temperature and radiant temperature (Figure C.64).

Table 4.18 Summary of the statistical value of Annual Dehumidification Condition for 1.0 percentile: Wall Type WB11

	Mean Value	Max. Value	Min. Value	Range	Standard deviation
Outdoor Air DBT	27.12	32.00	22.90	9.10	2.38
Outdoor Air WBT	26.40	29.11	22.90	6.22	2.38
Mean Air Temperature: Zone 1	28.39	32.11	25.12	6.99	2.55
Mean Air Temperature: Zone 2	29.03	32.25	26.26	5.98	2.16
Mean Air Temperature: Zone 3	27.40	32.07	23.34	8.73	3.12
Mean Radiant Temperature: Zone 1	29.32	30.11	28.40	1.71	0.58
Mean Radiant Temperature: Zone 2	30.21	31.13	29.30	1.83	0.60
Mean Radiant Temperature: Zone 3	30.24	32.74	27.96	4.78	1.59
Mean Operative Temperature: Zone 1	28.86	31.03	26.80	4.23	1.49
Mean Operative Temperature: Zone 2	29.62	31.59	27.81	3.78	1.32
Mean Operative Temperature: Zone 3	28.82	32.26	25.72	6.54	2.25
Mean Humidity: Zone 1	89.47	95.23	83.03	12.20	3.53
Mean Humidity: Zone 2	86.36	93.46	82.36	11.10	3.52
Mean Humidity: Zone 3	93.66	98.89	80.87	18.02	6.39

Relative humidity:

Since Relative humidity is inversely correlated with air temperature, its highest value coincide with lowest air temperature and vice versa. For zone 1, zone 2, and zone 3 the lowest relative humidity of 83.03%, 82.36%, and 80.87% respectively occurs at 2 p.m. in the afternoon (Figure C.65).

Surface Inside and Outside temperature:

Four walls types and their corresponding outside and inside surface temperature of the of inpatient room for envelope type WB11 are shown in Figure C.66. Higher time lag and decrement factor can be observed for north and west wall which is exposed to outdoor. On the contrary south and east wall demonstrate almost no time lag and relatively lower decrement factor compared to other two walls. This is may be due to the fact that both of them are in shaded region of the case inpatient room.

4.7.9 Thermal Condition for Zones from March to August: Wall Type WB11

In this section thermal condition from March to August (Pre monsoon to monsoon period) are presented for the three zones. Wall type WB11 denotes the envelope condition with 11.5” brick cavity wall (5” brick construction on either side with 1.5” cavity) with plastered and tiled finish on outside. The simulation results from EnergyPlus are summarized in the form of descriptive statistics in Table 4.19. The detailed value for each output variable are shown in graph as line plot in the figures from C.67 to C.81.

Three temperature indices are used (Mean Air Temperature, Mean Radiant Temperature, and Mean Operative temperature) to discern the variation of thermal performance of WB11 for three thermal zones. The simulation results indicates that in all of the cases of thermal indices, zone 3 (corridor and toilets) varies significantly with outside conditions as it has the maximum exposure to the outdoor.

Mean Air Temperature:

All three zone show the trend of greater variation during pre-monsoon period compared to monsoon period (Figures from C.68 to C.70).

From standard deviation it is apparent that zone 2’s (office) variation is the least (2.46) and zone 3’s (corridor) (3.49) is the highest. Zone 1 (inpatient room) moderately (2.80) fluctuate with outdoor air temperature. Zone 1, Zone 2, and Zone 3 shows a negative skew of -0.46, -0.40 and -0.24 respectively (Table 4.19).

Mean Operative Temperature:

Mean Operative Temperature demonstrate similar pattern as it represents the combined effect of air temperature and radiant temperature (Figures from C.71 to C.73).

Mean Radiant Temperature:

Pre-monsoon period show greater variation than monsoon period (Figures from C.74 to C.76) .

From standard deviation it is apparent that zone 2's (office) variation is the least (1.86) and zone 3's (corridor) (2.26) is the highest. Zone 1 (inpatient room) moderately (1.86) fluctuate with outdoor air temperature. Zone 1, Zone 2, and Zone 3 shows a negative skew of -0.95, -0.66 and -0.27 respectively (Table 4.19).

Table 4.19 Summary of the statistical value of thermal Condition from March to August: Wall Type WB11

	Mean Value	Median	Mode	Standard deviation	Skewness	Kurtosis	Max. Value	Min. Value	Range
Outdoor Air DBT	27.92	25.48	26.17	3.63	-1.22	0.89	42.50	12.60	29.90
Outdoor Air WBT	24.36	25.48	26.17	3.09	-1.22	0.89	29.76	12.23	17.52
Mean Air Temperature: Zone 1	29.65	29.67	-	2.80	-0.46	1.26	39.96	17.80	22.16
Mean Air Temperature: Zone 2	30.35	30.39	-	2.46	-0.40	1.27	39.74	20.16	19.57
Mean Air Temperature: Zone 3	28.19	28.12	-	3.49	-0.24	1.27	42.16	13.46	28.70
Mean Radiant Temperature: Zone 1	30.70	31.07	-	1.97	-0.95	1.42	36.59	23.12	13.46
Mean Radiant Temperature: Zone 2	31.45	31.71	-	1.86	-0.66	1.18	37.48	24.69	12.79
Mean Radiant Temperature: Zone 3	31.10	31.16	-	2.26	-0.27	0.96	39.12	21.99	17.13
Mean Operative Temperature: Zone 1	30.18	30.39	-	2.24	-0.72	1.52	38.13	20.57	17.56
Mean Operative Temperature: Zone 2	30.90	31.08	-	2.06	-0.56	1.35	38.48	22.51	15.97
Mean Operative Temperature: Zone 3	29.64	29.64	-	2.77	-0.26	1.20	40.37	17.91	22.46
Mean Humidity: Zone 1	70.81	74.00	-	13.45	-1.25	1.27	93.24	18.66	74.58
Mean Humidity: Zone 2	68.19	71.21	-	12.90	-1.15	0.98	90.40	19.18	71.22
Mean Humidity: Zone 3	75.59	79.94	-	16.77	-1.20	1.04	99.04	14.48	84.56

Relative humidity:

A common trend of higher variation during the pre-monsoon period and lower variation during the monsoon period can be observed for all three zones (Figures from C.77 to C.79) . As like other thermal parameters zone 3 (corridor) shows a greater standard deviation of 16.77 compared to other two zones with value of 13.45 and 12.90 for zone 1 and zone 2 respectively (Table 4.19).

Surface Inside and Outside temperature:

Two walls types (North and South wall) and their corresponding outside and inside surface temperature of the of inpatient room for envelope type WB11 are shown in figures from C.80 to C.81. Higher time lag and decrement factor can be observed for north wall which is exposed to outdoor. On the contrary south wall demonstrate relatively lower time lag and decrement factor which has a corridor adjacent with it.

4.7.10 Annual Cooling Condition for 1.0 percentile: Wall Type WC04

Annual cooling condition for 1.0 percentile represent the hot day of a typical meteorological year with a probability of 1% occurrence. Here wall type WC04 denotes the envelope condition with 04" concrete hollow block in core with plastered and tiled finish on outside. The simulation results from EnergyPlus are summarized in the form of descriptive statistics in Table 4.20. The detailed value for each output variable are shown in graph as line plot in the figures from C.82 to C.87.

Three temperature indices are used (Mean Air Temperature, Mean Radiant Temperature, and Mean Operative temperature) to discern the variation of thermal performance of WC04 for three thermal zones. The simulation results indicates that in all of the cases of thermal indices, zone 3 (corridor and toilets) varies significantly with outside conditions as it has the maximum exposure to the outdoor.

Mean Air Temperature:

From standard deviation it is apparent that zone 2's (office) diurnal variation (6.24 deg C) is the least and zone 3's (corridor) is the highest (8.75 deg C). Zone 1 (inpatient room) (6.24 deg C) moderately fluctuate with outdoor air temperature.

The mean max air temperature for all three zones converges at about 37 deg C whereas lowest temperature vary from 28.47 deg C to 31.08 deg C Figure C.83).

Mean Radiant Temperature:

Same as aforementioned mean air temperature, zone 3 has the highest diurnal range (5.83 deg C) of Mean Radiant Temperature. Although from standard deviation it is apparent that zone 1 (inpatient room) and zone 2 (office) has a similar pattern, zone 2 shows higher mean radiant temperature than zone 1 (Figure C.84). Close proximity of the surfaces and lesser volume of zone 2 may be contributing to this thermal characteristics.

Mean Operative Temperature:

Mean Operative Temperature demonstrate similar pattern as it represents the combined effect of air temperature and radiant temperature (Figure C.85).

Relative humidity:

Since Relative humidity is inversely correlated with air temperature, its highest value coincides with lowest air temperature and vice versa. For zone 1, zone 2, and zone 3 the lowest relative humidity of 48.08%, 47.37%, and 45.17% respectively occurs at 2 p.m. in the afternoon (Figure C.86).

Surface Inside and Outside temperature:

Four walls types and their corresponding outside and inside surface temperature of the of inpatient room for envelope type WC04 are shown in Figure C.87. Higher time lag and decrement factor can be observed for north and west wall which is exposed to outdoor. On the contrary south and east wall demonstrate almost no time lag and relatively lower decrement factor compared to other two walls. This is may be due to the fact that both of them are in shaded region of the case inpatient room.

Table 4.20 Summary of the statistical value of Annual Cooling Condition for 1.0 percentile: Wall Type WC04

	Mean Value	**Max. Value**	**Min. Value**	**Range**	**Standard deviation**
Outdoor Air DBT	32.32	37.20	28.10	9.10	0.81
Outdoor Air WBT	25.60	26.80	24.54	2.26	0.81
Mean Air Temperature: Zone 1	33.32	36.98	30.08	6.90	2.46
Mean Air Temperature: Zone 2	34.05	37.33	31.08	6.24	2.20
Mean Air Temperature: Zone 3	32.55	37.22	28.47	8.75	3.12
Mean Radiant Temperature: Zone 1	34.17	35.34	32.88	2.46	0.84
Mean Radiant Temperature: Zone 2	35.29	36.98	33.59	3.39	1.16
Mean Radiant Temperature: Zone 3	35.13	38.16	32.33	5.83	1.97
Mean Operative Temperature: Zone 1	33.74	35.96	31.54	4.42	1.53
Mean Operative Temperature: Zone 2	34.67	36.98	32.41	4.57	1.57
Mean Operative Temperature: Zone 3	33.84	37.43	30.49	6.93	2.40
Mean Humidity: Zone 1	57.78	67.41	48.08	19.33	6.74
Mean Humidity: Zone 2	55.52	63.81	47.37	16.44	5.65
Mean Humidity: Zone 3	59.26	73.46	45.17	28.29	10.09

4.7.11 Annual dehumidification Condition for 1.0 percentile: Wall Type WC04

Annual dehumidification condition for 1.0 percentile represent the humid day of a typical meteorological year with a probability of 1% occurrence. Here wall type WC04 denotes the envelope condition with 04" concrete hollow block in core with plastered and tiled finish on outside. The simulation results from EnergyPlus are summarized in the form of descriptive statistics in Table 4.21. The detailed value for each output variable are shown in graph as line plot in the figures from C.88 to C.93.

Three temperature indices are used (Mean Air Temperature, Mean Radiant Temperature, and Mean Operative temperature) to discern the variation of thermal performance of WC04 for three thermal zones. The simulation results indicates that in all of the cases of thermal indices, zone 3 (corridor and toilets) varies significantly with outside conditions as it has the maximum exposure to the outdoor.

Mean Air Temperature:

From standard deviation it is apparent that zone 2's (office) diurnal variation is the least (6.44 deg C) and zone 3's (corridor) is the highest (8.79 deg C). Zone 1 (inpatient room) moderately (7.14 deg C) fluctuate with outdoor air temperature.

The mean max air temperature for all three zones converges at about 32 deg C whereas lowest temperature vary 23.3 deg C to 26.09 deg C (Figure C.89).

Mean Radiant Temperature:

As mentioned in the previous passage, zone 3 has the highest diurnal range (5.97 deg C) of Mean Radiant Temperature. Although from standard deviation it is apparent that zone 1 (inpatient room) and zone 2 (office) has a similar pattern, zone 2 shows higher mean radiant temperature than zone 1 (Figure C.90). Close proximity of the surfaces and lesser volume of zone 2 may be contributing to this thermal characteristics.

Mean Operative Temperature:

Mean Operative Temperature demonstrate similar pattern as it represents the combined effect of air temperature and radiant temperature (Figure C.91).

Relative humidity:

Since Relative humidity is inversely correlated with air temperature, its highest value coincide with lowest air temperature and vice versa. For zone 1, zone 2, and zone 3 the lowest relative humidity of 82.52%, 81.33%, and 80.77% respectively occurs at 2 p.m. in the afternoon (Figure C.92).

Surface Inside and Outside temperature:

Four walls types and their corresponding outside and inside surface temperature of the of inpatient room for envelope type WC04 are shown in Figure C.93. Higher time lag and decrement factor can be observed for north and west wall which is exposed to outdoor. On the contrary south and east wall demonstrate almost no time lag and relatively lower decrement factor compared to other two walls. This is may be due to the fact that both of them are in shaded region of the case inpatient room.

Table 4.21 Summary of the statistical value of Annual Dehumidification Condition for 1.0 percentile: Wall Type WC04

	Mean Value	Max. Value	Min. Value	Range	Standard deviation
Outdoor Air DBT	27.12	32.00	22.90	9.10	2.38
Outdoor Air WBT	26.40	29.11	22.90	6.22	2.38
Mean Air Temperature: Zone 1	28.45	32.23	25.08	7.14	2.58
Mean Air Temperature: Zone 2	29.17	32.54	26.09	6.44	2.29
Mean Air Temperature: Zone 3	27.40	32.09	23.30	8.79	3.14
Mean Radiant Temperature: Zone 1	29.52	30.77	28.14	2.63	0.90
Mean Radiant Temperature: Zone 2	30.52	32.25	28.75	3.51	1.20
Mean Radiant Temperature: Zone 3	30.30	33.39	27.42	5.97	2.02
Mean Operative Temperature: Zone 1	28.99	31.28	26.67	4.61	1.61
Mean Operative Temperature: Zone 2	29.84	32.21	27.49	4.73	1.63
Mean Operative Temperature: Zone 3	28.85	32.47	25.45	7.02	2.43
Mean Humidity: Zone 1	89.16	94.78	82.52	12.26	3.47
Mean Humidity: Zone 2	85.67	93.88	81.33	12.55	3.35
Mean Humidity: Zone 3	93.63	99.10	80.77	18.33	6.44

4.7.12 Thermal Condition for Zones from March to August: Wall Type WC04

In this section thermal condition from March to August (Pre monsoon to monsoon period) are presented for the three zones. Wall type WC04 denotes the envelope condition with 04” concrete hollow block in core with plastered and tiled finish on outside. The simulation results from EnergyPlus are summarized in the form of descriptive statistics in Table 4.22. The detailed value for each output variable are shown in graph as line plot in the figures from C.94 to C.108.

Three temperature indices are used (Mean Air Temperature, Mean Radiant Temperature, and Mean Operative temperature) to discern the variation of thermal performance of WC04 for three thermal zones. The simulation results indicates that in all of the cases of thermal indices, zone 3 (corridor and toilets) varies significantly with outside conditions as it has the maximum exposure to the outdoor.

Mean Air Temperature:

All three zone show the trend of greater variation during pre-monsoon period compared to monsoon period (Figures from C.95 to C.97).

From standard deviation it is apparent that zone 2's (office) variation is the least (2.63) and zone 3's (corridor) (3.51) is the highest. Zone 1 (inpatient room) moderately (2.86) fluctuate with outdoor air temperature. Zone 1, Zone 2, and Zone 3 shows a negative skew of -0.41, -0.30 and -0.24 respectively (Table 4.22)

Table 4.22 Summary of the statistical value of thermal Condition from March to August: Wall Type WC04

	Mean Value	Median	Mode	Standard deviation	Skewness	Kurtosis	Max. Value	Min. Value	Range
Outdoor Air DBT	27.92	25.48	26.17	3.63	-1.22	0.89	42.50	12.60	29.90
Outdoor Air WBT	24.36	25.48	26.17	3.09	-1.22	0.89	29.76	12.23	17.52
Mean Air Temperature: Zone 1	29.75	29.76	-	2.86	-0.41	1.24	40.38	17.51	22.87
Mean Air Temperature: Zone 2	30.45	30.46	-	2.63	-0.30	1.11	40.23	19.54	20.69
Mean Air Temperature: Zone 3	28.20	28.13	-	3.51	-0.24	1.26	42.27	13.36	28.90
Mean Radiant Temperature: Zone 1	30.94	31.25	-	2.15	-0.73	1.31	37.79	22.43	15.36
Mean Radiant Temperature: Zone 2	31.62	31.77	-	2.16	-0.39	0.94	38.86	23.43	15.43
Mean Radiant Temperature: Zone 3	31.25	31.25	-	2.59	-0.21	0.77	40.08	20.99	19.08
Mean Operative Temperature: Zone 1	30.34	30.54	-	2.38	-0.58	1.39	38.75	20.13	18.63
Mean Operative Temperature: Zone 2	31.04	31.15	-	2.31	-0.35	1.07	39.26	21.70	17.56
Mean Operative Temperature: Zone 3	29.73	29.70	-	2.92	-0.23	1.10	40.69	17.42	23.28
Mean Humidity: Zone 1	70.47	73.74	-	13.57	-1.21	1.16	93.36	18.58	74.78
Mean Humidity: Zone 2	67.89	70.81	-	13.22	-1.09	0.84	91.09	19.10	71.99
Mean Humidity: Zone 3	75.55	79.85	-	16.82	-1.19	1.01	99.03	14.49	84.54

Mean Operative Temperature:

Mean Operative Temperature demonstrate similar pattern as it represents the combined effect of air temperature and radiant temperature (Figures from C.98 to C.100).

Mean Radiant Temperature:

Pre-monsoon period show greater variation than monsoon period (Figures from C.101 to C.103). From standard deviation it is apparent that zone 1's (inpatient room) variation is the least (2.15) and zone 3's (corridor) (2.59) is the highest. Zone 2 (office) moderately (2.16) fluctuate with outdoor air temperature. Zone 1, Zone 2, and Zone 3 shows a negative skew of -0.73, -0.39 and -0.21 respectively (Table 4.22).

Relative humidity:

A common trend of higher variation during the pre-monsoon period and lower variation during the monsoon period can be observed for all three zones (Figures from C.104 to C.106). As like other thermal parameters zone 3 (corridor) shows a greater standard deviation of 16.82 compared to other two zones with value of 13.57 and 13.22 for zone 1 and zone 2 respectively (Table 4.22).

Surface Inside and Outside temperature:

Two walls types (North and South wall) and their corresponding outside and inside surface temperature of the of inpatient room for envelope type WC04 are shown in figures from C.107 to C.108. Higher time lag and decrement factor can be observed for north wall which is exposed to outdoor. On the contrary south wall demonstrate relatively lower time lag and decrement factor which has a corridor adjacent with it.

4.8 Result Analysis

To facilitate passive cooling inside inpatient room, four envelope condition for hospital building including existing one were considered for simulation study to assess the performance in terms of thermal condition. Analysis and comparison are presented in the following sections as graph representation and statistical summary. Thermal performance of four envelope types are compared for zone 1 (inpatient room) in respect to Mean Air Temperature, Mean Radiant Temperature, and Mean Operative Temperature for time span of 1.0 percentile annual cooling condition, pre-monsoon, and monsoon seasons.

Mean air temperature:

Table 4.23 summarizes thermal performance for mean air temperature of the four envelope conditions for zone 1. Annual cooling condition for 1.0 percentile is considered. For all types of envelope condition similar performance with slight variation is observed. The mean value of air temperature inside zone 1 for four envelope types are slightly higher than the outdoor air DBT. Although the diurnal variation for all of the envelope conditions are alike and lower than the outdoor diurnal variation (Figure 4.19).

Table 4.23 Annual Cooling Condition for 1.0 percentile: Mean air temperature for 4 wall types of Zone 1

Wall types	**WWB10**	**WWB05**	**WWB11**	**WWC04**	**Outdoor Air DBT**
Mean Value	33.24	33.31	33.23	33.32	32.32
Max. value	36.85	36.90	36.85	36.98	37.20
Min. value	30.09	30.15	30.08	30.08	28.10
Range	6.75	6.74	6.77	6.90	9.10
Standard Deviation	2.43	2.42	2.44	2.46	3.27

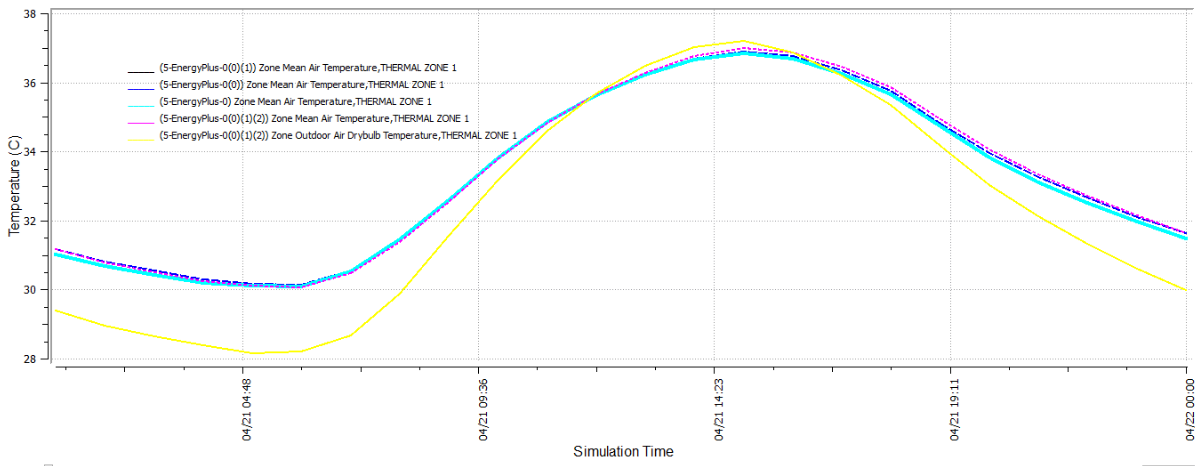


Figure 4.19 Zone 1-Mean Air Temperature for Envelope type (a) WB10, (b) WB05, (c) WB11, and (d) WC04.

Table 4.24 and Table 4.25 represents summary of the statistical value of mean air temperature for pre-monsoon and post monsoon period respectively.

Table 4.24 Pre-monsoon period: Mean air temperature for 4 wall types of Zone 1

Wall types	**WWB10**	**WWB05**	**WWB11**	**WWC04**	**outdoor air DBT**
Mean Value	29.15	29.18	29.12	29.25	27.39
Median	29.09	29.11	29.06	29.16	27.20
Mode	-	-	-	-	25.00
Standard deviation	3.53	3.55	3.53	3.62	4.65
Skewness	-0.13	-0.12	-0.13	-0.11	0.00
Kurtosis	-0.03	-0.01	-0.03	0.00	-0.02
Max. Value	40.07	40.13	39.96	40.38	42.50
Min. Value	17.86	17.72	17.80	17.51	12.60
Range	22.21	22.41	22.16	22.87	29.90
Count	2208.00	2208.00	2208.00	2208.00	2208.00

Table 4.25 Monsoon period: Mean air temperature for 4 wall types of Zone 1

Wall types	WWB10	WWB05	WWB11	WWC04	outdoor air DBT
Mean Value	30.22	30.22	30.18	30.25	28.45
Median	29.97	30.01	29.93	30.03	28.10
Mode	-	-	-	-	27.20
Standard deviation	1.60	1.63	1.61	1.68	2.05
Skewness	0.38	0.33	0.38	0.32	0.44
Kurtosis	-0.38	-0.38	-0.40	-0.39	-0.14
Max. Value	36.04	36.11	35.98	36.32	36.60
Min. Value	26.68	26.53	26.67	26.42	23.50
Range	9.36	9.58	9.31	9.90	13.10
Count	2208.00	2208.00	2208.00	2208.00	2208.00

The data patterns reveals that WB11 and WB10 has yielded lower Mean Air Temperature for zone 1. Contrary WB05 and WB04-04 yielded slightly higher mean temperature. Pre-monsoon period show higher standard deviation than the monsoon period.

Mean Radiant Temperature:

Table 4.26 summarizes thermal performance for Mean Radiant Temperature of the four envelope conditions for zone 1. Annual cooling condition for 1.0 percentile is considered. For all types of envelope condition similar performance with slight variation is observed. All the statistical indicators i.e. mean, max., and min. value for WB11 is slightly lower than the other envelope conditions. Comparing to all other envelope condition WC04 shows higher standard deviation value and range for mean radiant temperature (Figure 4.20).

Table 4.26 Annual Cooling Condition for 1.0 percentile: Mean Radiant temperature for 4 wall types of Zone 1

Wall types	WB10	WB05	WB11	WC04
Mean Value	33.91	34.13	33.90	34.17
Max. value	34.64	34.97	34.65	35.34
Min. value	33.06	33.15	33.05	32.88
Range	1.58	1.82	1.60	2.46
Standard Deviation	0.54	0.63	0.55	0.84

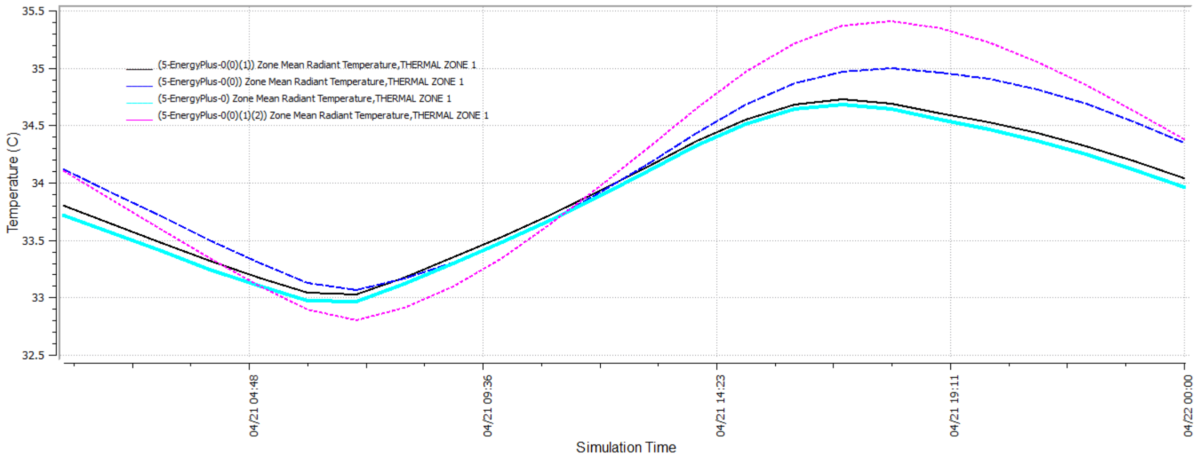


Figure 4.20 Zone 1-Mean Radiant Temperature for Envelope type (a) WB10, (b) WB05, (c) WB11, and (d) WC04.

Table 4.27 Pre-monsoon period: Mean Radiant temperature for 4 wall types of Zone 1

Wall types	**WB10**	**WB05**	**WB11**	**WC04**
Mean Value	30.14	30.22	30.07	30.38
Median	30.32	30.36	30.25	30.51
Mode	-	-	-	-
Standard deviation	2.49	2.59	2.49	2.70
Skewness	-0.24	-0.20	-0.27	-0.21
Kurtosis	-0.27	-0.22	-0.28	-0.13
Max. Value	36.74	37.10	36.59	37.79
Min. Value	23.22	22.90	23.12	22.43
Range	13.52	14.21	13.46	15.36
Count	2208.00	2208.00	2208.00	2208.00

Table 4.28 Monsoon period: Mean Radiant temperature for 4 wall types of Zone 1

Wall types	**WB10**	**WB05**	**WB11**	**WC04**
Mean Value	31.41	31.41	31.33	31.50
Median	31.50	31.50	31.42	31.53
Mode	-	-	-	-
Standard deviation	0.89	1.02	0.87	1.13
Skewness	-0.18	-0.20	-0.19	-0.11
Kurtosis	-0.30	-0.28	-0.30	-0.26
Max. Value	33.93	34.23	33.79	34.80
Min. Value	28.77	28.44	28.72	28.35
Range	5.16	5.79	5.08	6.45
Count	2208.00	2208.00	2208.00	2208.00

Table 4.27 and Table 4.28 represents summary of the statistical value of Mean Radiant Temperature for pre-monsoon and post monsoon period respectively. The data patterns reveals that WB11 and WB10

has yielded lower Mean Air Temperature for zone 1. On the contrary WB05 and WB04-04 yielded slightly higher mean temperature. Pre-monsoon period show higher standard deviation than the monsoon period. For both seasons WB11 yielded lower Mean Radiant Temperature.

Mean Operative Temperature:

Table 4.29 summarizes thermal performance for Mean Operative Temperature of the four envelope conditions for zone 1. Annual cooling condition for 1.0 percentile is considered. For all types of envelope condition similar performance with slight variation is observed.

All the statistical indicators i.e. mean, max., and min. value for WB11 is slightly lower than the other envelope conditions. Comparing to all other envelope condition WC04 shows higher standard deviation value and range for mean radiant temperature (Figure 4.21).

Table 4.29 Annual Cooling Condition for 1.0 percentile: Mean Operative temperature for 4 wall types of Zone 1

Wall types	WB10	WB05	WB11	WC04
Mean Value	33.57333	33.71964	33.56648	33.74369
Max. value	35.66221	35.7846	35.67324	35.96317
Min. value	31.62348	31.70862	31.6065	31.54224
Range	4.038734	4.07598	4.066742	4.420929
Standard Deviation	1.412756	1.409409	1.424568	1.532565

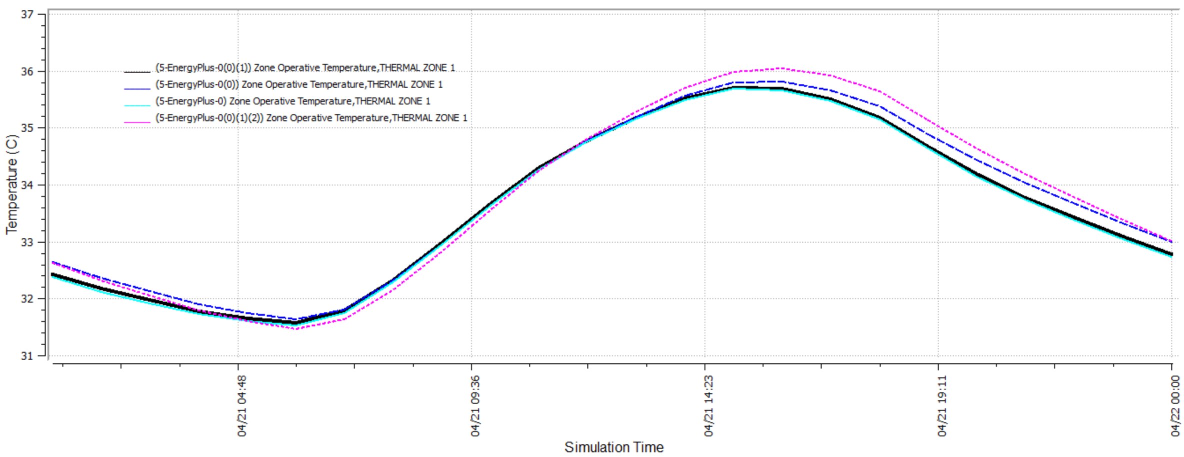


Figure 4.21 Zone 1-Operative Temperature for Envelope type (a) WB10, (b) WB05, (c) WB11, and (d) WC04.

Table 4.30 and Table 4.31 represents summary of the statistical value of Mean Operative Temperature for pre-monsoon and post monsoon period respectively. The data patterns reveals that WB11 and WB10 has yielded lower Mean Operative Temperature for zone 1. On the contrary WB05 and WB04-04 yielded slightly higher mean temperature. Pre-monsoon period show higher standard deviation than the monsoon period. For both seasons WB11 yielded lower Mean Operative Temperature.

Table 4.30 Pre-monsoon period: Mean Operative temperature for 4 wall types of Zone 1

Wall types	WB10	WB05	WB11	WC04
Mean Value	29.65	29.70	29.59	29.81
Median	29.71	29.75	29.66	29.88
Mode	-	-	-	-
Standard deviation	2.83	2.89	2.84	3.00
Skewness	-0.19	-0.17	-0.21	-0.16
Kurtosis	-0.02	-0.01	-0.03	0.02
Max. Value	38.25	38.39	38.13	38.75
Min. Value	20.65	20.44	20.57	20.13
Range	17.61	17.95	17.56	18.63
Count	2208.00	2208.00	2208.00	2208.00

Table 4.31 Monsoon period: Mean Operative temperature for 4 wall types of Zone 1

Wall types	WB10	WB05	WB11	WC04
Mean Value	30.82	30.82	30.76	30.88
Median	30.74	30.76	30.67	30.80
Mode	-	-	-	-
Standard deviation	1.15	1.23	1.15	1.32
Skewness	0.18	0.11	0.19	0.14
Kurtosis	-0.25	-0.26	-0.28	-0.28
Max. Value	34.90	35.01	34.80	35.36
Min. Value	28.00	27.76	27.96	27.56
Range	6.90	7.25	6.84	7.79
Count	2208.00	2208.00	2208.00	2208.00

Inside Surface Temperature:

Figure 4.22 and Figure 4.23 depicted the inside surface temperature of the four envelope type. These two figure, which represents inside surface temperature of north and south wall, clearly shows the thermal behavior of these four envelope type. Two of the envelope type namely WB10 and WB11 vary slightly from their mean value, which can be read as the walls relative ability to insulate interior from outside heat flux.

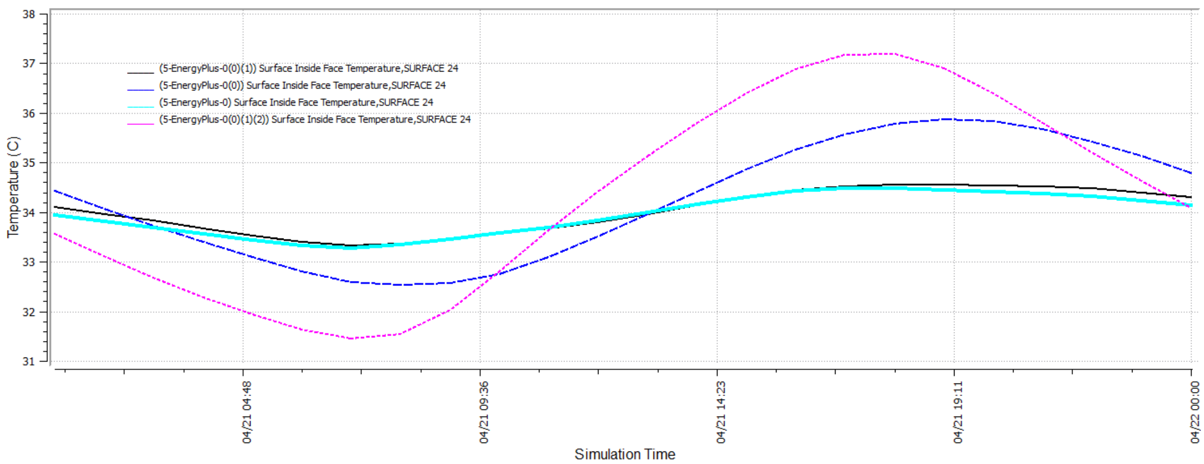


Figure 4.22 Inside surface temperature of North wall of inpatient room for Envelope type (a) WB10, (b) WB05, (c) WB11, and (d) WC04.

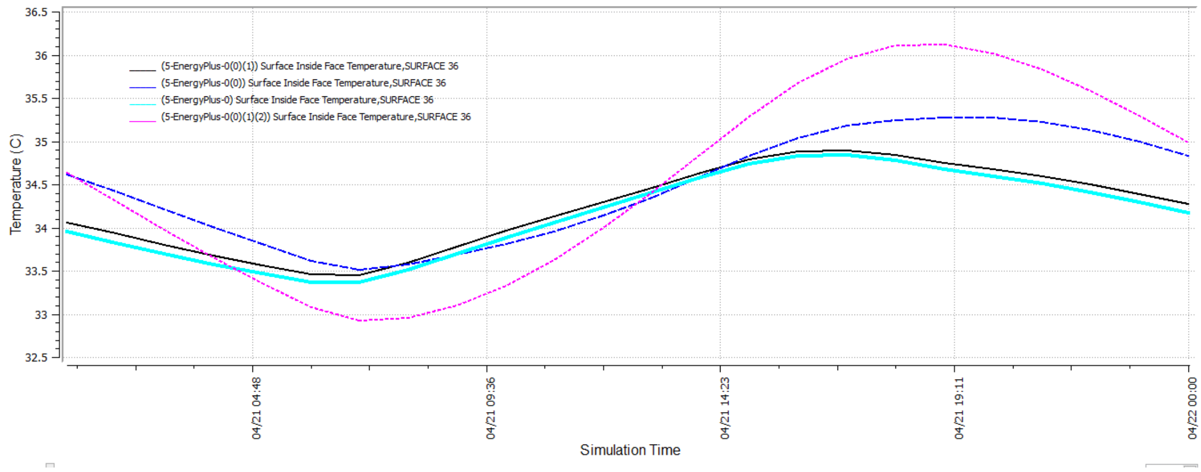


Figure 4.23 Inside surface temperature of South wall of inpatient room for Envelope type (a) WB10, (b) WB05, (c) WB11, and (d) WC04.

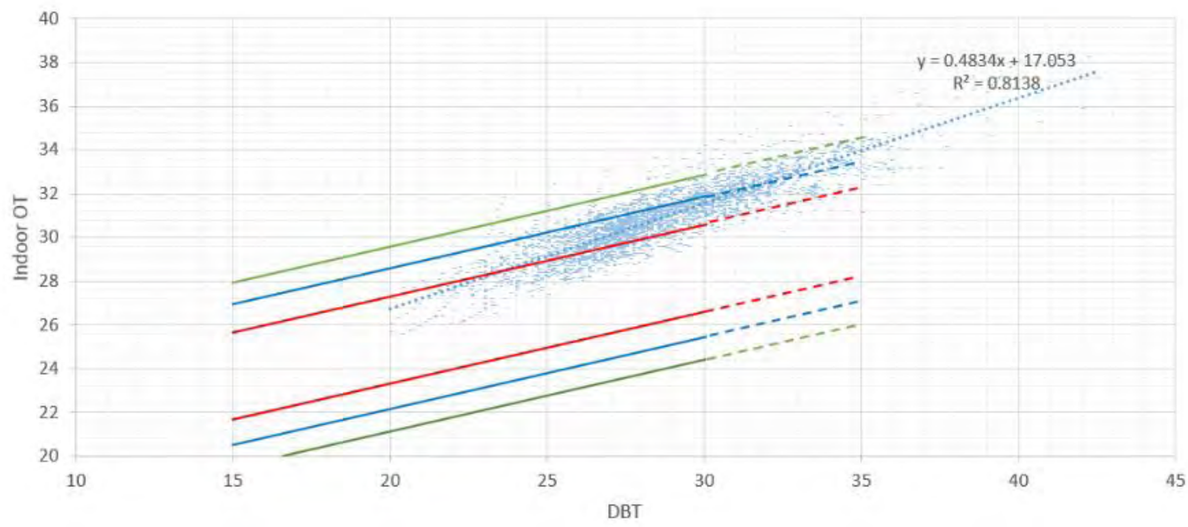
4.9 Comparison

In the literature review of this thesis a brief focus on BNBC (2006) elucidate guideline for mechanically ventilated inpatient room for hospital occupancy type. Standards published by ASHRAE, CIBSE, and BSEN15251 provide model for thermal comfort for naturally ventilated building. Especially BSEN15251 standards provide scopes for adaptive thermal comfort in hospitals. BSEN15251 standard provide dynamic range rather than a static one for operative temperature which adjusts alongside with outdoor Dry Bulb Temperature. This range is flexible for different occupancy type and space under consideration. This range is in turn classified into three categories. Category I calls for most stern and limiting margins on thermal range. Therefore the bar associated with this regard (range) has a high expectation of thermal comfort and suggested for occupants of very sensitive and fragile nature. Especially for patient in hospital wards. Thereupon this range can only deviate 6%.

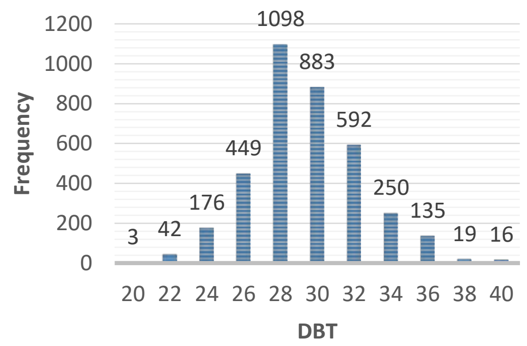
Category II and Category III represents normal and moderate level of expectation respectively. Category II is recommended for new buildings and for renovation with a dissatisfaction rate of less than

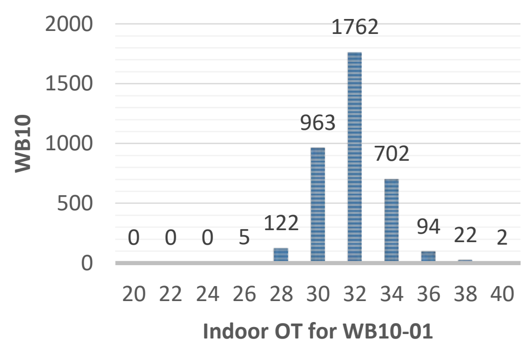
10%. On the contrary Category III should be used in existing buildings and allows provision up to 15% dissatisfaction.

