STUDY ON INDOOR THERMAL PERFORMANCE OF TRADITIONAL TIMBER HOUSES IN BANGLADESH

By

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DEDICATION

To My Parents Dr. Quamrul Islam & Nazneen Monowar

and

My Late Daughter Shayra Bintay Showkat (Arshia)

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ABSTRACT:

Traditional timber houses enhance the shape of local Bangladeshi architecture which is the product of a century-long trial and error processes resulting in region-specific sustainable, economic and culture-specific commodities that presumably provide a comfortable indoor environment. With the advent of metal sheets more and more buildings are being replaced or built with manufactured iron sheets. In the process indigenous knowledge of timber architecture along with adaptive measures suitable to local climate are in the process of being lost. There is a great need for scientifically observing the environmental performance of such building types. There is a lack of quantitative data and scientific justification of often claimed performance of these buildings of being comfortable. In the current study thermal performance of a traditional timber house envelope has been evaluated in relation to previously established indoor thermal comfort for rural subjects. Over time in-situ data on indoor environmental condition has been monitored continuously through data logger. Surface temperature and thermal images have been recorded by laser non-contact thermometer and thermal imaging camera respectively. A three-dimension model of the traditional timber house has been developed and whole building parametric studies using EnergyPlus simulation engine have been performed to visualize year-round thermal performance and to identify most discomfort period of the year. Following this, several simulation studies have been conducted considering material and construction as variables where performance of thirty-three walls, six roofs and two floors' constructions have been observed towards enhanced indoor thermal comfort. The focus of this study is to evaluate the indoor thermal performance of the traditional timber houses in the local climatic situation towards clarifying some accurate understanding and improvement of these houses which will contribute professionals and policy-makers establish architectural design strategies that will help improve occupant's well-being in the future.

ABBREVIATIONS

ASHREA: American Society of Heating, Refrigerating and Air-Conditioning Engineers
AT: Air Temperature (°C)
BMD: Bangladesh Meteorological Department
BNBC: Bangladesh National Building Code
CC: Cement Concrete
C.I.: Corrugated Iron
Clo.: Clothing insulation
DBT: Dry Bulb Temperature (°C)
DOE: Department of Energy
EP: Energy Plus
Fig.: Figure
HIES: Household Income Expenditure Survey
HOBO: Honest Observer By Onset
IDF: Intermediate Data Format
ISO: International Organization for Standardization
JICA: Japan International Cooperation Agency
LR: Linear Regression
Met: Metabolic Rate
MRT: MRT (°C)
NBCI: National Building Code of India
NV: Naturally Ventilated
OT: Operative Temperature (°C)
RH: Relative Humidity (%)
SC: Sky Condition
STD: Standard Deviation
SWERA: Solar and Wind Energy Resource Assessment
Tab.: Table
TARP: Thermal Analysis Research Program
UNDP: United Nations Development Programme
WBT: Wet Bulb Temperature (°C)

CHAPTER ONE: PREAMBLE

1.1 Background:

Nowadays, Bangladesh is frequently referred as one of the most vulnerable countries to climate change (Rahman and Alam 2003; Huq, Reid et al. 2004; (UNDP) 2007; Huq and Ayers 2007). Various studies on the trend of climate change in climatic parameters over Bangladesh have pointed towards a significant increase in temperature (Chowdhury and Debsharma, 1992; Mia, 2003) (Fig. 1.1). Increasing summer temperature and higher levels of solar radiation directly affects thermal environment within buildings. This climate change creates an increasing energy demand for heating-cooling in residential sectors of Bangladesh. Today, residential sector alone is responsible for 60% of total energy consumption of the country(World-Bank 2014). Sector-wise break down of electricity consumption for residential sector shows that 40.9% of electricity is consumed for heating-cooling towards indoor thermal comfort(JICA-report 2016).

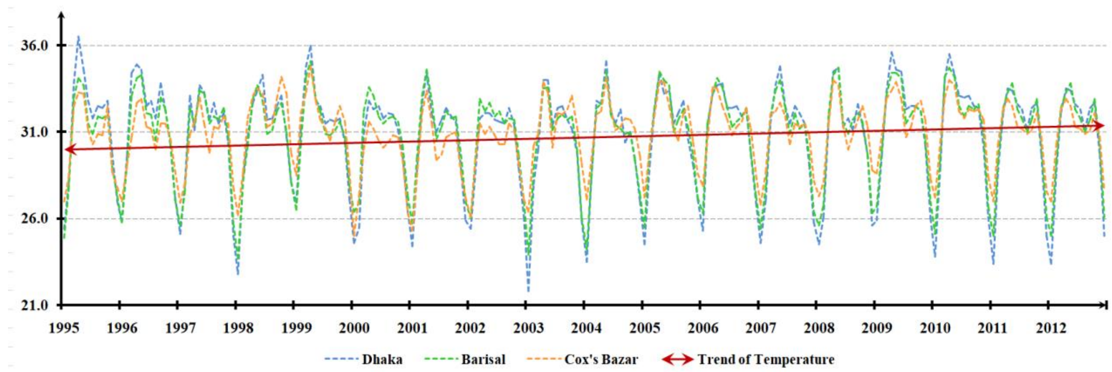
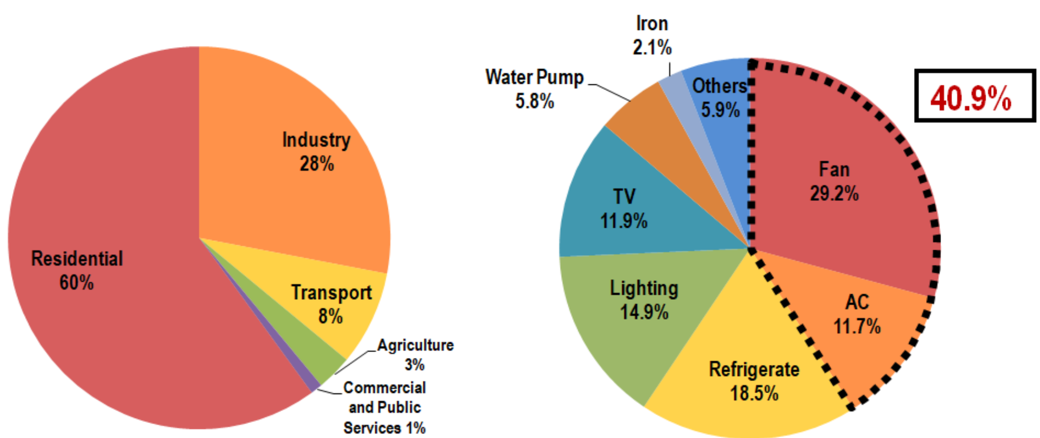


Figure 1.1 Observed trend of AT of Bangladesh (Bangladesh-Meteorological-Department).



(a) **(b)**

Figure 1.2 Sector-wise consumption in Bangladesh: (a) Energy and (b) Residential electricity consumption (Source: World Bank report and Surveyed data by JICA project team)

In Bangladesh there are different types of local building fabricated with sustainable envelope materials where 62.6% of total country's population live in (World-Bank:2018_Revision 2019). Traditional timber house is one of the examples of local building. At present wooden houses are found in a little quantity mostly in north-eastern (most of east and south Sylhet and a wedge-shaped strip south of the Meghalaya Plateau), south-eastern (Chittagong sub-region and a strip of land extending from southwest Sundarbans to the south of Comilla) and south-western region of Bangladesh. According to previous research houses of low-lying regions are in vulnerable condition due to climate change (Kabir, Khan et al. 2016). Besides that energy consumption by the occupants of traditional houses has changed. Today domestic household in rural areas consumes 43% of total electricity (Taheruzzaman and Janik 2016).Increase in AT due to climate change also affected the occupant's energy consumption scenario within local houses. From the BSS (Bangladesh Bureau of Statistics) report on household income expenditure survey-2010 (HIES 2011) it is observed that expenditure for electricity among rural and urban people is nearly same in seven divisions (Fig. 1.3). Whereas in 1996-1997 main electrical accessory used by rural households were clock, radio and television in rural households, while in 2011, about 41.2% households have owned electric fan (Mitra 2013) (Fig. 1.4). Fig. 1.5 illustrates sector-wise breakdown of energy consumption for rural areas. From the figure it is observed that in every sector operating fan absorbs a great portion of energy where it is highest for residential buildings(Khan, Huque et al. 2016). All these pointed towards a changing indoor thermal performance of local houses in the changed climatic condition.

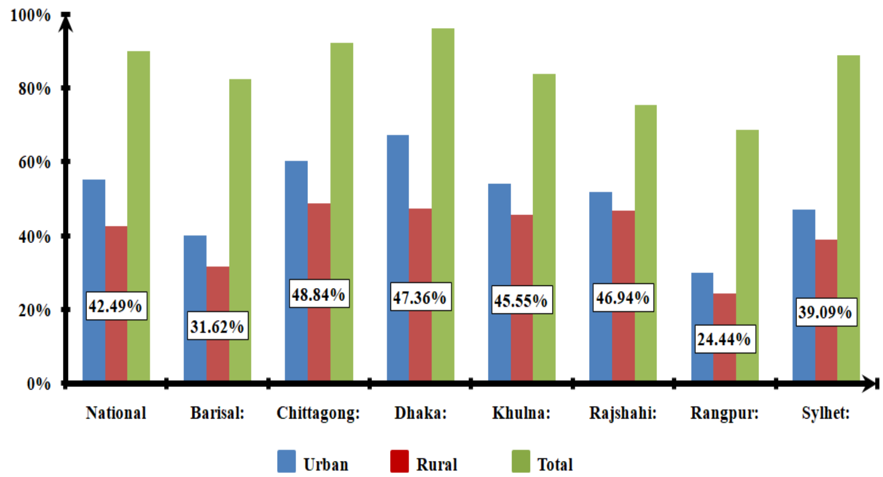


Figure 1.3 Energy access based on presence of expenditure for electricity (HIES 2011)

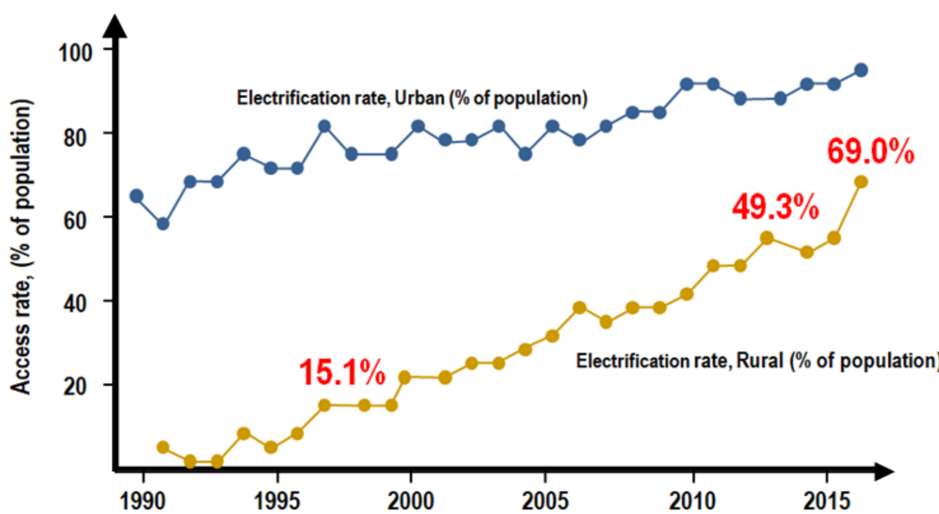


Figure 1.4 Urban and rural electricity access in Bangladesh (Mitra 1997; Mitra 2013; Tracking_SDG7 2018)

In addition to this due to increased affordability, wealthy households are shifting towards manufactured materials subsequently diminishing the production and use of traditional building materials (Islam and M. Islam 2005). These manufactured materials have low thermal capacity and further contribute towards high indoor temperature (Mallick and Ali 2003). But these traditional rural houses lack proper investigation. Therefore, it is vital to study the environmental performance of traditional rural houses in the prevailing climatic condition.

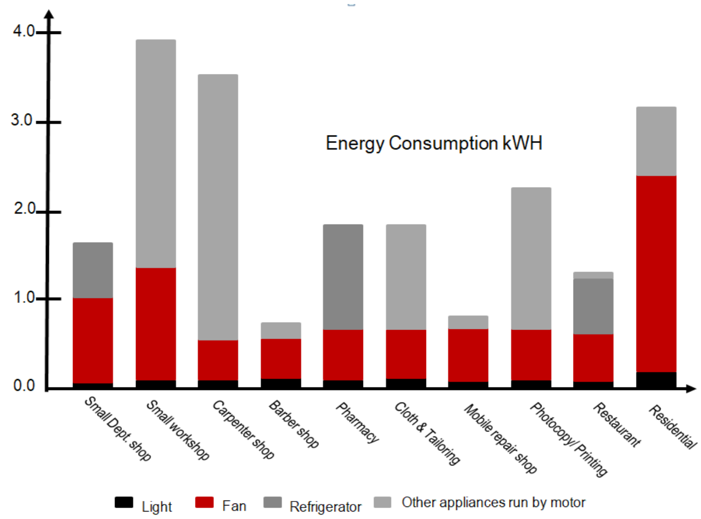


Figure 1.5 Daily energy consumption of different sector in rural areas (Khan, Huque et al. 2016)

1.2 Keywords

i) Indoor Thermal Performance

Indoor thermal environment of a building mostly depends on numbers of factors: local climate, building orientation, indoor activities and building envelope. But envelope materials act as a barrier between indoor and outdoor where the heat exchange takes place, hence, plays vital role for maintaining thermal environment within the comfort level inside the building (Fig. 1.6). Therefore, thermo-physical properties of building envelope material which determines the heat exchange rates between the building envelope and outdoor environment needed to be considered while selecting building envelope materials. Here building envelope means all the outer shell of building (wall, roof, foundation and door-window) responsible for maintaining indoor thermal environment and facilitate its climate control. Current study focuses on wall and roof envelope materials of traditional timber houses of Bangladesh.

ii) Natural Ventilation

Natural ventilation (NV) is specified as the airflow through apertures in the building fabric resulting from natural wind or buoyancy effect (pressure gradient induced by temperature variances between the indoor and outdoor), or a combination of both action(BSI 1991). In tropics buoyancy driven ventilation is not that significant due to little variation in indoor and outdoor AT. Again, naturally ventilated buildings are provided with considerable openings in the external façade which significantly enhance cross ventilation.

NV affects occupants' thermal sensation by:(i) introducing airflow within building influencing indoor AT and evaporative heat loss from human body, (ii) replacing hot air with cold air and (iii) affecting surface temperature of the structure hence, overall indoor MRT(Amos-Abanyie, Akuffo et al. 2013; Catalina, Iordache et al. 2013).

iii) Traditional Timber House

In Bangladesh there are different types of timber houses. Timber framed houses are commonly categorized as timber house. Wood, bamboo knitted mat, C.I. sheet or plain sheet are frequently used by local people as wall envelope material. But people near coastal areas commonly constructed traditional timber houses using wood as wall envelope material. Traditionally 'Golpata' was used for roof covering but today C.I. (corrugated iron) is widely used as roof covering material. For this study timber framed houses with wooden wall envelope and C.I. sheet roof have been selected for case study houses. From reconnaissance survey three typology of traditional timber houses were found out: single-storied, double-storied and stilt houses (Fig. 1.6). Details of traditional timber houses are presented in next chapter (Chapter-2, section 2.4).

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

Figure 1.6 Traditional timber houses of Bangladesh: (a) single-storied, (b) Double-storied and (c) Stilt

1.3 Statement of the Problem

Buildings are made to shelter human beings from adverse effects of outdoor environment. Thus, indoor environmental quality within the building is important. Studies have indicated that indoor environmental quality and health related issues are linked to characteristics of building, especially its indoor thermal environment. It bears a close relationship to human thermal comfort and directly influences human health, general well-beings and performance in a specific indoor environment (Woods 1989; Lorsch 1994; Lorsch and Abdou 1995; SeppÃ¤nen, Fisk et al. 1999; Roelofsen 2002; Fang, Wyon et al. 2004). The relationship among indoor environmental quality, human health-wellbeing and performance is illustrated in Fig. 1.7.

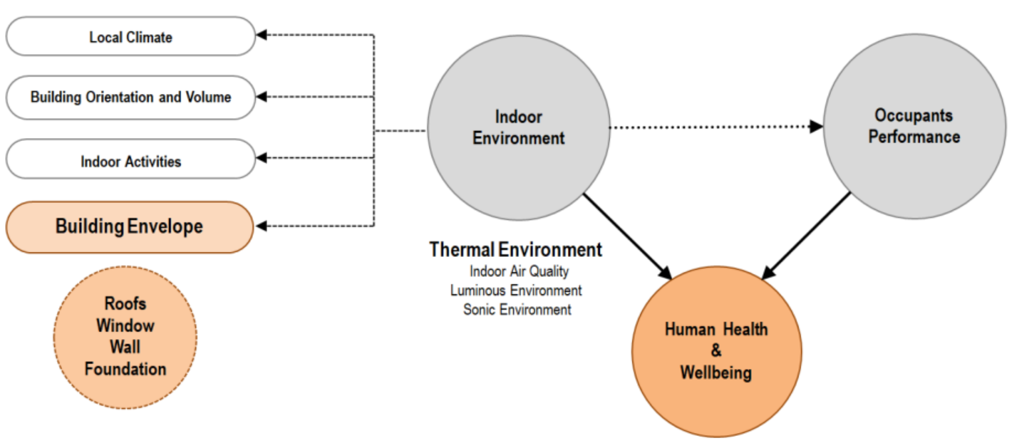


Figure 1.7 Indoor environmental quality, health-wellbeing and performance (Tanabe, Haned et al. 2007)

Globally high degree of comfort has been achieved using mechanical control system regardless of climate, although achieving thermal comfort inside the buildings through passive control is the best solution for ensuring a healthy and energy efficient indoor environment (Supic 1982; Sharples and Malama 1996; Malama and Sharples 1997). With response to climate change (global warming and greenhouse gas emission reduction), world-wide there is an increased concern towards sustainable solution to improve indoor situation without compromising environment. But traditional materials have the potential to sustain indoor thermal comfort with passive control when they are used in advanced way(Latha, Darshana et al. 2015).

In the tropics, where energy consumption are associated with indoor thermal comfort (Vyas 2005) it should be given supreme importance for buildings. Analytical study on local buildings regarding traditional materials provides with better understanding of relationship between climate and built-form towards enhanced indoor environment (Hyde 2000).However, traditional timber houses of Bangladesh are commonly believed to be thermally comfortable but analysis regarding indoor thermal performance in the changing climatic condition is marginal. Therefore, this study aims at evaluating thermal performance of traditional timber house's envelope through field monitoring and parametric studies. The study will provide a base to develop advanced timber-based material towards improving the indoor thermal environment with a reduction of temperature during heat stress within the buildings at the present urban level.

1.4 Aim and Objectives of the Study

The overarching aim of this research is to evaluate the thermal performance of traditional timber houses' envelope with respect to indoor comfort that can be achieved by proper designing of residential houses. To achieve the aim of this study worked on the following objectives:

i) To study and analyze the construction material and construction details related to indoor thermal performance of timber house

ii) To study the indoor thermal environment (AT(°C), RH (%), surface temp etc.) of timber house regarding indoor thermal comfort

iii) To develop envelope construction database for designing timber house envelope regarding thermal performance in the context of Bangladesh

1.5 Research Question

The study aims to evaluate thermal performance of traditional timber houses' envelope regarding indoor thermal comfort, hence, based on the following research question:

'How effective is the existing envelope of traditional timber house in sustaining indoor thermal comfort in the prevailing local climate of Bangladesh?'

i) What materials are used in construction of traditional timber house?

ii) What are the strategies adapted within tradition timber house regarding indoor thermal comfort?

iii) What is the impact of envelope material on indoor thermal environment of traditional timber house?

iv) Are the traditional timber houses of Bangladesh thermally comfortable in the prevailing local climate?

1.6 Outlines of the Thesis

The thesis consists of seven chapters. Introduction and outline of the whole thesis is presented in the first chapter. Second chapter presents knowledge regarding climatic context of Barisal (Pirojpur) and Cox's Bazaar- location of traditional timber house and reconnaissance survey conducted to specify typology of traditional timber house to be selected for the study. In chapter three, four, five and six both field and simulation studies conducted has been discussed to determine the thermal performance of envelope of traditional timber house. Chapter seven summarizes the conducted study findings and conclusions drawn from the former chapters which provide a basis for recommendation. From the summery recommendation and future research directions have been identified at the end of this section.

- ***Chapter 1_Introduction***

  This chapter presents an overview of the study conducted. Research background, major keywords, problem statement, study aim and objectives, research questions, possible outcomes and scope and limitation is summarized in this chapter.

- ***Chapter 2_Literature Review***

  This chapter presents information on standard of indoor thermal comfort range for rural areas of Bangladesh and climatic context of the regions of traditional timber houses where they are located. Data have been collected and presented from previously published materials (Journals, books, websites etc.). A reconnaissance survey prior to detail field monitoring has been conducted to specify typology and select study cases for on-site environmental data monitoring. Information regarding this reconnaissance survey is also presented in this chapter.

- ***Chapter 3_ Methodology***

  In this chapter research methodology adopted for the current study has been explained in detail. Process of field monitoring, instruments used, installation of instruments, questionnaire survey details and an overview of selected simulation engine used for parametric study has been presented. Finally result analysis and synthesis process has been discussed at the end of this chapter.

- ***Chapter 4_Field Survey***

  Findings of field survey (Fig. 1.8) have been discussed in detail in this chapter. Qualitative and quantitative information collected from on-site environmental data monitoring, questionnaire survey and observations have been analyzed and synthesized to present an overview of current scenario of traditional timber house.