An attempt have been made in this research to facilitate passive cooling inside inpatient room using locally available construction material and methods through simulation to assess the performance of four envelope condition.



(a)





(b) (c)

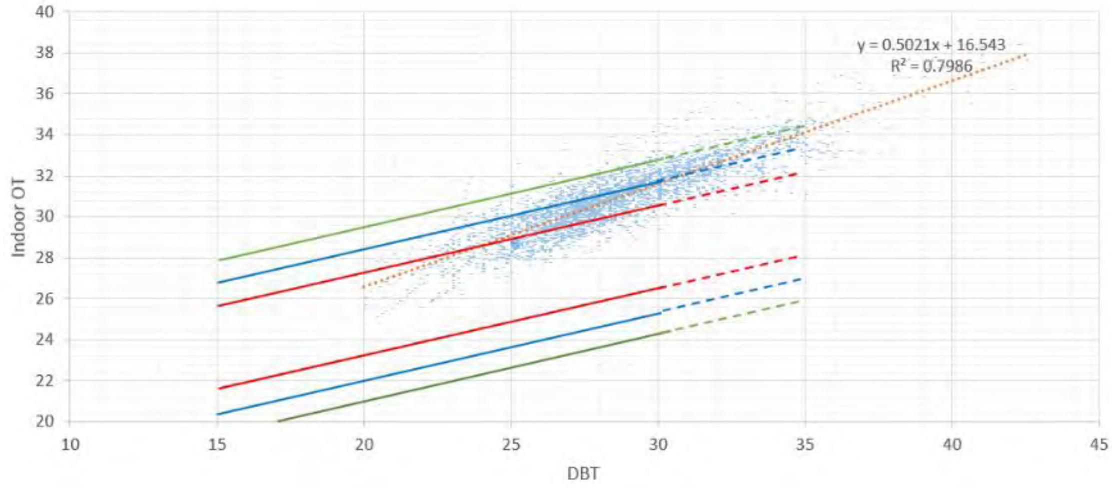
Figure 4.24 (a) BSEN15251 Adaptive thermal comfort model. Indoor operative temperature inside inpatient room (surgery ward 05) from March-August: Wall type WB10. (b) Frequency distribution of DBT from March to August. (c) Frequency distribution of Indoor OT from March to August.

Four graph plots from Figure 4.24 to Figure 4.27 depicts the thermal performance of four envelope condition in terms of indoor operative temperature of inpatient room; plotted with outdoor dry bulb temperature for duration of March to August in reference with BSEN15251 three categories standards.

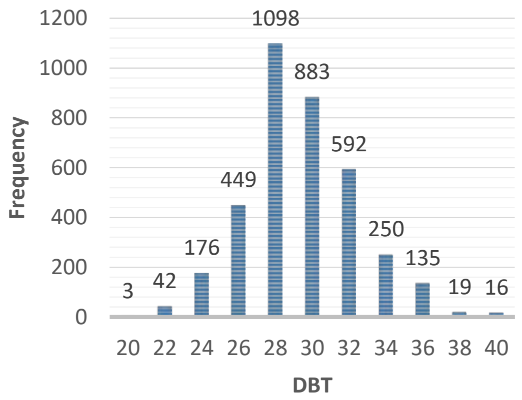
Figure 4.24 presents indoor operative temperature plotted against outdoor dry bulb temperature for envelope type WB10. Most of the data points resides within the outside boundary condition of Category

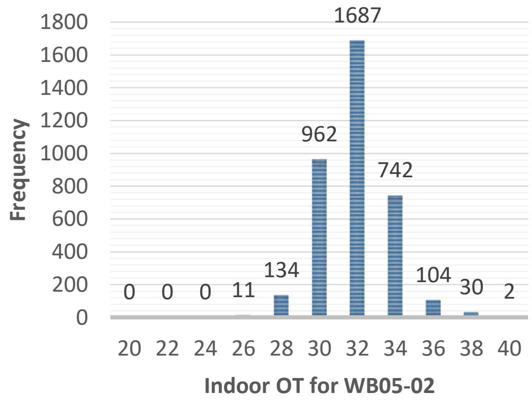
I and category II of BSEN15251 standard. The DBT range is from 20 deg C to 40 deg C (100%). The dot's most densely resides within 24 deg C to 36 deg C range (Figure 4.24 (b)) which translated as 97.80% data stay within this range.

The inside operative temperature range is from 26 deg C to 40 deg C (100%). From graph (Figure 4.24 (c)) it is apparent that the temperature for the intended time duration is most densely exist in the range from 30 deg C to 34 deg C which translated as 93.55% data stay within this range. According to the BSEN15251 for envelope type WB10, 77.86% indoor OT stays within the Category III comfort zone range.



(a)





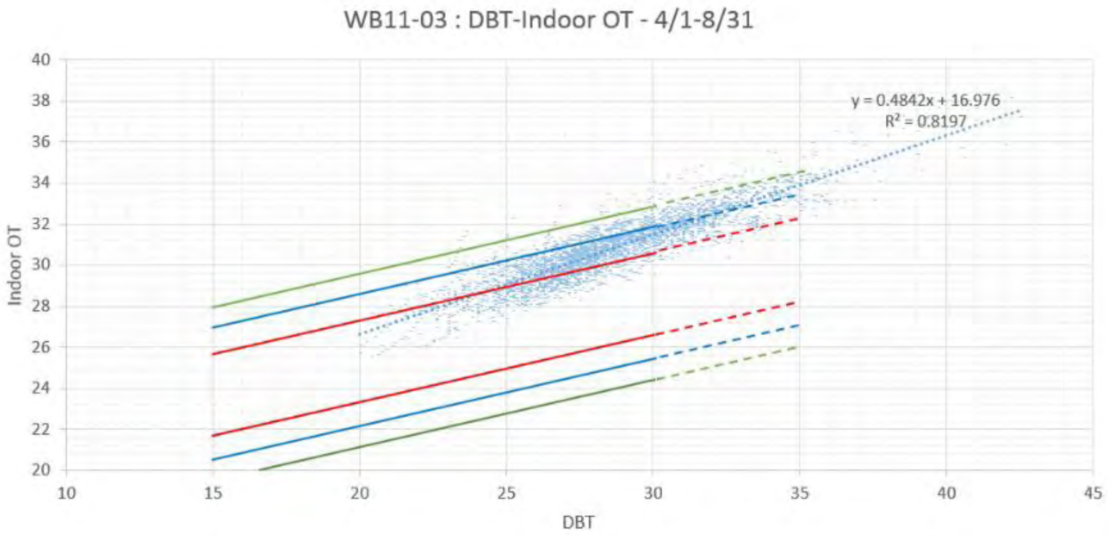
(b) (c)

Figure 4.25 (a) BSEN15251 Adaptive thermal comfort model. Indoor operative temperature inside inpatient room (surgery ward 05) from March-August: Wall type WB05. (b) Frequency distribution of DBT from March to August. (c) Frequency distribution of Indoor OT from March to August.

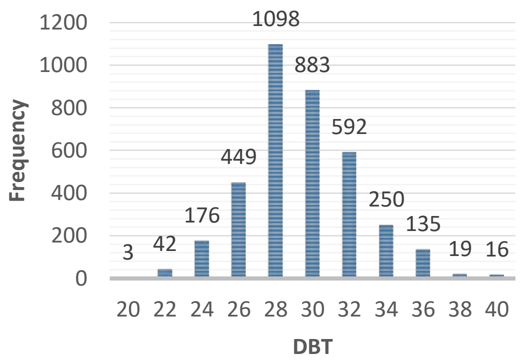
Figure 4.25 presents indoor operative temperature plotted against Outdoor Dry Bulb temperature for envelope type WB05. Most of the data points resides within the outside boundary condition of Category I and category II of BSEN15251 standard.

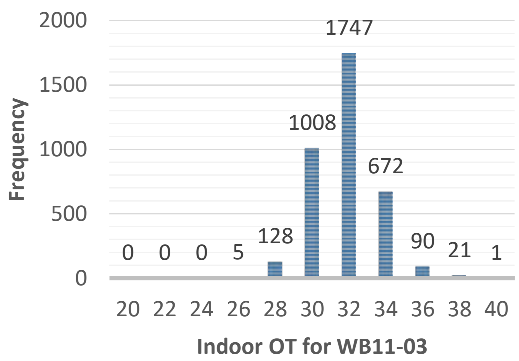
The inside operative temperature range is from 26 deg C to 40 deg C (100%). From graph (Figure 4.25 (c)) it is apparent that the temperature for the intended time duration is most densely exist in the range from 30 deg C to 34 deg C which translated as 92.57% data stay within this range.

According to the BSEN15251 for envelope type WB10, 76.28% indoor OT stays within the Category III comfort zone range.



(a)





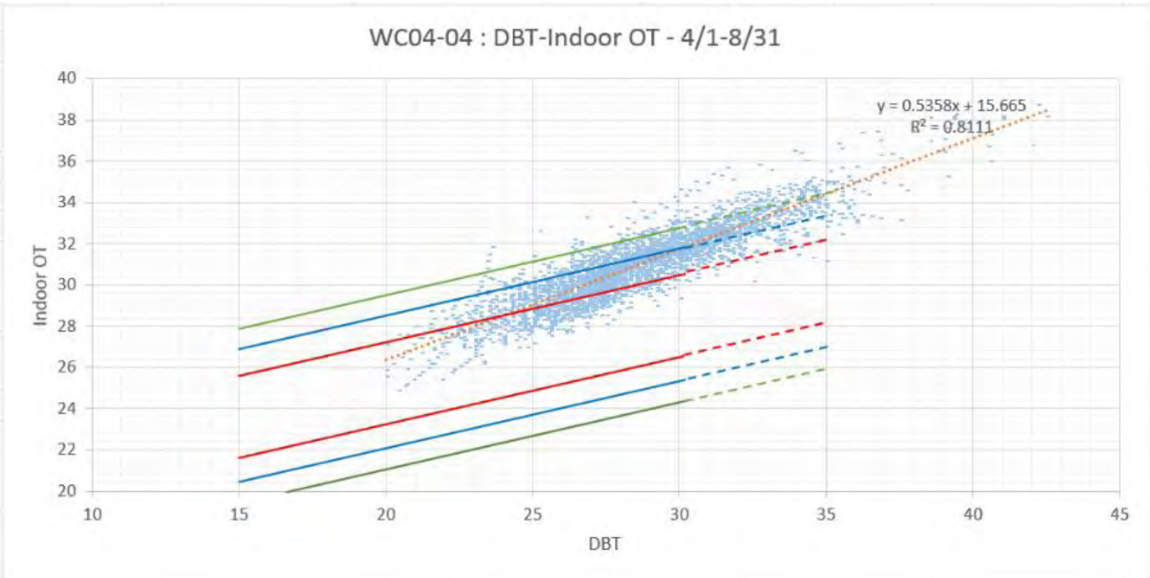
(b) (c)

Figure 4.26 (a) BSEN15251 Adaptive thermal comfort model. Indoor operative temperature inside inpatient room (surgery ward 05) from March-August: Wall type WB11. (b) Frequency distribution of DBT from March to August. (c) Frequency distribution of Indoor OT from March to August.

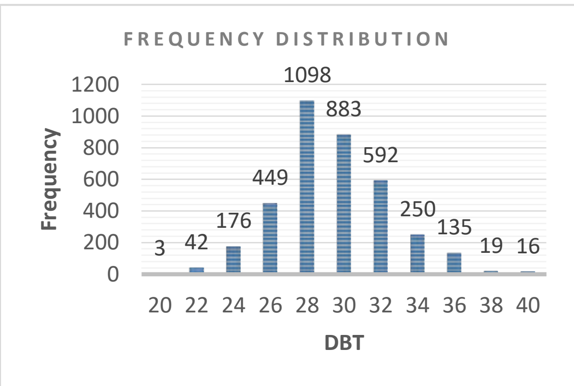
Figure 4.26 presents indoor operative temperature plotted against outdoor dry bulb temperature for envelope type WB05. Most of the data points resides within the outside boundary condition of Category I and category II of BSEN15251 standard.

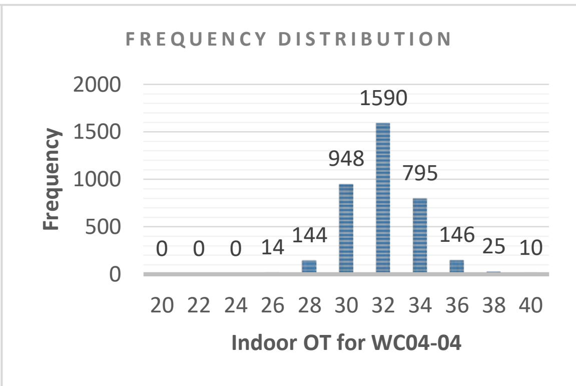
The inside Operative Temperature range is from 26 deg C to 40 deg C (100%). From graph (Figure 4.26 (c)) it is apparent that the temperature for the intended time duration is most densely exist in the range from 30 deg C to 34 deg C which translated as 93.55% data stay within this range.

According to the BSEN15251 for envelope type WB10, 78.84% indoor OT stays within the Category III comfort zone range.



(a)





(b) (c)

Figure 4.27 (a) BSEN15251 Adaptive thermal comfort model. Indoor operative temperature inside inpatient room (surgery ward 05) from March-August: Wall type WC04. (b) Frequency distribution of DBT from March to August. (c) Frequency distribution of Indoor OT from March to August.

Figure 4.27 presents indoor operative temperature plotted against outdoor dry bulb temperature for envelope type WB05. Most of the data points resides within the outside boundary condition of Category I and category II of BSEN15251 standard.

The inside Operative Temperature range is from 26 deg C to 40 deg C (100%). From graph (Figure 4.27 (c)) it is apparent that the temperature for the intended time duration is most densely exist in the range from 30 deg C to 34 deg C which translated as 90.99% data stay within this range.

According to the BSEN15251 for envelope type WB10, 73.60% indoor OT stays within the Category III comfort zone range.

4.10 Conclusion

In this chapter the simulation outputs of the thermal performance of four envelope conditions based on available local construction materials of inpatient room (surgery ward) in Rajshahi Medical College hospital were discussed. This simulation study provided a comprehensive understanding of the envelope conditions and other physical and environmental factors of the building which are responsible for the thermal comfort condition inside the inpatient room. From the analysis and comparison of four envelope conditions in section 5.3 it was found that WB11 is the better performing wall construction in terms of the thermal comfort condition in the context of Rajshahi. In the next chapter strategies and guidelines has been considered based on the findings of this chapter to improve the overall performance of the building envelope to facilitate passive cooling inside inpatient room.

5 CHAPTER FIVE: CONCLUSION

Introduction

Achievement of the objectives

Outcome

Scope for future research

5.1 Introduction

At the beginning, Chapter 1 hypothesizes the research by stating the background and describing the context. Then theoretical framework is established in chapter 2 as a basis of this research. Chapters 2 also provides comprehensive understanding of the related aspects e.g. climatic factors, thermal comfort, building type, passive cooling techniques, and envelope condition. Chapter 3 elaborated the detailed procedure of field survey and summarizes the output from field investigation for next chapter. Simulation method was outlined in chapter 4 using the information obtained from chapter 2 and chapter 3. Chapter 4 also describes the four wall construction types that are used in the parametric simulation for performance analysis. After setting up the simulation parameter simulation is conducted for the four envelope types and the results are presented as graphical output in chapter 5. The results are then analyzed and compared to find out the best possible envelope condition for the four wall construction types. This chapter includes the summary of chapter 3, 4, and 5 and presented the observation and recommendation. This chapter will culminate by restating the fulfilment of the objectives of the research which was described in chapter first chapter. At last recommendations for envelope design to facilitate passive cooling inside inpatient are discussed with provision for future research scope.

5.2 Achievement of the objectives

The objectives of the research, established in first Chapter, are restated here as following.

Objectives 1: To understand scopes and applications of passive cooling techniques for hospital building.

Objectives 2: To compare different passive cooling techniques in order to incorporate in hospital building design in the climatic context of Rajshahi.

Objectives 3: To identify parametric combination and configuration of envelope condition to facilitate passive cooling and to maximize comfort and minimize energy consumption.

5.3 Outcomes

The outcomes of the research are as follows:

5.3.1 Passive cooling techniques for hospital building

The first objective is to understand the scopes and applications of passive cooling techniques for hospital building. In order to achieve this objective literature review was conducted on passive cooling techniques. This review shows that passive cooling techniques can be broadly categorized into three tiers when applying them in building. The 1st tier involves heat gain protection, 2nd tier heat gain modulation and 3rd tier heat dissipation.

Heat gain protection can be achieved by microclimatic measures and solar control. Careful placement of the building in the site considering the landscaping, vegetation, water surface and orientation can significantly reduce solar heat gain. Another major source of heat gain in the building is direct and diffuse radiation through the openings and transmitted heat through the opaque surfaces (wall, roof, floor) of the envelop. Heat gain from opaque surfaces of the envelop can be protected by using appropriate insulation in first tier of passive cooling. However, insulation of the building must be carefully considered with physical parameters of the building and climate of the region. Openings cannot be completely negated/abandoned because of other factors such as ventilation, light and view. Therefore heat gain should be controlled by insulation, opening size, glazing material, and shading devices.

Heat gain can be modulated by thermal mass and night ventilation or night flush cooling. Building thermal mass is used to absorb radiation and act as a heat sink during day time and to moderate the indoor temperature swings. This could be attained by using heavy construction material or by using Phase Change Material (PCM) with high thermal inertia in the construction material. In night ventilation the cool night air is used to flush out the heat from a building mass and the precooled building is then act as a heat sink during the following day. Both of these two passive cooling techniques of heat gain modulation work best in hot and dry climates because of the large diurnal temperature variations.

Heat dissipation techniques involve natural ventilation and natural cooling. Temperature difference or pressure difference is necessary to induce natural ventilation. Cross ventilation, single sided ventilation, and buoyancy driven stack ventilation are different types of natural ventilation. Knowledge of regional and local wind flow pattern with seasonal variation, principles of air flow, location of opening, orientation and size of opening must be taken into consideration to effectively use natural ventilation for passive cooling. Natural cooling uses natural sources as a heat sink to disseminate heat. Evaporative cooling, ground cooling and radiative cooling are time-tested techniques of natural cooling. Evaporative cooling uses elements with high latent heat (e.g. water) for phase change to remove sensible heat from the environment. Air with low moisture content will encourage rapid evaporation hence building in hot and dry climate is the best candidate for evaporative cooling. Ground cooling uses ground as a heat sink and radiative cooling uses night sky as a sink to disseminate heat from indoor to outdoor. Both of later two techniques require larger surface area for efficiently transfer heat to the outside.

This study focuses on the passive cooling systems that can be incorporated into the building envelop. In the first tier, the techniques that are directly related to building envelop are opening (size, orientation and material), opaque surfaces and their insulation. In the second tier, thermal mass can be used to modulate temperature gain and it is related to building envelop. Also related to the building envelop are ground cooling and radiative cooling as the two techniques belonged to 3rd tier that can be used to dissipate heat from inside to outside.

5.3.2 Comparison of passive cooling techniques

The second objective was to compare the passive cooling techniques that can be incorporated into the envelop and find out an effective configuration for inpatient room of hospital building in context of Rajshahi. In order to achieve this objective at first climate of Rajshahi was studied then literature review on passive cooling techniques was conducted to find out the suitable passive cooling techniques for envelop of inpatient room in a case hospital.

From the climatic study of Rajshahi (Section 2.3) it can be concluded that climatic elements vary considerably from the country average. Hot dry and hot wet season outweigh the cold dry season. Therefore a combination of passive cooling techniques are required to ensure the thermal comfort condition. Hot wet season requires passive cooling techniques of microclimatic control (landscaping, vegetation, water surface, orientation) and solar control (window size and glazing, insulation of the opaque surface, shading devices) from 1st tier and natural ventilation (wind flow pattern, principles of air flow and location of opening, orientation and size of the opening) from the 3rd tier. For hot dry season envelop properties are crucial and must be taken into consideration to facilitate passive cooling otherwise it will be liability in the hot wet season. Envelop can be used to prevent heat gain, modify heat gain or dissipate heat to the outside. Dissipation of the heat involve ground cooling and radiative cooling in the 3rd tier. These two techniques of dissipation work best in hot dry climate and the conditions for their application suggest that they may not be suitable for inpatient room in the climatic context of Rajshahi. Therefore, this study focuses on heat prevention and modulation technique of passive cooling that can be integrated into building envelop of the inpatient room in the climatic context of Rajshahi. Heat prevention by insulation and heat modulation by the thermal mass of the envelop were considered for the envelop of the case in patient room of Rajshahi medical college hospital. After literature review four configuration of wall construction was considered for simulation (Figure 5.1).

5.3.3 Parametric combination and configuration of envelope condition

Considering the climate of Rajshahi, available local construction techniques and nature of the hospital building i.e. naturally ventilated, two types of wall envelop found to be thermally performing well out of four configurations. Existing 10” brink construction and 11.5” cavity wall construction performed better than 5” brick construction with tiled and plastered finish and 4” light weight concrete block construction with tiled and plastered finish due to their better insulation and thermal mass.

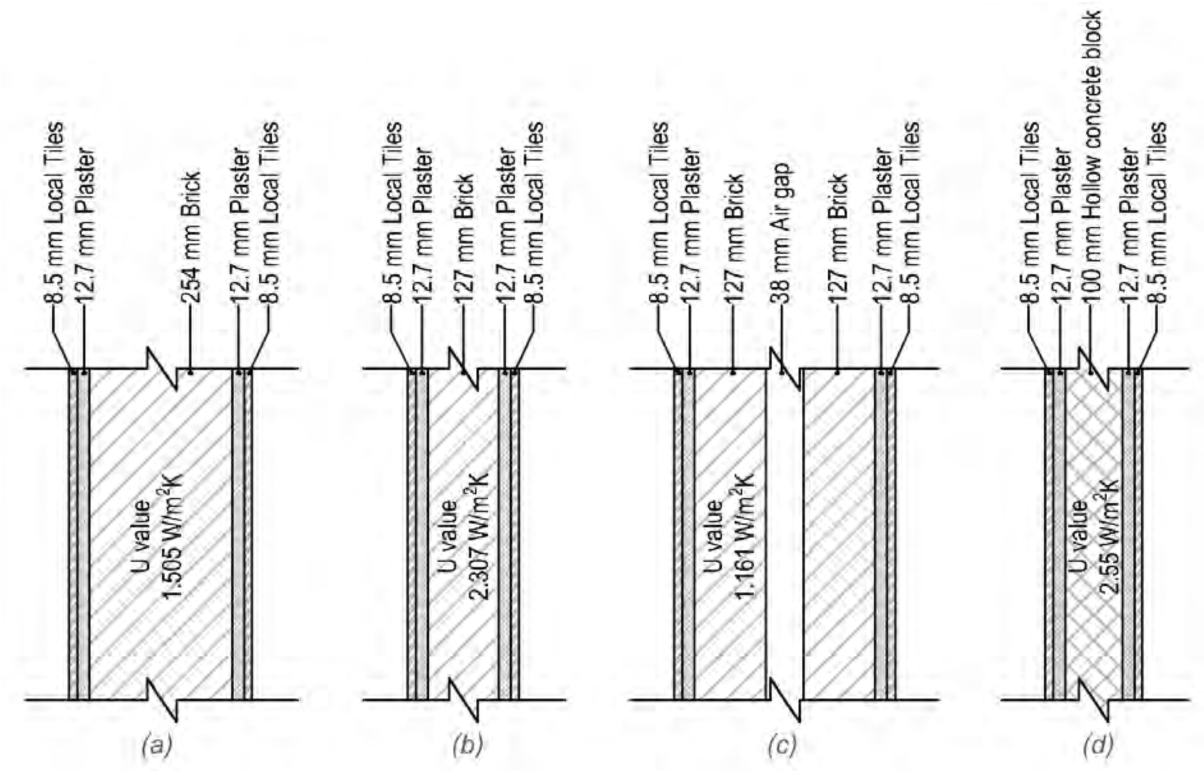


Figure 5.1 Detailed sections of the simulated four envelop configurations (a) WB10 (b) WB05 (c) WB11 (d) WC04.

From Figure 5.2 and Table 5.1 it is clear that due to better insulation and thermal mass of envelope type WB10 and WB11; indoor thermal condition is slightly better than the other two envelope types. From the results, it is also apparent that WC04 is the least performing envelop type in terms of thermal environment to provide passive cooling inside inpatient room.

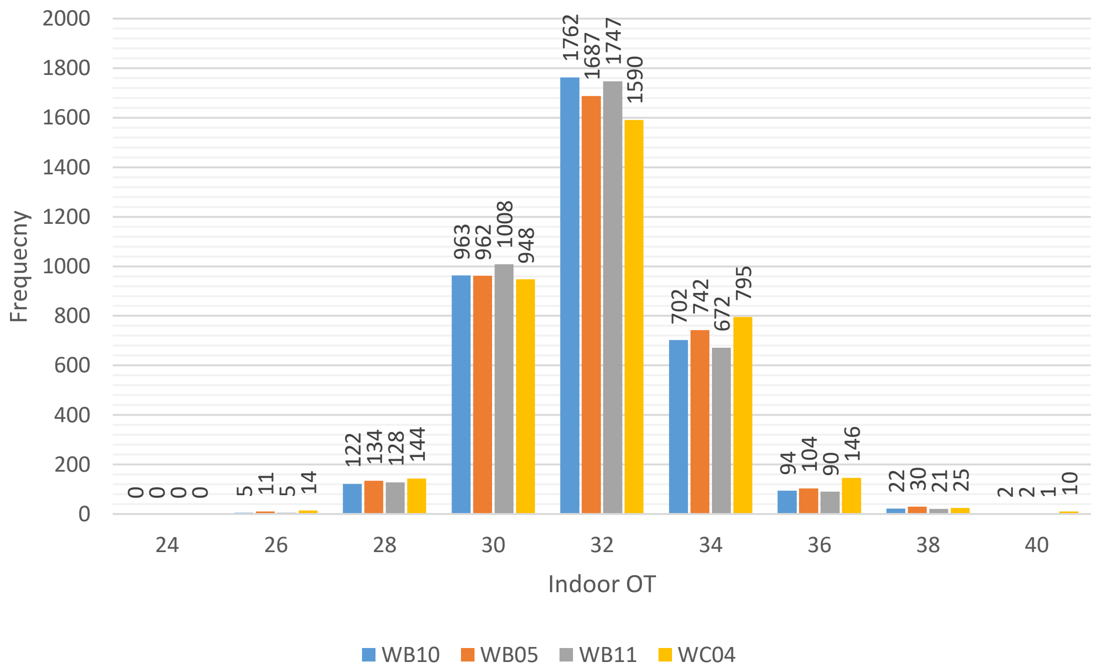


Figure 5.2 Comparison Indoor OT frequency distribution of four envelop type

Table 5.1 Comparison Indoor OT frequency distribution and percentage of four envelop type

Indoor OT range	WB10		WB05		WB11		WC04	
	Count	%	Count	%	Count	%	Count	%
OT<30	1090	29.68	1107	30.15	1141	31.07	1106	30.12
OT<32	2852	77.67	2794	76.09	2888	78.65	2696	73.42
OT>32	820	22.33	878	23.91	784	21.35	976	26.58
OT>34	118	3.21	136	3.70	112	3.05	181	4.92
20≤OT<40	3672	100	3672	100	3672	100	3672	100

5.4 Scope for Future Research

Present day knowledge is the culmination of collective knowledge of the human. Any research open new horizon and thus in turn open infinitive possibilities and scope for newer research topics. This research topics is of no exception. Due to the various constrain and limited scope of the research, many aspects that are related with this research are not explored. The scope for future research topics are enumerated below:

- For comprehensive energy savings measure it is paramount to adopt plan consists of extensive energy performance audit, analyzing and scope for optimizing energy performance of existing hospital.
- From the three broad categories of passive cooling a combination of techniques can be applied to upscale the cooling for hospital building.

Hybrid cooling-technique combining passive cooling and minimum active cooling can be explored to achieve thermal comfort standard in critical area of hospital with strict environmental control.

Passive cooling can also be achieved through envelope type other than wall i.e. floor and ceiling.

- Physical dimension of the inpatient room, opening size, shading device, air flow, and ventilation can be considered for detailed parametric study to incorporate passive cooling.
- Advanced PCM (phase change material) material can be used to retain heat in building envelope can be studied for future research.
- Natural cooling i.e. evaporative, ground, and radiative cooling singly or a combination of these three can be used to dissipate heat and thus achieving passive cooling can be studied.

A research functioned as a basis for further research to explore other avenues as mentioned above to facilitate passive cooling in hospital building.

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APPENDIX

Appendix A	Specification
Appendix B	Meteorological data of Rajshahi
Appendix C	Simulation data

Appendix A: Specification

The instruments used in field survey are listed in Table A.1.

Table A.1 Instruments used for field survey. (Source: All environmental data collection instruments used in field survey were provided by BUET)

Sl. No.	Equipment	Manufacturer	Instrument
1	Mini Thermo-Anemometer Model no: 45118	Extech Instruments	
2	Thermo-Hygrometer	Zeal	
3	Camera	Canon 70D	

EnergyPlus

EnergyPlus™ is a whole building energy simulation program to model both energy consumption—for heating, cooling, ventilation, lighting and plug and process loads—and water use in buildings.

EnergyPlus is a console-based program that reads input and writes output to text files. It ships with a number of utilities including IDF-Editor for creating input files using a simple spreadsheet-like interface, EP-Launch for managing input and output files and performing batch simulations, and EP-Compare for graphically comparing the results of two or more simulations. Several comprehensive graphical interfaces for EnergyPlus are also available. DOE does most of its work with EnergyPlus using the OpenStudio software development kit and suite of applications.

EnergyPlus is free, open-source, and cross-platform—it runs on the Windows, Mac OS X, and Linux operating systems. Its development is funded by the U.S. Department of Energy's (DOE) Building Technologies Office (BTO). Along with OpenStudio, EnergyPlus is part of BTO's building energy modeling program portfolio.

EnergyPlus version 8.5.0 is used for simulation. For modelling of the geometry of the inpatient room OpenStudio plug-in version 1.11.0 is used as a plugin with popular 3D modelling tool SketchUp. SketchUp version 2016 is used in this simulation study.

Appendix B: Meteorological data of Rajshahi

Following tables present climatic data of Rajshahi. These climatic data is obtained from Bangladesh Meteorological Department website.

Table B.1 Daily Normal maximum temperature in degree Celsius

Day/Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
D_01	23.9	25.5	29.8	34.6	34.7	34.6	32.2	31.9	32.3	32.8	30.2	27.4
D_02	23.5	25.8	30.3	36.2	33.9	35.5	32.2	32.3	32.6	32.7	30.5	27.2
D_03	23.8	25.8	30.7	35.5	34.2	34.9	32.0	31.8	32.4	32.0	30.4	27.4
D_04	23.7	26.0	31.2	35.8	35.1	34.8	32.7	32.0	32.2	32.5	30.3	27.0
D_05	24.1	25.5	31.6	35.7	35.0	34.0	32.4	32.3	32.3	32.4	30.5	27.0
D_06	24.1	26.1	31.8	36.5	34.4	34.6	32.4	31.8	32.2	32.3	30.4	27.1
D_07	24.3	25.8	31.6	36.5	34.4	34.4	31.7	32.1	32.5	32.6	30.5	26.7
D_08	24.1	26.2	32.2	36.7	34.4	34.2	32.4	32.4	32.4	32.2	30.2	26.5
D_09	23.7	26.4	32.3	36.0	34.9	33.9	32.2	32.3	31.9	32.1	29.8	26.2
D_10	24.4	26.6	32.4	35.5	34.7	34.0	32.1	32.8	31.9	32.2	30.0	26.3
D_11	24.2	26.9	32.4	35.4	34.8	33.3	31.9	32.6	32.0	32.4	29.7	25.9
D_12	24.4	26.9	32.9	36.0	34.8	33.0	31.9	32.3	32.2	32.8	29.8	26.3
D_13	24.5	27.9	33.1	36.5	34.1	33.8	32.4	32.5	32.2	32.0	29.5	25.8
D_14	24.5	27.7	32.4	36.5	34.3	33.6	32.4	32.7	32.2	31.9	29.5	25.5
D_15	24.4	28.1	33.7	36.6	34.0	33.6	32.1	31.9	32.3	31.8	29.5	26.0
D_16	24.1	28.4	33.3	35.3	33.8	33.3	32.1	32.0	32.3	32.1	29.5	25.9
D_17	24.2	29.0	34.5	35.6	34.1	33.0	31.5	32.5	32.2	32.1	29.5	25.9
D_18	24.4	28.7	35.0	35.9	34.8	32.0	31.7	32.3	32.6	31.3	29.3	25.9
D_19	24.2	29.1	34.9	35.9	34.7	32.5	32.0	32.1	32.8	31.6	29.1	25.6
D_20	24.2	28.9	34.8	35.8	34.5	33.4	31.9	32.4	32.6	31.4	29.2	25.6
D_21	24.2	28.9	35.0	36.0	35.0	33.1	32.1	32.5	32.5	31.3	28.9	25.3
D_22	24.6	28.8	34.6	36.1	34.9	32.9	31.9	32.5	32.3	31.2	28.8	25.3
D_23	25.0	28.2	34.7	35.4	34.8	31.9	32.2	32.3	32.4	30.9	28.8	25.5
D_24	24.6	28.9	33.8	35.0	34.8	32.7	32.3	32.8	32.1	31.1	28.6	25.3
D_25	25.0	29.6	33.2	35.3	34.3	32.5	32.4	32.0	32.0	31.4	28.5	24.9
D_26	25.2	29.6	33.8	35.3	33.8	32.5	32.3	32.7	31.8	31.3	28.4	24.7
D_27	25.6	29.5	34.0	35.3	34.6	32.2	31.8	32.4	32.1	30.8	28.3	24.6
D_28	26.1	30.0	34.2	34.0	35.0	32.0	31.6	32.6	31.5	30.3	27.7	24.4
D_29	25.5	28.8	34.7	33.9	34.4	32.4	32.0	32.2	32.0	30.4	27.4	24.9
D_30	25.4		32.9	34.7	34.2	32.6	32.4	32.4	32.7	30.3	27.6	24.0
D_31	26.0		34.2		34.8		31.7	32.4		29.9		24.2

Table B.2 Daily Normal minimum temperature in degree Celsius

Day/Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
D_01	11.0	12.3	15.4	21.3	23.8	25.8	26.1	25.9	26.2	24.9	21.2	14.5
D_02	11.0	12.2	15.2	21.6	23.3	25.9	25.7	26.1	26.1	25.0	20.6	14.5
D_03	10.9	12.0	14.7	21.2	23.6	25.6	25.8	25.9	25.9	25.1	20.2	13.9
D_04	10.6	12.2	14.5	21.4	23.7	25.7	26.0	25.8	25.6	24.9	20.1	13.7
D_05	10.6	12.5	15.8	21.7	23.9	25.3	25.8	26.1	25.7	25.0	19.9	13.5
D_06	11.0	11.8	16.3	22.2	23.0	25.5	26.1	25.9	25.7	24.8	19.5	13.6
D_07	11.1	11.4	16.5	22.2	24.1	25.6	25.9	26.0	26.0	24.9	19.0	13.7
D_08	10.7	11.6	15.8	22.1	24.0	25.5	26.0	26.1	26.1	24.3	19.1	13.2
D_09	11.4	12.0	16.3	22.6	24.0	25.7	26.1	26.2	25.8	24.6	19.3	13.6
D_10	11.4	12.4	16.3	22.3	24.3	25.4	25.8	26.3	25.7	24.3	19.1	13.3
D_11	11.6	12.3	17.5	22.8	24.5	25.9	26.0	26.3	25.5	24.2	18.6	13.1
D_12	11.2	12.9	17.1	22.4	24.0	25.8	25.9	26.3	25.3	24.0	18.4	12.8
D_13	11.4	12.9	18.0	22.6	24.0	25.8	26.0	25.9	25.4	24.1	18.0	12.8
D_14	10.8	13.6	17.2	22.9	24.1	26.0	26.1	26.2	25.7	23.9	17.6	12.8
D_15	10.6	13.7	17.1	23.4	24.0	26.0	26.2	25.9	25.6	23.7	17.4	12.2
D_16	11.1	13.7	16.9	22.7	24.0	25.9	25.9	25.8	25.3	23.6	17.3	11.8
D_17	11.0	13.9	17.5	23.4	24.4	25.5	25.8	26.2	25.8	23.0	17.5	12.4
D_18	10.3	13.9	18.7	22.7	24.3	25.4	25.8	26.0	25.8	23.3	17.6	12.5
D_19	10.0	13.7	18.6	23.3	24.7	25.5	25.9	26.1	25.9	23.0	17.8	12.3
D_20	10.0	13.6	19.0	23.4	24.8	25.9	26.0	26.2	25.9	22.9	17.3	11.5
D_21	10.3	14.1	18.8	23.2	24.7	26.1	26.0	26.1	25.9	22.8	17.2	11.9
D_22	10.5	14.1	18.6	23.6	24.6	26.0	25.8	26.0	25.6	22.4	16.6	11.5
D_23	10.9	13.8	19.7	23.5	24.2	25.9	25.9	26.0	25.4	21.9	16.5	12.1
D_24	11.1	14.0	19.3	23.4	24.9	25.9	26.2	26.1	25.4	21.7	16.8	12.4
D_25	10.5	14.0	19.5	23.4	24.8	25.9	26.1	26.4	25.6	21.3	16.4	12.0
D_26	11.2	14.0	19.7	23.4	24.6	25.9	26.1	26.0	25.1	21.0	15.8	12.0
D_27	11.1	14.8	19.4	23.6	25.0	26.0	26.1	26.1	24.9	21.2	15.6	12.2
D_28	11.8	14.4	19.5	23.0	25.2	25.9	25.8	25.9	24.8	21.1	15.5	11.9
D_29	12.2	13.3	20.1	23.6	24.4	26.1	25.9	25.9	24.8	20.6	14.9	11.2
D_30	11.9		20.8	23.3	25.0	26.1	26.1	26.0	24.9	20.8	14.7	11.0
D_31	11.9		21.3		24.6		26.1	26.3		20.7		11.4

Table B.3 Monthly maximum temperature in degree Celsius recorded from 1995 to 2012 in Rajshahi

Day/Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1995	23.3	26.8	32.4	38.5	37.8	33.5	31.9	32.4	32.1	32.2	28.7	25.9
1996	24.4	28	34.2	37	36.7	32.9	32.9	32.5	33.3	31.1	29.4	26.1
1997	24	26.8	32.8	32.3	36.3	34.6	31.8	32.5	31.8	31.4	29.1	23.4
1998	21.3	27.6	30.7	34	34.9	35.7	32.8	32.8	32.3	32.6	29.8	26.7
1999	24.9	30	35.2	37.8	34.6	34.3	32.2	32.1	31.3	31.6	29.7	26.6
2000	24.1	25.2	32	34.6	33.3	33.6	32.7	33.3	31.2	32.1	30.2	26.1
2001	24.2	28.6	33.6	37	33	32.5	32.7	33.5	33.2	31.9	29.7	25
2002	25	28.7	33.2	33.5	32.9	33.5	33.2	32.6	33.1	31.9	29.1	25.5
2003	22	28.1	34.5	34.8	37.1	33.5	32.4	33.1	31.5	31.1	29.5	26.3
2004	22	28.1	34.5	34.8	37.1	33.5	32.4	33.1	31.5	31.1	29.5	26.3
2005	23.8	29.1	32.9	35.8	35.1	36	32.2	33.2	33.7	29.8	28.3	26.5
2006	24.9	31.3	33.5	35.3	35	34.1	33.2	33.3	32.9	32.6	28.7	26.3
2007	24.5	26.4	31.1	35.4	36.1	33.8	32.4	33.2	32.8	31.9	29.8	25.4
2008	23.7	25.7	33	36.3	35.6	32.7	31.9	32.9	33.2	31.8	29.6	25
2009	24.5	29.5	33.4	37.4	34.9	36.7	33.5	32.9	33.6	31.9	29.7	25.4
2010	22.4	28.8	35.9	38.3	35.9	35	34	34	33.2	32	29.8	25.1
2011	22.6	28.3	33.7	34.8	34.6	34.1	33.5	32.2	32.8	32.9	29.1	24.2
2012	22.6	28.3	33.7	34.8	34.6	34.1	33.5	32.2	32.8	32.9	29.1	24.2

Table B.4 Monthly minimum temperature in degree Celsius recorded from 1995 to 2012 in Rajshahi

Day/Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1995	9.6	12.9	17.3	23.1	26.5	26.5	26.1	26.1	25.8	23.8	18.1	12.5
1996	11	13.2	19.4	22.5	25.3	25.1	26.3	26	26.1	22.8	16.8	12
1997	9.8	12.2	18.7	20.4	24.4	25.2	26	26.4	25.2	22	18.7	13.5
1998	10.4	13.9	16.2	22.1	24.9	27.5	26.5	26.8	26.2	25	20.3	14
1999	11.2	14.1	17.8	25.7	24.9	26.3	25.9	26	25.6	24.3	18.2	14.1
2000	10.7	12.9	17.6	23.1	24.3	25.9	26.6	26.4	25.3	24	18.3	12.7
2001	9.4	12.9	17.5	22.9	23.8	25.6	26.4	26.6	26.1	24	19.2	12.9
2002	12.3	13.3	18.4	22.6	24.2	25.7	26.6	26.2	25.6	22.3	17.8	12.9
2003	10.9	13.4	20.1	23.3	25.3	25.4	25.9	26.3	25.5	22.2	16.3	14.2
2004	10.9	13.4	20.1	23.3	25.3	25.4	25.9	26.3	25.5	22.2	16.3	14.2
2005	11.3	15	19.7	23.5	24.4	26.1	26.1	26.7	26	23.2	16.6	13
2006	10.6	16.2	18.5	23	24.4	26.2	26.6	26	25.5	23.5	17.8	12.7
2007	9.4	14.6	17.1	23.7	24.9	25.6	26	26.7	26.1	23.3	18.5	11.5
2008	11.1	12	20.1	23.1	24.2	25.7	26	26.4	25.8	22.6	16.5	15
2009	12.3	12.6	18	23.9	24.4	26.6	26.6	26.4	25.9	22.1	17.8	11.6
2010	9.4	13.1	19.8	25.7	25.4	26.1	26.6	26.6	25.8	23.4	18.4	11.9
2011	8.6	12.6	18.7	22.2	23.9	25.8	26.4	26.2	25.9	23.3	17	12.5
2012	8.6	12.6	18.7	22.2	23.9	25.8	26.4	26.2	25.9	23.3	17	12.5