- ***Chapter 5_Simulation Parameters and Validation***

  This chapter presents the overall consideration and process of parametric database preparation for the simulation study. Several simulation studies have been conducted for validation of prepared three-dimensional model prepared. A detail process regarding how the model was validated has been illustrated at the end of this chapter.

- ***Chapter 6_Parametric Result and Analysis***

  In this chapter presents results of parametric studies. Furthermore, the chapter correlates the results of the field study and simulation experiments in order to determine envelopes thermal performance. Finally results of different design strategies examined have been analyzed regarding indoor thermal comfort standard specified in chapter 2. This provides the base for recommendation for design developments regarding improved indoor thermal performance and suggesting future research directions.

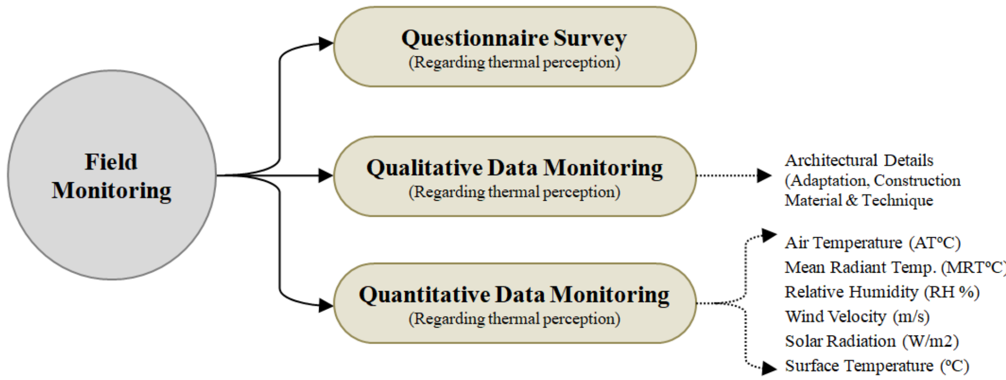


Figure 1.8 Field survey

- ***Chapter 7_Conclusions and Recommendations***

  Conclusions and recommendations of the research and suggestion future research work have been presented in this chapter. Finally, recommendations for envelope design with reference to locally available materials in the context of Bangladesh have been discussed.

1.7 Scope and Limitations

This study principally focused on thermal performance evaluation of traditional timber houses' envelope towards enhanced indoor thermal condition in the context of rural areas of Bangladesh. For performance evaluation all the four elements of envelope: floor, wall, window and roof have been considered. Parametric studies have been conducted to evaluate year-round performance of the envelope for identifying discomfort period of the year. Finally, several design strategies have been examined towards improved indoor thermal environmental condition during the discomfort period. Study will provide base regarding study on energy-efficient wood-based envelope material in the future.

Field monitoring have been conducted to identify the existing indoor thermal condition of traditional timber houses. During field monitoring air-leakage at different part of house may lead to certain degree of uncertainty in collected data. Due to scope and time limitation, as whole year seasonal on-site data monitoring was not feasible, that's why 24hrs-48hrs environmental data has been collected and parametric simulation tool EnergyPlus has been conducted for predict of whole year indoor thermal condition. Validation of EnergyPlus three-dimensional model has been done before conducting the parametric studies. However, unlike other parametric studies, a margin of error may occur in the simulation result compared to practical conditions. For field and simulation studies thermal environmental parameters i.e., AT, MRT, OT, solar radiation and wind speed is considered. But other factors like air-leakage, energy related issues, fire safety, security etc. are out of scope of the research. Due to time and resource restrictions, assumptions were made and study areas and prospects were left for future investigations.

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CHAPTER TWO: LITERATURE REVIEW AND RECONNAISSANCE SURVEY

2.1 Introduction

Worlds' climatic regions are broadly categorized as: Cold, Moderate, Hot-humid, Hot-dry and Composite in terms of their thermal and seasonal characteristics . Each regional climate is the environment for the design of buildings and each region requires distinctive design responses. For example, a house in the tropics reflects a contrast of building and operating in harsh climatic conditions (Givoni 1998; Lauber et al. 2005). The micro-climate of a site (i.e., temperature, relative humidity and wind movement) resulted in changes in the building's indoor thermal environment. Therefore, the outdoor factors that influence the indoor thermal environment are fundamental to improving comfortable and healthy indoor environment in residential building. Because the indoor thermal environment affect the performance of human activities, and maintenance of health and well-being (Omer 2008; Arif et al. 2016).

Occupants need thermally comfortable environments within the houses (Renaud 1984; ASHRAE 2010) and a building is an environment to enhance the living, function or leisure of the residents. Studies reveal that for shelter, security and comfortable living conditions people spent over 15-25% of all savings in both developed and developing countries (Renaud 1984). But the traditional houses being the socio-economic and environmentally sustainable product reduced the energy cost for ensuring a comfortable indoor thermal environment by promoting passive techniques (Santamouris et al. 2006; Omer 2008). In tropics temperature, relative humidity, solar radiation, rainfall and prevailing wind are the most common climate parameters that impacts both positively and adversely to the building design. While a strong understanding of the environment helps efficient construction. Hence it is important to analyze and collect data that are relevant to a suitable strategic design in order to benefit from the climate in order to meet the thermal needs of a building (Pretlove and Oreszczyn 1998).

Envelope of building is the interface between indoor and outdoor which directly interacts with the climate and result in the creation of a desirable indoor environment. In Bangladesh the outdoor is usually warmer than building indoor environment and the traditional houses are believed to be thermally comfortable. These houses optimize the use of locally available materials as well as local climatic benefit and technology. That's why the country has a wide variety of region-specific traditional architecture which is believed to be sensitive to the local climate. So, to understand the indoor thermal performance of the traditional houses it is crucial to understand the climate of the region. Again detailed information about the local AT, humidity, and wind patterns is required to define the local climate more precisely (Gonzalo and Habermann 2006) as these are the essential climatic factors that influence the indoor conditions of the house. The following sections are concerned with the literature review of the local climatic condition, typology and socioeconomic influence on traditional timber house.

2.2 World Trend and Benefit of Using Wood

Nowadays using wood in construction is a growing global trend because of its manifold benefits. High-rise buildings are constructed with wood. Because of its strong insulating properties, bio-climatic material wood is appropriate for providing enhanced indoor thermal environment in tropical climates. Studies reveal that residents in buildings with wooden walls feel more comfortable than occupants in dwellings with exposed brick walls (Hermawan et al. 2014; Hendriani et al. 2017). Wooden envelope is capable of reducing 0.7°C compared to exposed brick envelope. Besides that using wood instead of steel results in one-third less carbon emission. In terms of life-cycle carbon emission use of wood instead of steel and concrete results in 74% and 69% less carbon emission (Cao 2021). Again, one cubic meter of young sequesters one liter of CO_2 and release 0.7 liter of O_2 in return (Fig. 2.1). But the rate of producing O_2 decreases with age of trees. Therefore, using old trees for constructions means storing away CO_2 from atmosphere for decades as well as more space for trees and more CO_2 sequestration (Hurmekoski 2017).

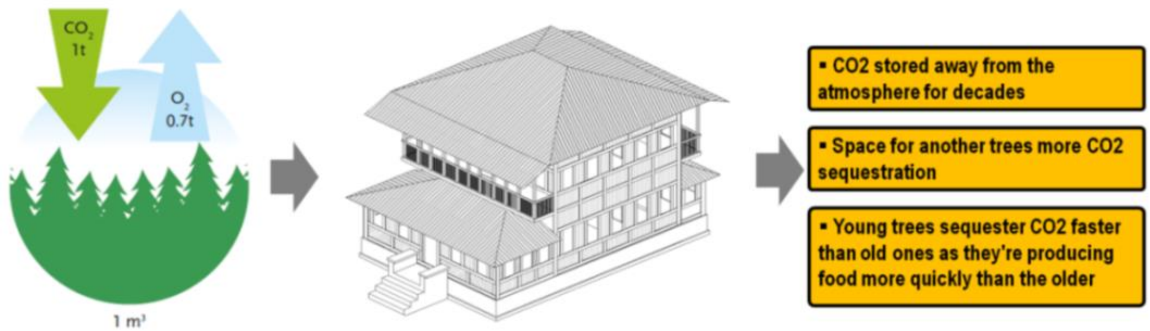


Figure 2.1 Wood in construction and CO_2 sequestration(Hurmekoski 2017)

2.3 Challenges of Architecture in Hot-humid Climate

The hot-humid climate is characterized by characterized by hot and humid summers and cool to mild winters. Hot-humid period is typically long which has high AT combined with high humidity. This poses problem while designing as for restricting penetration of high heat to the indoor environment thick envelope is advantageous but because of high humidity in air may cause mold growth/ condensation within the envelope, hence, thin envelope is preferable. Again, humid envelope is easily subjected to insect attack and rust formation which leads to quick decay of construction materials. Therefore, a balance is needed to be made to deal with this paradoxical condition.

As hot-humid period lasts long, therefore structure should allow prevention of heat gain through passive/active cooling system while maximizing heat loss (Olgyay 1963). Hence, hence, in this climate usually ventilation and shading are important features for buildings in this climate. Roof envelope being the largest exposed element should be capable of restricting heat penetration.

Subjective discomfort in hot-humid climate is associated with wet skin and high moisture in the air (Koenigsberger et al, 1973). Again, radiant heat causes rise AT higher than skin temperature. Ventilation help replacing indoor hot air with outdoor fresh wind and this also enhance evaporative heat loss from human body. But when the outdoor AT is higher than indoor AT evaporative cooling is not possible even if RH is below 100%. Still airflow introduces psychological cooling effect to the occupants. Therefore, structures should allow free air movement around and continuous ventilation within the buildings (Koenigsberger et al, 1973).

2.3.1 Natural Ventilation in Tropics

Natural ventilation is the air movement which takes place through the openings of structure due to stack effect caused by temperature variation between indoor and outdoor, natural wind pressure or a combination of both actions (B.S.I. 1991). Structure with this condition is known as naturally ventilated building. There are three types of ventilation: one-sided, cross and courtyard/atria ventilation (Awbi 1996; CIBSE 1997). In single-sided ventilation system, ventilation effectiveness depends on opening numbers and their relative position (Gan 1999; Eftekhari et al. 2003). Cross ventilation occurs when room has openings on two horizontal sides of room. Effectiveness of cross ventilation depends on depths of room (Murakami et al. 1991; Kato et al. 1997). On the other hand, in courtyard ventilation hot airs rises up and cool air enters through the openings at lower level (Saxon 1986; Andersen 1995; Wong et al. 2000).

In tropical climate stack effect induced natural ventilation is not considerable because of relatively little temperature difference between indoor and outdoor and permeable external envelope combined with horizontal connection of openings with the building (Andersen 1995; Feriadi 1999).

2.3.2 Heat Exchange through Building Envelope

Building envelope acts as a barrier between indoor and outdoor environment. Therefore, indoor thermal environment is influenced by the thermo-physical properties of the envelope materials. Studies reveal that wall envelope is subjected to 35% of total heat gain/loss within a space where for roof, floor and ‘ventilation and infiltration’ the percentage is 25, 15 and 15 respectively (Anderson et al. 2011). Fig. 2.2 shows the heat transfer rate and process through building envelopes. When solar radiation falls on an exposed opaque surface part of it is absorbed and converted into heat whereas a part of it is lost to the outer environment by convection and radiation while the remaining part is conducted to the indoor (Markus and Morris 1980). Some of the conducted heat is stored in the wall and the rest of the part is researched to the indoor surface. Heated inner surface radiate heat in the indoor environment and rest of the heat is transferred through convection process raising the indoor AT (Fig. 2.2). Similar process also takes place between different envelopes resulting in the ultimate indoor thermal environment which in turn effects the occupant’s thermal perception and satisfaction.

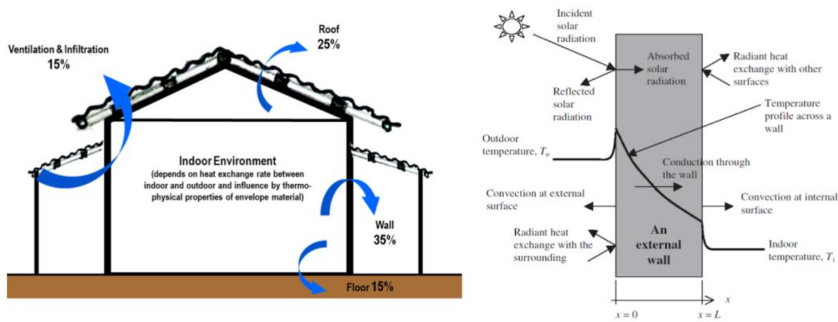


Figure 2.2 Heat loss & transfer process through wall (Givoni 1998; Anderson, Antkowiak et al. 2011)

2.4 Traditional Timber House of Bangladesh

In Bangladesh, a traditional house is primarily a shelter concerning its environment and social space with its cultural context. Beyond meeting the practical needs of the family, the house represents human aspirations, aspires, and identity and its connection to the society and to the environment in which it resides. Not only are the practical requirements of regular life impaired in the organization of spaces within the house but, more significantly, social norms, traditions, and expectations are culturally defined. The traditional house construction and layout developed over the years very slowly under the influence of several factors, including the land, culture, the environment and the resources available, etc., where the growing trends in human desire have always been a real concern in the practice of this housing technology, especially among groups of people who have been living near nature for ages.

Bangladesh is located in the subtropical monsoon climate zone. The nature of the seasons in different regions of the country varies considerably. Based on the current weather conditions, climatic regions can be broken up in Bangladesh: South-eastern, North-eastern, Northern part of the Northern region, North-western, Western, South-western, and South-central zone (Rashid 1991). Architecture possesses identical characteristics to sustain within a specific climatic region resulting in a contextual variety of houses. Besides that, people's economic capacity, social values, and limited resources also shape the characteristics of traditional houses. People like to construct houses using their proverbial materials. Raw materials transportation with local means, indigenous expert's knowledge of handling the material, and local construction techniques have a prime role in the construction process of the house. Such expertise is built over a long period through the trial-and-error process. This trial-error method combines the socio-economic facts of cost, quality, simplicity of work, climate resilience at the same time sense of prestige and beauty. That's why these traditional houses are believed to be responsive towards the prevailing climate, function closely with the local creeds and customs using the local materials, which offer comfortable indoor in turn (Baker 1987; Bansal 1994; Chancellor 1994; Sayigh et al. 1998). Several generations lived and maintained their culture and traditions for centuries. This illustrates the adaptability and resilience of conventional rural architecture. It is the legacy of the past; it remains today and has a future promise.

Rural Bangladesh provides an impressive variety in terms of floors, walls, and roofs in typical house styles. Based on this construction material, used as an envelope, these houses can usually be classified as mud-house, bamboo house, timber house, stilts house, etc. Timber-framed houses are often recognized as wooden houses locally. But in this study 'Traditional Timber House' only refers to the houses whose frame and envelope both are constructed with wood. This traditional timber house is mainly native to the South-eastern part of Bangladesh. During the reconnaissance survey, this timber house is found near coastal areas: Barisal district, southern part of Khulna district and among the Rakhain tribal group of Cox's Bazar district (Ramu, Maheshkhali etc.). These houses, because of its location, are challenged by high wind and cyclone like phenomenon. Therefore, in addition to thermal comfort and protection from rain, adaptation to this unique situation has highly influenced the design and construction of the traditional timber house in Bangladesh. But indigenous peoples with distinct cultural traditions have been living in the coastal areas for centuries thus have had a strong interaction with the environment. They are supposed to develop an indigenous cyclone understanding and have thus good strategies for survival. They have successfully upheld this traditional knowledge from generation to generation. The local builders who have an outstanding ability to place their homes in a natural setting and building methods that satisfy the climatic requirements quite well. Each detail of the house surprisingly has its strong explanation and interaction with nature.

Figure 2.3 Floating wood market of Swarupkathi (Nesarabad), Barisal (Source: Author)

There is no significant study on when these timber houses in Bangladesh have been evolved. But, the famous floating wood market of Barisal started its journey in this region in 1918 on a canal of the Sandha (Fig. 2.3) River based on the logs coming from Sundarbans. Thus, it can be assumed that extensive use of wood in houses flourished nearly at that time. At that time trading of the "Sundari" tree collected from the largest mangrove swamp forest of Sundarbans, was the main business here. But soon after banning of this tree by the govt. of Bangladesh in 1987, the local traders started trading other trees coming from different parts of the country. Today this is the largest wood market in the country. This abundance of wood and the climate in this region reflect a widespread utilization of wood in this region. During the field survey, the residents (houses that are 100+ years old) of traditional stilt timber in Cox's Bazar claimed that the timbers are brought from Assam. The large river network in this area and the Bay of Bengal were made it possible to bring a huge log of wood easily from nearer areas.

2.4.1. Location of Traditional Timber House

Timber houses are detached residential units used for living purposes only. These houses are found in south-eastern, north-eastern and south-western climatic zones of Bangladesh. Fig. 2.4 shows the location of timber houses in different climatic regions. But for the study traditional timber houses which uses wooden structure and wooden envelope were selected. These types of houses are found exclusively in south-eastern zone and locations are encircled in Fig.2.1 (red marked). During reconnaissance survey three (03) typologies of these traditional timber houses were found: (i) single-storied, (ii) double-storied and (iii) stilt timber houses. Among these, single and double-storied houses are built by local people in many areas of Barisal and Khulna. In contrast, stilt ones are constructed exclusively by Rakhine ethnic groups in some regions of Cox's Bazar, Barguna and Patuakhali.

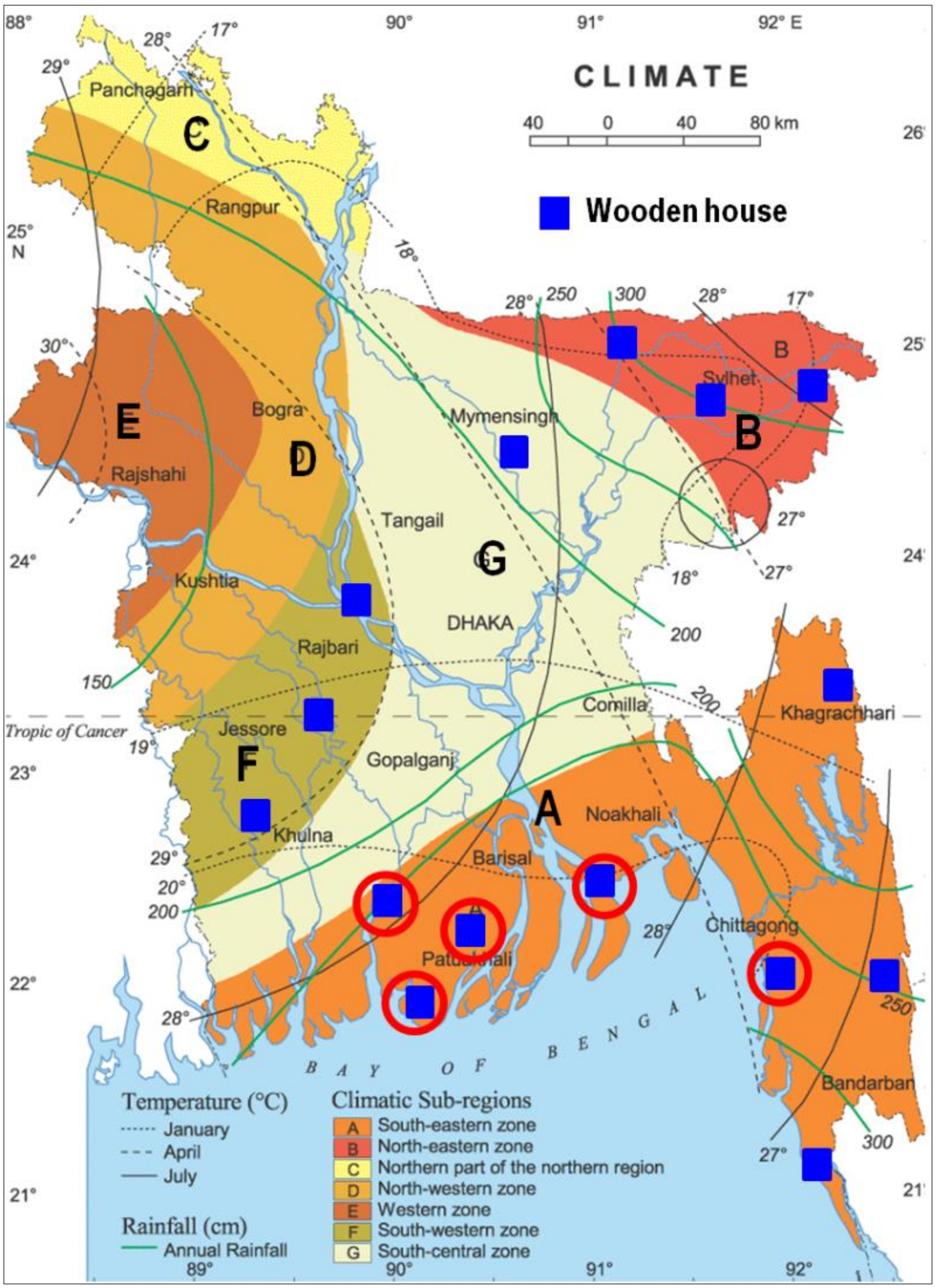


Figure 2.4 Traditional timber house locations in different climatic regions (Rashid 2007)
(Map source: *http://lib.pmo.gov.bd/maps/images/bangladesh/Climate.gif*)

2.4.2. Typology of Tradition Timber house

During the reconnaissance survey, three types of timber houses have been found which can be classified as single-storied, double-storied and stilt timber house (Fig. 2.5) based on number of floors. Among these, the single and double-storied timber house is commonly constructed by local people in most of the areas of Barisal and South part of Khulna districts. But the stilt timber house is a unique artifact of Rakhain tribes mostly found in some areas of South Chittagong (Cox's Bazar municipality, Khuruskul, Chowfaldandi, RamuSadar, Panerchhara, Ashkor Kata, TeknafSadar, Kharangkhali, Hneela, Harbang of Chokoria, Gorokhghata of Maheskhali); Patuakhali (Khepupara and Kuakata) and some areas of Barguna.