Table B.5 Daily Normal Rainfall in mm in Rajshahi

Day/Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
D_01	0.8	0.8	0.8	0.5	5.3	2.4	10.2	5.7	8.1	7.0	1.7	0.1
D_02	0.4	0.4	0.9	1.1	2.2	2.5	11.8	9.2	7.4	7.3	0.8	0.0
D_03	0.1	0.1	0.0	0.9	2.8	0.9	11.7	9.2	7.5	9.2	2.2	0.0
D_04	0.0	0.0	0.2	0.9	2.4	7.7	8.1	14.4	6.7	3.9	0.1	0.0
D_05	0.0	0.0	1.1	0.1	2.9	8.1	7.5	12.9	12.1	4.1	0.5	0.0
D_06	0.1	0.1	0.5	0.9	1.1	6.3	8.2	10.6	9.5	4.4	0.0	0.0
D_07	0.1	0.1	0.3	0.4	3.4	13.8	8.7	7.4	6.5	8.2	0.0	0.0
D_08	0.1	0.1	0.7	1.2	2.3	7.5	8.1	4.8	9.5	2.8	0.7	0.1
D_09	0.4	0.4	0.9	1.1	4.3	6.0	13.8	4.4	8.6	7.7	1.7	1.2
D_10	0.0	0.0	0.0	1.8	2.6	5.8	9.0	5.2	7.8	3.6	3.0	2.7
D_11	1.1	1.1	0.7	2.1	3.7	6.7	10.0	5.1	6.5	1.7	0.1	0.3
D_12	0.4	0.4	0.4	1.6	5.5	10.8	13.5	8.8	16.2	7.5	0.0	0.1
D_13	0.0	0.0	0.2	0.4	4.2	6.1	10.7	6.2	9.8	5.4	2.2	0.1
D_14	0.0	0.0	0.1	4.2	4.1	8.7	7.9	16.9	7.3	2.4	0.1	0.4
D_15	0.6	0.6	0.1	5.2	2.8	7.7	11.3	10.7	12.2	1.6	0.1	0.0
D_16	0.8	0.8	0.0	1.3	7.2	8.9	10.8	7.9	6.1	1.6	0.1	0.1
D_17	0.0	0.0	1.2	1.3	4.6	12.8	10.5	7.6	6.0	3.5	0.0	0.0
D_18	0.0	0.0	0.8	4.4	4.7	9.5	7.9	8.0	8.7	2.7	0.0	0.0
D_19	0.3	0.3	0.9	1.3	4.4	10.6	8.1	8.3	10.7	1.9	0.0	0.0
D_20	0.3	0.3	0.0	5.9	4.0	5.6	12.4	7.1	8.0	6.2	0.0	0.0
D_21	0.2	0.2	0.0	0.9	4.5	14.0	13.9	6.7	8.5	0.5	0.0	0.0
D_22	0.5	0.5	0.8	3.4	12.9	10.8	17.5	9.0	6.2	2.4	0.2	0.1
D_23	0.0	0.0	0.3	1.5	3.0	10.4	7.7	8.1	8.2	2.9	0.2	0.0
D_24	1.1	1.1	1.4	1.8	5.2	15.3	9.2	12.4	13.2	0.0	0.0	2.1
D_25	0.0	0.0	1.2	2.7	1.8	12.1	9.0	11.4	16.6	1.2	0.0	1.2
D_26	0.7	0.7	2.6	2.5	6.2	11.2	13.5	6.4	18.3	0.2	0.0	0.9
D_27	0.1	0.1	0.4	5.7	5.7	7.4	20.3	7.2	18.3	2.1	0.0	0.9
D_28	0.6	0.6	0.0	3.1	7.2	8.5	12.8	10.6	11.2	2.2	0.6	0.3
D_29	1.2	1.2	3.4	2.3	6.4	14.0	4.6	11.5	12.2	0.2	1.2	0.0
D_30	0.6	0.6	2.3	3.1	5.5	12.5	5.5	10.8	8.1	1.0	0.9	0.0
D_31	0.8	0.8	2.6		3.5		6.3	9.3		1.3		0.0

Appendix C: Simulation data

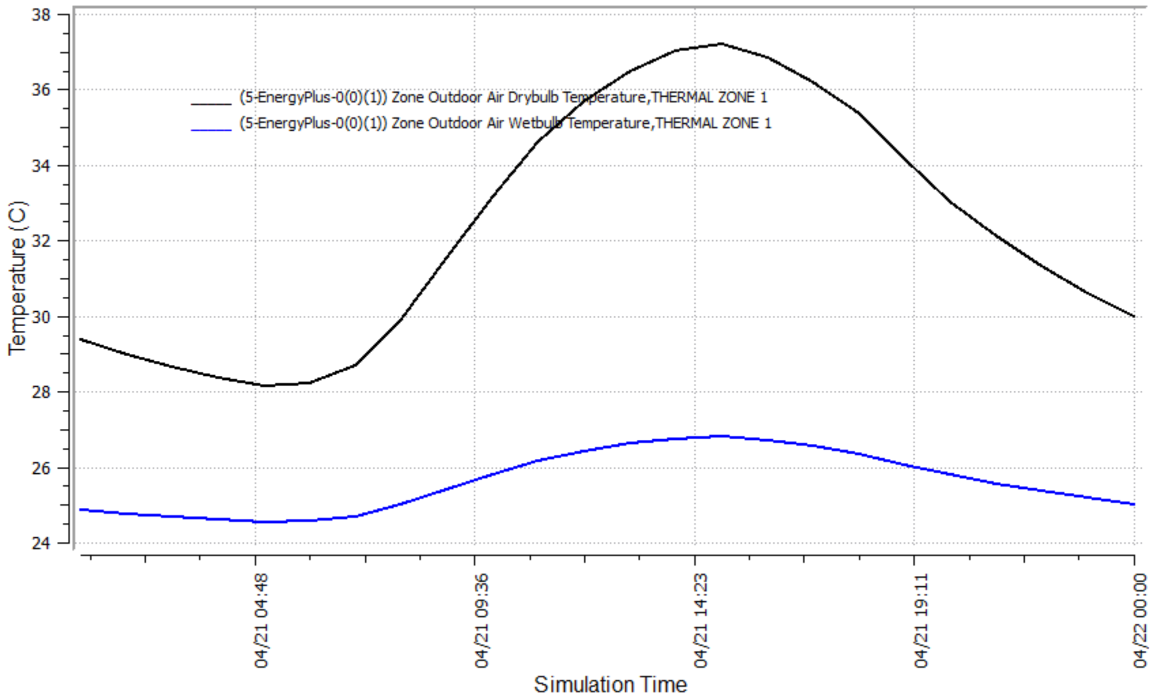


Figure C.1 Outdoor Air DBT and WBT for 1.0 percentile cooling condition: Wall Type WB10

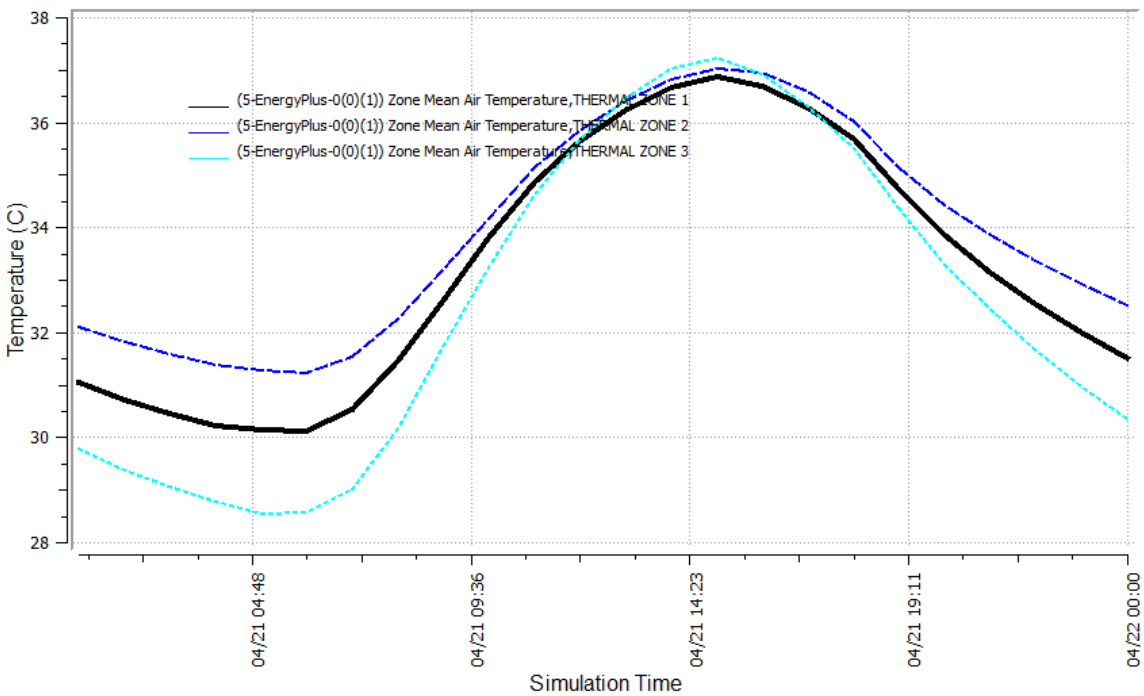


Figure C.2 Mean Air Temperature of zone 1, zone 2 and zone 3 for 1.0 percentile cooling condition: Wall Type WB10

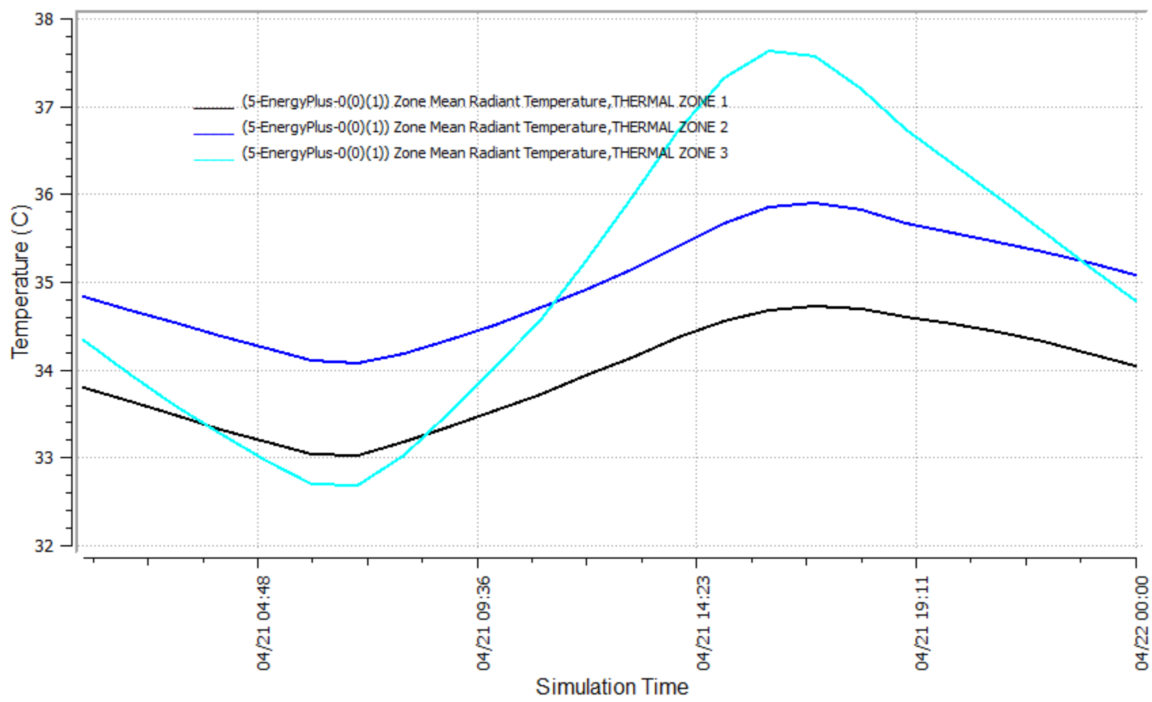


Figure C.3 Mean Radiant Temperature of zone 1, zone 2 and zone 3 for 1.0 percentile cooling condition: Wall Type WB10

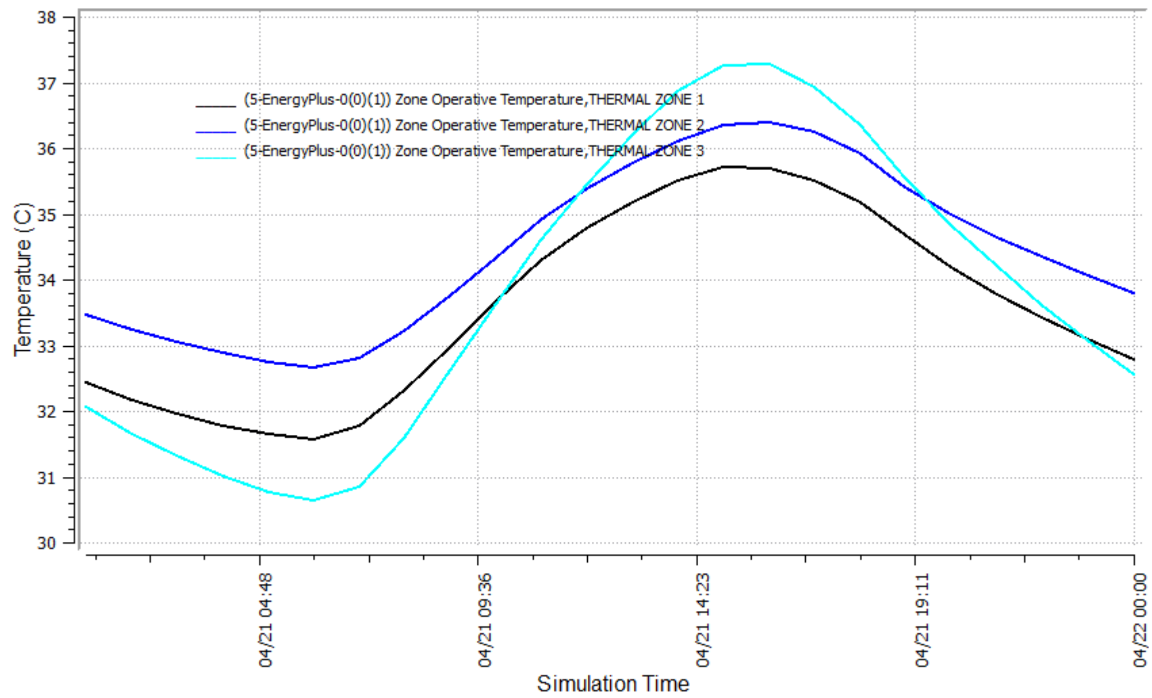


Figure C.4 Mean Operative Temperature of zone 1, zone 2 and zone 3 for 1.0 percentile cooling condition: Wall Type WB10

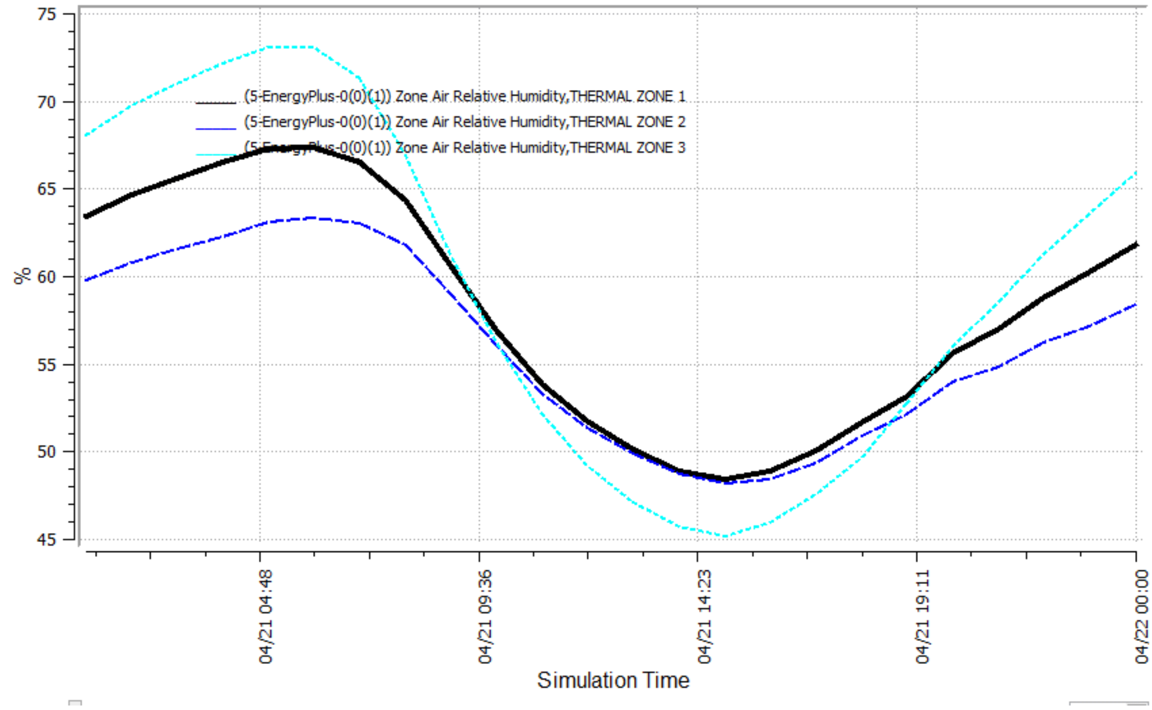
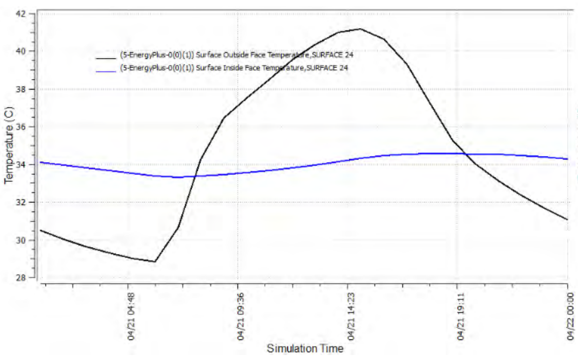
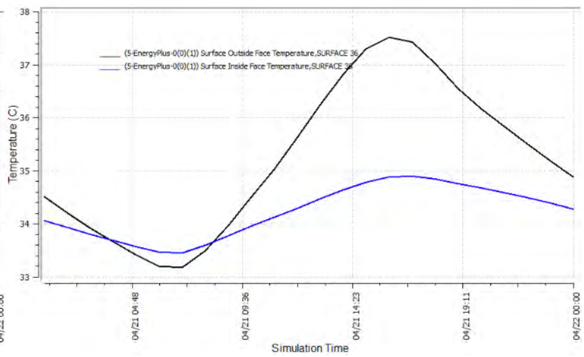


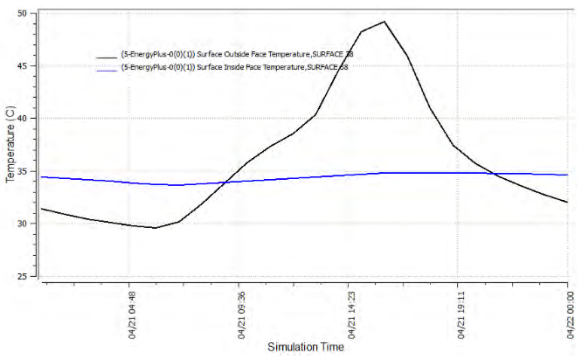
Figure C.5 Relative Humidity of zone 1, zone 2 and zone 3 for 1.0 percentile cooling condition: Wall Type WB10



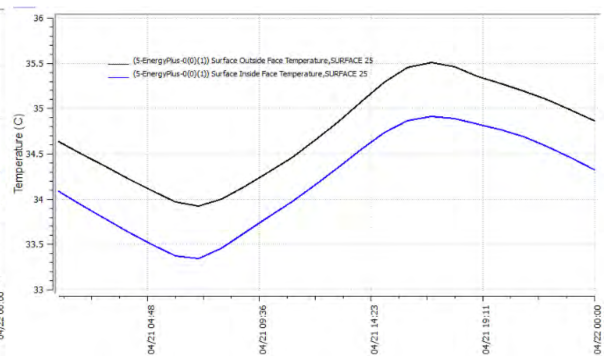
(a)



(b)



(c)



(d)

Figure C.6 Outside and inside surface temperature for 1.0 percentile cooling condition (a) North wall (b) South wall (c) West wall and (d) East wall: Wall Type WB10

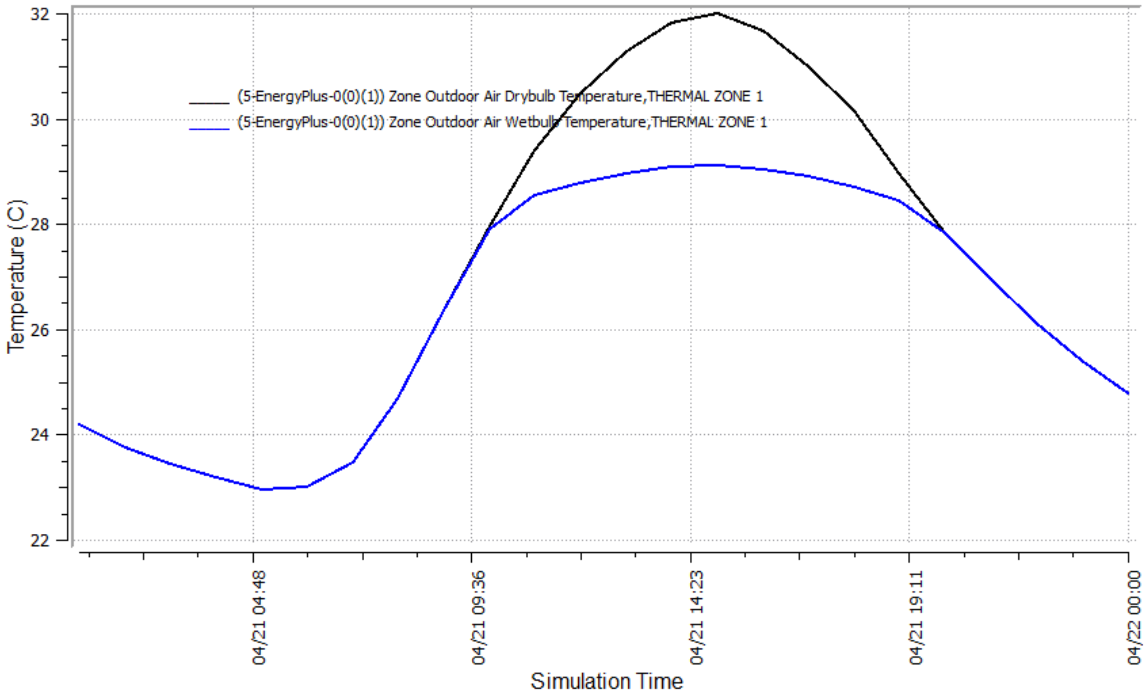


Figure C.7 Outdoor Air DBT and WBT for 1.0 percentile dehumidification condition: Wall Type WB10

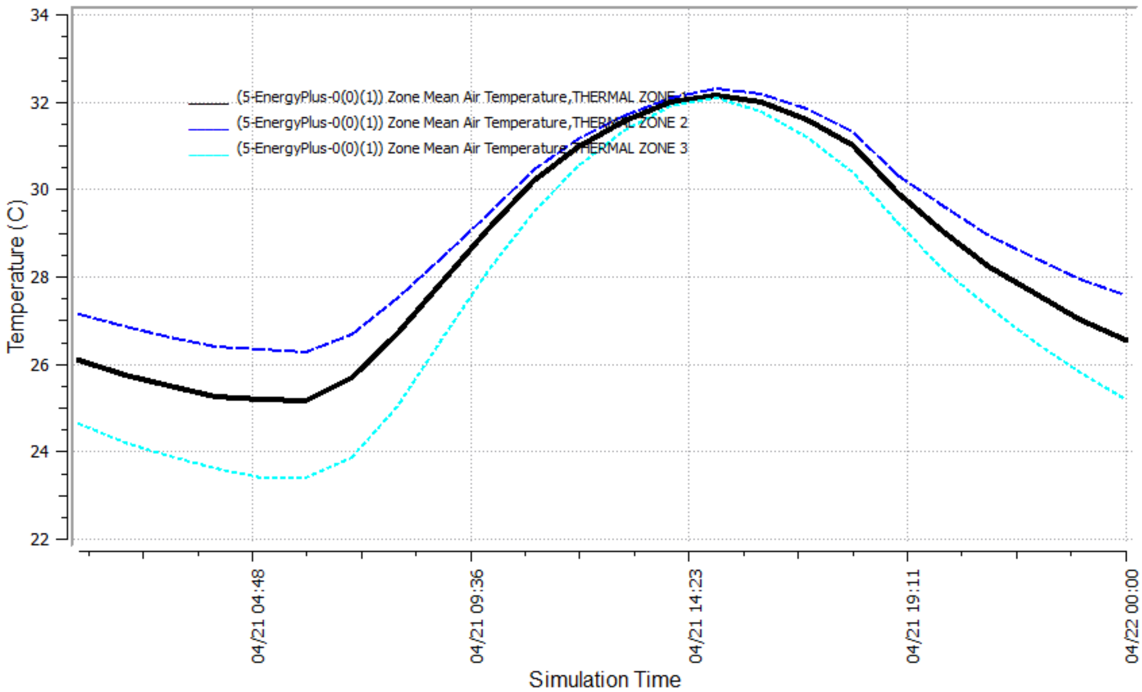


Figure C.8 Mean Air Temperature of zone 1, zone 2 and zone 3 for 1.0 percentile dehumidification condition: Wall Type WB10

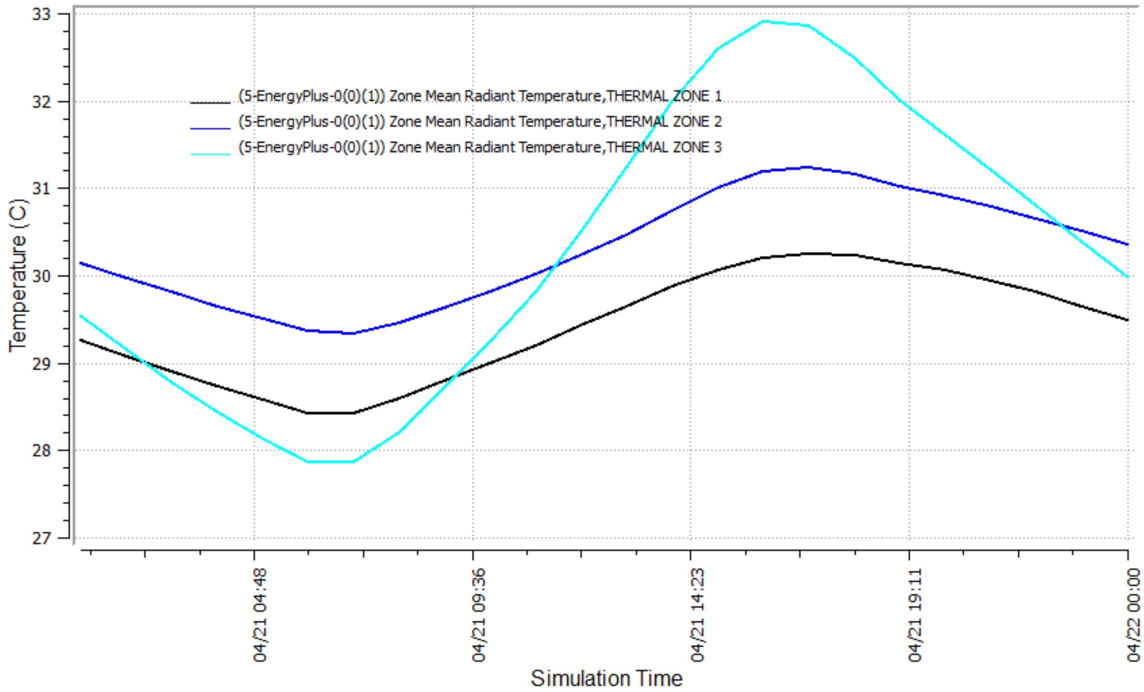


Figure C.9 Mean Radiant Temperature of zone 1, zone 2 and zone 3 for 1.0 percentile dehumidification condition: Wall Type WB10

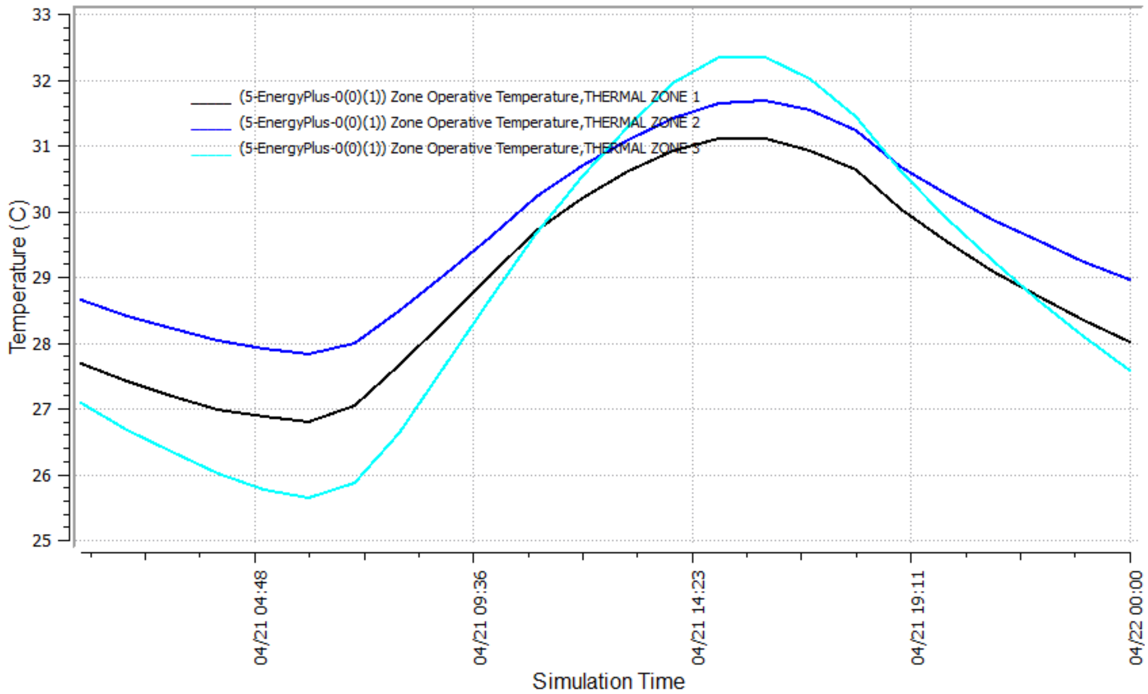


Figure C.10 Mean Operative Temperature of zone 1, zone 2 and zone 3 for 1.0 percentile dehumidification condition: Wall Type WB10

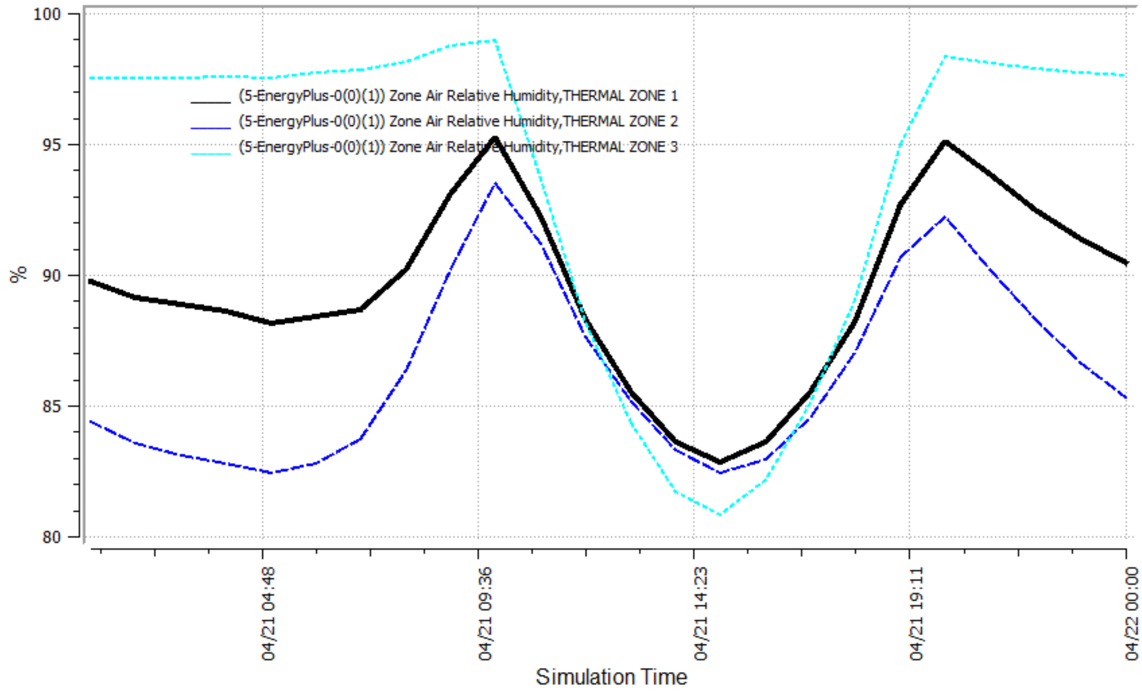
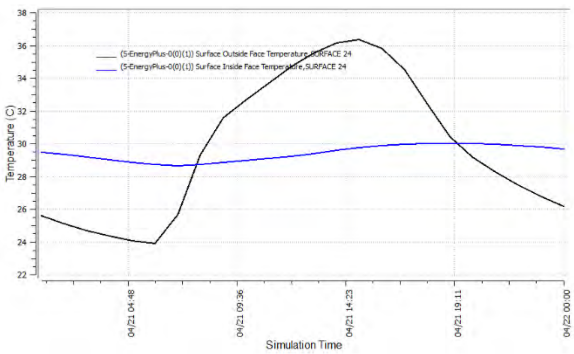
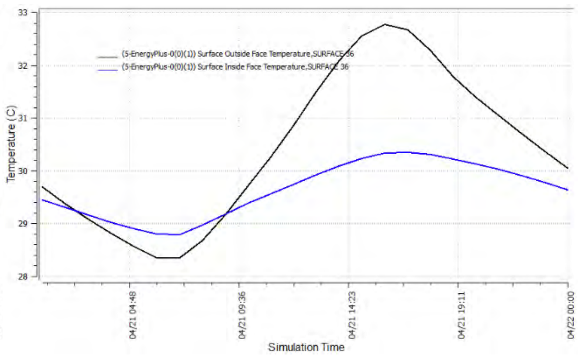


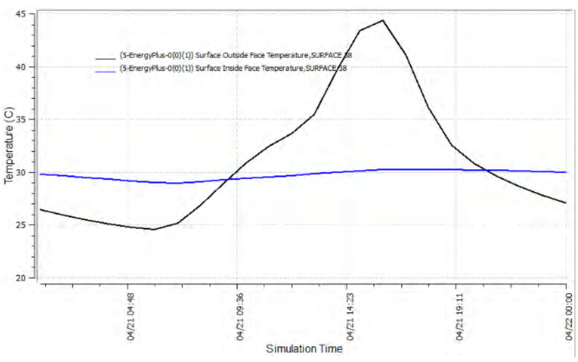
Figure C.11 Relative Humidity of zone 1, zone 2 and zone 3 for 1.0 percentile dehumidification condition: Wall Type WB10



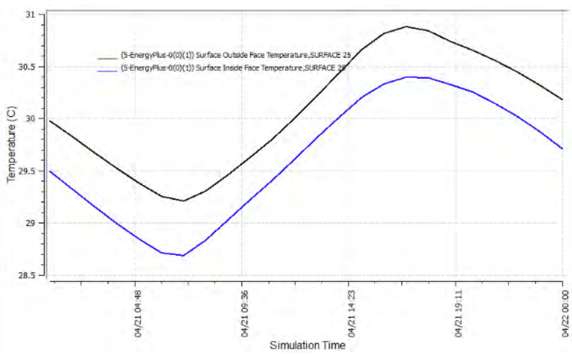
(a)



(b)



(c)



(d)

Figure C.12 Outside and inside surface temperature for 1.0 percentile dehumidification condition (a) North wall (b) South wall (c) West wall and (d) East wall: Wall Type WB10