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

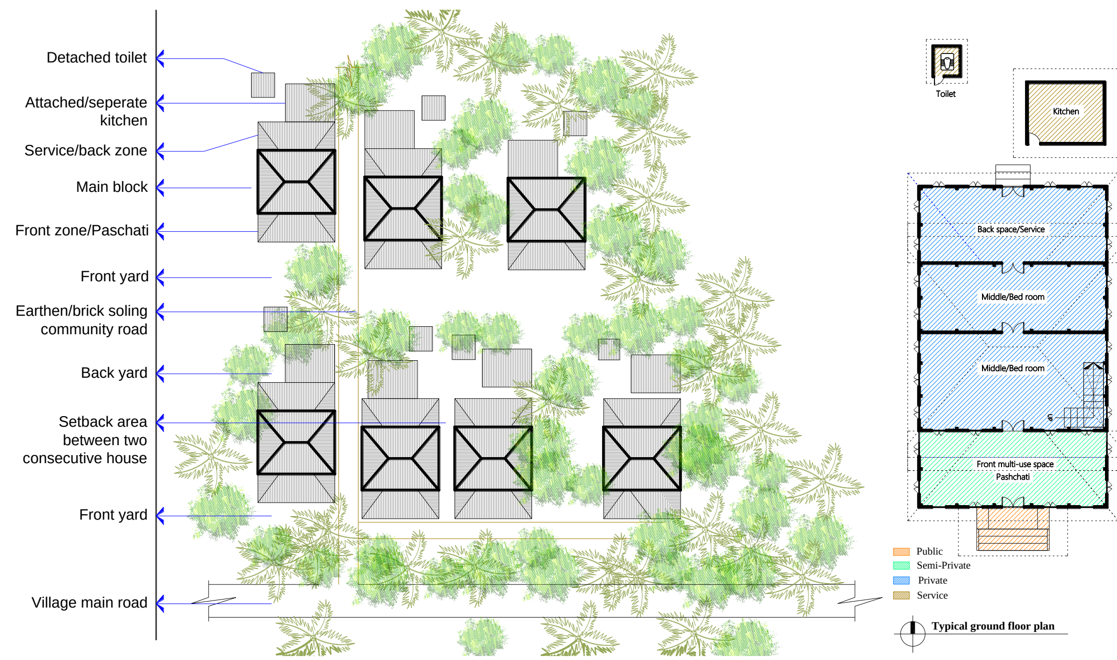
Figure 2.5 Typology of traditional timber house: (a) single-storied, (b) double-storied and (c) stilt
(Source: Author (single and double-storied timber house) and Google (stilt timber house))

a) Single and Double-storied

Traditional vernacular houses cannot be seen in isolation from the settlement but should be considered concerning the way of life, settlement, and yet landscape (Rapoport 1969). There have been differences in settlement patterns in Bangladesh in various physiographic regions with diverse characteristics. In the formation of unique forms and patterns of settlements, various physical, cultural, and local contexts have also played a vital role. From the beginning, there have been diverse settlement patterns in different parts of the country, such as linear, scattered, clustered and nucleated, dispersed and isolated, etc. (Choudhury and Zaman 1976). Traditional timber house settlements found near coastal and offshore land, follow linear patterns near the river levees and the reason for following the rivers is the transportation facility. But the scattered pattern is also found. Fig. 2.6 illustrates settlement pattern and zoning of traditional double-storied timber house.

Family structure is mostly a joint family type but a nucleated family is common among the poor. Occupation is agriculture dominated but because of the vast network of the river trading, fishing, boating is also common among people. The size, construction material, and technique, etc. of the house varies according to the socio-economic status of the inhabitants but the basic concept of the timber house remains the same for all. Double-storied houses are common among the rich people but single-storied are popular among poor for constraints of land and minimizing maintenance cost.

Main design of the traditional Bengali home consists of two wide zones, regardless of geographical changes, materials, temperature, etc. and all house activities are arranged in these zones: (a) formal zone and (b) informal zone (Khan 1982). Formal zone is outer part of the house which is male oriented whereas the informal zone is female oriented and inner part of the house where cooking, washing, sleeping etc basic activities take place. Generally, in the settlements of traditional timber house, every house has the front space used as a courtyard with large trees as a visual barrier and backspace as the backyard with tube-well, toilet, and kitchen facilities for the female members of the family. Hence the backyard serves as the private space for the women of the community. This is the result of local perception of privacy which shapes the functional organization of space. The house has two basic parts: the front part and the inner part. The front part is the formal part mostly public in nature and male dominating. This is usually a multifunctional space for the family to react with the larger community. In the front part of almost every double-storied house has accommodation for sitting which reflects the social bondage among the people of this region. The inner part is informal and private in nature and female dominating. This occupies the resting and service space. All functions such as sleeping, cooking, washing, caring for babies, etc. takes place in this part.



(a) **(b)**

Figure 2.6 Double-storied Timber house: (a) settlement pattern and (b) internal zoning
(Source: literature and field survey, Illustrated by Author)

b) Traditional Stilt Timber House

Rakhain, an ethnic community from Arakan, migrated from Myanmar to Bangladesh in the late 18th century and settled in the coastal districts of Cox's Bazar and Patuakhali. According to the census of 1991 (Bangladesh-Bureau-of-Statistics-(BBS) 1991), Rakhain community population in Bangladesh is about 7,000. At present, majority Rakhain people are concentrated in the areas of South Chittagong's coastal belt (Cox's Bazar municipality, Khuruskul, Chowfaldandi, RamuSadar, Panerchhara, Ashkor Kata, TeknafSadar, Kharangkhali, Hneela, Harbang of Chokoria, Gorokhghata of Maheskhali); Patuakhali (Khepupara, and Kuakata) and Kalapara and a part of Barguna districts (Bangladesh-Bureau-of-Statistics-(BBS) 1991). Though the basic features are the same but in this study houses of the Chittagong district of this typology have been surveyed in detail and hence discussed.

Stilt timber traditional timber house is a unique house form that originates among the Rakhain ethnic group of Bangladesh. It meets not only practical and economic needs but also social, environmental, and spiritual needs. The unique characteristics of traditional houses are not only a product of the geographical location but also the lifestyle, history, and regional culture of individuals. Those are the main factors that contribute to the development of regional architecture.

Religious belief and life-style of the Rakhain people intensely influenced the physical structure. They are the followers of Buddhist ideology this in turns shapes their lifestyle. The Rakhain craftsman interpreted ‘Buddhist philosophies’ into buildings, paintings, sculptures and other physical structures. But the information about traditional construction is not preserved in written form. The exchange of information is down through generations by a process of understood and communicate. They build their settlements on flat landscape especially near river to make the agricultural procedure simple. The settlement is organized linearly where houses are constructed on both sides of the linear spine (Fig. 2.7). Houses are extended towards east-west direction and house plan emphasizes recti-linearity since in Buddhism straight lines represent purity, focus, and determination (Aris and Hutt 1994).

(a) **(b)**

Figure 2.7 Stilt Timber house: (a) settlement pattern and (b) internal zoning
(Source: literature and field survey, Illustrated by Author)

The functional space division is based on vertical hierarchies, where the spaces with their distinctive functions are designed at a different level. House is elevated from the ground representing the religious beliefs of the Buddhist community, where such a raised platform exerts a higher value of mind. The number of stilts/posts and the height of the wall have religious influences. Usually, there are 38 numbers of posts/stilts which refer to Mingalasutta - contains 38 rules for a beatific life (Moe 2019). The upper floor is dedicated to living with sacred areas. Functionally the house has three major parts: the public shaded space on the ground floor, both semi-public guest and prayer space and restroom and service space on the upper floor. The column and height of the wall of the prayer room are higher than the rest of the wall in the house. The central part of the house occupies the owner’s room/’Kyun’ supported by a total of 9 posts (red posts in Fig. 2.8) from east to west arranged in three rows having three posts in each row. This room is surrounded on four sides by 14 posts (pink posts in Fig.2.7) supporting the "Kyunyan"/children's room and service block. The floor of the 'Kyunyan' is kept 100-150mm lower than the 'Kyun'. Again except for the western block posts, the other three sides of the house have 16 posts (orange circle in Fig. 2.8), known as 'dragon-wise'. A total of 36 posts are used with the western side posts to elevate the house. Again two sides at the front are kept outside 'dragon-wide' from where the guests are welcomed. With these two posts, the house has a total of 38 posts.

Figure 2.8 Activity area at ground level (Source: Author)

The use of elevated platforms supported by stilts helps the house to float above the eye level of people creates a sense of lightness and floating. These light and floating feelings involve Buddhist teachings about meditation and calmness. Wooden staircase leading to upper floor has odd numbers of steps and according to these people, it is auspicious for them. Vacant space underneath is used as a weaving area, performing different domestic chores, stores and social interaction areas (Fig. 2.8). Roof represents the Buddhist cultures. They construct a high-pitched roof as according to the believers; it is the way to connect the earth to the sky. They believe it makes a connection between earth and heaven (Aris and Hutt 1994). Table 2.1 illustrates the common features of traditional single/double and stilt timber houses of Bangladesh.

Table 2.1 Common features of traditional single/double-storied and stilt timber house

Single-storied and double-storied house	Stilt timber house
Agriculture is the main occupation for majority of the people. Trading (wood/fish etc.) related activity has nearly the same percentage. Agricultural laborer, wage laborer, fishing, boating, etc. are also common. While women are rarely involved with economic activities.	Agriculture is the main occupation but fishing, boating, trading is common among people. Active participation of women in economic activities with the male.
Mainly a joint family. Average family members of 5-6. Nucleated family is common among poor/marginal people.	Joint family with 6-7 members.
Linear pattern with closely spaced detached house.	Linear pattern with closely spaced detached house or detached homestead at the center of a land plot. A well-cleared welcoming space for visitors in front of house.
Homestead is raised on a high plinth having separate kitchen and toilet from the main block.	Elevated on stilt usually accommodating space for kitchen, service, weaving, and other domestic chores.
Surrounded by trees creating a boundary and visual barrier for the occupants.	No boundary. Huge vegetation i.e. coconut and other evergreen trees around the compound especially on the south and south-western direction.
Size f the house varies with the economic status of the owner. Double-storied is common among affluent and single are popular among others.	Size of the house varies with economic status of owner. Affluent class constructs large house having more rooms.

Houses are rectangular in plan having a length-width ratio of 2:1/3:1.	Rectangular/ nearly squarest L-shaped. House plan emphasizes recti-linearity as in Buddhism it represents purity, focus, and determination.
House form is 'Introvert' in nature with front and backyard which is the materialistic expression of their sense of privacy of female from the male.	House is elevated from the ground as in Buddhism raised platform represents a higher value of mind. The space beneath the elevated platform is open and main social interaction space.
House has front and back yard, public, and private respectively.	The spaces have a level difference: 'Atherung' is the central space having height level. And other spaces are one/two-step down from it.
Functional divisions in internal space organization: Front multi-functional semi-open space (semi-public), Middle part for resting and Rear part as service zone, and the last two are private in nature and female domain.	'Prothong' (Front room/Living room) is the guest receiving part semi-public in nature. Sometimes in large house 'Agendurung' (guest room) is provided separately. The next is the 'Songowa' (prayer room) semi-private in nature. The next part is private accommodating 'Atherung' (owner's restroom), Nowpeirung (childbed), and 'Thamasarung (kitchen/service).
The front yard is public and formal. Multifunctional area to communicate with larger community/ space for social bondage. Backyard mainly female-dominated hence private that occupies kitchen and toilet, and water source (tube well/ pond), etc.	'Songowa' shares the holy (first erected post for house construction) post and the largest partition wall. And usually placed at the center of the house.

2.5 Climatic Profile of the Study Area

Climate is the complex result of several environmental factors (Sarma 2002) which are solar radiation, long-wave radiation to the sky, AT, humidity, wind and precipitation (Givoni 1969). Among them three major components temperature, humidity and air movement make the climate (Markus and Morris 1980). Temperature, solar radiation, relative humidity and air movement are the four important climatic parameters which directly affect thermal comfort. These climatic constituents play critical role towards building design within a specific region. Therefore, before evaluating thermal performance of traditional houses of a region it is necessary to understand the climatic parameters of that particular region.

Tropical region lies between the latitude of 15° South and 15° North within the tropics of Cancer and Capricorn having tropical climatic condition characterized as large amount solar radiation with high humidity and heavy rainfall. Bangladesh, located near the tropic of Cancer and Capricorn (Ahmed 1994), is one of the tropical countries lies between 20°34' N to 26°33' N and 88°01'E to 92°41'E, in the Indo-Malayan Realm (Lean, Hinrichsen et al. 1990) having North, East and West sides bounded by land and the South by the Bay of Bengal and exhibit tropical climatic condition (Mallick 1996). Four pre-dominant seasons: hot and dry pre-monsoon (March to May), hot and wet monsoon (June to September), post-monsoon (October to November) and dry winter (December to February) (Ahmed 1995; Mridha 2002; Ahsan 2009) with moderately noticeable seasonal variation all year round is noticed. Winter is cool and dry but other seasons are hot and humid (Ahmed 1995)that have high temperature combined with high humidity and heavy rainfall. Fig. 2.9 illustrates the climate of different regions of Bangladesh. But patterns of climatic factors among various parts of the country vary from region to region considering locations (Mallick 1996). Traditional timber houses are mostly found near the Southern part of Bangladesh and because of proximity of the Bay of Bengal, climatic condition of this region is different from rest of the country. Based on collected meteorological data, climatic parameters of the study area of traditional timber houses have been discussed in this section.

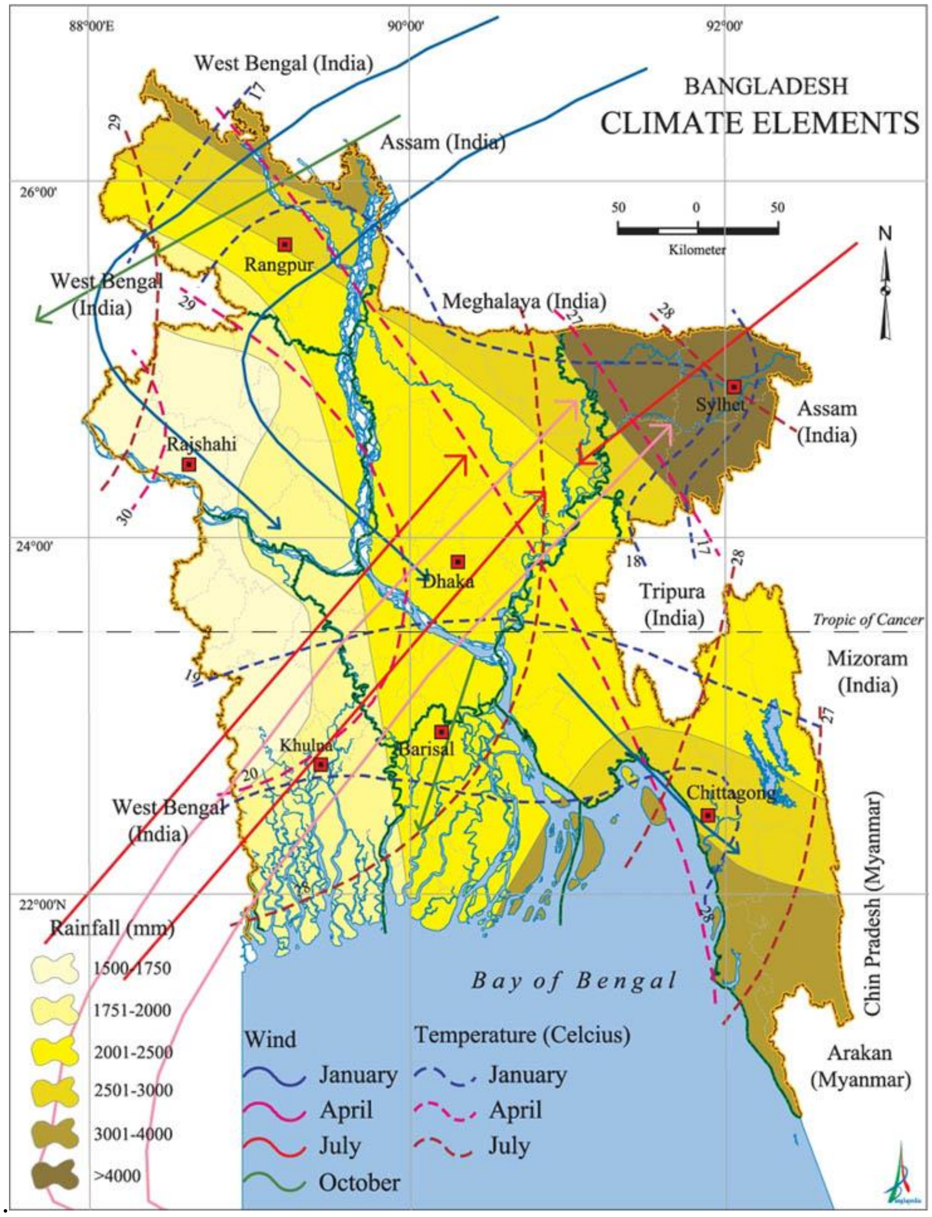


Figure 2.9 Climatic elements of Bangladesh

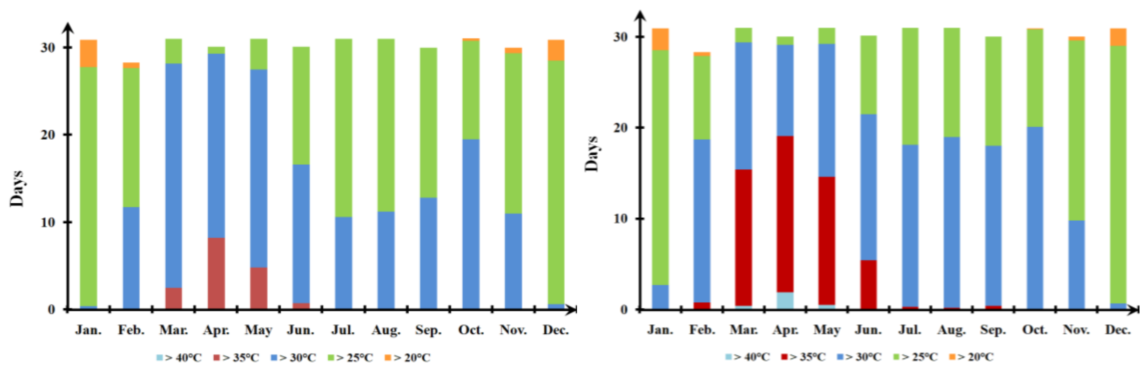
(Source: *http://galleryhip.com/gangetic-plain-map.html*, Accessed on: 25th May 2019)

2.5.1 Temperature

Pre-monsoon periods are the warmest month of Bangladesh because of clear sky, dry climate, greater sunlight angles, greater solar intensity, longer sunshine duration (Roy 2010). Temperature data of Bangladesh Meteorological Department shows that maximum temperatures of Cox's Bazar and Barisal are recorded in pre-monsoon period (March-May) and high temperature remains for most of the days compared to other months (Fig. 2.10). Table 2.2 illustrates the Monthly temperature data of Cox's Bazar and Pirojpur for 30 years' period (1981-2010). From the table it is observed that at Barisal, temperature is higher in April with a normal maximum value of 33.5ºC whereas at Cox's bazaar it is in May with a normal maximum value of 32.8C (Khatun, Rashid et al. 2016). During hot-humid period mean maximum temperature fluctuates between (30.5ºC-32ºC) and (31ºC-32ºC) at Cox's Bazar and Barisal respectively. January is the coldest month with an average high-temperature of 27.1°C and an average low-temperature of 15.4°C at Cox's Bazar while at Barisal average high-temperature is 25.5°C and an average low-temperature of 12°C.

Table 2.2 Monthly temperature (ºC) data of Cox's Bazar and Barisal (period 1981-2010)

Month/Variables		Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.
Season		Hot-dry			Hot-humid						Cool-dry		
		Pre-monsoon			Monsoon				Post-monsoon		Winter		
Cox' s Bazar	Max.	31.5	32.7	32.8	31.2	30.5	30.8	31.5	32.0	30.6	28.1	27.1	29.1
	Min.	21.2	24.2	25.3	25.4	25.3	25.3	25.1	24.5	21.1	17.0	15.4	17.6
	Dry bulb temp.	26.0	28.3	28.9	27.8	27.4	27.5	27.8	27.6	25.1	21.7	20.4	22.7
Barisal	Max.	32.4	33.5	33.4	32.0	31.2	31.4	31.7	31.7	29.8	26.8	25.5	28.5
	Min.	20.5	23.8	24.9	25.8	25.7	25.8	25.4	23.7	18.9	13.6	12.0	15.4
	Dry bulb temp.	25.9	28.3	28.9	28.7	28.2	28.4	28.2	27.2	23.6	19.2	17.9	21.5



(a) **(b)**

Figure 2.10 Days per month reach certain temperature: (a) Cox's Bazar and (b) Barisal
(Source: metaboule.html and Bangladesh Meteorological Department)

Analysis on changes in Bangladesh climate pointed towards higher rate of temperature increase for the southern regions of the country (Khatun, Rashid et al. 2016). During pre-monsoon and post monsoon season considerable rise of maximum temperature is observed at Cox's Bazar (+0.6°C and +0.5°C respectively) during the period 1981-2010. During winter season, maximum temperature increases both at Barisal and Cox's Bazar (+8°C). Significant rates of increase of maximum and minimum temperature per hundred years are 3.2ºC and 2.2ºC at Cox's Bazar. At Barisal increase of maximum temperature is less compared to Cox's Bazar while minimum temperature per hundred years shows a decreasing trend.