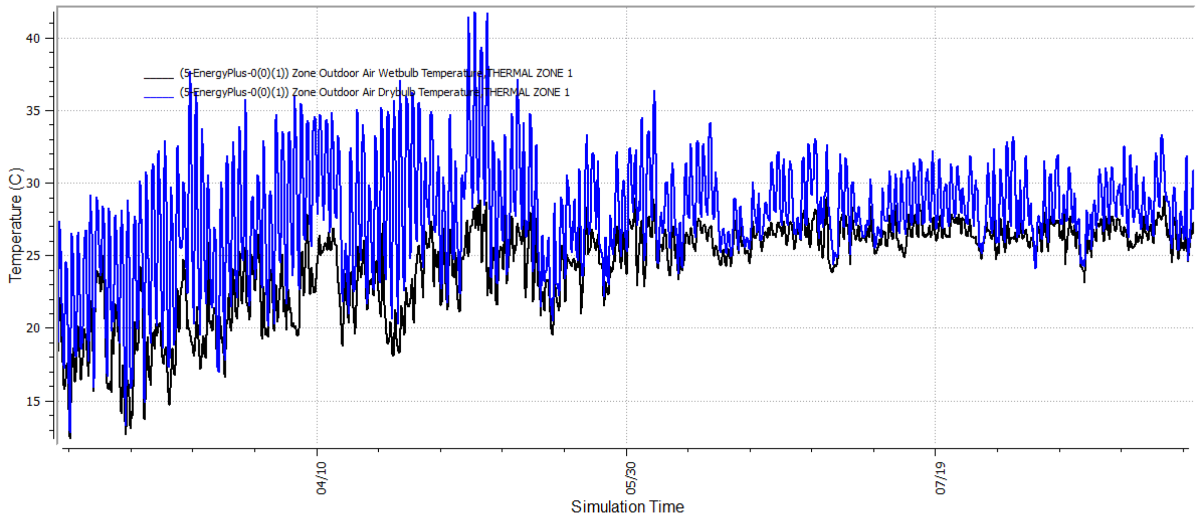


Figure C.13 Outdoor DBT and WBT from March to August: Wall Type WB10

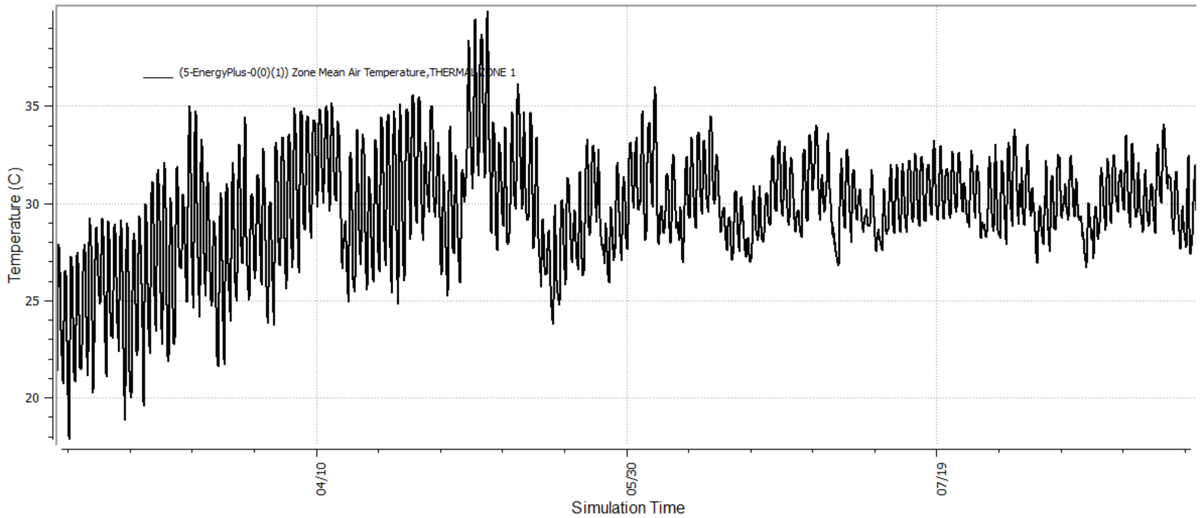


Figure C.14 Zone 1 Mean air temperature from March to August: Wall Type WB10

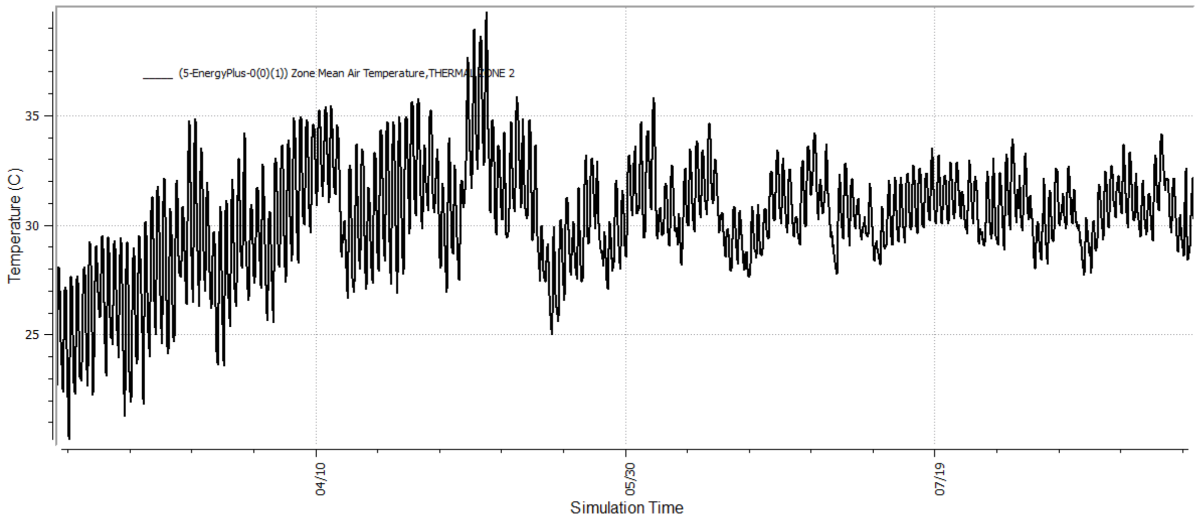


Figure C.15 Zone 2 Mean air temperature from March to August: Wall Type WB10

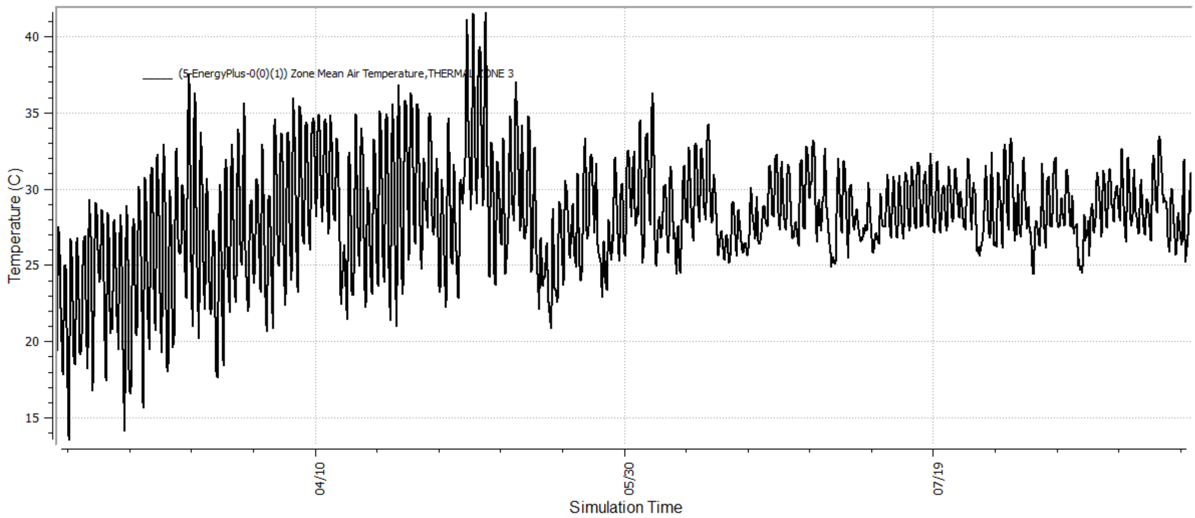


Figure C.16 Zone 3 Mean air temperature from March to August: Wall Type WB10

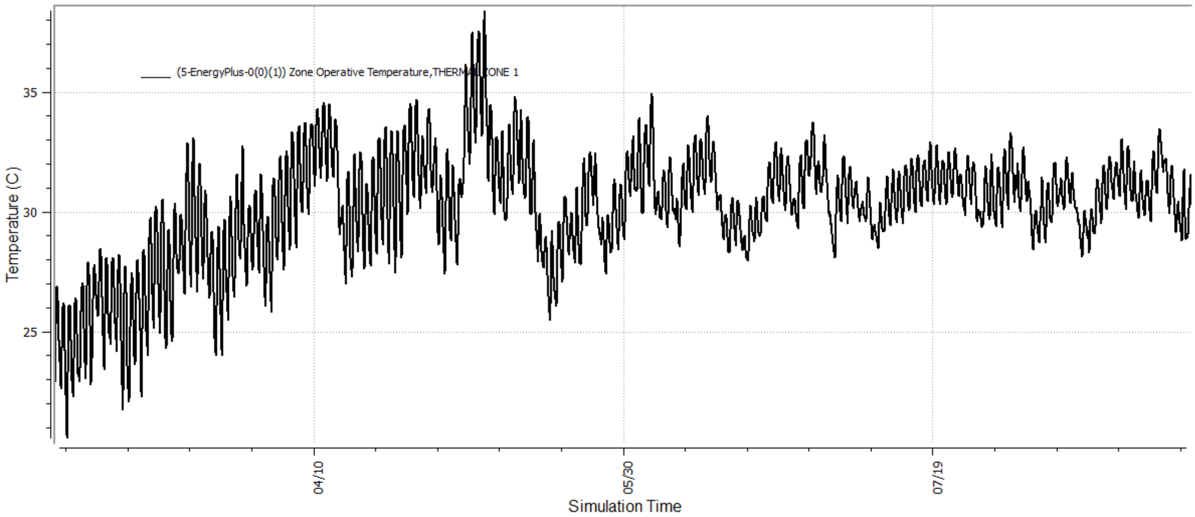


Figure C.17 Zone 1 Operative temperature from March to August: Wall Type WB10

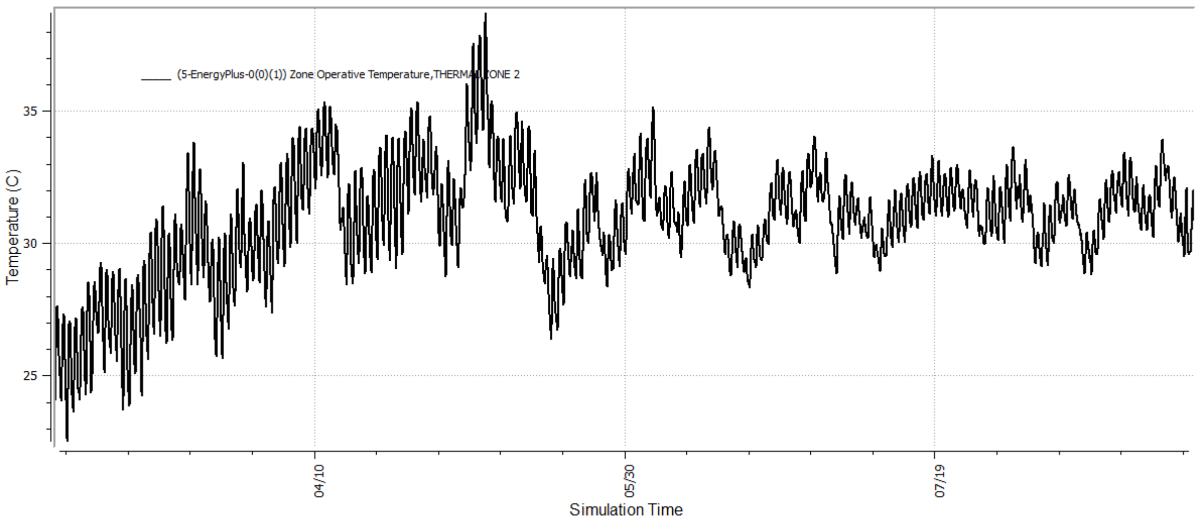


Figure C.18 Zone 2 Operative temperature from March to August: Wall Type WB10

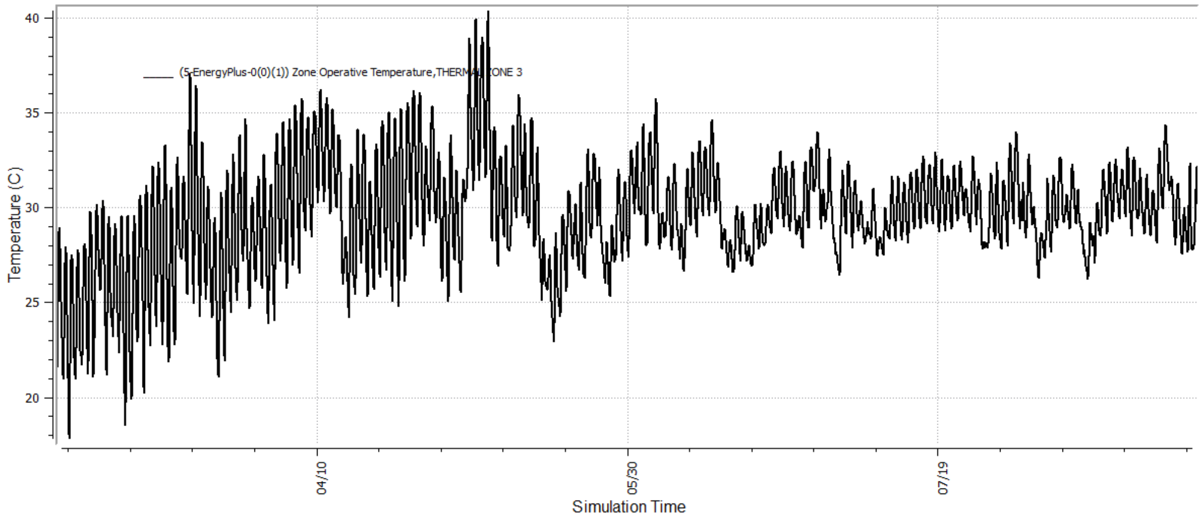


Figure C.19 Zone 3 Operative temperature from March to August: Wall Type WB10

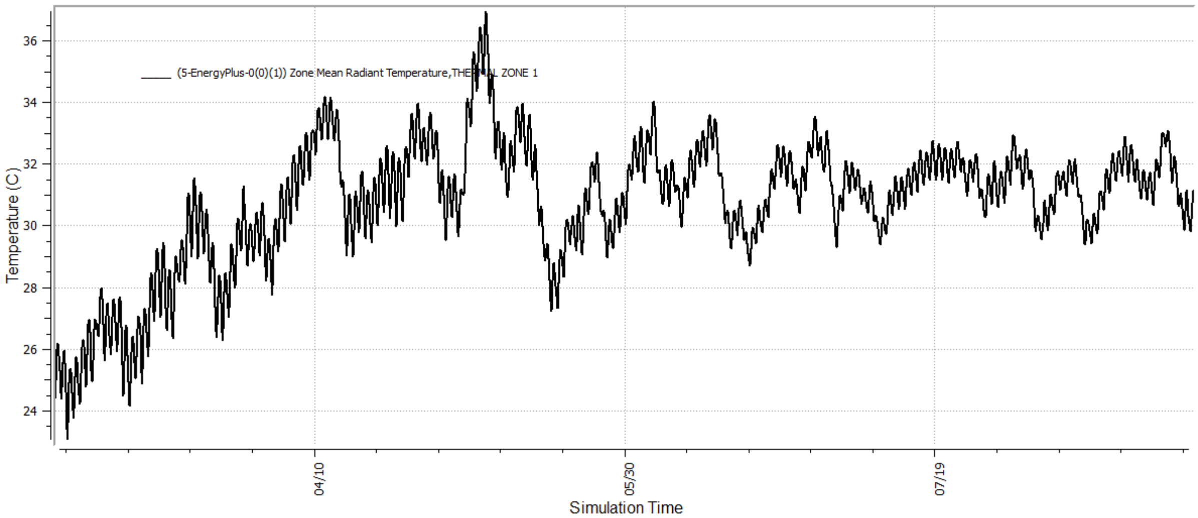


Figure C.20 Zone 1 Mean Radiant temperature from March to August: Wall Type WB10

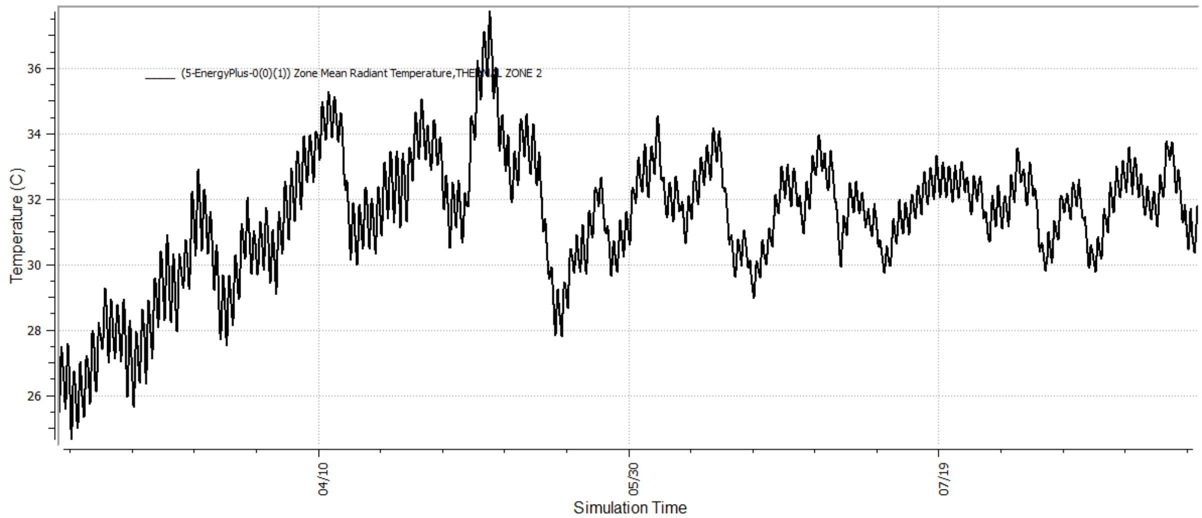


Figure C.21 Zone 2 Mean Radiant temperature from March to August: Wall Type WB10

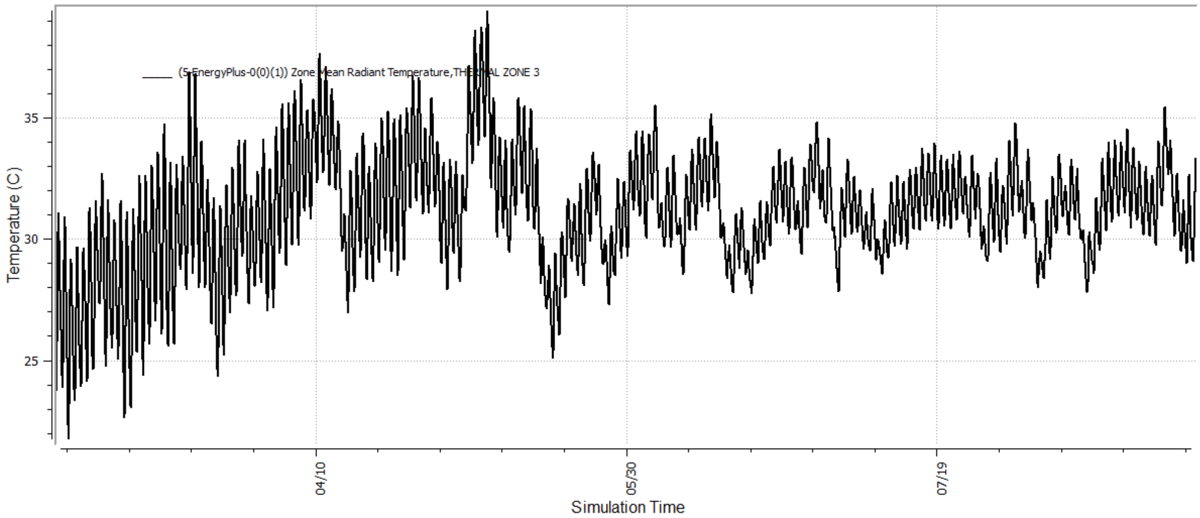


Figure C.22 Zone 3 Mean Radiant temperature from March to August: Wall Type WB10

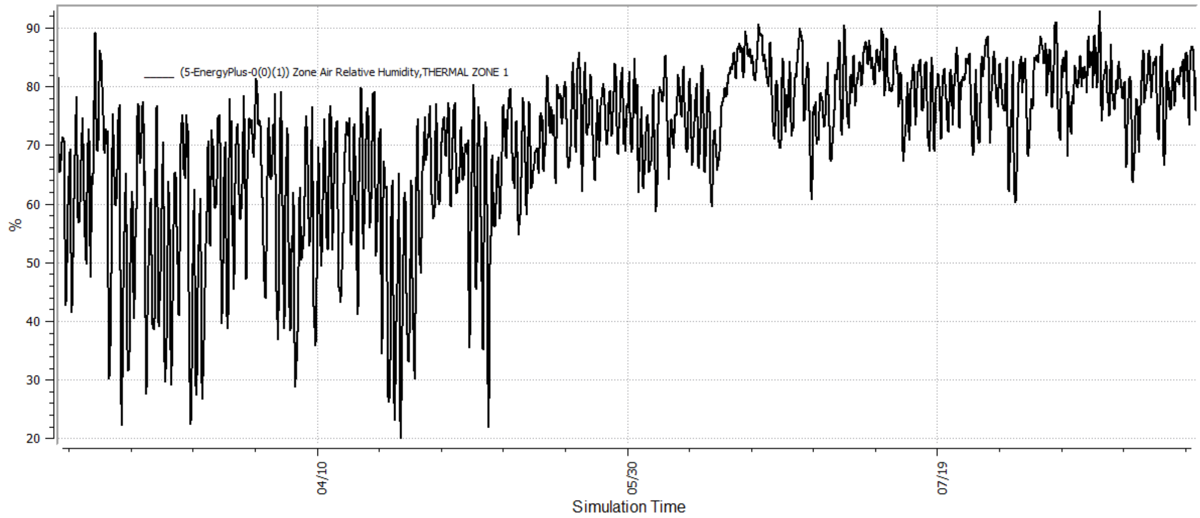


Figure C.23 Zone 1 Relative Humidity from March to August: Wall Type WB10

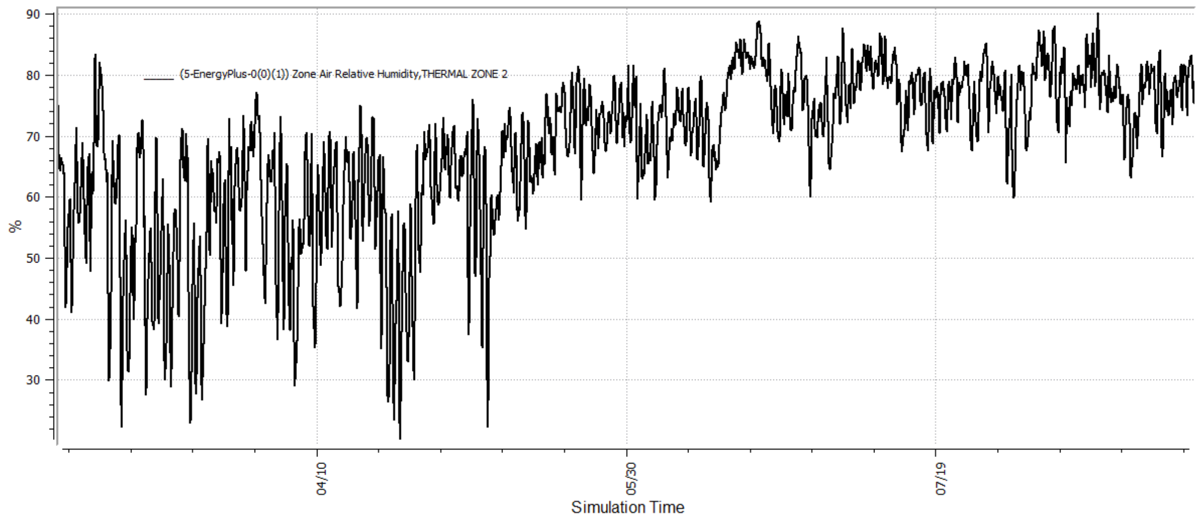


Figure C.24 Zone 2 Relative Humidity from March to August: Wall Type WB10

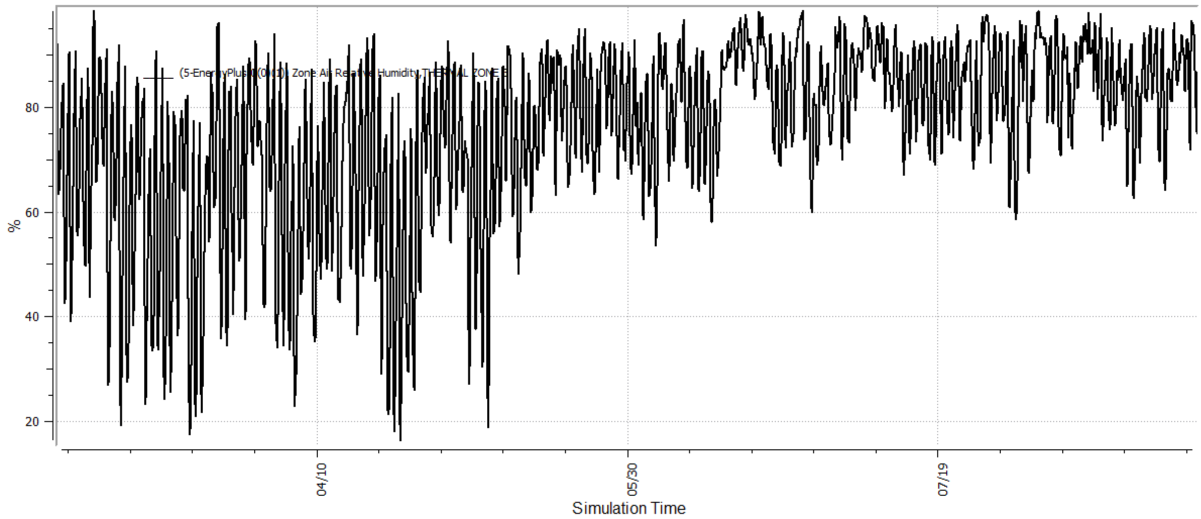


Figure C.25 Zone 3 Relative Humidity from March to August: Wall Type WB10

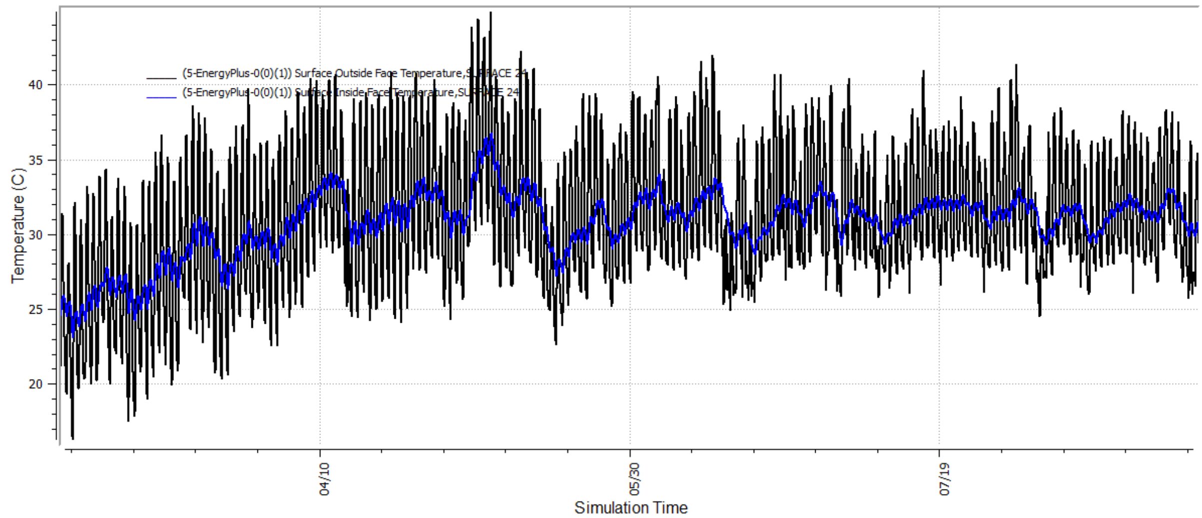


Figure C.26 Outside & inside surface temperature of North wall of inpatient room from March to August: Wall Type WB10

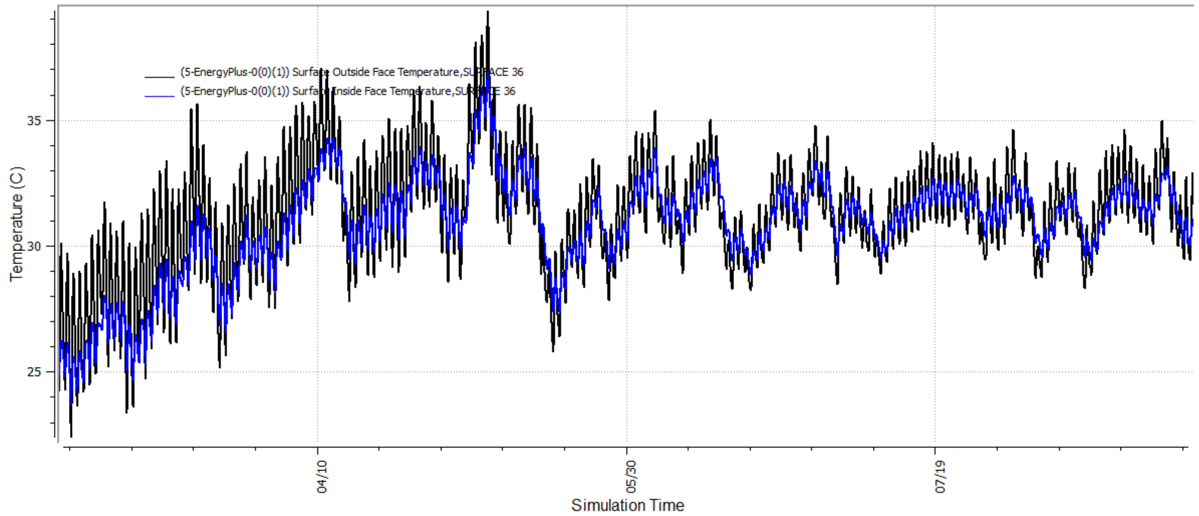


Figure C.27 Outside & inside surface temperature of South wall of inpatient room from March to August: Wall Type WB10

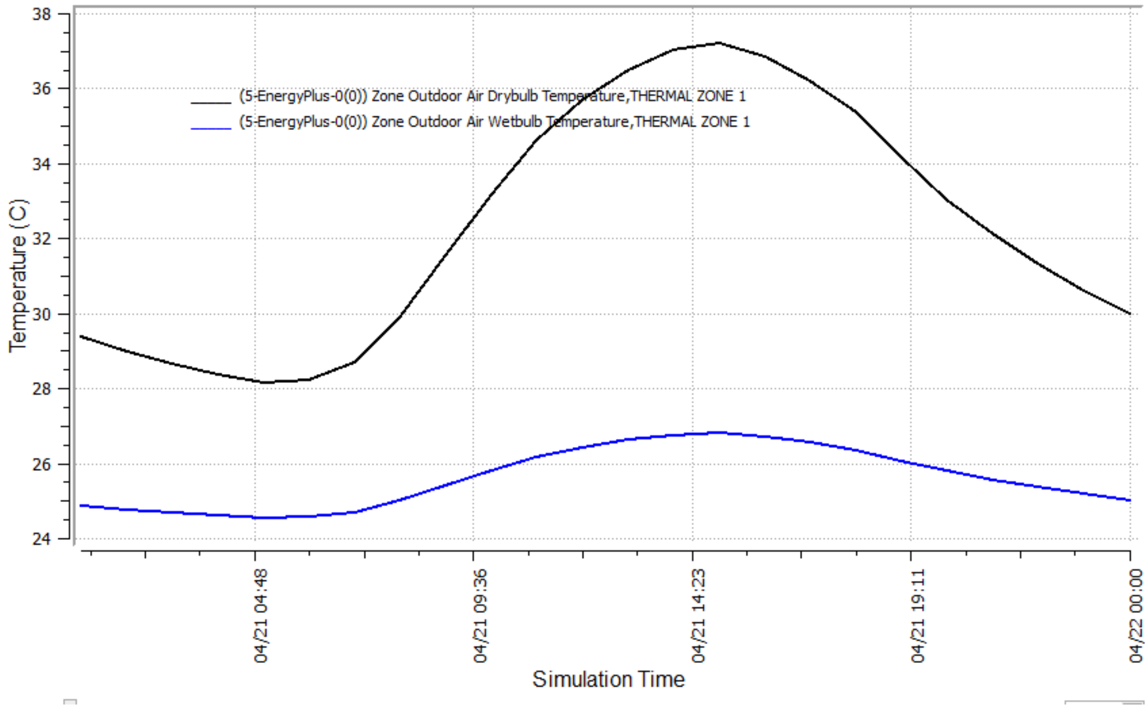


Figure C.28 Outdoor Air DBT and WBT for 1.0 percentile cooling condition: Wall Type WB05

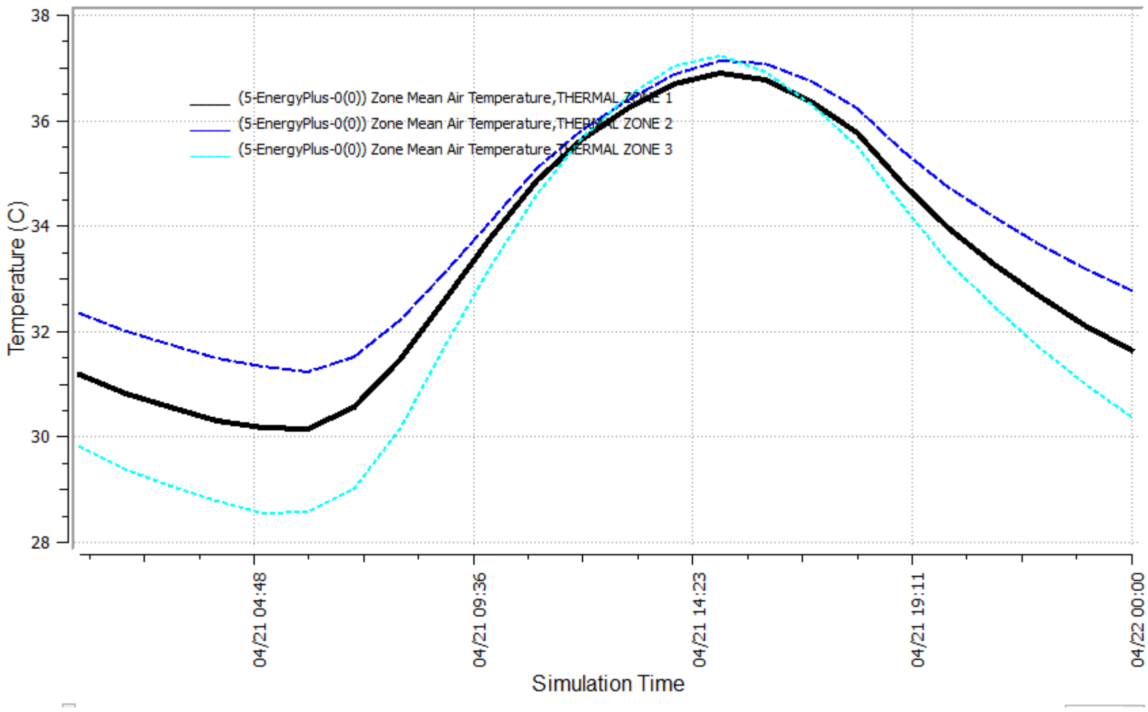


Figure C.29 Mean Air Temperature of zone 1, zone 2 and zone 3 for 1.0 percentile cooling condition: Wall Type WB05

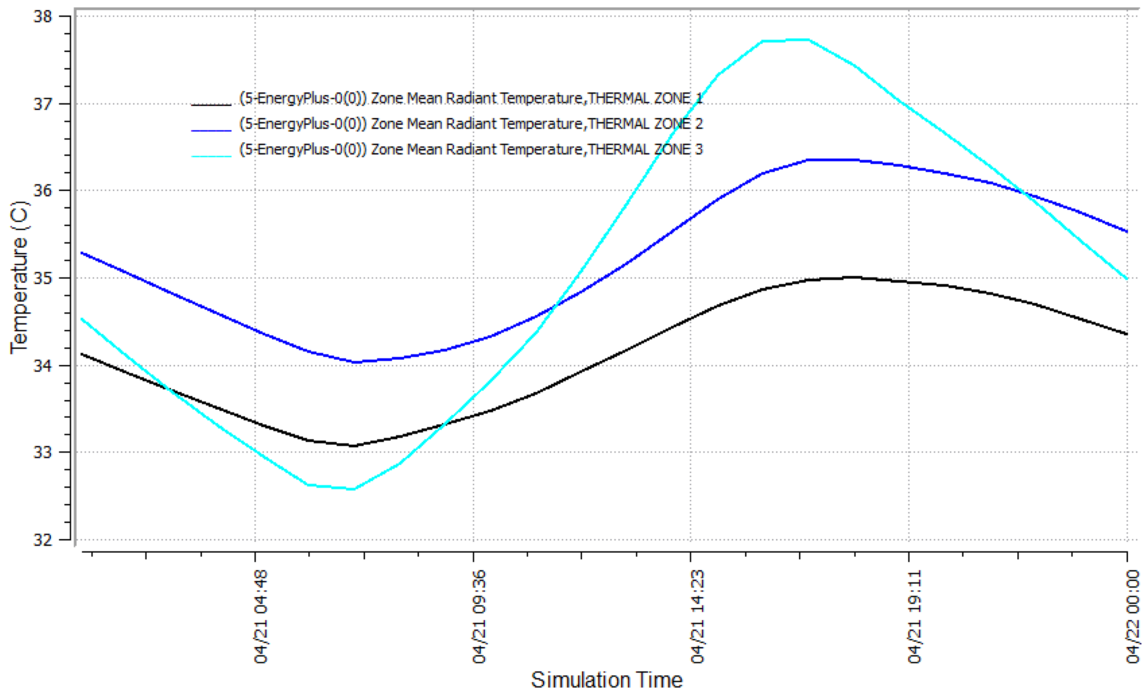


Figure C.30 Mean Radiant Temperature of zone 1, zone 2 and zone 3 for 1.0 percentile cooling condition: Wall Type WB05

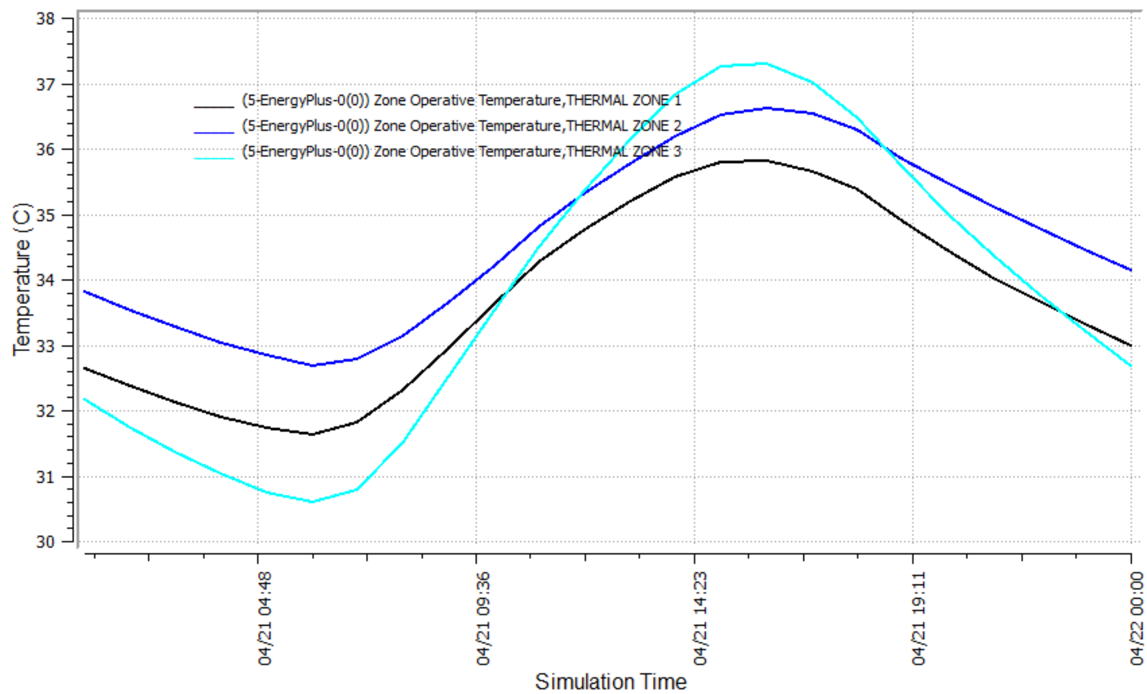


Figure C.31 Mean Operative Temperature of zone 1, zone 2 and zone 3 for 1.0 percentile cooling condition: Wall Type WB05

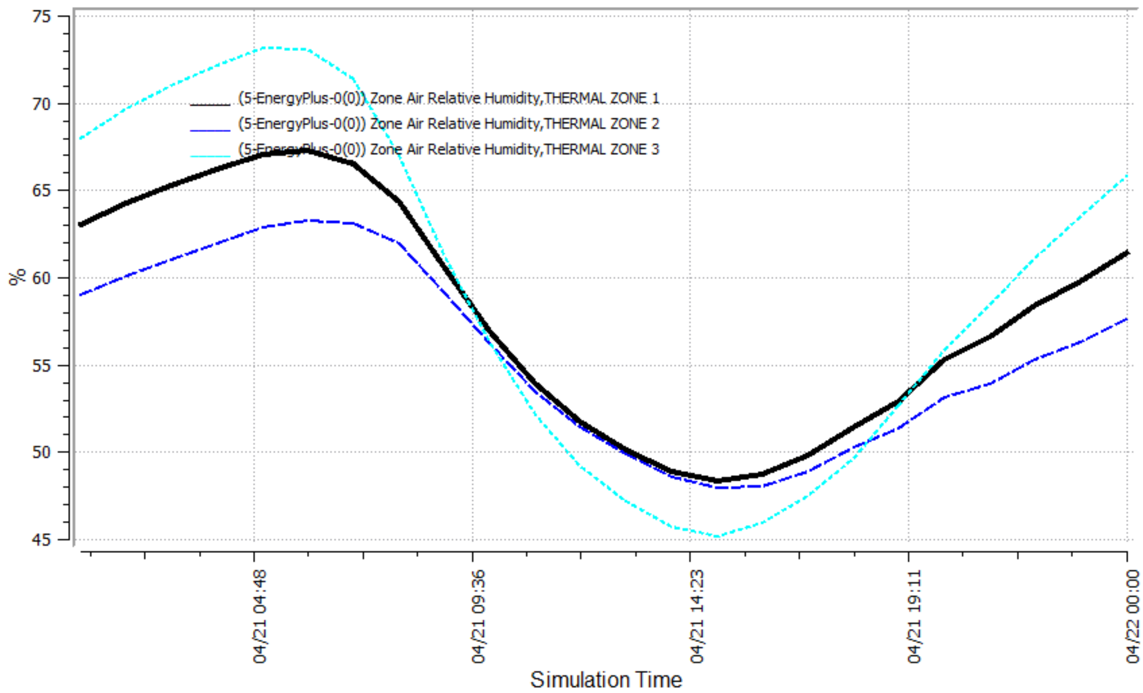


Figure C.32 Relative Humidity of zone 1, zone 2 and zone 3 for 1.0 percentile cooling condition: Wall Type WB05

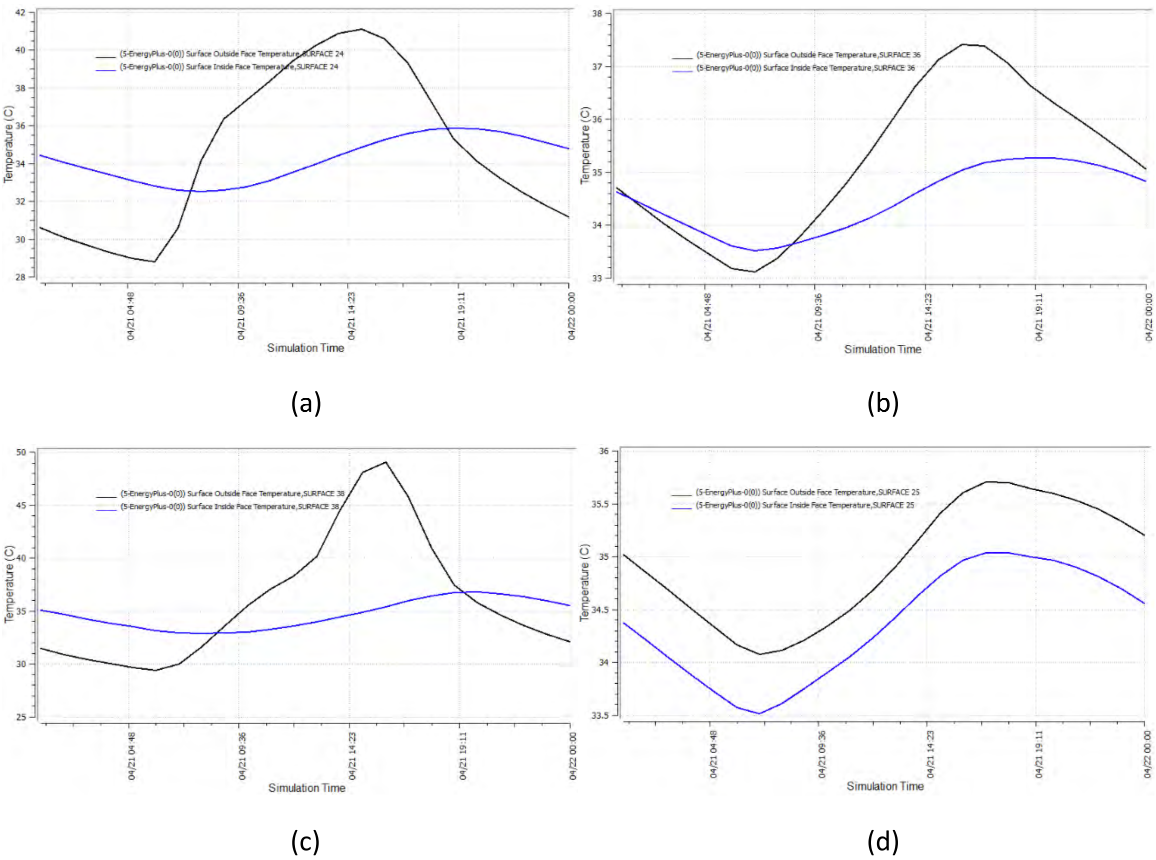


Figure C.33 Outside and inside surface temperature for 1.0 percentile cooling condition (a) North wall (b) South wall (c) West wall and (d) East wall: Wall Type WB05

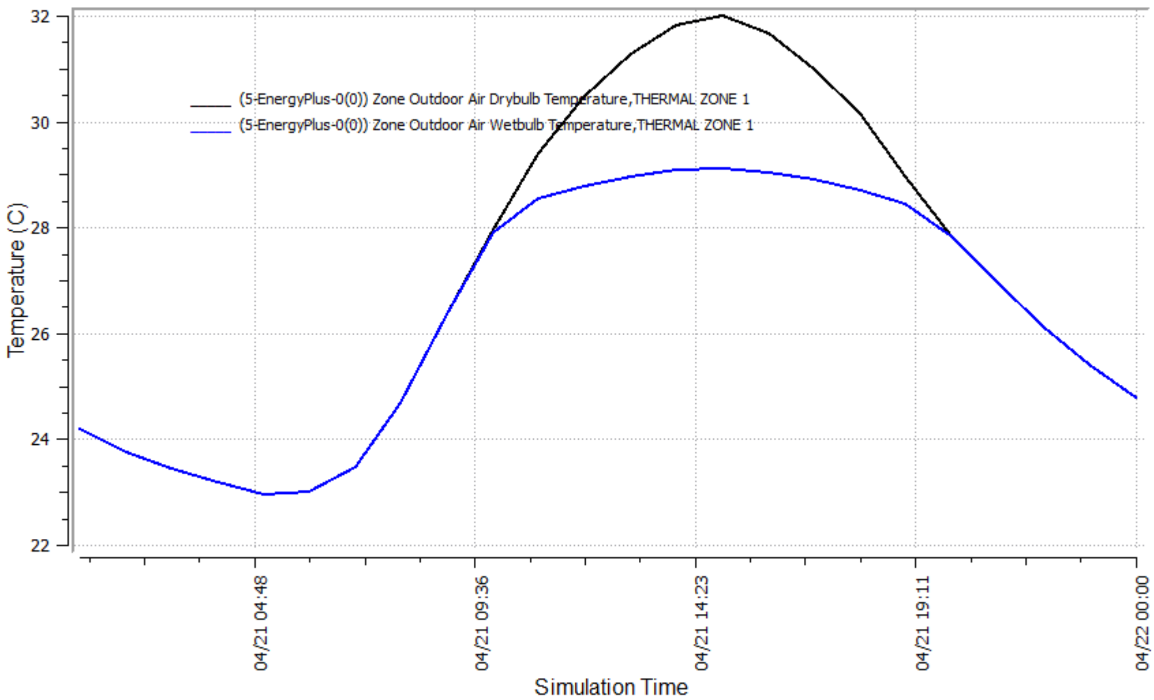


Figure C.34 Outdoor Air DBT and WBT for 1.0 percentile dehumidification condition: Wall Type WB05

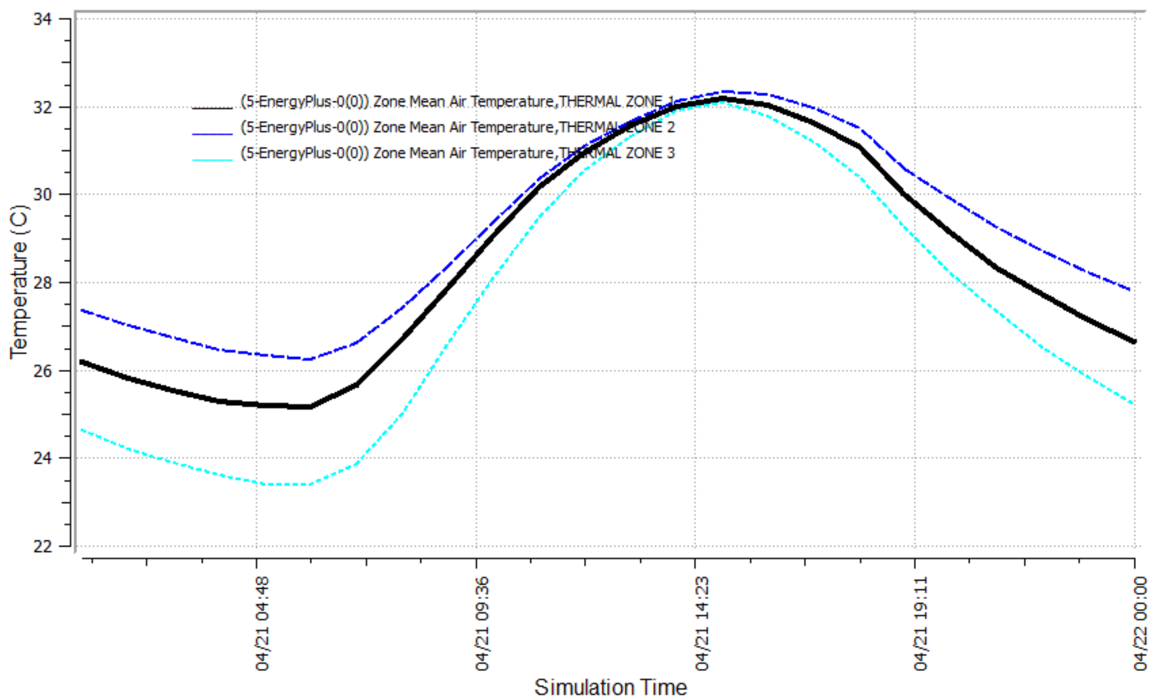


Figure C.35 Mean Air Temperature of zone 1, zone 2 and zone 3 for 1.0 percentile dehumidification condition: Wall Type WB05

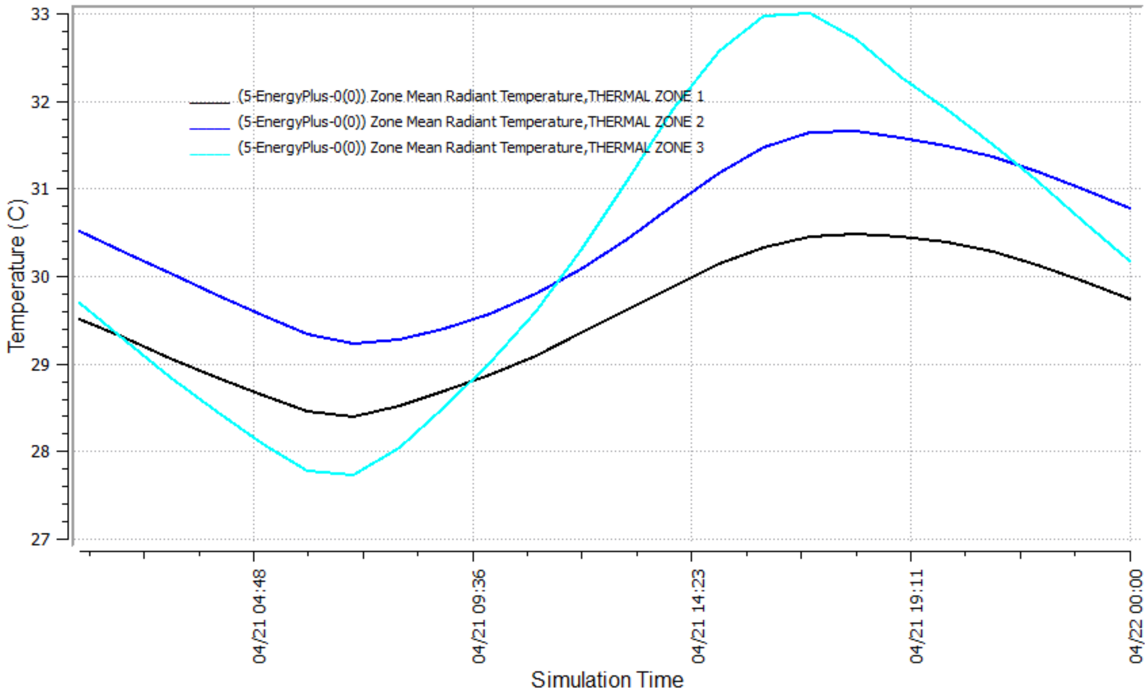


Figure C.36 Mean Radiant Temperature of zone 1, zone 2 and zone 3 for 1.0 percentile dehumidification condition: Wall Type WB05

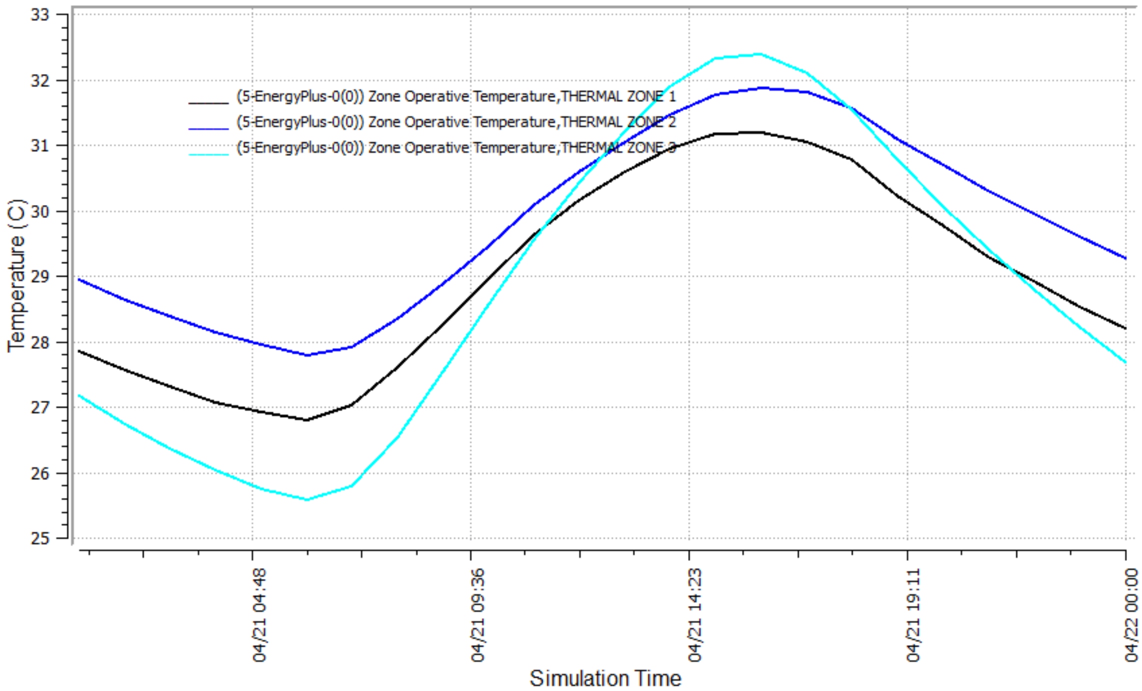


Figure C.37 Mean Operative Temperature of zone 1, zone 2 and zone 3 for 1.0 percentile dehumidification condition: Wall Type WB05

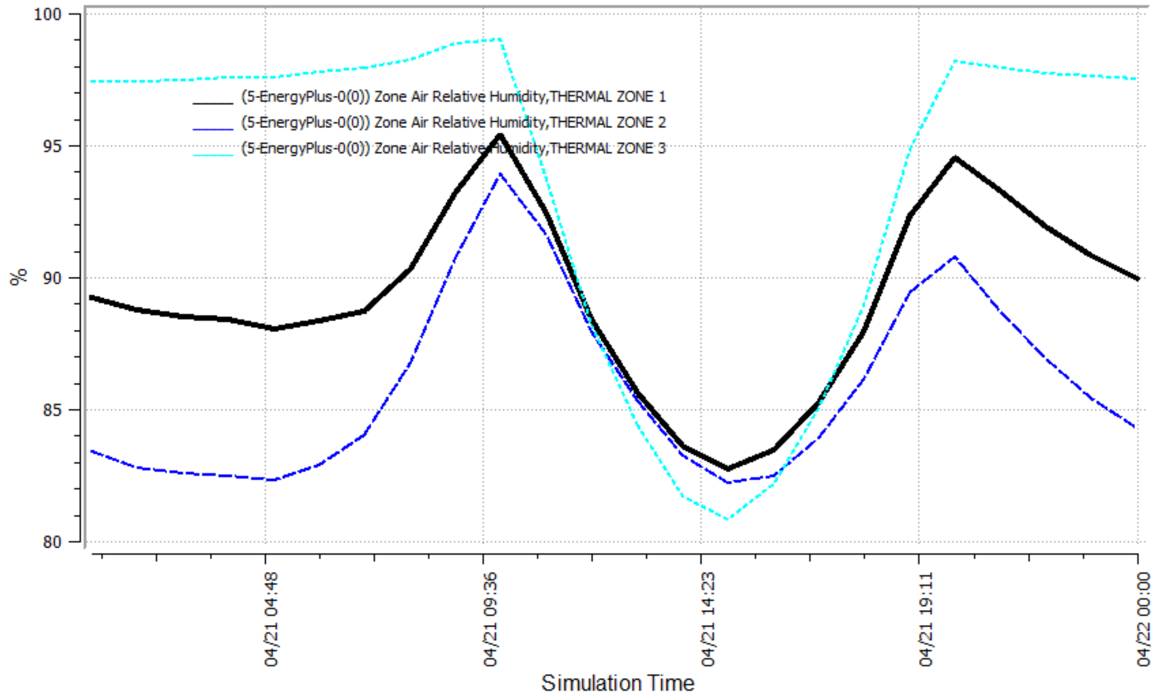
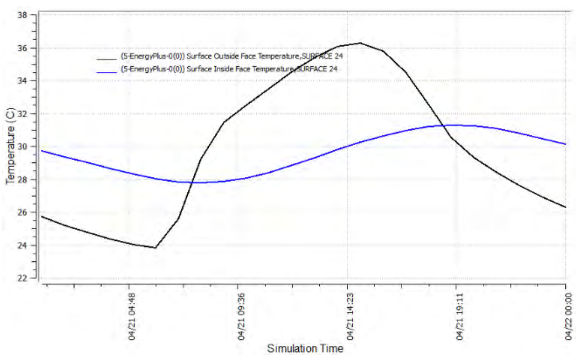


Figure C.38 Relative Humidity of zone 1, zone 2 and zone 3 for 1.0 percentile dehumidification condition: Wall Type WB05



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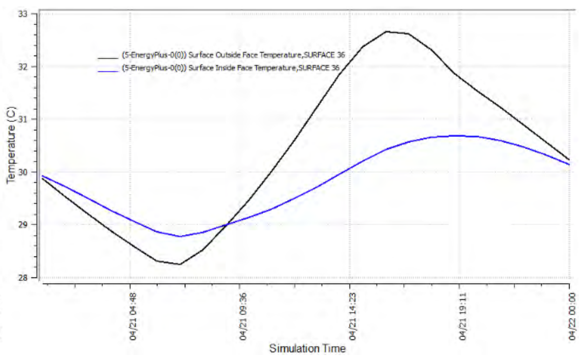

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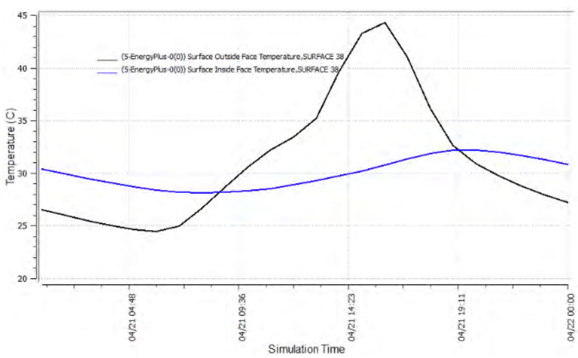

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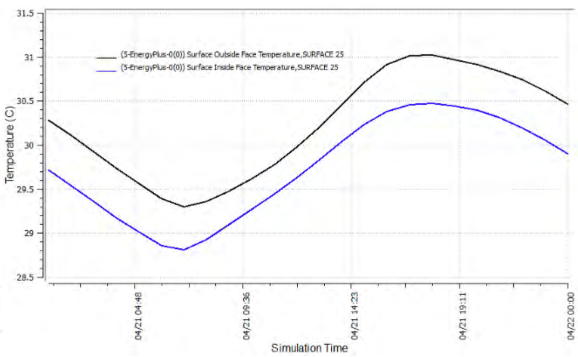


(d)

Figure C.39 Outside and inside surface temperature for 1.0 percentile dehumidification condition (a) North wall (b) South wall (c) West wall and (d) East wall: Wall Type WB05

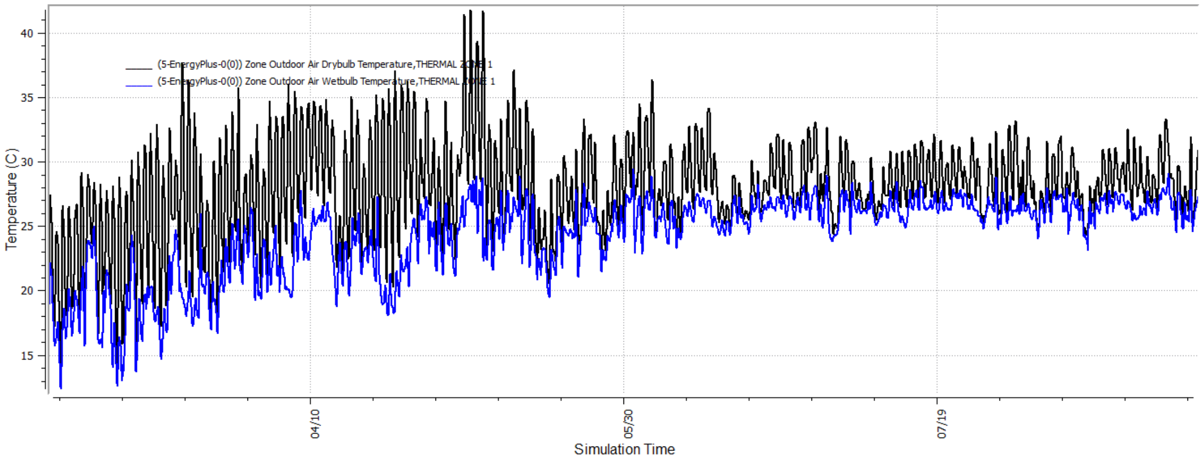


Figure C.40 Outdoor DBT and WBT from March to August: Wall Type WB05

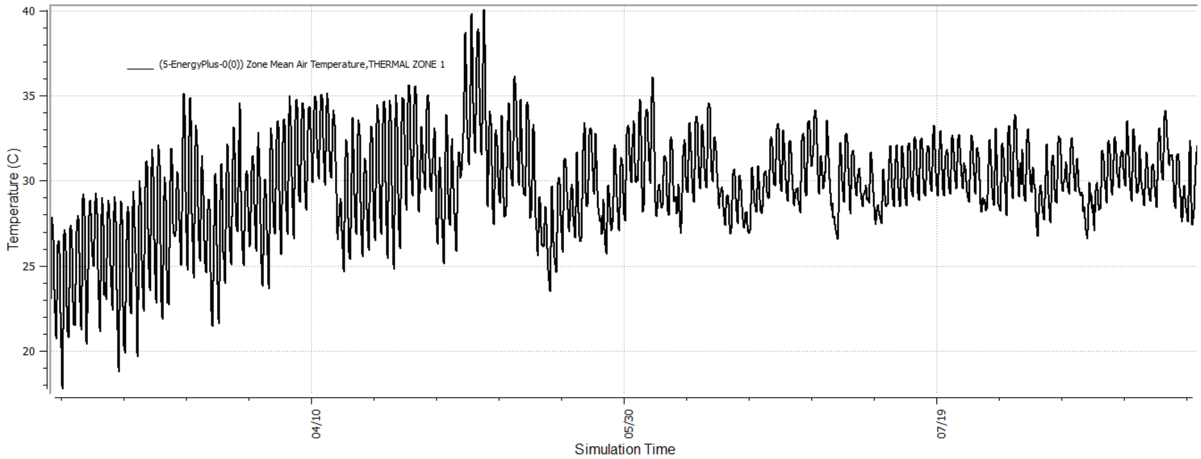


Figure C.41 Zone 1 Mean air temperature from March to August: Wall Type WB05

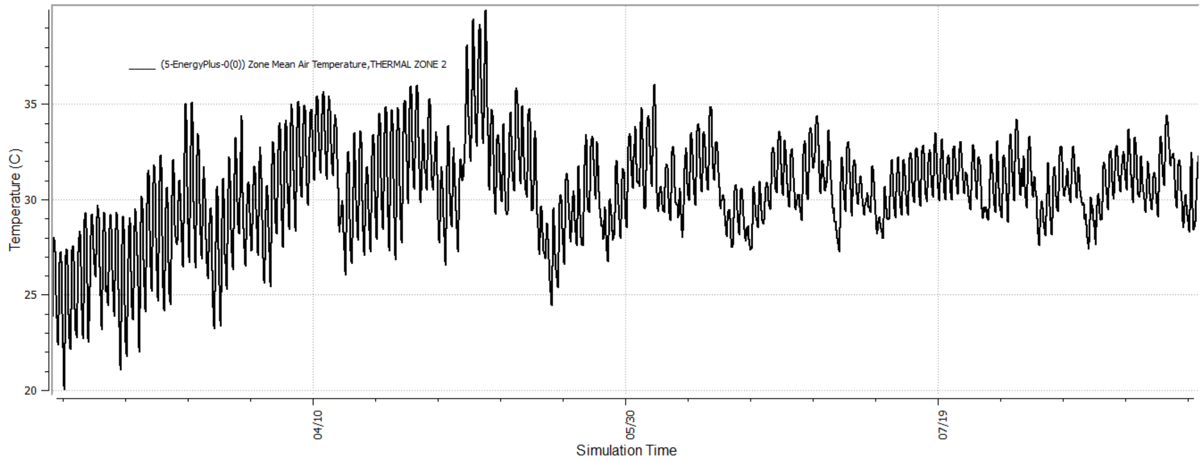


Figure C.42 Zone 2 Mean air temperature from March to August: Wall Type WB05

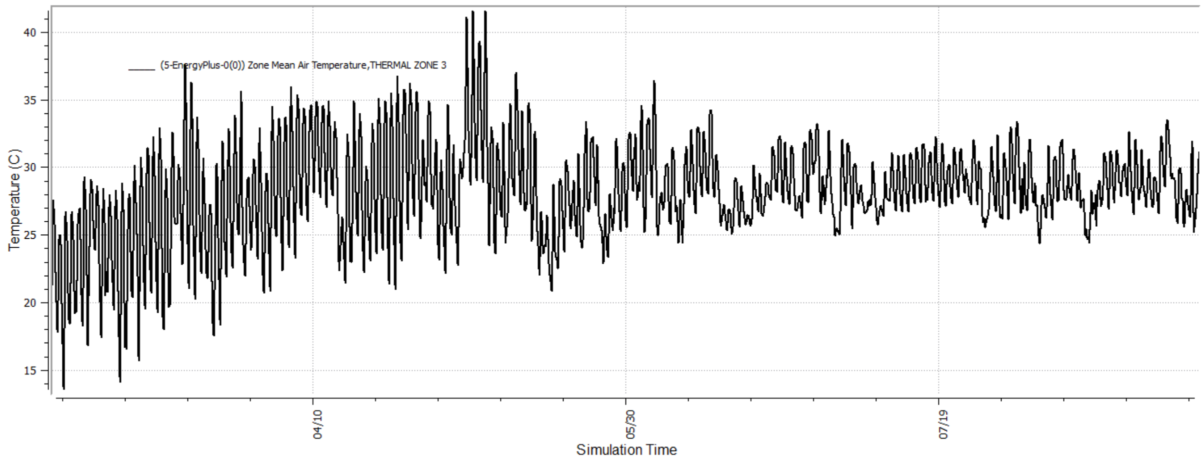


Figure C.43 Zone 3 Mean air temperature from March to August: Wall Type WB05

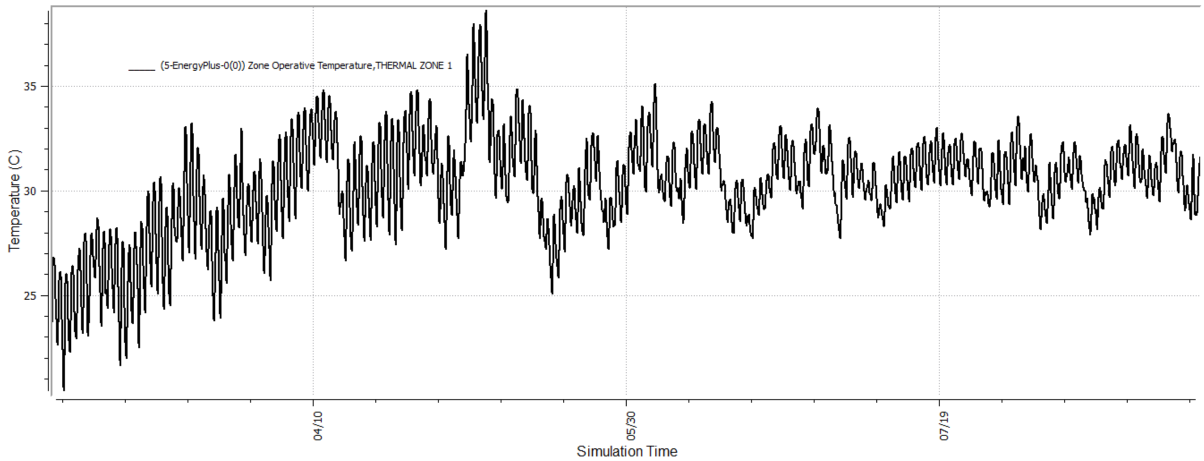


Figure C.44 Zone 1 Operative temperature from March to August: Wall Type WB05

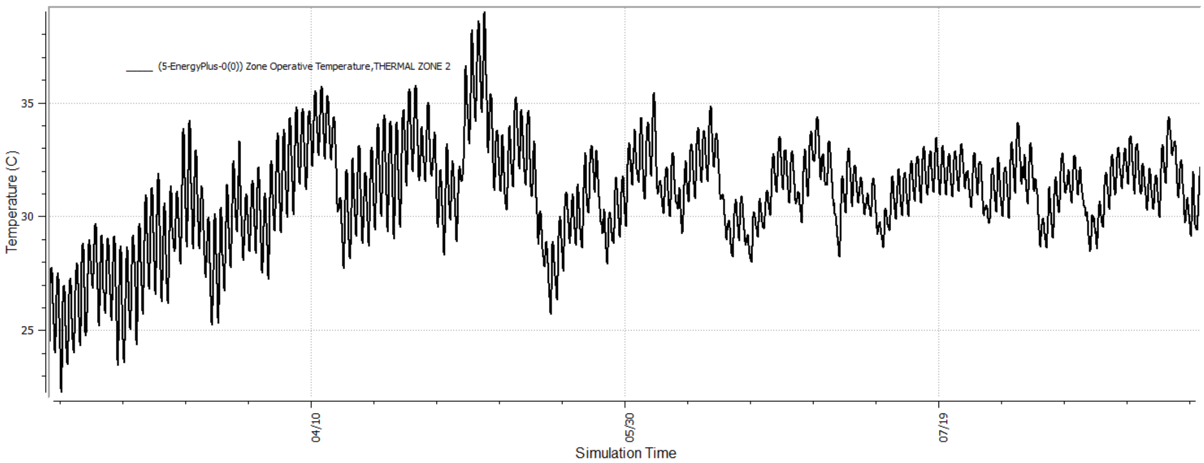


Figure C.45 Zone 2 Operative temperature from March to August: Wall Type WB05

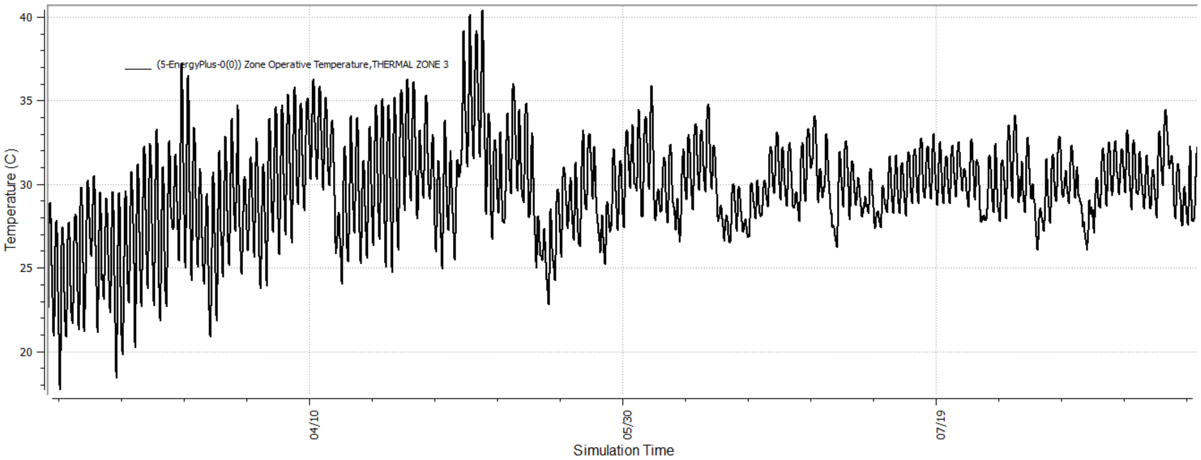


Figure C.46 Zone 3 Operative temperature from March to August: Wall Type WB05

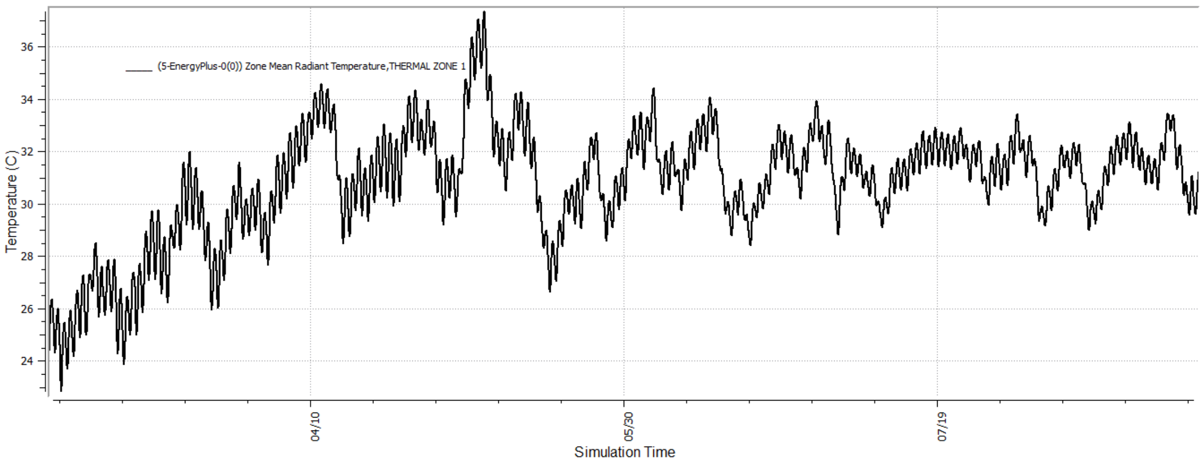


Figure C.47 Zone 1 Mean Radiant temperature from March to August: Wall Type WB05

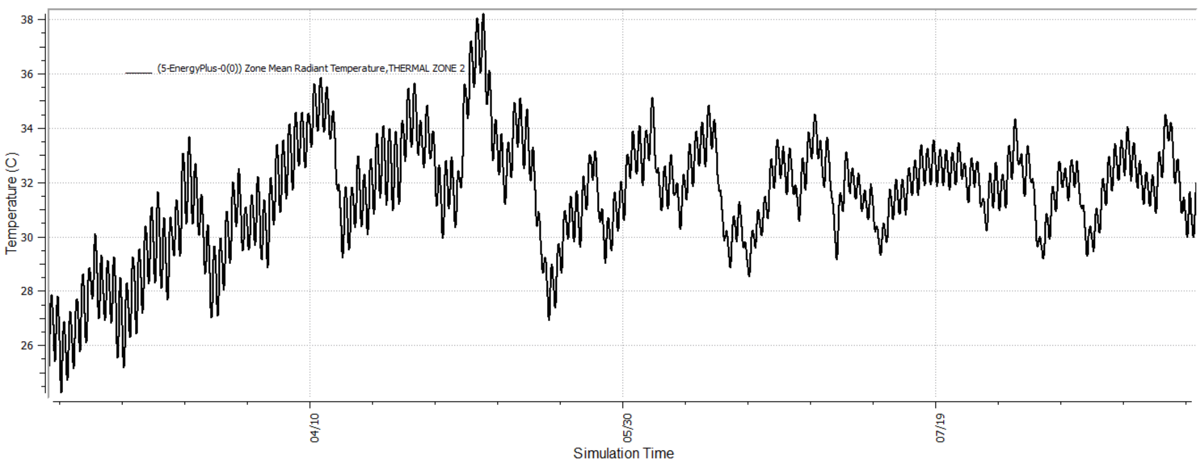


Figure C.48 Zone 2 Mean Radiant temperature from March to August: Wall Type WB05

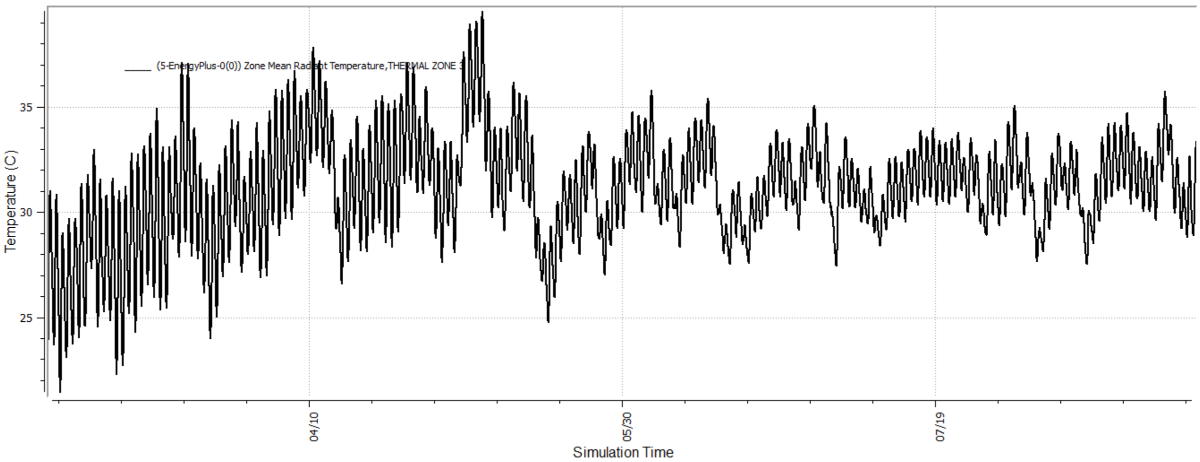


Figure C.49 Zone 3 Mean Radiant temperature from March to August: Wall Type WB05

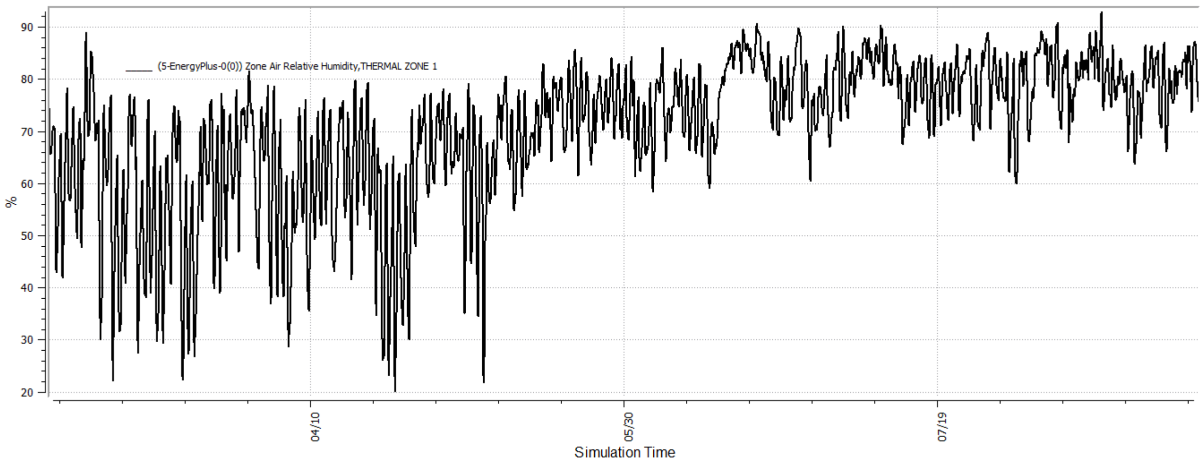


Figure C.50 Zone 1 Relative Humidity from March to August: Wall Type WB05

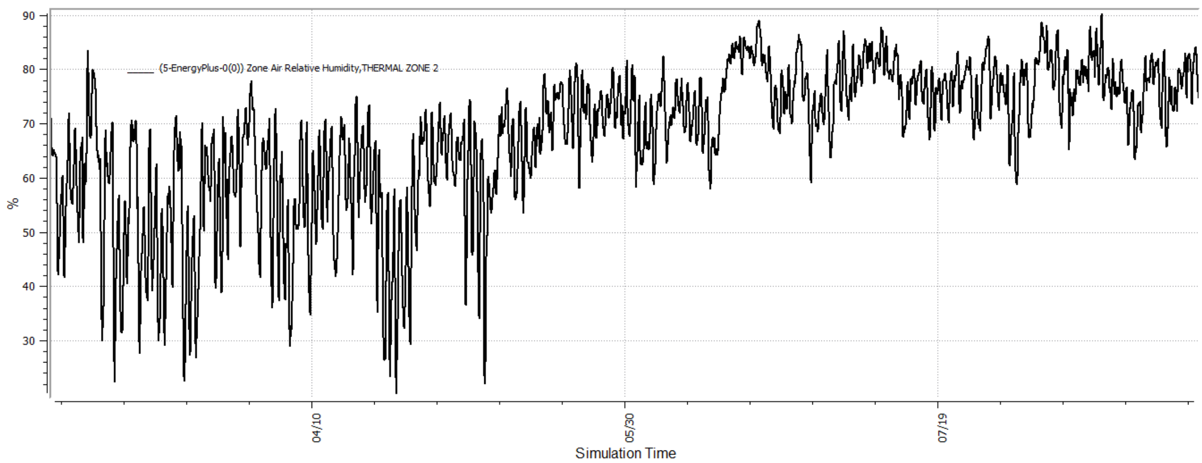


Figure C.51 Zone 2 Relative Humidity from March to August: Wall Type WB05

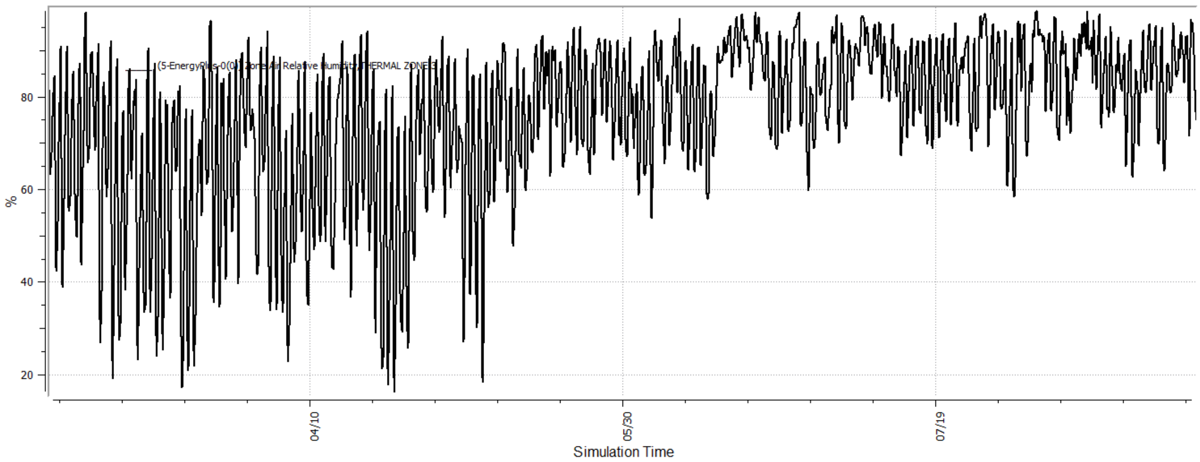


Figure C.52 Zone 3 Relative Humidity from March to August: Wall Type WB05

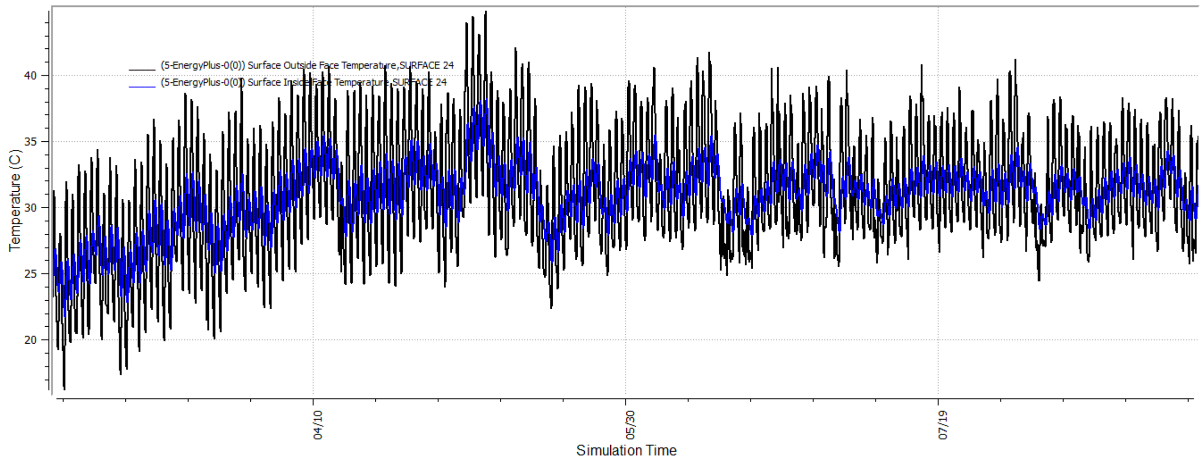


Figure C.53 Outside & inside surface temperature of North wall of inpatient room from March to August: Wall Type WB05