2.5.2 Relative Humidity

Relative humidity has been found to be inversed to existing temperature and therefore a temperature increase reduces the relative humidity level in a particular situation, if all other conditions remain the same (Mridha 2002). Relative humidity of Cox's bazaar and Barisal remains very high all through the year, however, pre-monsoon and winter season it remains comparatively low. Highest relative humidity observed during monsoon (June-September). Table 2.3 shows monthly normal relative humidity data of Cox's Bazar and Barisal. From the table it is observed that the least humid month is January and February, with an average relative humidity of 71-72% while July is the most humid month with an average relative humidity of 89%

at Cox's Bazar. Similarly, at Barisal February is the least humid and July is the most humid month with an average relative humidity of 78% and 90% respectively.

Table 2.3 Monthly normal relative humidity (%) data of Cox's Bazar and Barisal

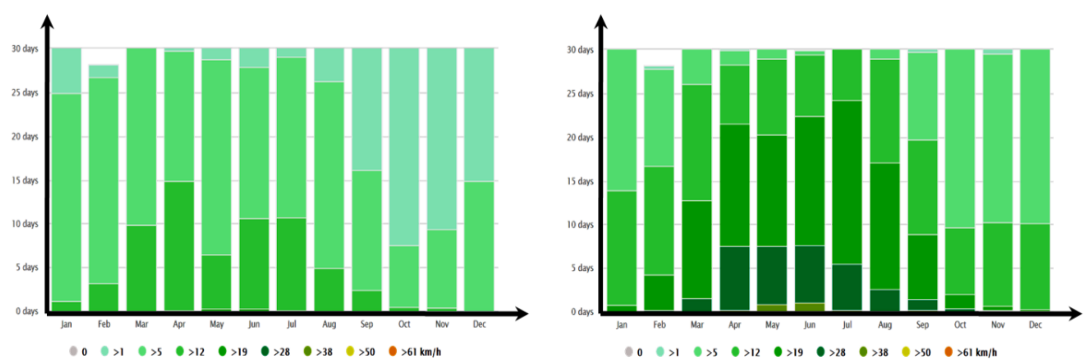
Month/Variables	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.
Season	Hot-dry			Hot-humid						Cool-dry		
	Pre-monsoon			Monsoon				Post-monsoon		Winter		
Cox's Bazar	75	78	80	87	89	88	86	82	77	74	72	71
Barisal	76	80	83	88	90	89	89	87	84	83	81	78

(Source: Bangladesh Meteorological Department)

Evaluation of humidity comfort level based on the dew point determines the facility of evaporation of perspiration from the skin in other word possibility of evaporative cooling. Lower and higher dew point corresponds to drier and more humid feeling. Usually, a humid day is followed by a humid night because, though AT varies considerably between day and night, but dew point changes more gradually. Statistical analysis of weather data during the period 1980-2016 shows that both Cox's Bazar and Barisal experience severe seasonal variation regarding relative humidity. This shows that humid period lasts for 9.9 (February-December) and 9.3 (February to November) months at Cox's Bazar and Barisal respectively. During July and August 31% and 28% of the time comfort level remains muggy, oppressive or miserable at Cox's Bazar and Barisal respectively.

2.5.3 Wind Speed and Direction

Monthly normal wind speed data (1981-2010) of Cox's Bazar and Barisal show that wind speed of Cox's Bazar is higher compared to Barisal. It is comparatively high pre-monsoon and monsoon period (March-September). For both regions highest speed observed during June and July. At Cox's Bazar highest wind speed is 6.41m/s (July) whereas for Barisal it is 2.92m/s (June). Annual average wind speed of Cox's Bazar and Barisal is 4.48m/s and 1.78m/s respectively. Fig. 2.11 shows the days/month wind speed and hours/year wind direction while Table 2.4 presents monthly normal wind speed of Cox's Bazar and Barisal.



(a) (b)

Figure 2.11 Days/month wind speed (1985-2014): (a) Cox's Bazar and (b) Barisal
(Source: metaboule.html and Bangladesh Meteorological Department)

From the figure it is observed that at Cox's Bazar, during monsoon, more than 50% and 30% time wind speed remains above 1.3m/s and 3.3m/s respectively whereas during post-monsoon more than 65% time wind speed remains above 0.3m/s. Rest of the seasons more than 75% time wind speed remains above 1.3m/s at Cox's Bazar. Yearly wind direction illustrates that majority of the year wind blows from SSE-ESE (nearly 27.7%), NNE-ENE (22.5%), West (10%) and South (7.3%) directions at Cox's Bazar. Similarly, during pre-monsoon and monsoon, more than 50%-75% time wind speed remains above 1.3m/s-3.3m/s whereas during post-monsoon more than 65% time wind speed remains above 1.3m/s and during winter more than 40% time wind speed remains above 1.3m/s-3.3m/s at Barisal. Yearly wind direction illustrates that majority of the year wind blows from S-SE (nearly 52.6%) and N-NW (17%) directions at Barisal.

Table 2.4 Monthly normal wind speed (m/s) data of Cox's Bazar and Barisal

Month/Variables	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.
Season	Hot-dry			Hot-humid						Cool-dry		
	Pre-monsoon			Monsoon				Post-monsoon		Winter		
Cox's Bazar	4.30	4.84	5.36	6.15	6.41	5.75	4.20	3.15	2.93	3.13	3.60	3.85
Barisal	1.85	3.11	3.00	2.92	2.84	2.45	1.62	0.83	0.54	0.56	0.64	0.96
Wind Direction	S			S/SE				S/SE		N/NW		

(Source: Bangladesh Meteorological Department)

2.5.4 Solar Radiation

Bangladesh Meteorological Department started collecting radiation data from 2000, but collected data after 2000 was not processed yet. Hence, solar radiation data were collected from NASA, SSE database. Solar radiation is high during pre-monsoon season and reaches its highest value during the month of April (6.04 and 5.93 at Cox's Bazar and Barisal respectively) (Table 2.5).

Table 2.5 Monthly solar radiation (kWh/m²/d) data of Cox's Bazar and Barisal

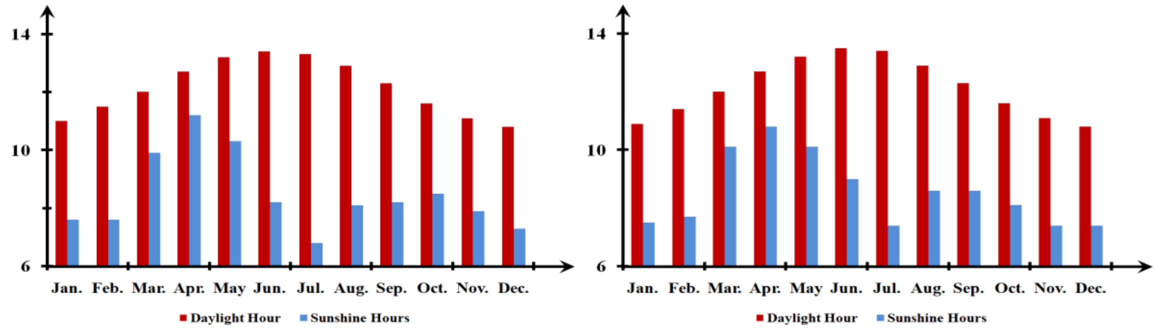
Month/Variables	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.
Season	Hot-dry			Hot-humid						Cool-dry		
	Pre-monsoon			Monsoon				Post-monsoon		Winter		
Cox's Bazar	6.08	6.04	5.35	3.91	3.83	3.99	4.35	4.44	4.32	4.35	4.67	5.34
Barisal	5.89	5.93	5.44	4.57	4.22	4.32	4.18	4.49	4.36	4.09	4.28	5.16

(Source: NASA)

Lowest insolation level is recorded during the month of July for both areas (3.83kWh/m²/d and 4.22kWh/m²/d at Cox's Bazar and Barisal respectively) (Table 2.4).

2.5.5 Sunshine Days and Hour

Sunshine hour indicates cloudiness of a region, hence, differs from insolation. It quantifies amount of energy provided by sunlight over a period. For both Cox's Bazar and Barisal, Februray has the highest number of daily sunshine hours on average. Fig 2.12 illustrates monthly average daylight and sunshine hours of Cox's Bazar and Barisal. Sunshine hours during February are normally 9.84 hours and 9.23 hours a day and a total of 305.11 hours and 286.02 hours throughout February at Cox's Bazar and Barisal respectively. Month with least sunshine in Cox's Bazar and Barisal is June which lasts for 4.3 days and 2.3 days with an average of nearly 3h of sunshine at Cox's Bazar and Barisal respectively. After June it starts increasing as during this period atmospheric condition remains cloudy resulting in considerably high diffused daylight component.

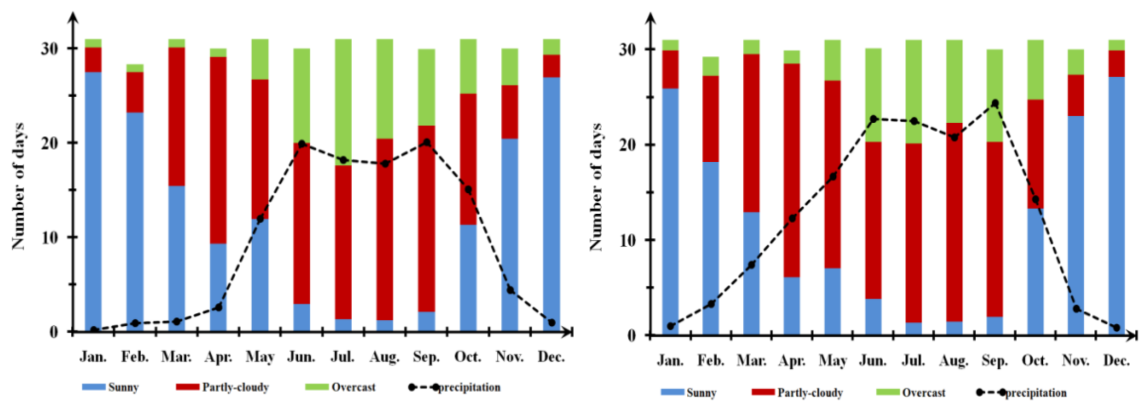


(a) **(b)**

Figure 2.12 Monthly daylight and sunshine hours: (a) Cox's Bazar and (b) Barisal
(Source: http://weather-atlas.com and Bangladesh Meteorological Department)

2.5.6 Sky Condition

Monthly sunny, partly cloudy, overcast and precipitation days for the areas Cox's Bazar and Barisal are shown in Fig. 2.13.