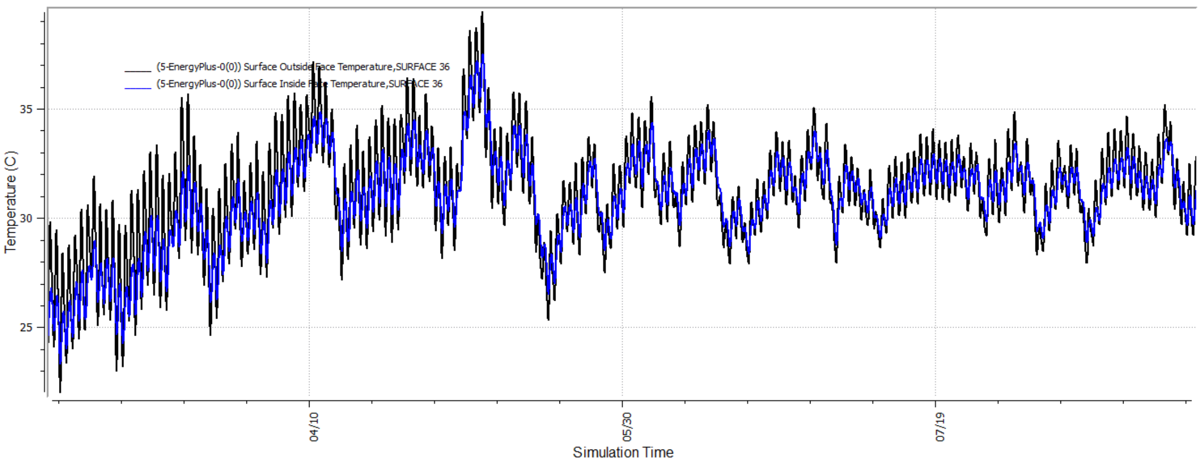


Figure C.54 Outside & inside surface temperature of South wall of inpatient room from March to August: Wall Type WB05

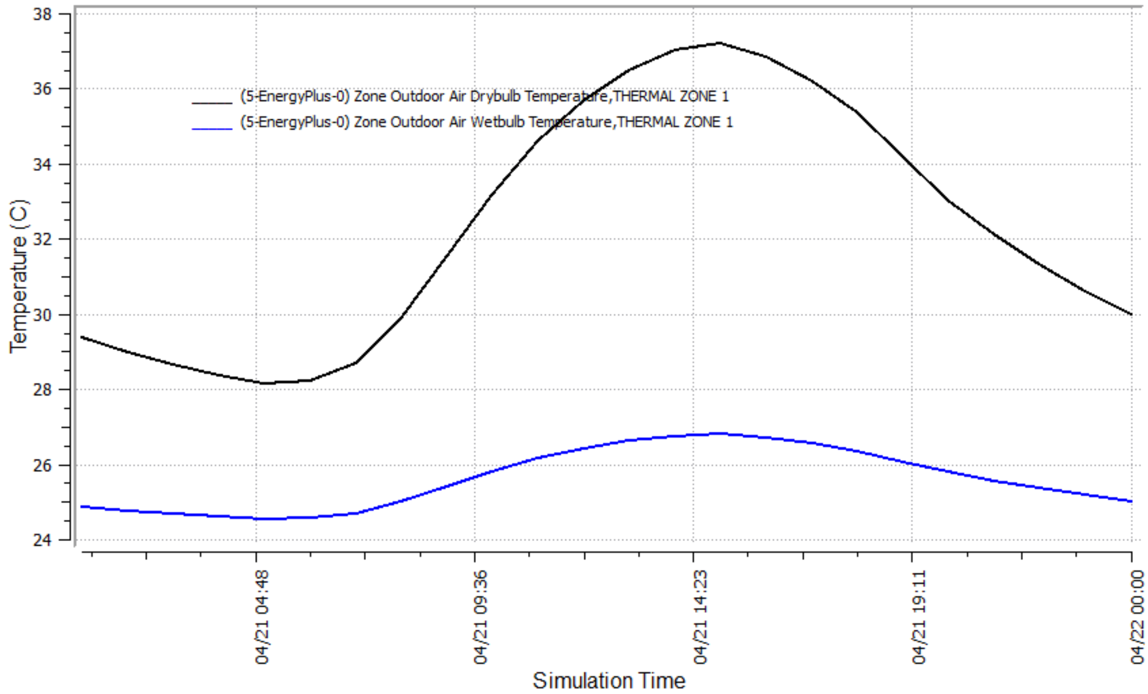


Figure C.55 Outdoor Air DBT and WBT for 1.0 percentile cooling condition: Wall Type WB11

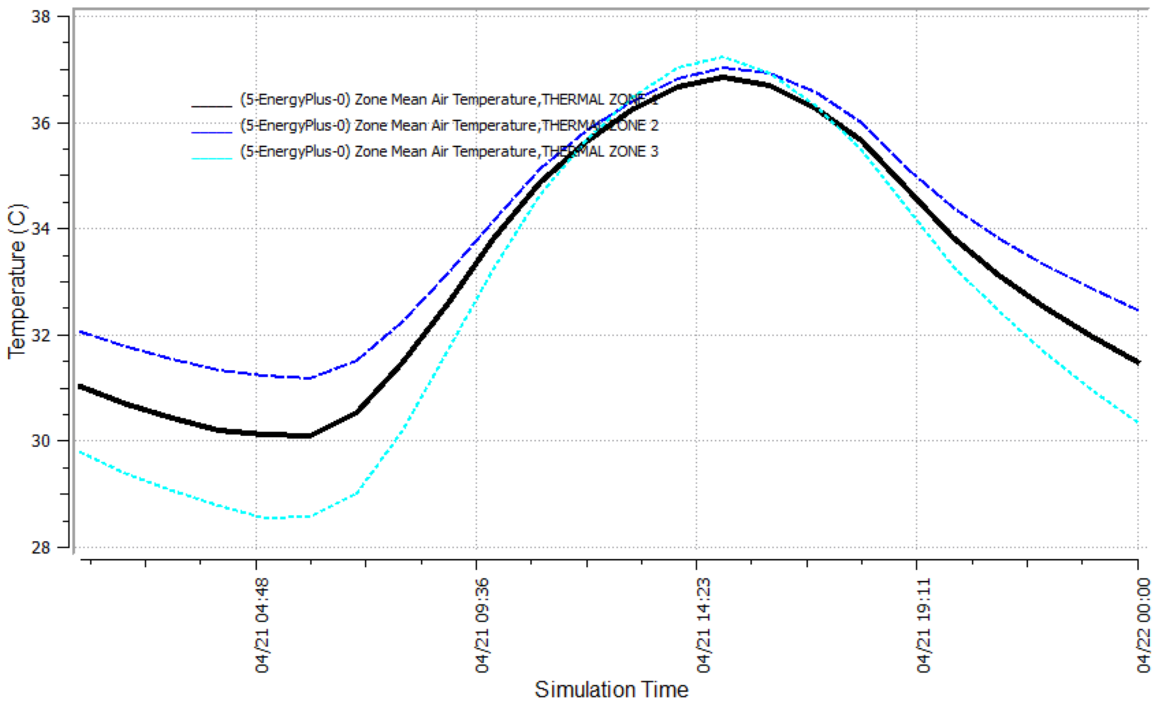


Figure C.56 Mean Air Temperature of zone 1, zone 2 and zone 3 for 1.0 percentile cooling condition: Wall Type WB11

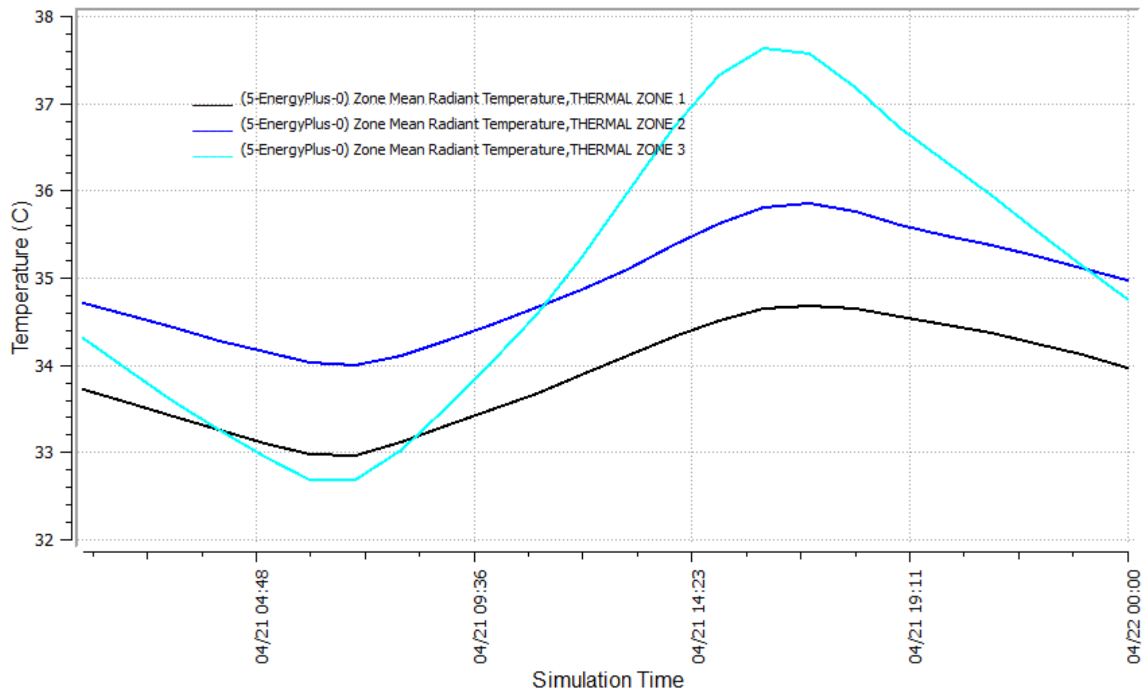


Figure C.57 Mean Radiant Temperature of zone 1, zone 2 and zone 3 for 1.0 percentile cooling condition: Wall Type WB11

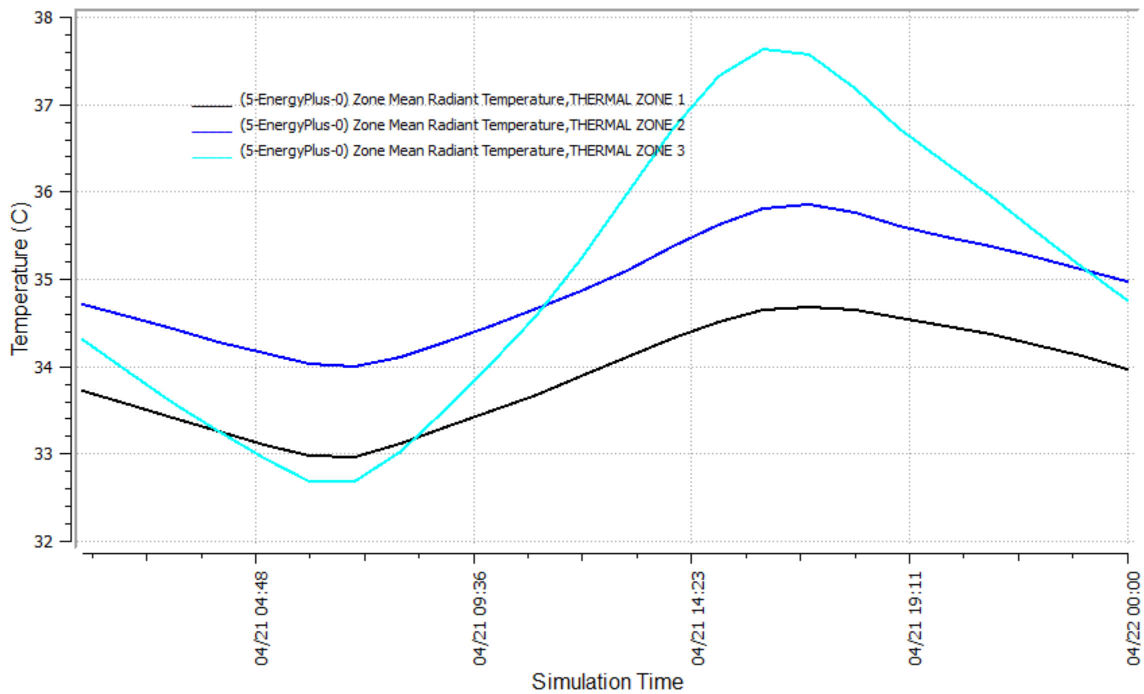


Figure C.58 Mean Operative Temperature of zone 1, zone 2 and zone 3 for 1.0 percentile cooling condition: Wall Type WB11

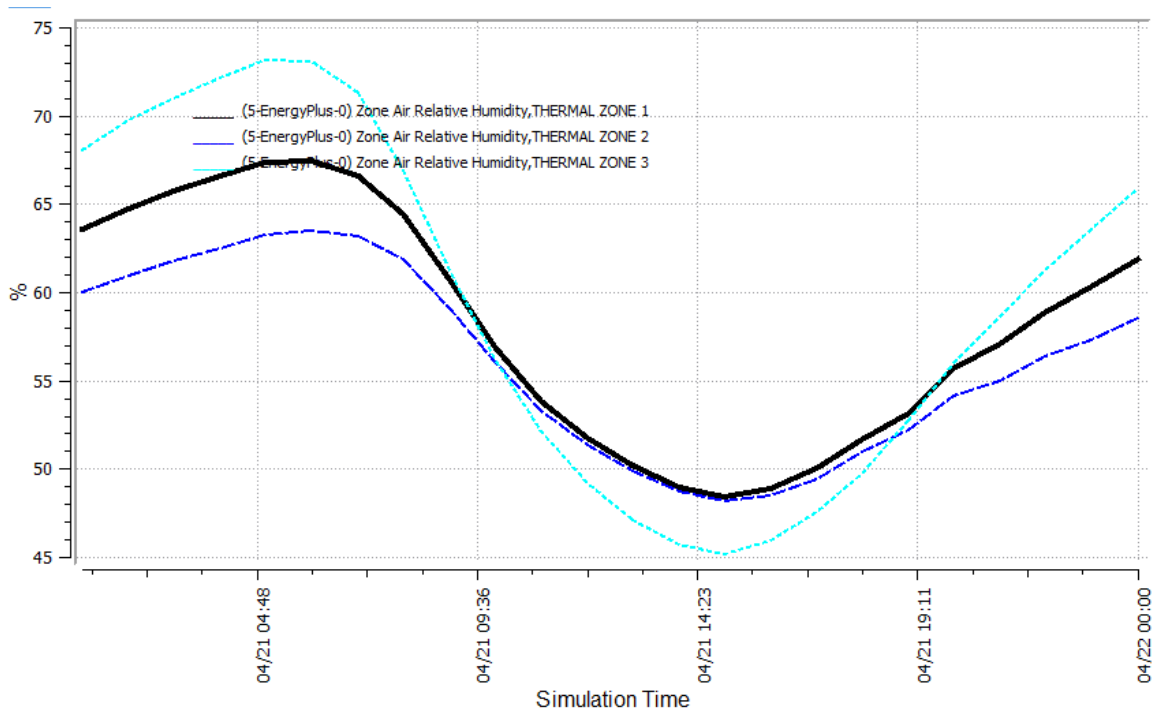
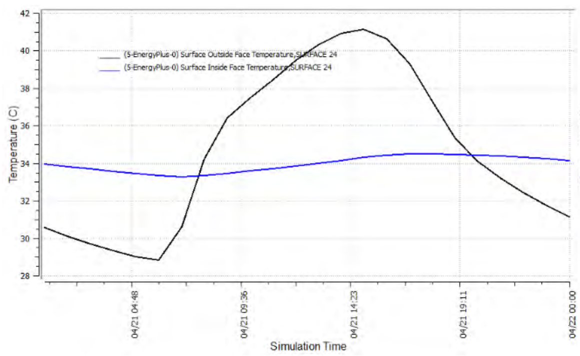


Figure C.59 Relative Humidity of zone 1, zone 2 and zone 3 for 1.0 percentile cooling condition: Wall Type WB11



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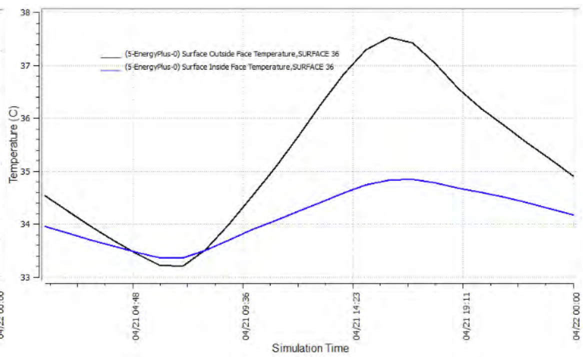

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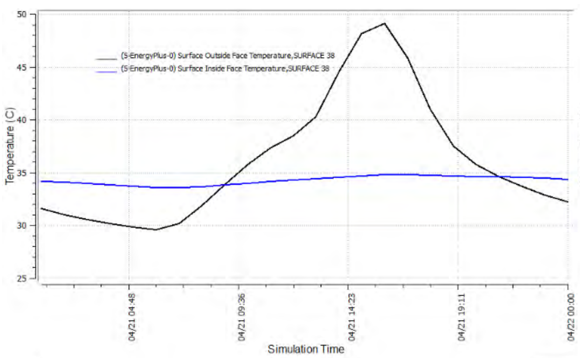

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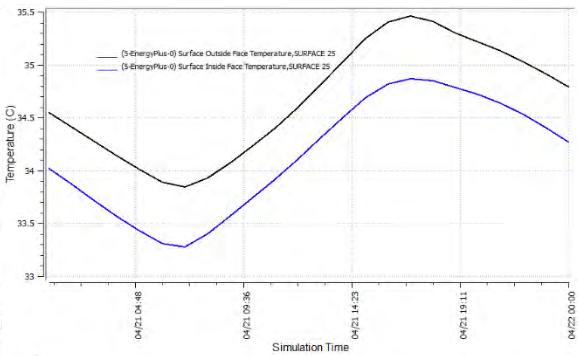


(d)

Figure C.60 Outside and inside surface temperature for 1.0 percentile cooling condition (a) North wall (b) South wall (c) West wall and (d) East wall: Wall Type WB11

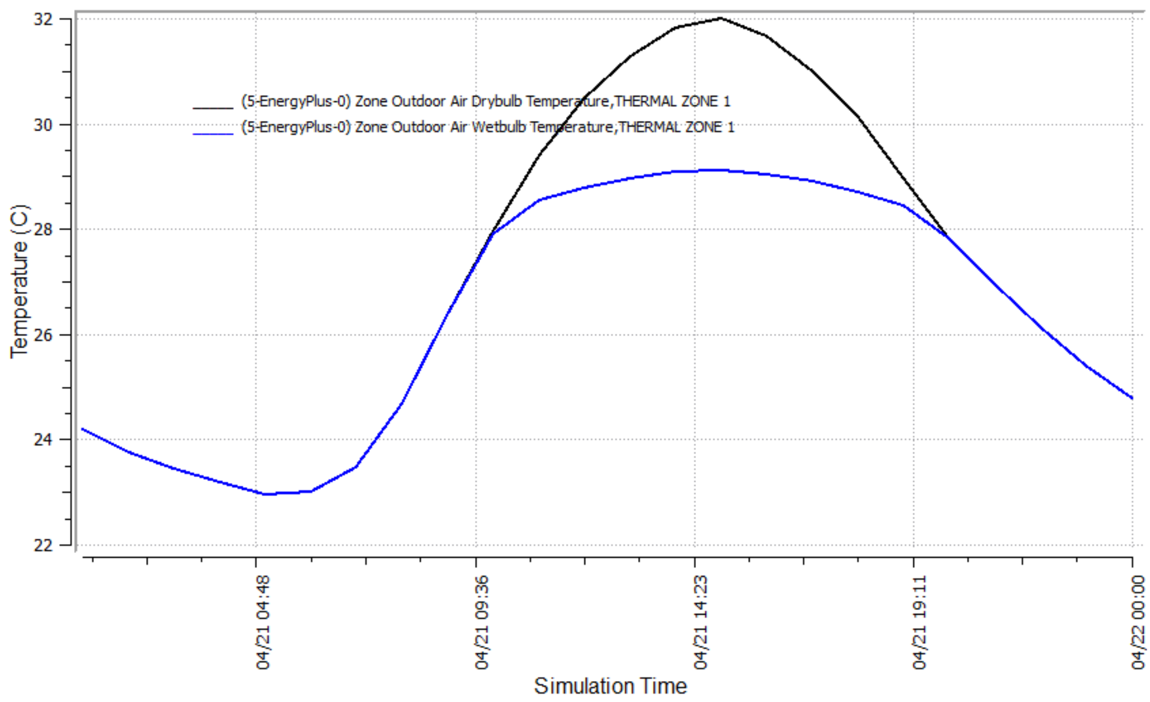


Figure C.61 Outdoor Air DBT and WBT for 1.0 percentile dehumidification condition: Wall Type WB11

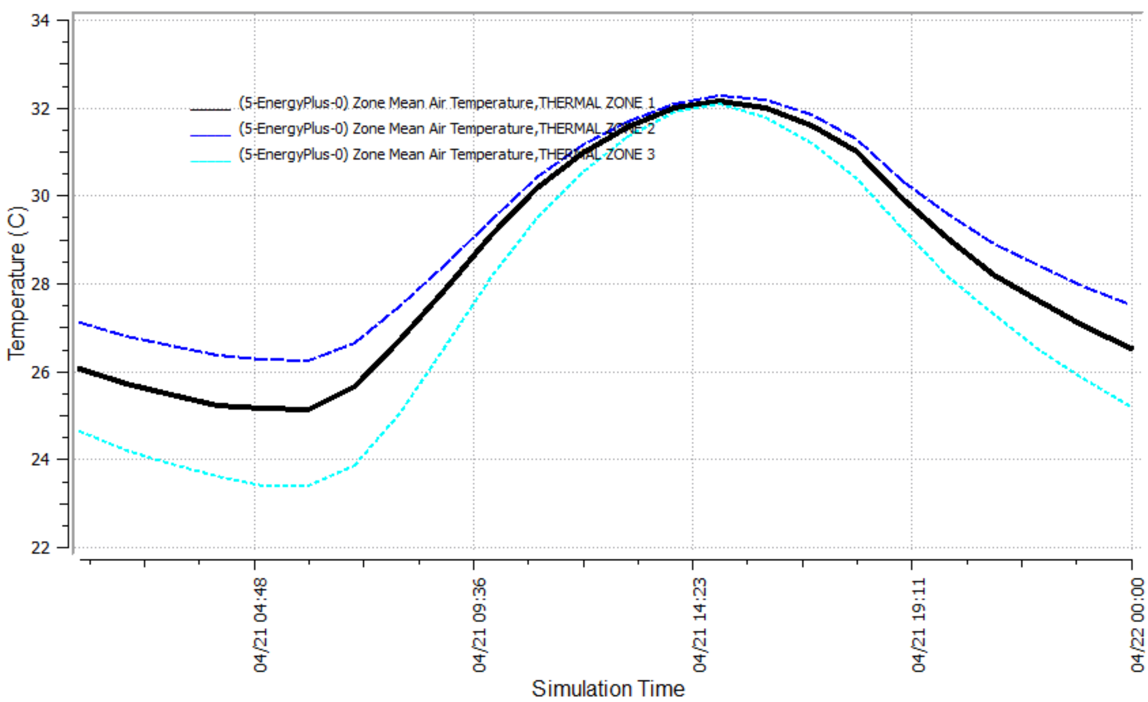


Figure C.62 Mean Air Temperature of zone 1, zone 2 and zone 3 for 1.0 percentile dehumidification condition: Wall Type WB11

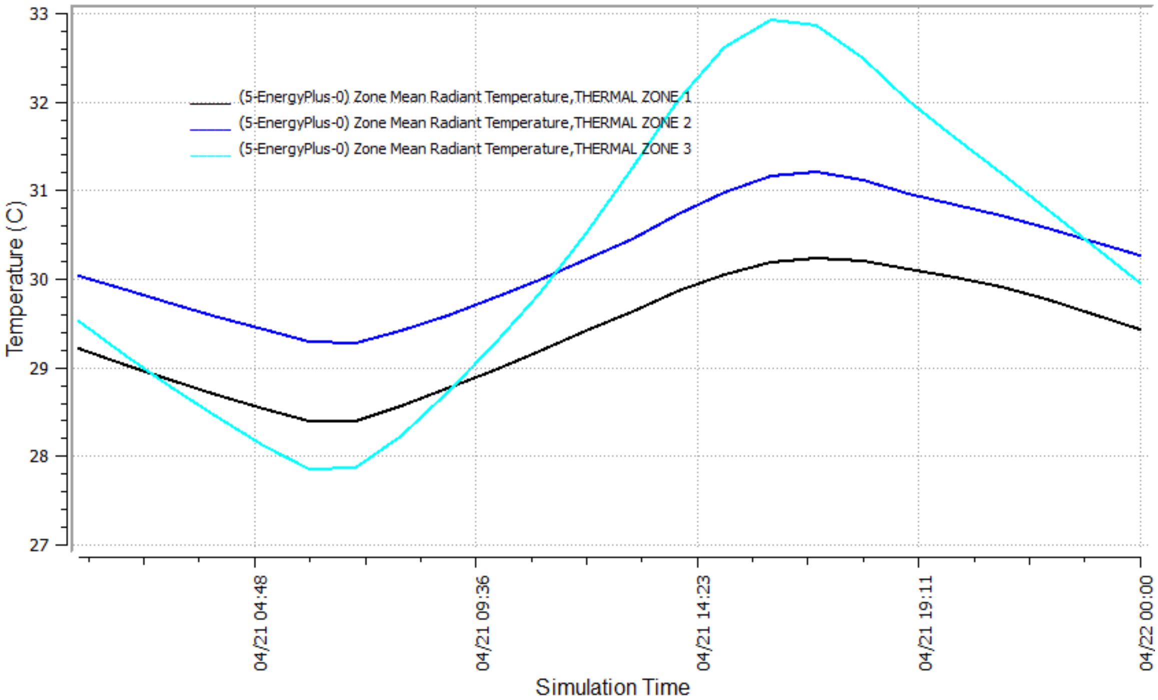


Figure C.63 Mean Radiant Temperature of zone 1, zone 2 and zone 3 for 1.0 percentile dehumidification condition: Wall Type WB11

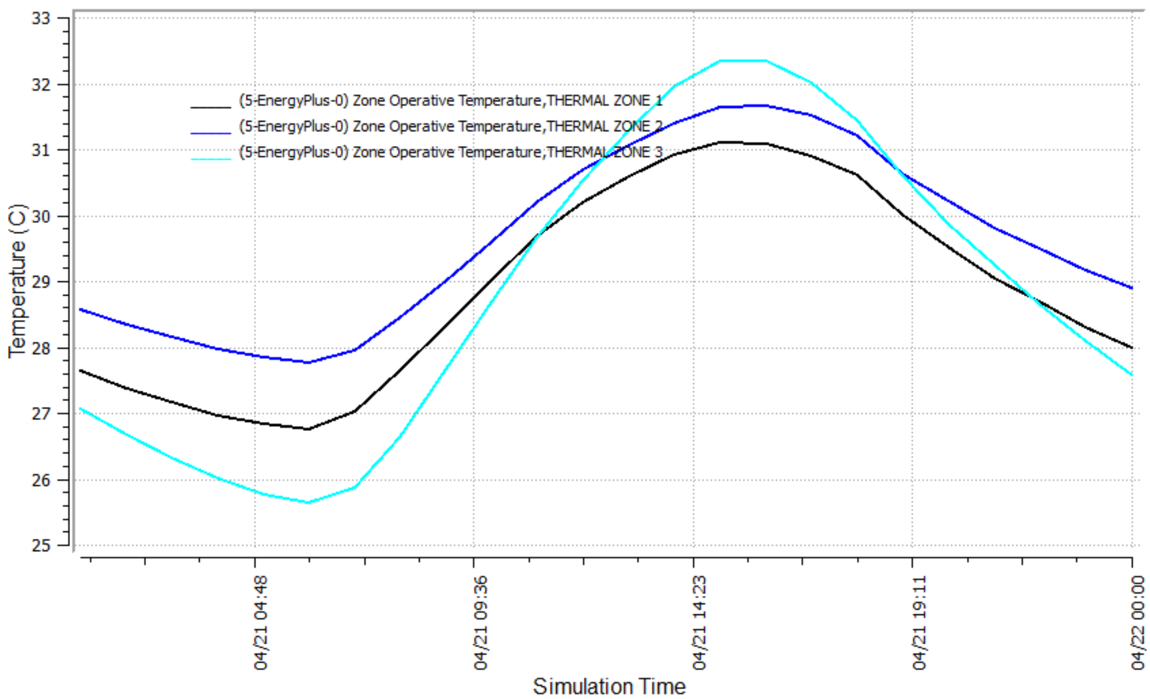


Figure C.64 Mean Operative Temperature of zone 1, zone 2 and zone 3 for 1.0 percentile dehumidification condition: Wall Type WB11

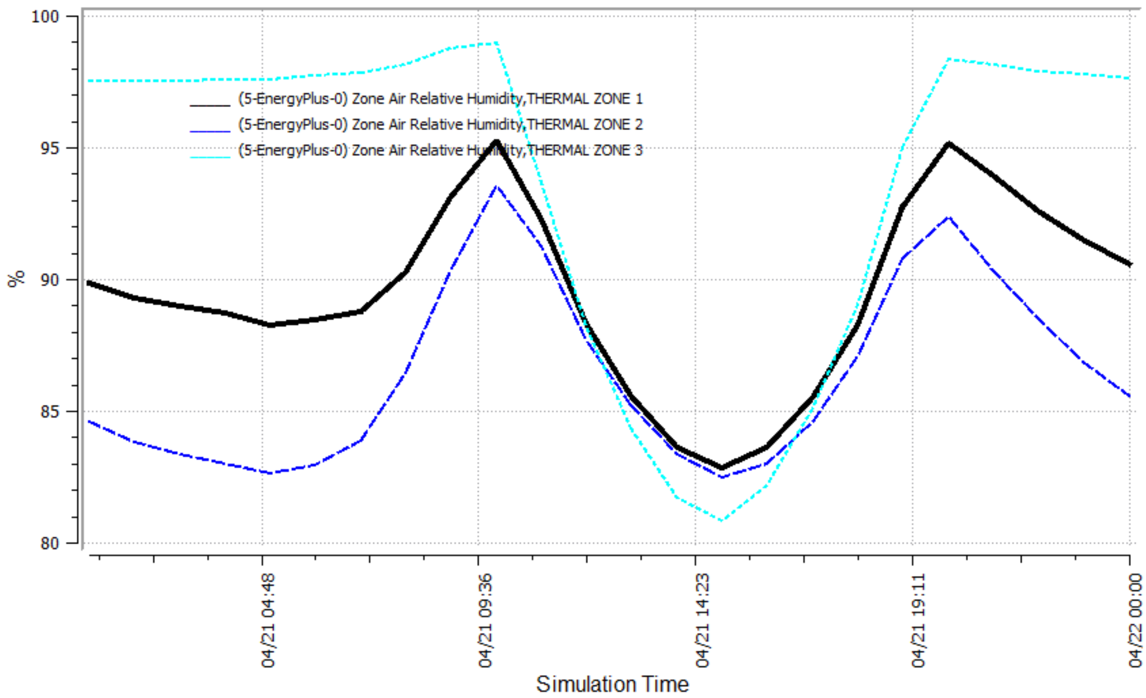
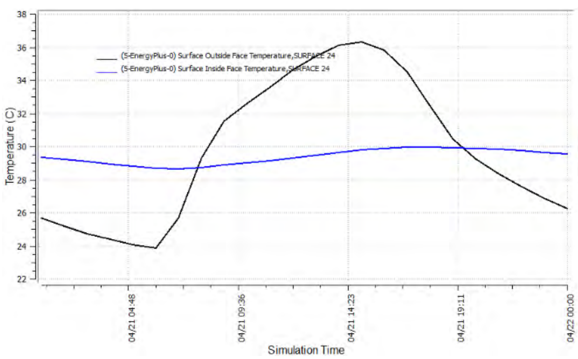


Figure C.65 Relative Humidity of zone 1, zone 2 and zone 3 for 1.0 percentile dehumidification condition: Wall Type WB11



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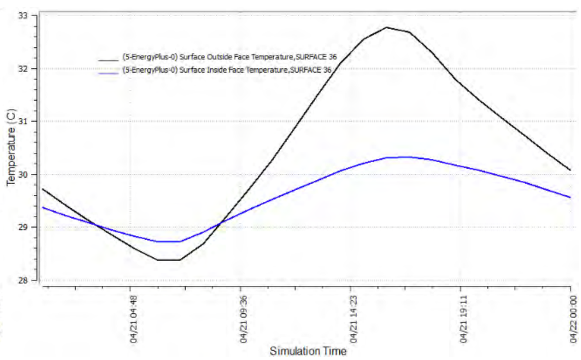

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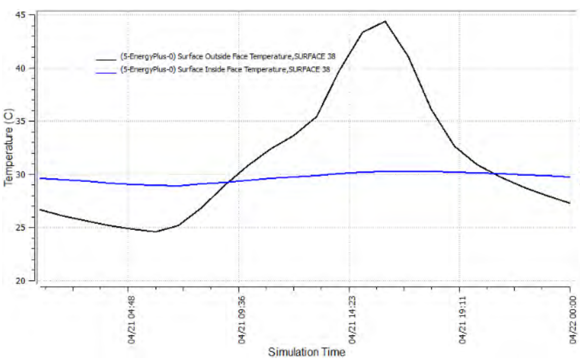

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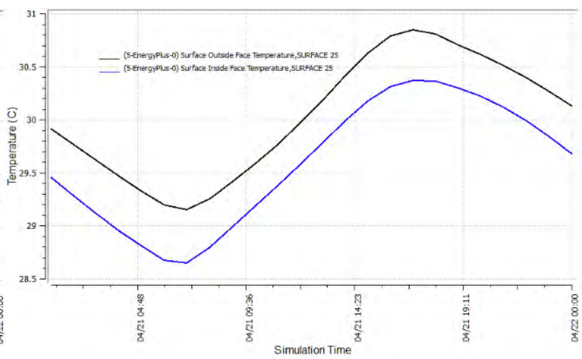


(d)

Figure C.66 Outside and inside surface temperature for 1.0 percentile dehumidification condition (a)North wall (b) South wall (c) West wall and (d) East wall: Wall Type WB11

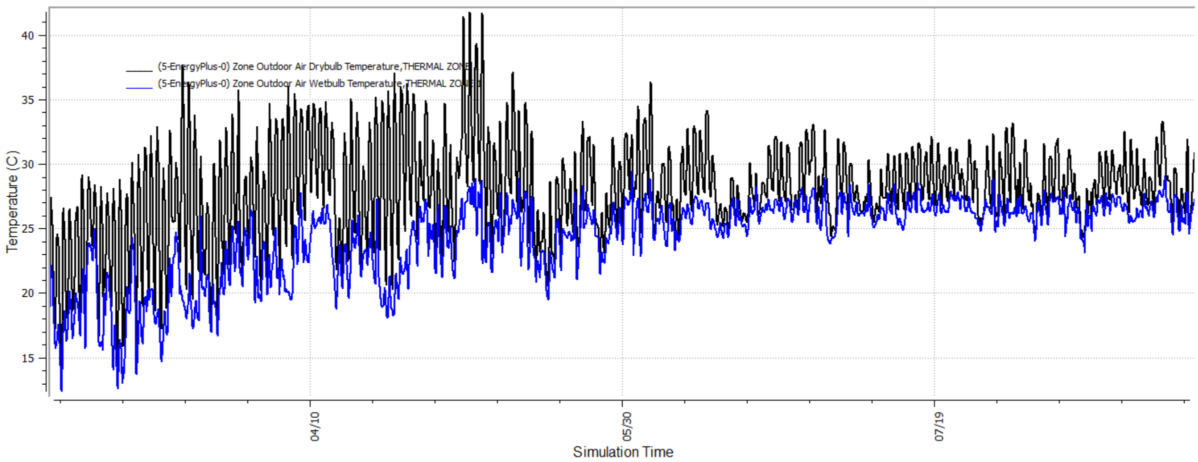


Figure C.67 Outdoor DBT and WBT from March to August: Wall Type WB11

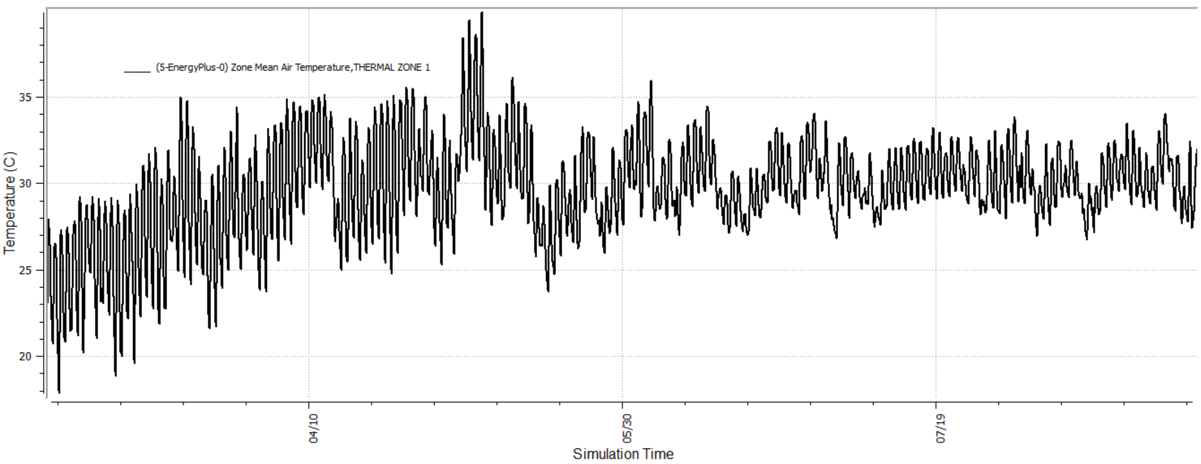


Figure C.68 Zone 1 Mean air temperature from March to August: Wall Type WB11

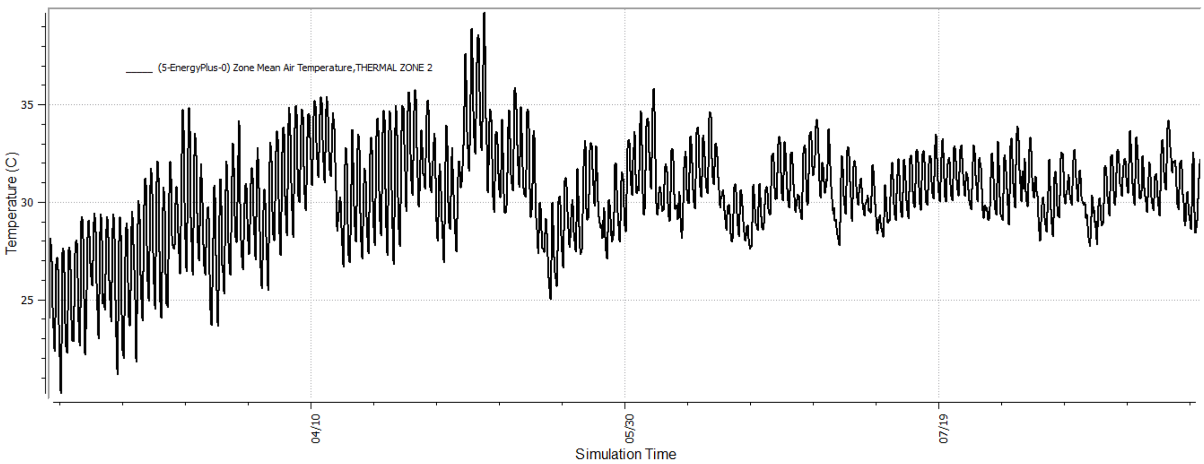


Figure C.69 Zone 2 Mean air temperature from March to August: Wall Type WB11

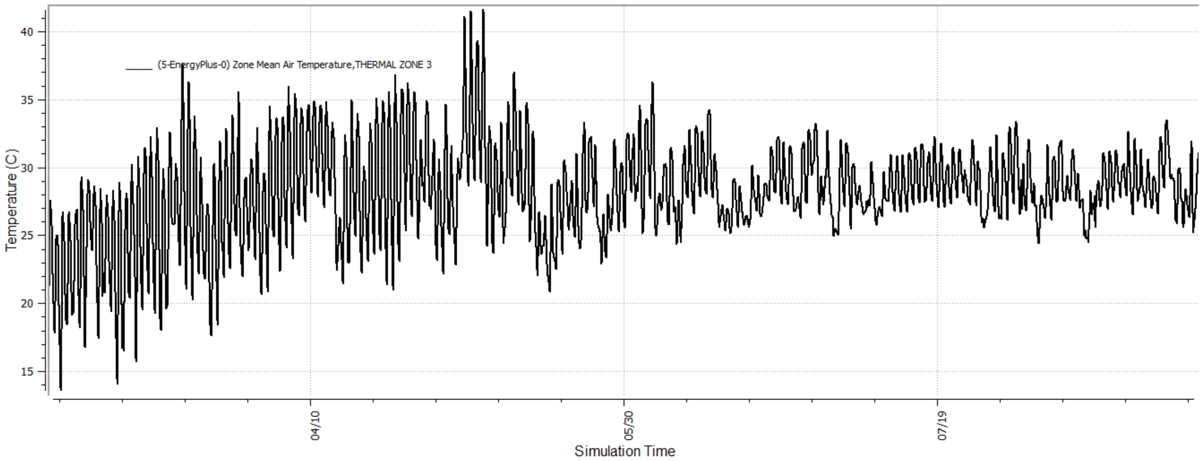


Figure C.70 Zone 3 Mean air temperature from March to August: Wall Type WB11

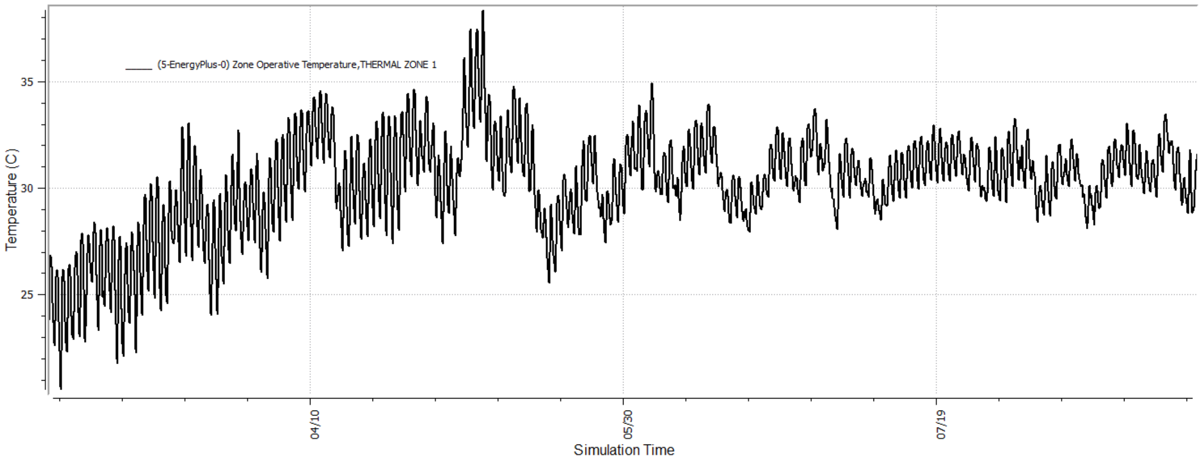


Figure C.71 Zone 1 Operative temperature from March to August: Wall Type WB11

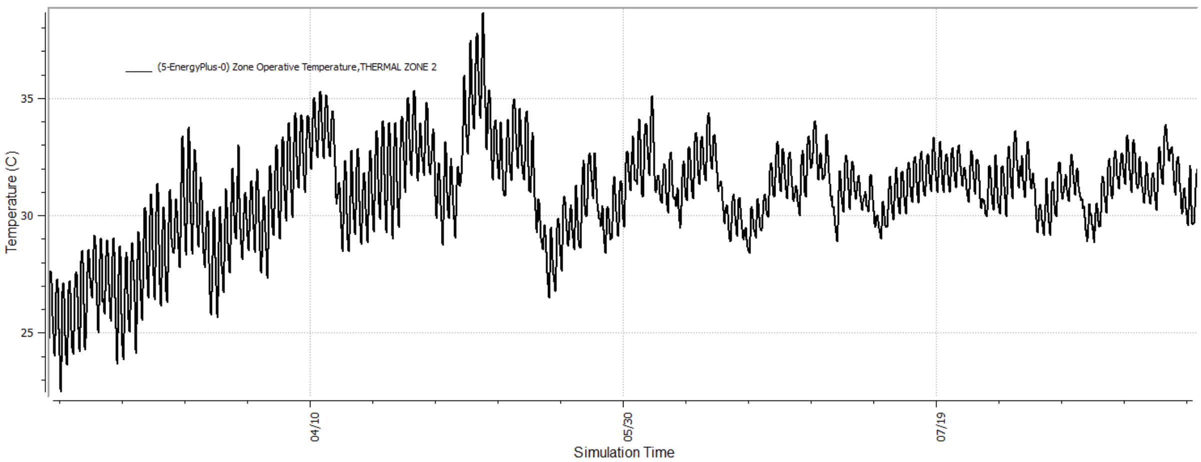


Figure C.72 Zone 2 Operative temperature from March to August: Wall Type WB11

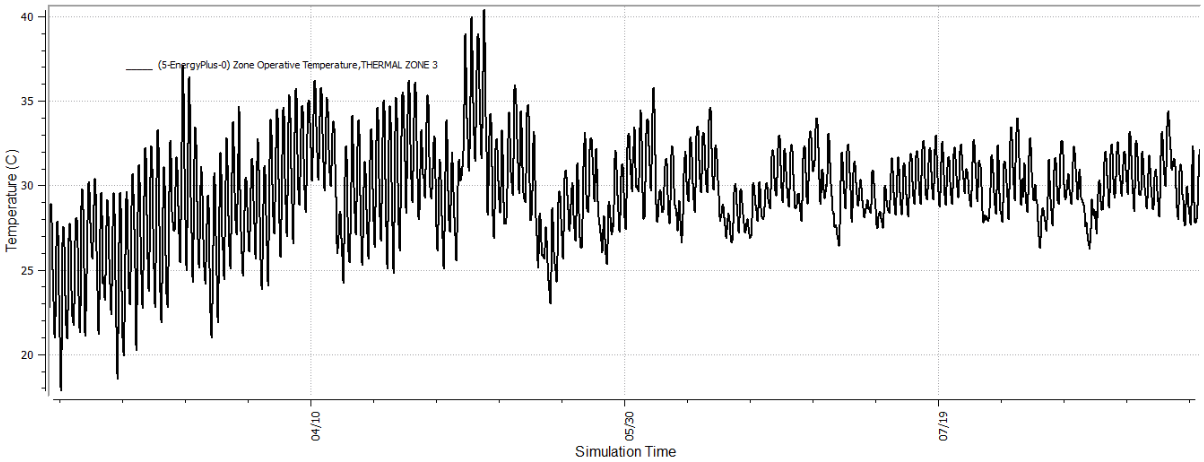


Figure C.73 Zone 3 Operative temperature from March to August: Wall Type WB11

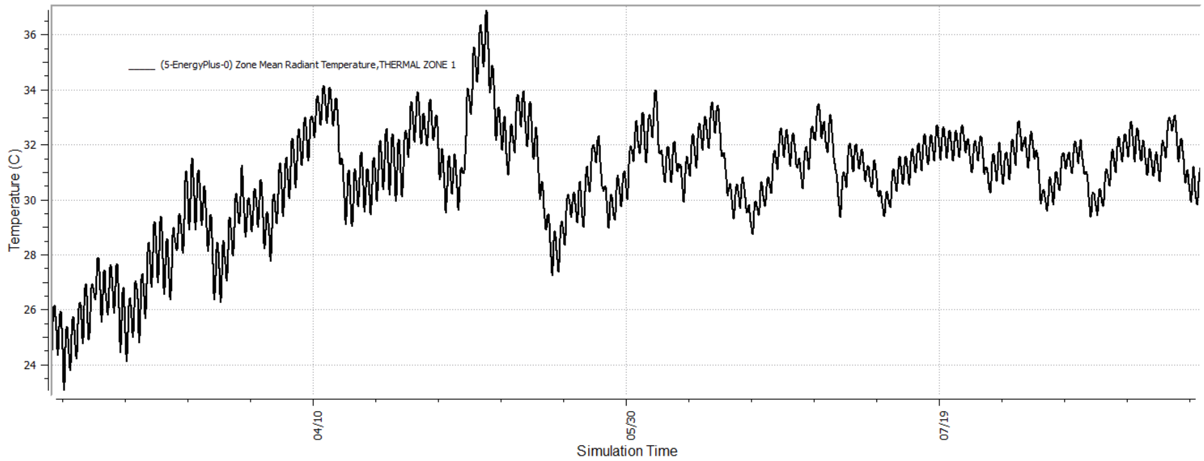


Figure C.74 Zone 1 Mean Radiant temperature from March to August: Wall Type WB11

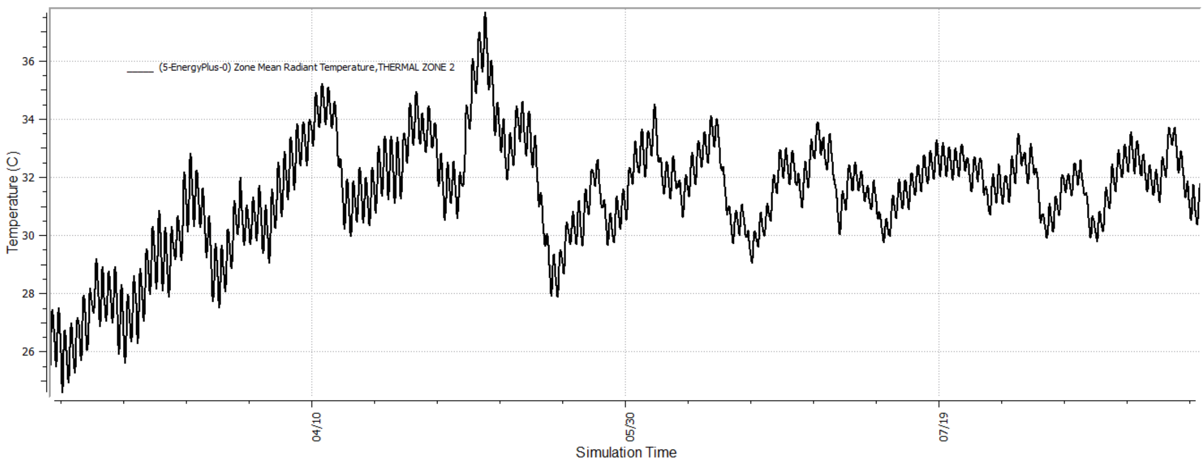


Figure C.75 Zone 2 Mean Radiant temperature from March to August: Wall Type WB11

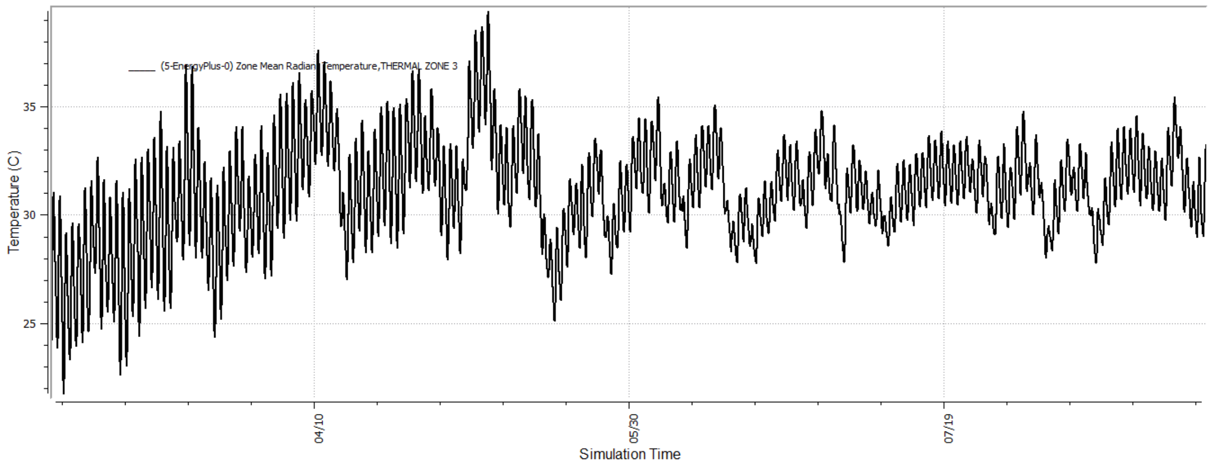


Figure C.76 Zone 3 Mean Radiant temperature from March to August: Wall Type WB11

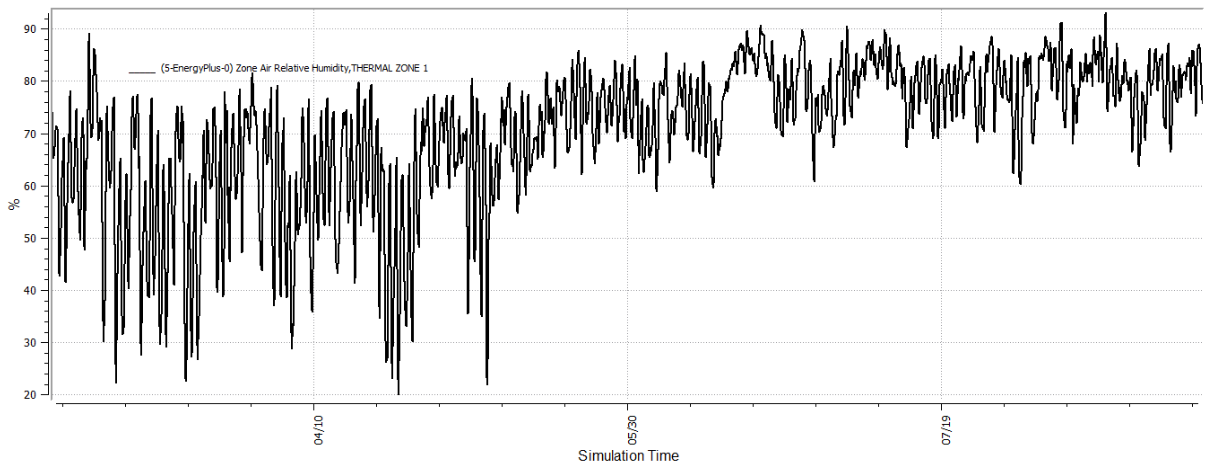


Figure C.77 Zone 1 Relative Humidity from March to August: Wall Type WB11

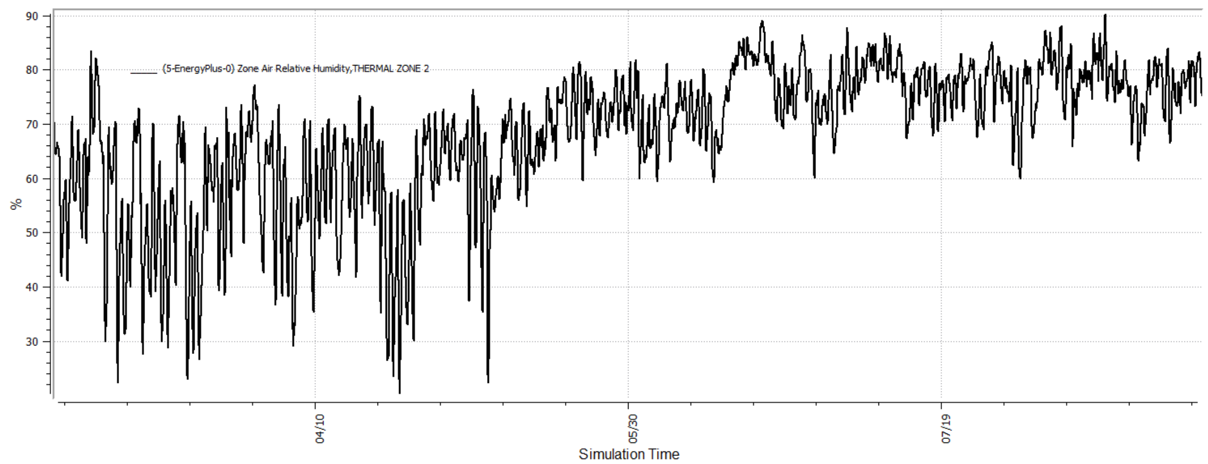


Figure C.78 Zone 2 Relative Humidity from March to August: Wall Type WB11

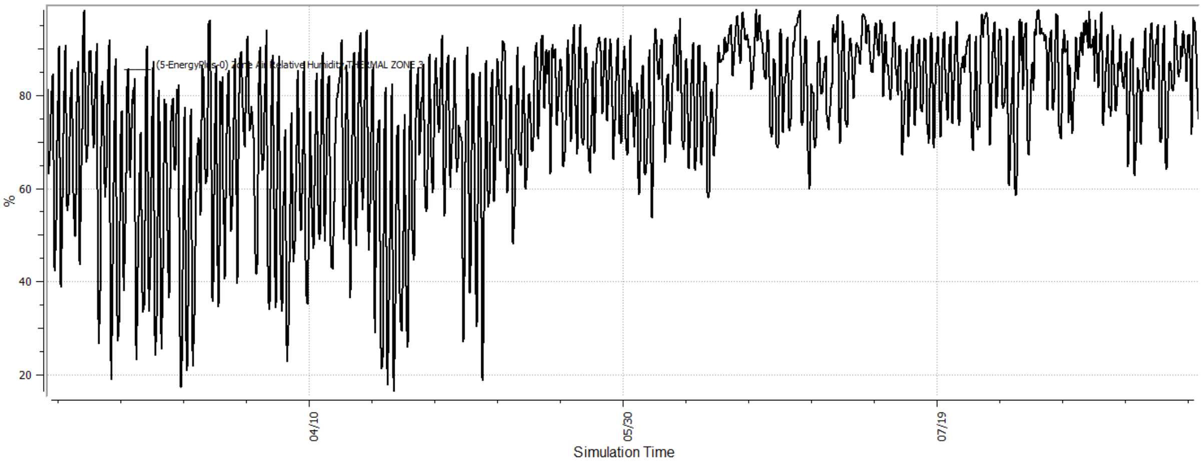


Figure C.79 Zone 3 Relative Humidity from March to August: Wall Type WB11

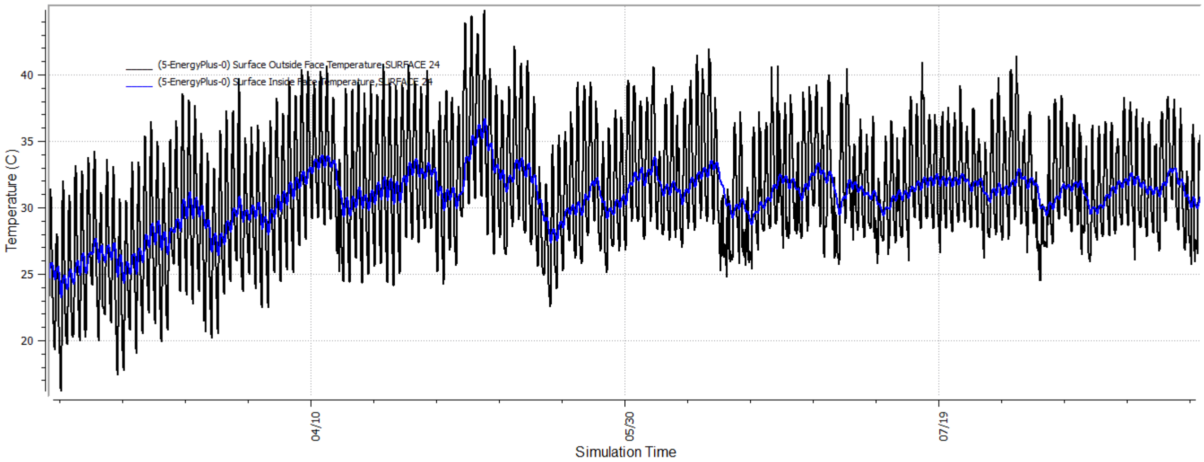


Figure C.80 Outside & inside surface temperature of North wall of inpatient room from March to August: Wall Type WB11

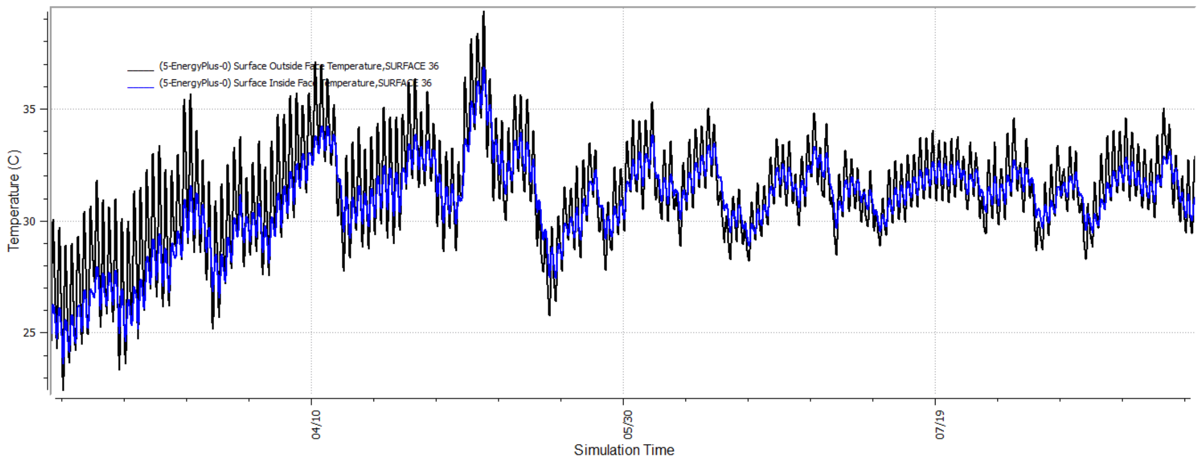


Figure C.81 Outside & inside surface temperature of South wall of inpatient room from March to August: Wall Type WB11

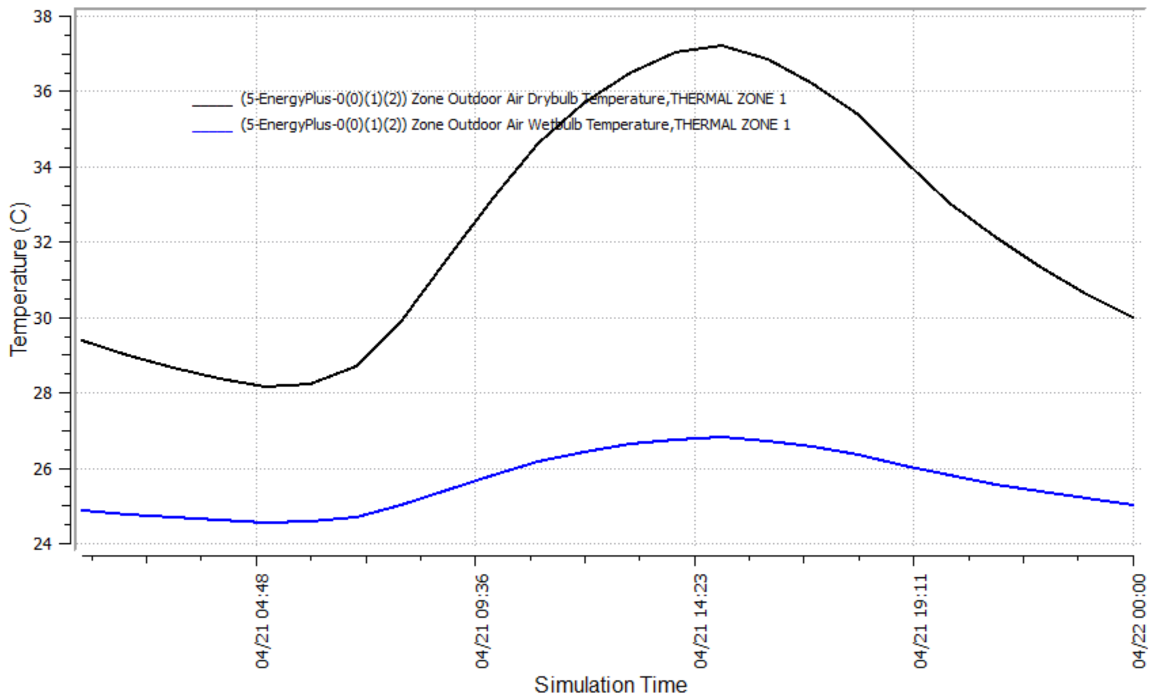


Figure C.82 Outdoor Air DBT and WBT for 1.0 percentile cooling condition: Wall Type WC04

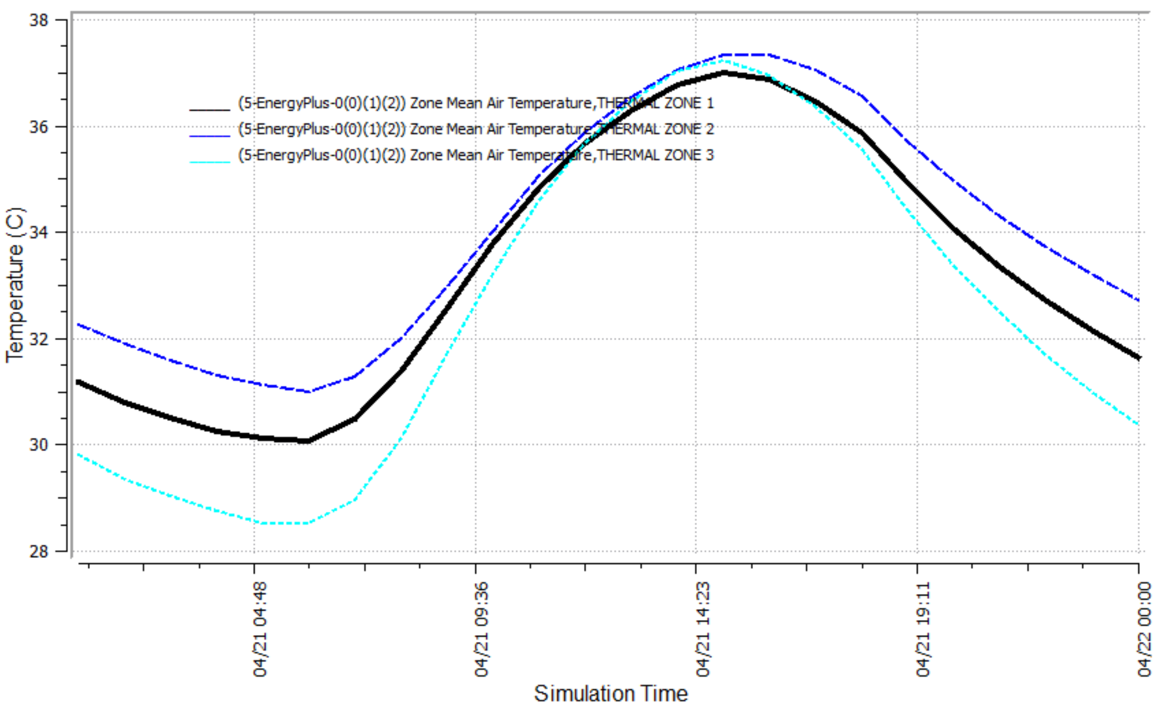


Figure C.83 Mean Air Temperature of zone 1, zone 2 and zone 3 for 1.0 percentile cooling condition: Wall Type WC04

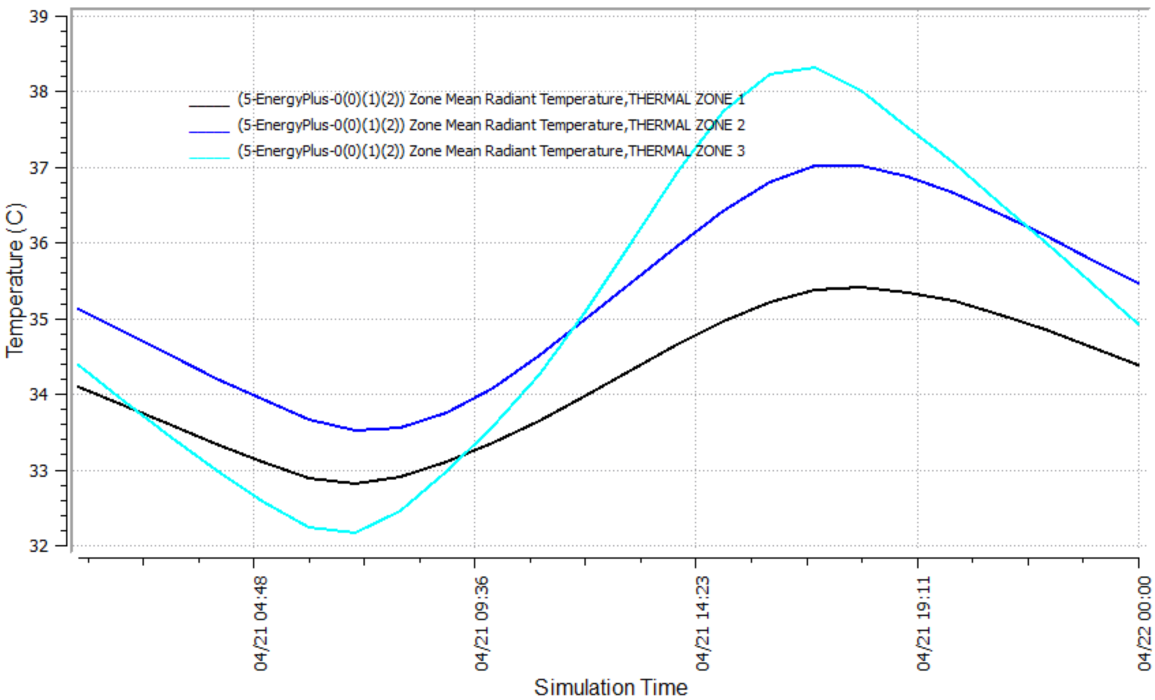


Figure C.84 Mean Radiant Temperature of zone 1, zone 2 and zone 3 for 1.0 percentile cooling condition: Wall Type WC04

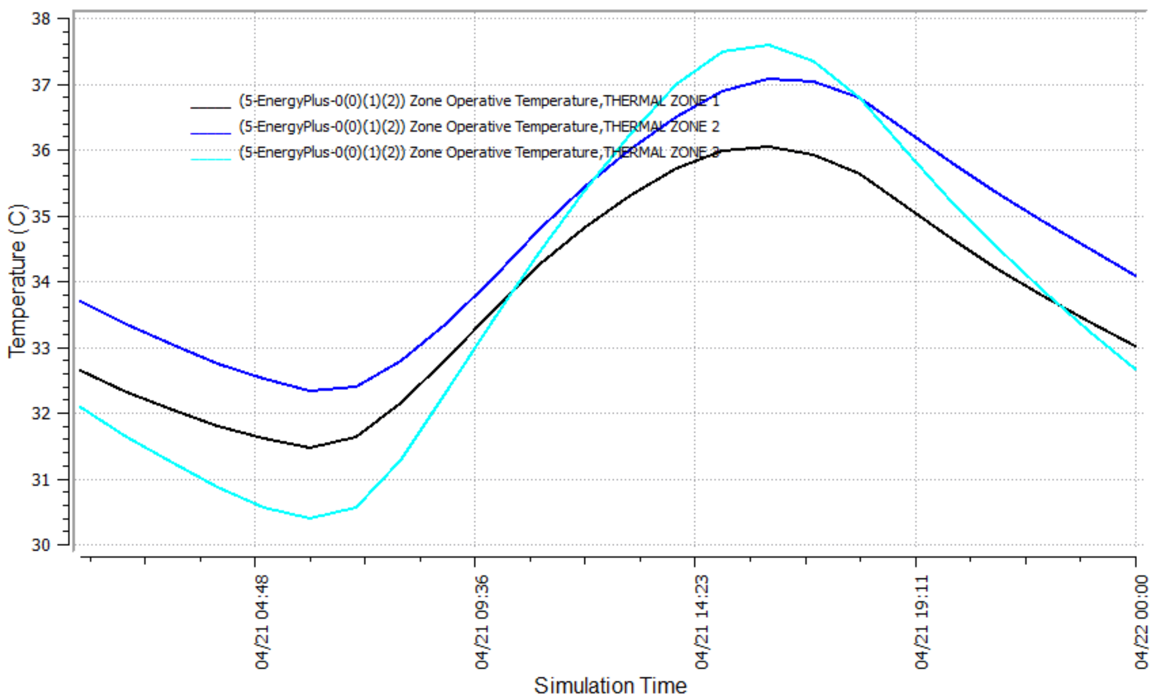


Figure C.85 Mean Operative Temperature of zone 1, zone 2 and zone 3 for 1.0 percentile cooling condition: Wall Type WC04

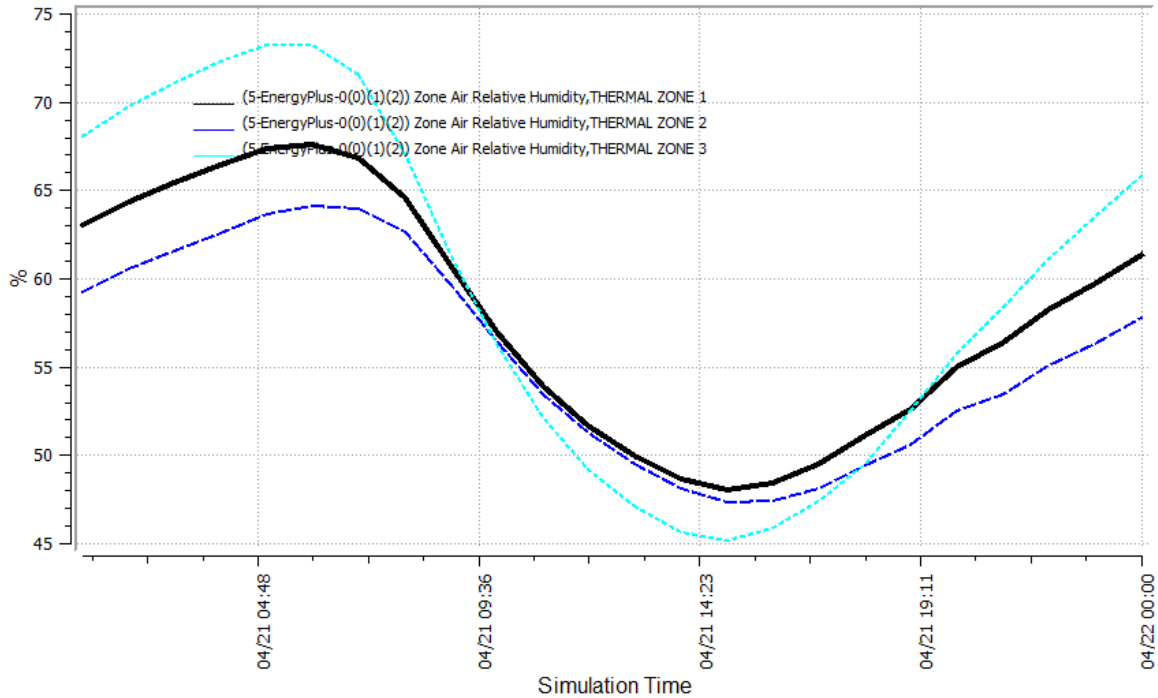


Figure C.86 Relative Humidity of zone 1, zone 2 and zone 3 for 1.0 percentile cooling condition: Wall Type WC04

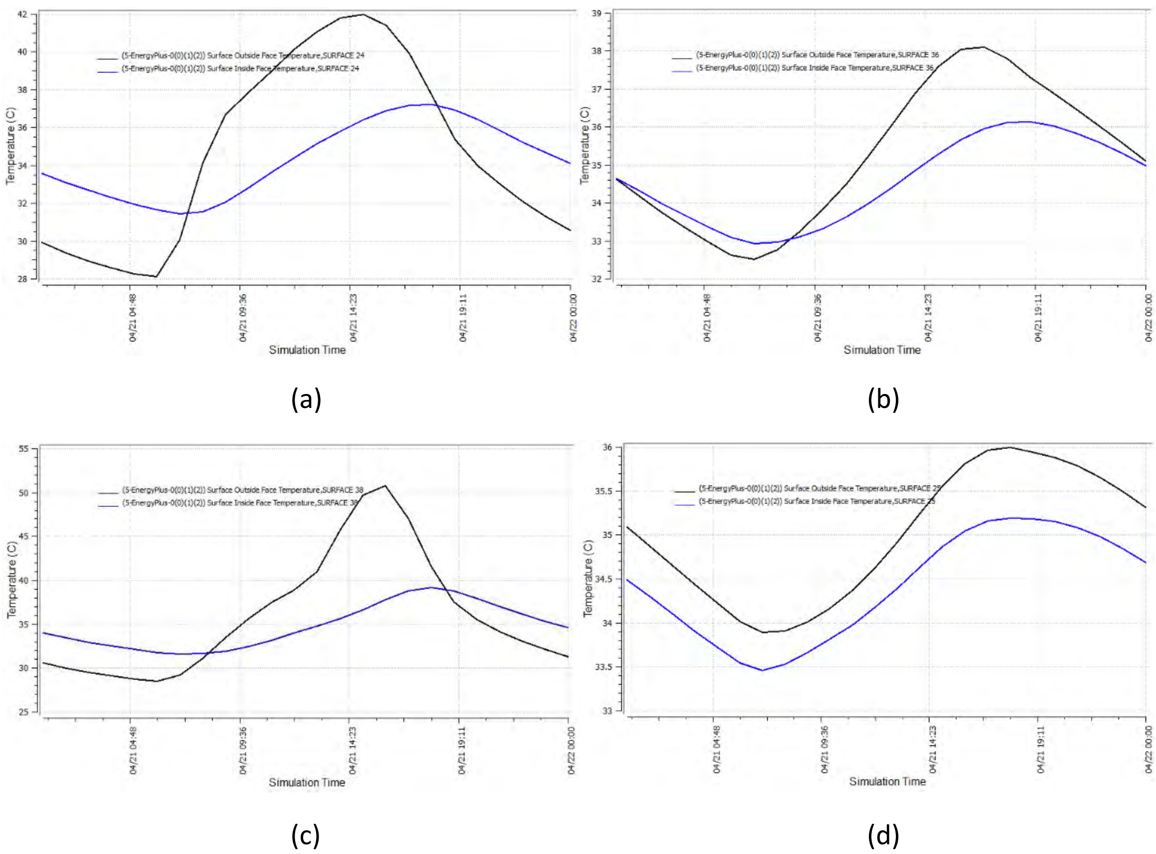


Figure C.87 Outside and inside surface temperature for 1.0 percentile cooling condition (a) North wall (b) South wall (c) West wall and (d) East wall: Wall Type WC04

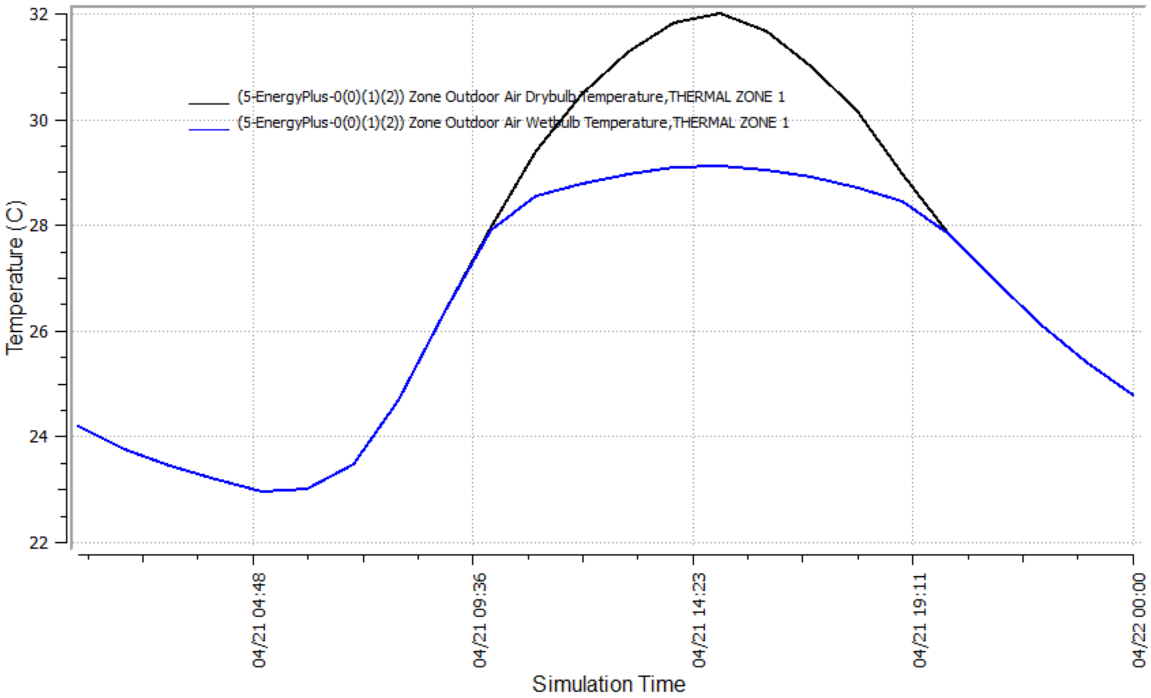


Figure C.88 Outdoor Air DBT and WBT for 1.0 percentile dehumidification condition: Wall Type WC04

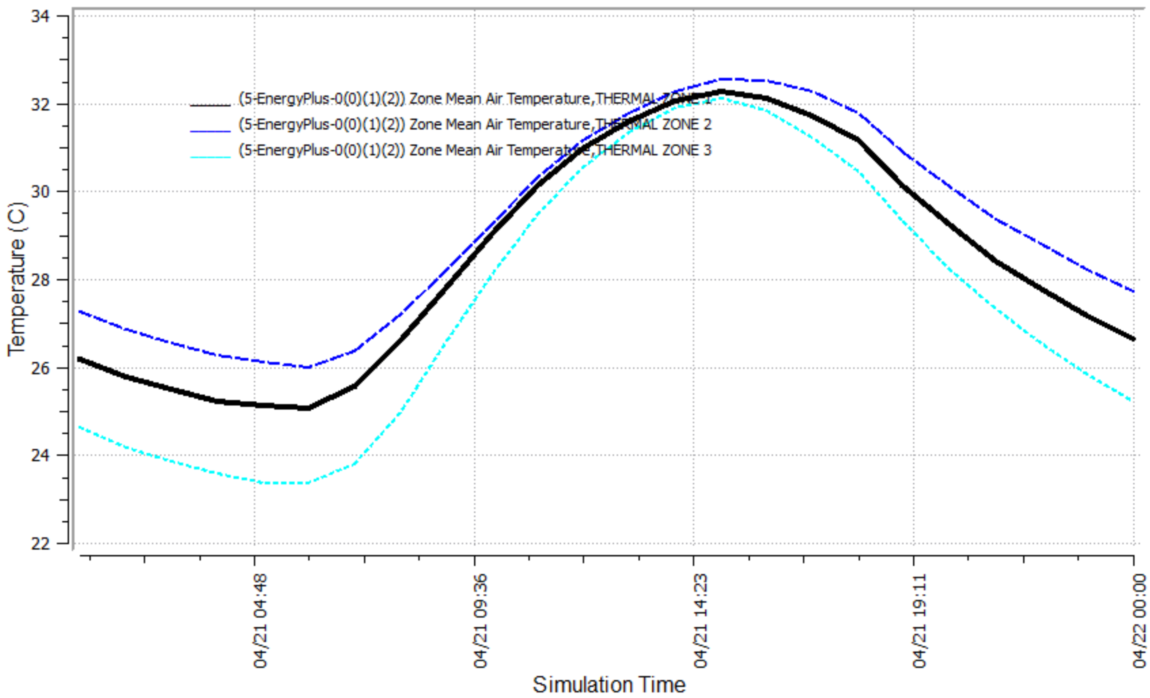


Figure C.89 Mean Air Temperature of zone 1, zone 2 and zone 3 for 1.0 percentile dehumidification condition: Wall Type WC04

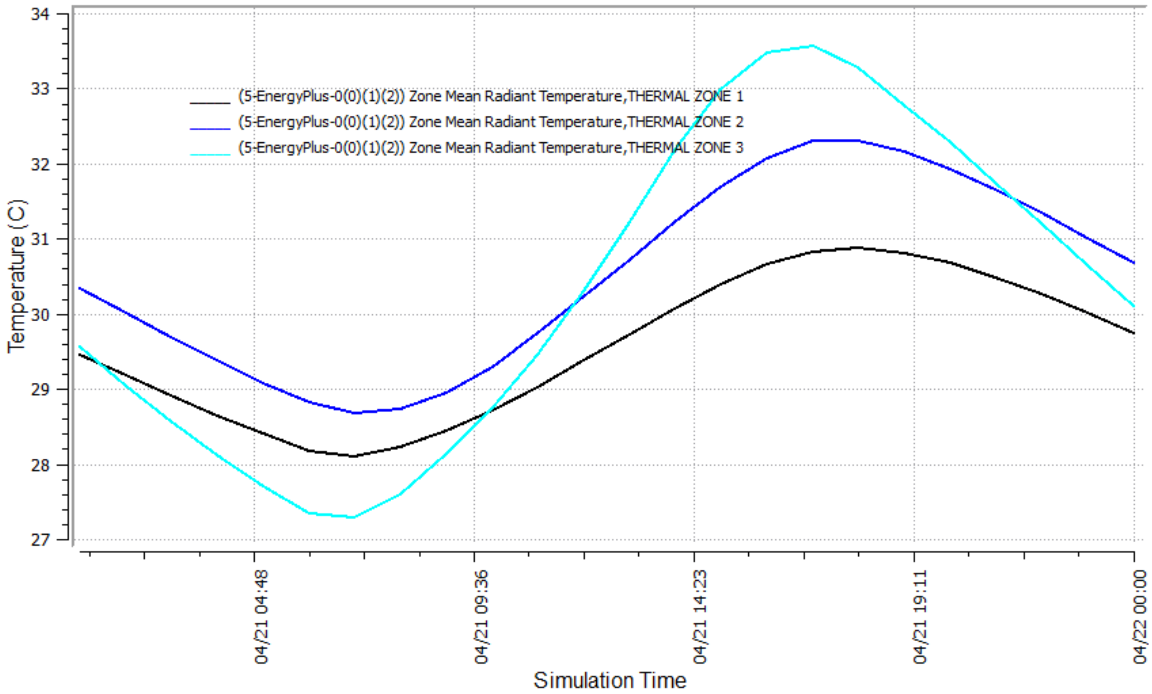


Figure C.90 Mean Radiant Temperature of zone 1, zone 2 and zone 3 for 1.0 percentile dehumidification condition: Wall Type WC04

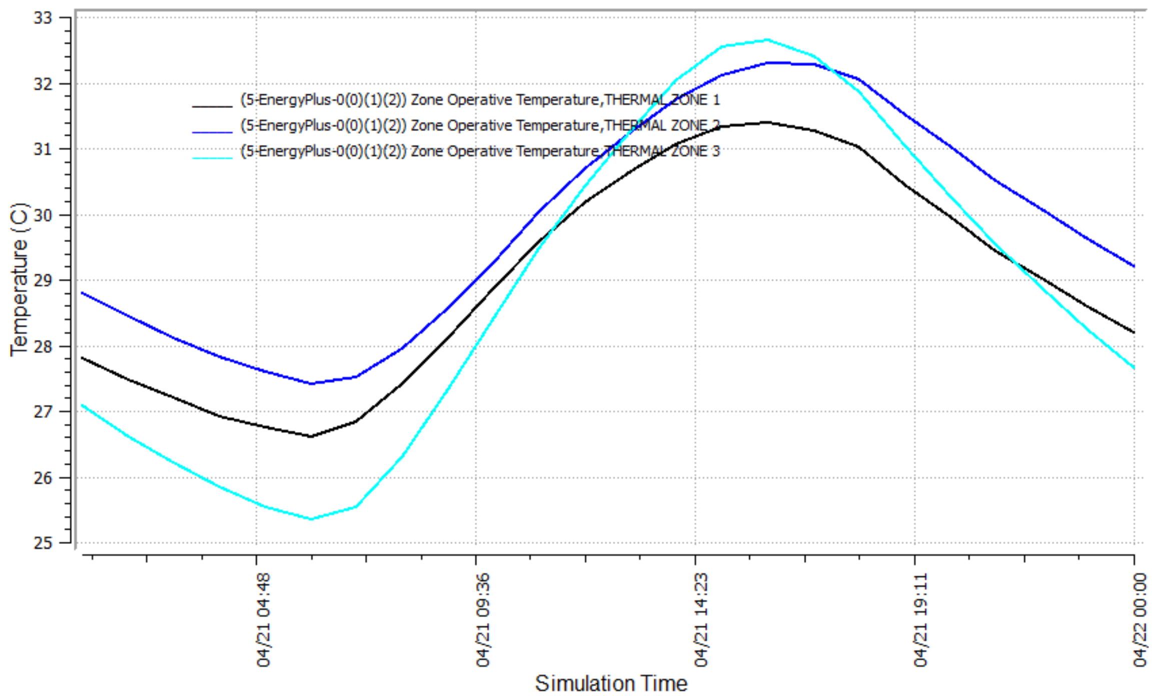


Figure C.91 Mean Operative Temperature of zone 1, zone 2 and zone 3 for 1.0 percentile dehumidification condition: Wall Type WC04

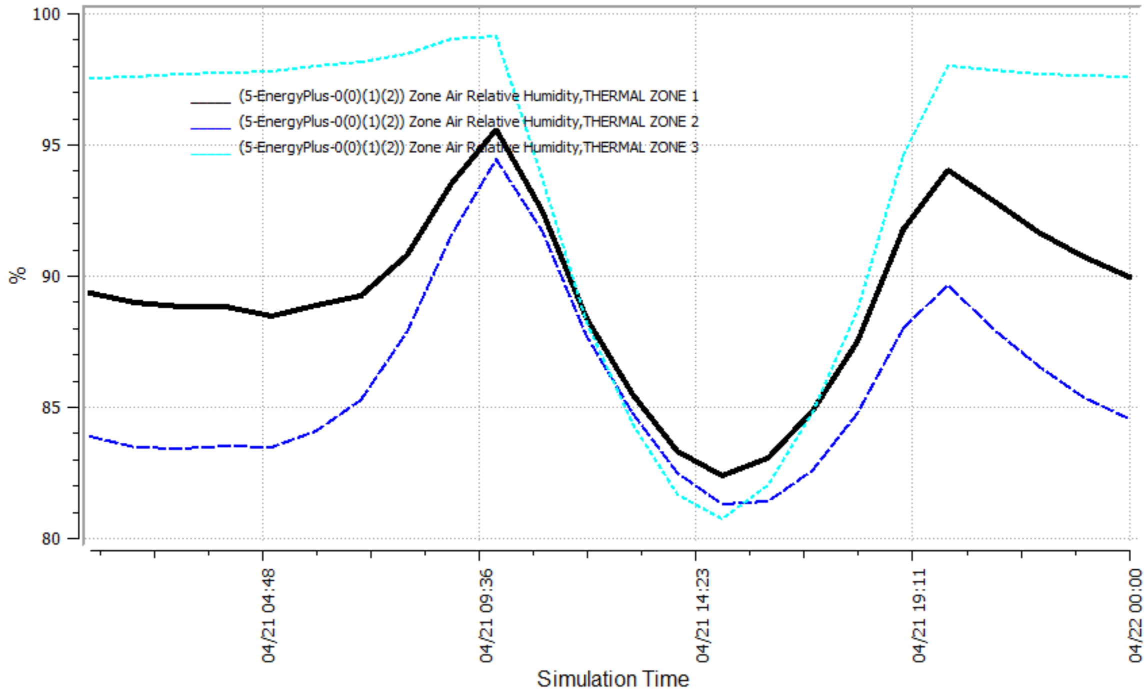
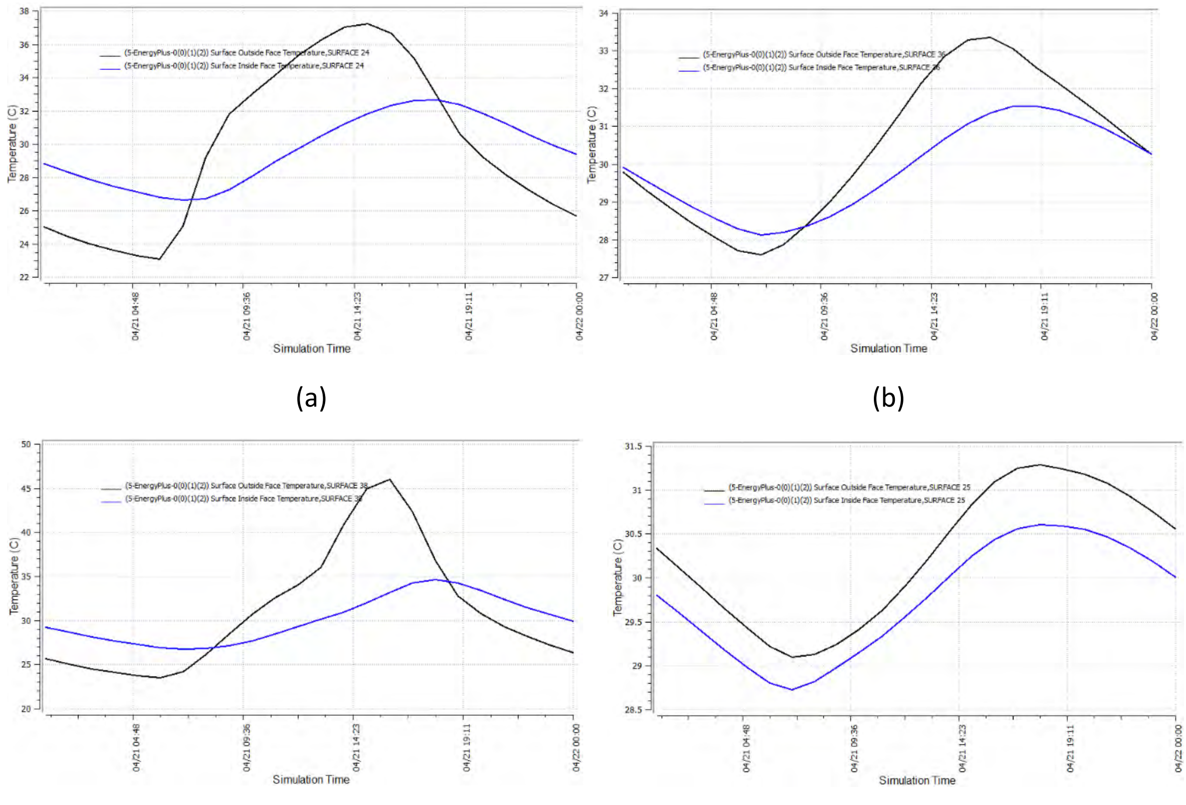


Figure C.92 Relative Humidity of zone 1, zone 2 and zone 3 for 1.0 percentile dehumidification condition: Wall Type WC04



(c) *(d)*

Figure C.93 Outside and inside surface temperature for 1.0 percentile dehumidification condition (a)North wall (b) South wall (c) West wall and (d) East wall: Wall Type WC04

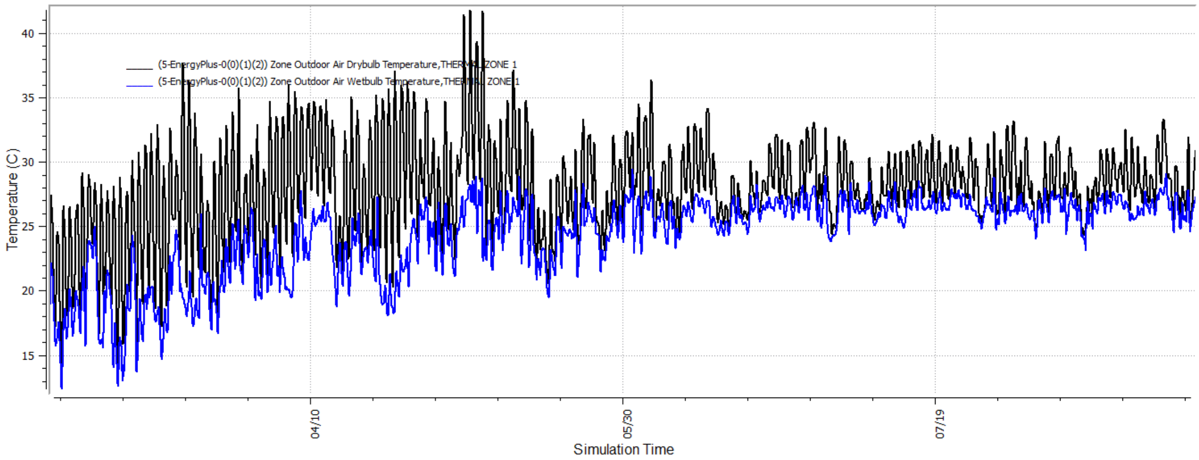


Figure C.94 Outdoor DBT and WBT from March to August: Wall Type WC04

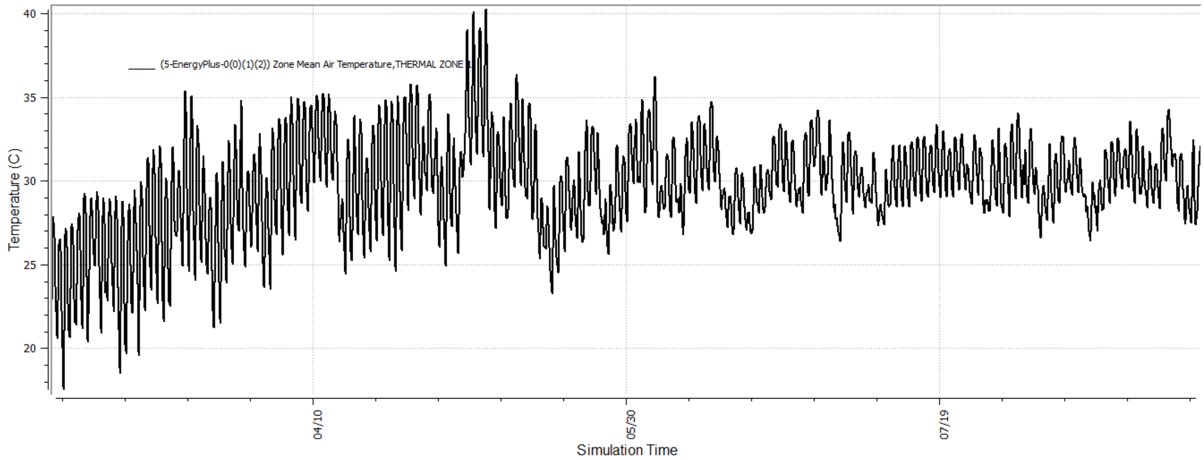


Figure C.95 Zone 1 Mean air temperature from March to August: Wall Type WC04

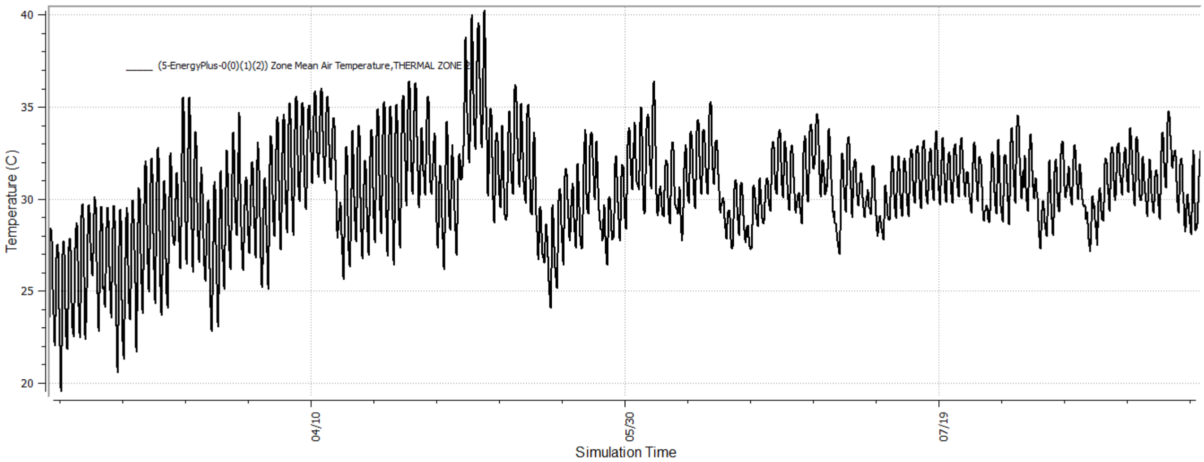


Figure C.96 Zone 2 Mean air temperature from March to August: Wall Type WC04

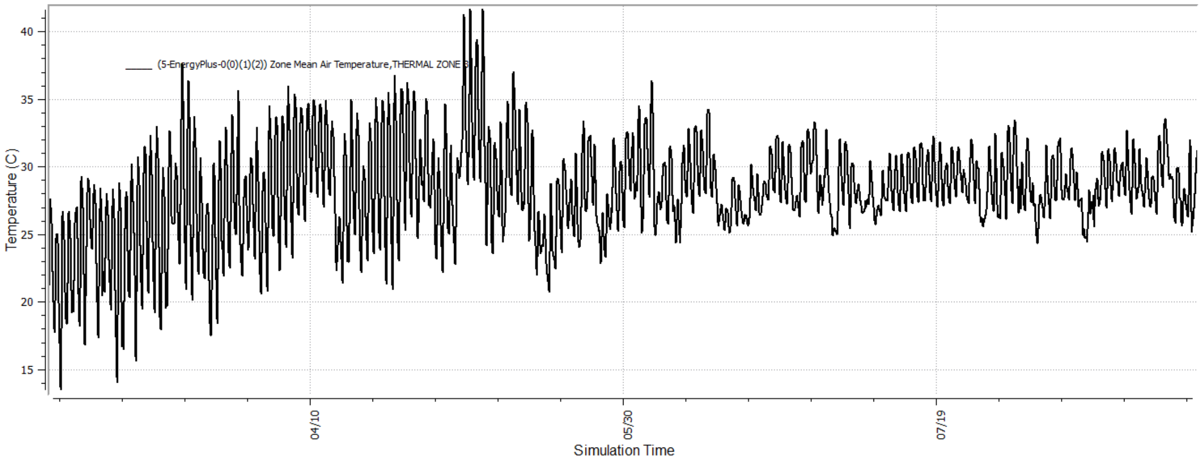


Figure C.97 Zone 3 Mean air temperature from March to August: Wall Type WC04

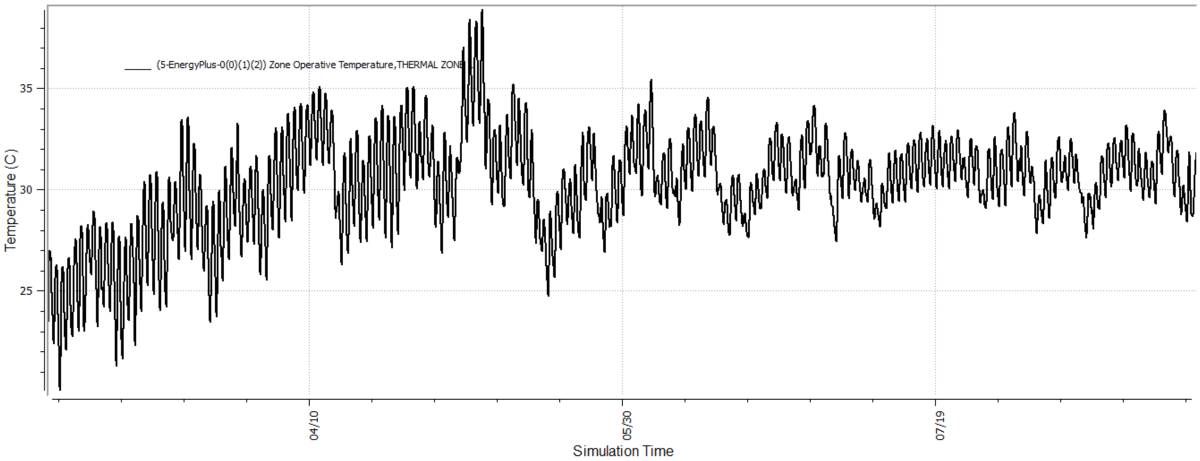


Figure C.98 Zone 1 Operative temperature from March to August: Wall Type WC04

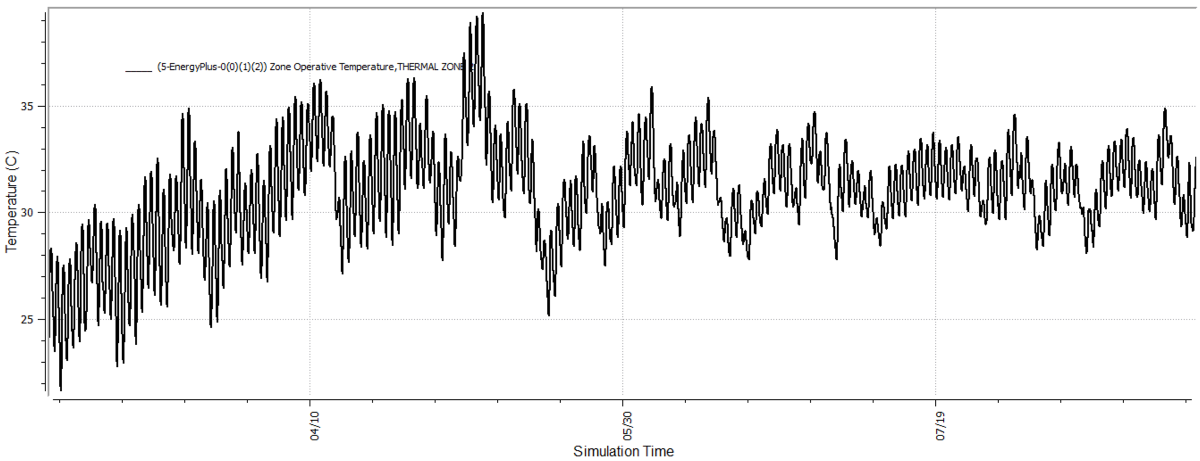


Figure C.99 Zone 2 Operative temperature from March to August: Wall Type WC04

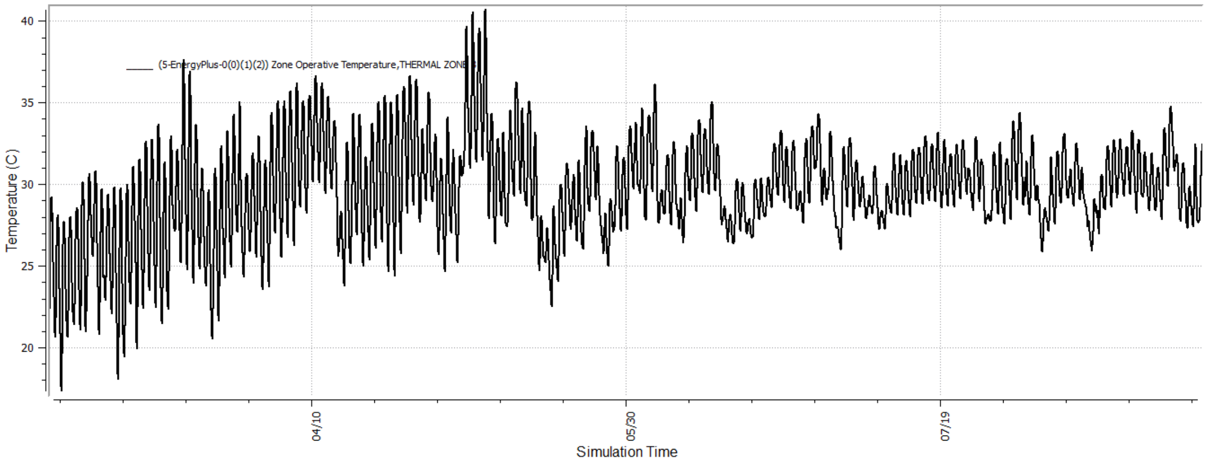


Figure C.100 Zone 3 Operative temperature from March to August: Wall Type WC04

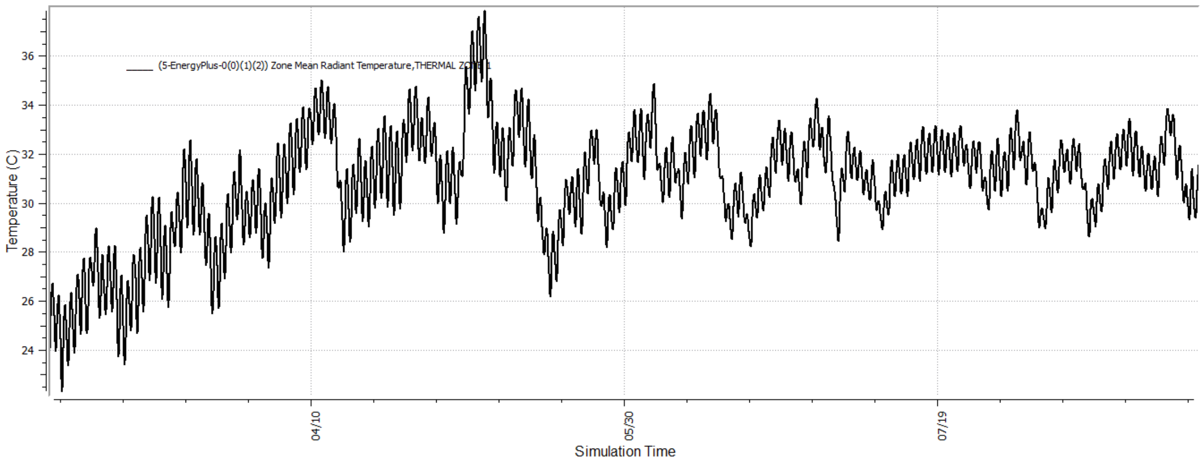


Figure C.101 Zone 1 Mean Radiant temperature from March to August: Wall Type WC04

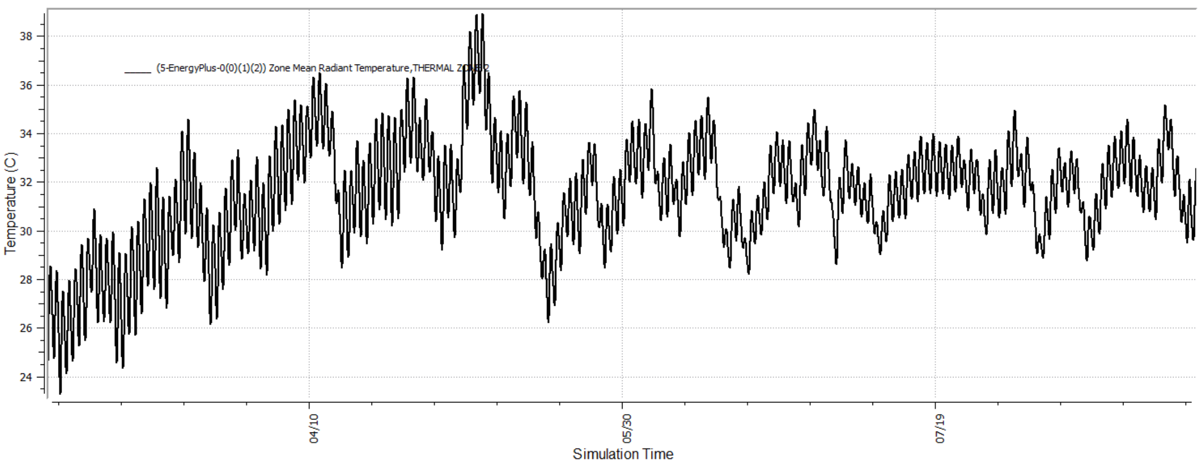


Figure C.102 Zone 2 Mean Radiant temperature from March to August: Wall Type WC04

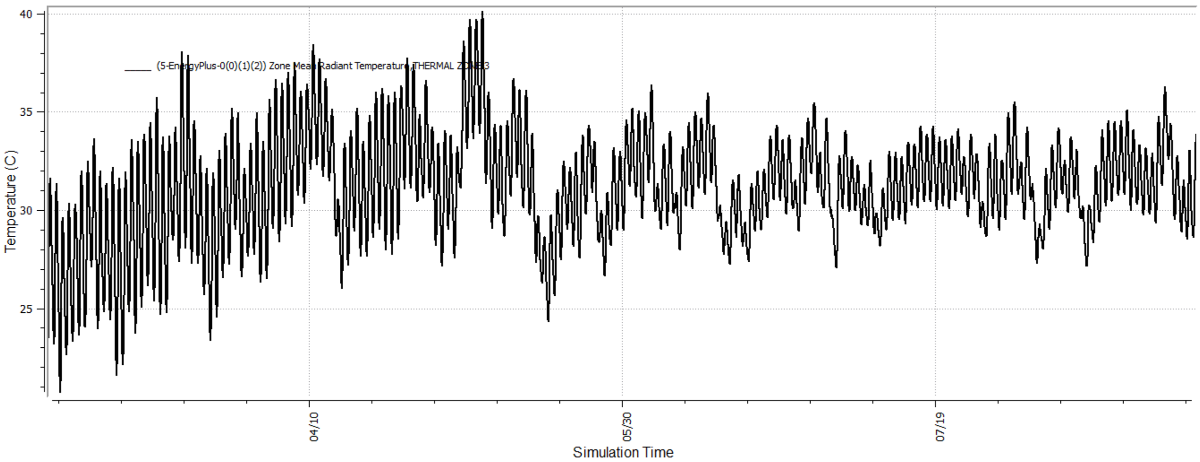


Figure C.103 Zone 3 Mean Radiant temperature from March to August: Wall Type WC04

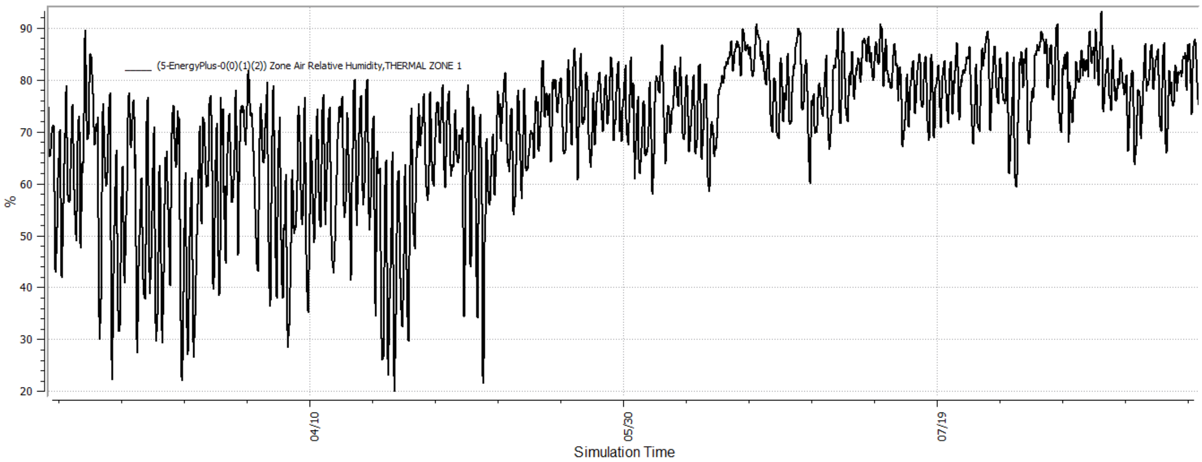


Figure C.104 Zone 1 Relative Humidity from March to August: Wall Type WC04

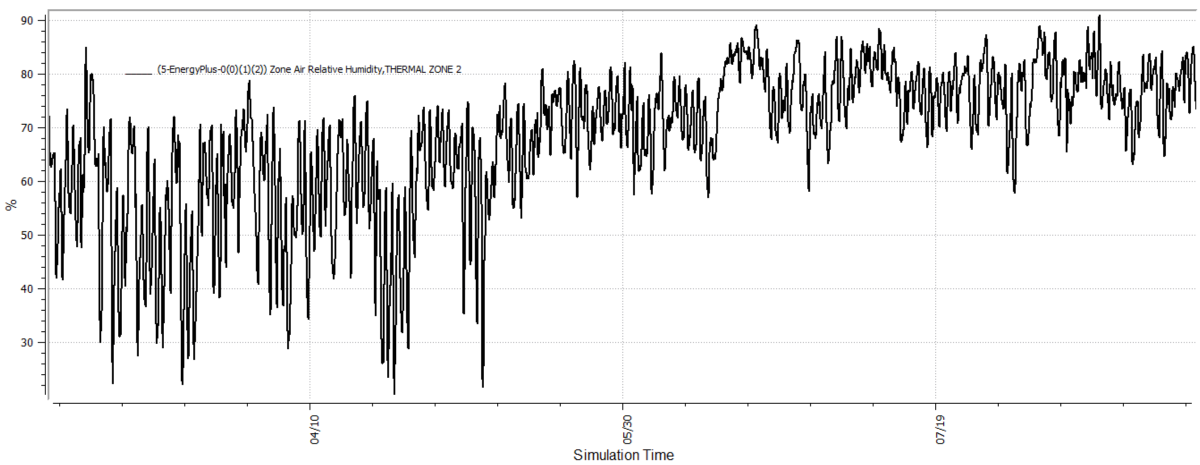


Figure C.105 Zone 2 Relative Humidity from March to August: Wall Type WC04

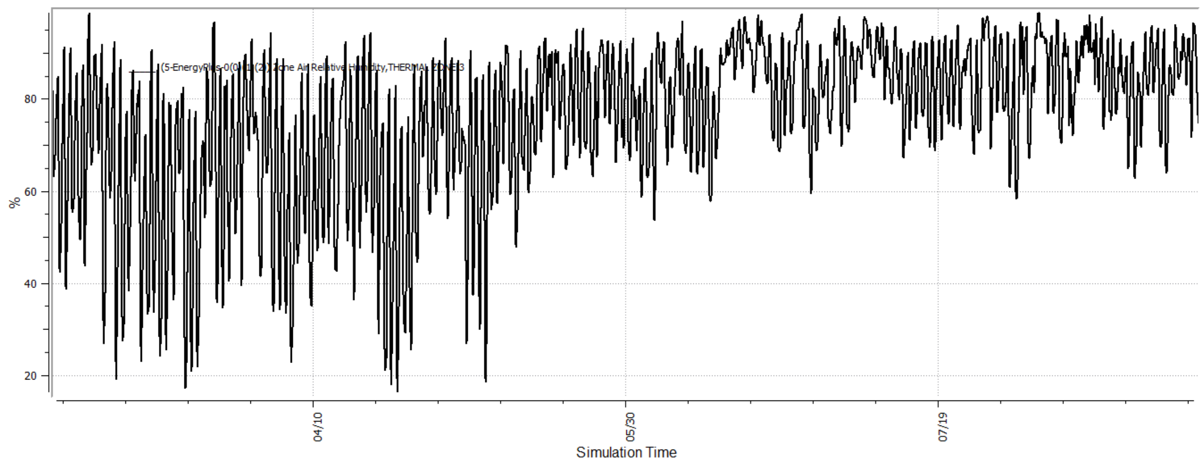


Figure C.106 Zone 3 Relative Humidity from March to August: Wall Type WC04

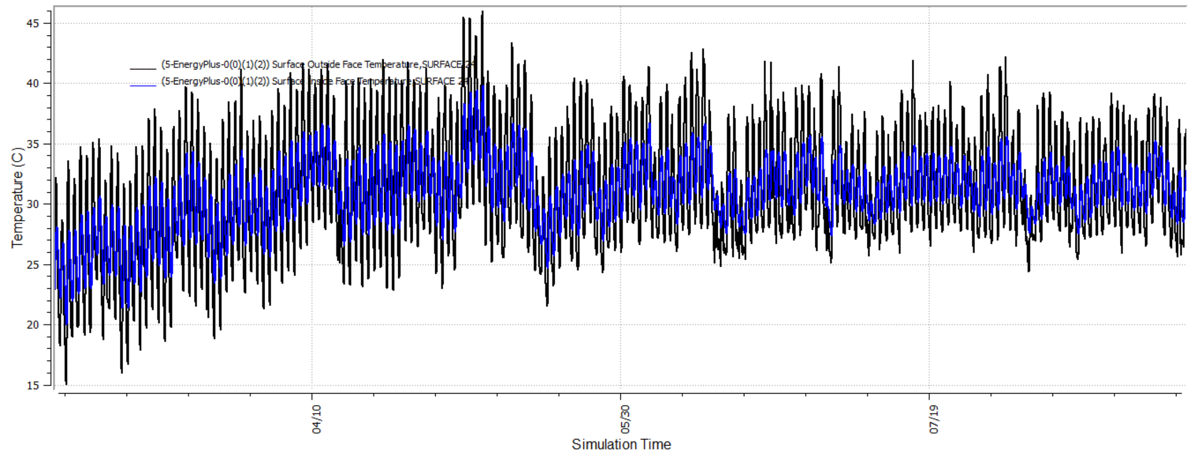


Figure C.107 Outside & inside surface temperature of North wall of inpatient room from March to August: Wall Type WC04

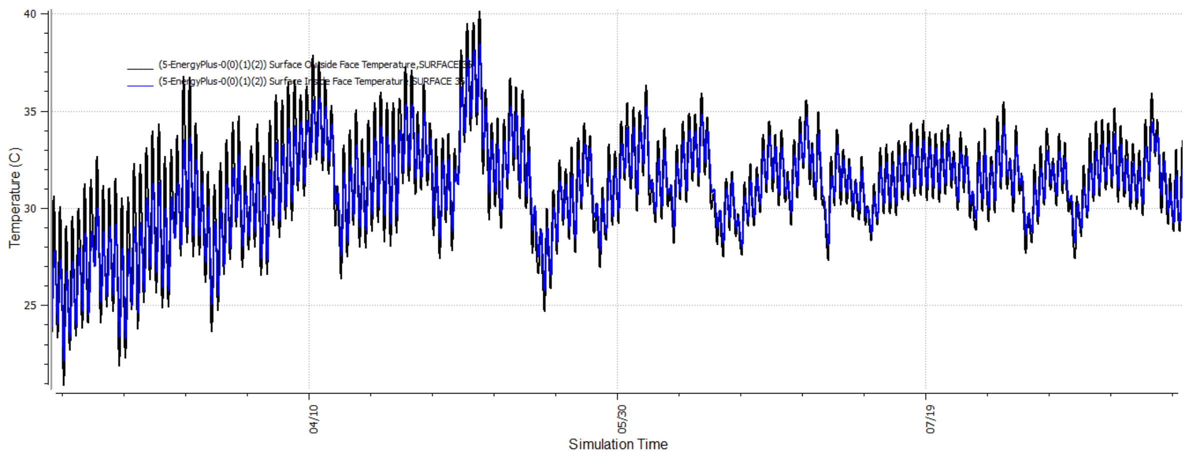


Figure C.108 Outside & inside surface temperature of South wall of inpatient room from March to August: Wall Type WC04