(a) **(b)**

Figure 2.13 Monthly sunny, partly cloudy, overcast and precipitation days: (a) Cox's Bazar and (b) Barisal
(Source: Bangladesh Meteorological Department)

Days with cloud coverage of less than 20% are considered sunny whereas 20–80% and over 80% cloud coverage are considered as partly cloudy and overcast respectively. From the figure it is observed that March-October most of the time sky remains partly cloudy whereas June-September one-third of the month sky remains overcast. During the months November-February 65-90% time sky remains sunny. During winter sky remains clear but one-third of the year (during pre and post-monsoon period) sky remains partly cloudy or overcast.

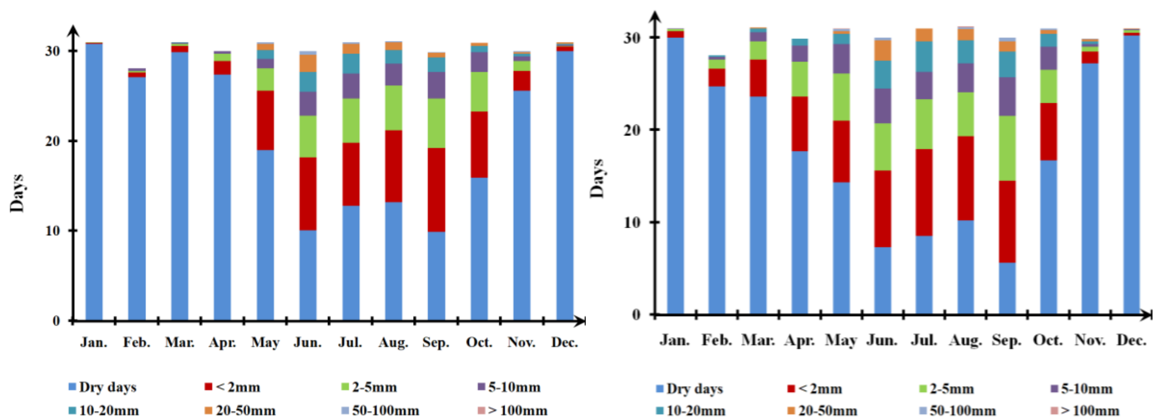
2.5.7 Precipitation

During monsoon months, normal rainfalls are higher while it is the highest in July at Cox's Bazar and in June at Barisal. During winter months (December-February), normal rainfalls are lower while it is the lowest in January. Monthly normal rainfalls of Cox's Bazar and Barisal during the period of 1981-2010 are presented in Table 2.6. Fig. 2.14 shows precipitation days/month at Cox's Bazar and Barisal. From the figure it is observed that 80% time of the months of November-April at Cox's Bazar and November-March at Barisal remain relatively dry.

Table 2.6 Monthly normal rainfalls during the period: 1981-2010 of Cox's Bazar and Barisal

Month/Variables	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.
Season	Hot-dry			Hot-humid						Cool-dry		
	Pre-monsoon			Monsoon				Post-monsoon		Winter		
Cox's Bazar	31.2	99.3	327.1	859.9	933.4	665.5	401.9	217.8	91.8	14.8	5.1	22.2
Barisal	52.4	103.7	199.0	401.7	409.9	342.6	284.4	185.5	48.5	5.9	10.3	26.1

(Source: Bangladesh Meteorological Department)



(a) **(b)**

Figure 2.14 Precipitation days per month: (a) Cox's Bazar and (b) Barisal
(Source: Bangladesh Meteorological Department)

Considering rainfall during the period 1971-2000, analysis of changes in rainfall pattern during the period 1981-2010 shows rise in rainfall during months of July-October and fall in rainfall during the period March-June. It remains nearly unchanged during remaining months (Khatun, Rashid et al. 2016). During winter 22% increases in rainfall at Cox's Bazar whereas at Barisal 38% deviation in rainfall is found.

2.6 Thermal Comfort

Thermal comfort is a subjective response and is defined as a state of mind expressing satisfaction with the existing environment(De Dear 1998; ASHRAE 2017). Being in the same thermal environment, different occupants can have other thermal sensations. Similarly, other occupants can express the same thermal feeling in various thermal environments. Therefore, it is difficult to mention the specific numerical value of thermal comfort (Auliciems and Szokolay 1997; De Dear and Brager 2002; Rajasekar and Ramachandraiah 2010). Again thermal comfort range vary with location, personal and climatic factors, i.e., comfort range, are higher for warmer climates than colder ones (Humphreys 1978; Givoni 1992).

2.6.1. Parameters Related to Thermal Comfort

Thermal comfort is more complex in naturally ventilated buildings since significant variables contribute directly and indirectly. In addition to this an ideal temperature is difficult to find for everyone in a particular space as physiological and psychological satisfaction varies widely from person to person. Previous study (Macpherson 1962) shows that thermal comfort within a building depends on occupants body heat balance which is affected by two primary factors: (a) personal and (b) ambient parameters. Personal parameters are the characteristics of the occupants such as metabolic rate and clothing level whereas ambient parameters are the factors of thermal environment i.e. AT (AT°C), MRT (MRT°C), air speed (m/s) and relative humidity (RH%) (Fig. 2.15).

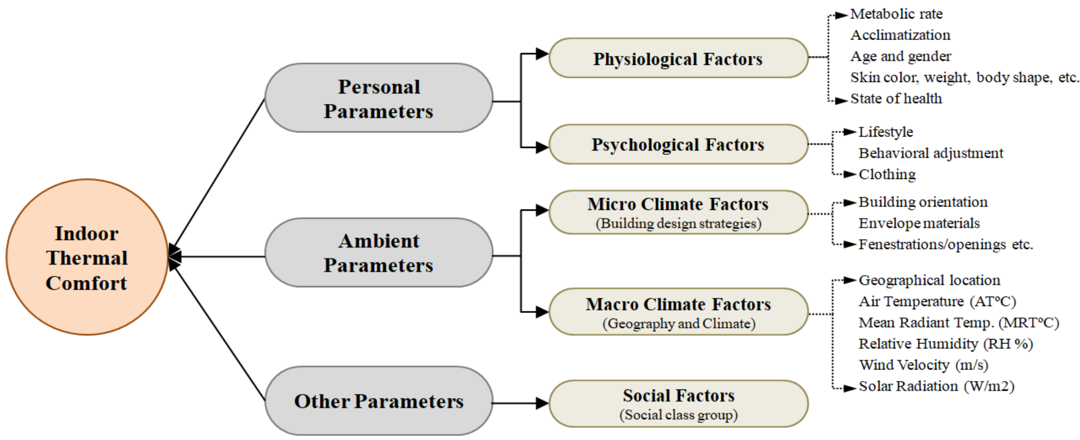


Figure 2.15 Parameters related to thermal comfort (Illustrated by Author)

(Givoni and Goldman 1973; Koenigsberger, Ingersoll et al. 1973; McLntyre 1980; Goulding, Lewis et al. 1992; de Dear 1993; Ahmed 1994; Baker and Standeven 1994; Mallick 1994; Ahmed 1995; Mallick 1996; Auliciems and Szokolay 1997; Givoni 1998; Ahmed 2002; Mridha 2002; Ahmed 2003)

Although all these elements can fluctuate over time, standards generally relate to a constant condition for thermal comfort, only permitting small changes in temperature. Besides there are additional factors affecting thermal comfort, i.e., acclimatization, activity level, body shape, subcutaneous fat, age and gender and state of health (McLntyre 1980; Auliciems and Szokolay 1997), social-class (Mridha 2002), geographical location (de Dear 1993) and building design (opening, orientation, building material) (Ahmed 1994; Mallick 1994; Mallick 1996; Ahmed 2002). Major personal and ambient parameters are discussed in the following section.

i) Personal Parameters

a) Clothing

Clothing acts as an intermediary insulation layer between human body and surrounding environment hence greatly affects thermal comfort. It is a significant way of behavioral thermoregulation to achieve thermal comfort at different temperatures (Parsons 2003; Bouden and Ghrab 2005) and user plays a critical function in achieving thermal comfort through their activities, clothes and behavioral changes (Brager and De Dear 1998; Fordham 2000; Raja, Nicol et al. 2001).

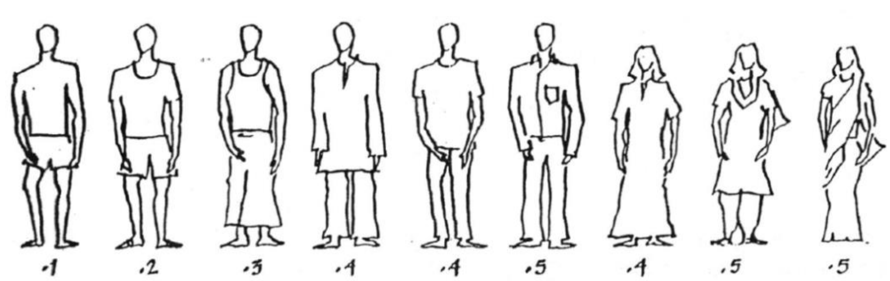


Figure 2.16 Clo. value of typical summer clothing of Bangladesh(Mallick 1994)

Clothing insulation level is expressed as m2K/W or simply clo. where 1 clo. roughly corresponds to 0.155 m2K/W which is the thermal resistance of normal winter business suit with cotton undergarments (Goulding, Lewis et al. 1992). In warm-humid condition clothing can play vital role towards heat loss from human body. In Bangladesh people usually wear light and loose dress clo. value of which varies nearly around o.5clo allowing air movement within body (Mallick 1994) hence enhances evaporative heat loss through direct wind action to skin (Ahmed 1995). Fig 2.16 shows thermal resistance values (clo.) of typical summer clothing of Bangladesh.

b) Metabolic Rate

Metabolism is the mechanism involved in transforming food into biological substance and usable sources of energy (Koenigsberger, Ingersoll et al. 1973). Energy generated from digestive process of the body is turned into work and heat that interacts with the peripheral environment. Metabolic heat production is classified as basal and muscular type. Basal metabolism is associated with biological process which takes place continuous and unconsciously. Muscular metabolism is dependent on levels of physical activity performed, hence consciously controllable.

Table 2.7 Metabolic rate associated with different works
(Source: Energy in architecture: The European passive solar handbook, 1992)

Activity		Metabolic rate (W/m^2)	Met
Sleeping		40	0.7
Reclining		45	0.8
Seated		60	1.0
Standing (sedentary works)		70	1.2
	Leisurely	1.7	100
Walking	Slow	2.0	115
	Fast	3.8	220
Reading		55	1.0
Writing		60	1.0
Cooking		95-115	3.0
House-cleaning		115-200	2.0-3.4

Human activity is described numerically by heat per square meter of a body surface (derived by Dubois empirical equation) (DuBois and Eugene 1915) which is called met where 1met is the metabolic rate of roughly 58 W/m^2 of a person sitting inactively in a still air room. Higher metabolism rates increase the generation of heat and make one feel comfortable when the condition is cold or worse when the condition is warm. Table 2.7 illustrates metabolic rate of some daily chores take place in residential building.

c) Acclimatization

Acclimation involves changes in physiological thermoregulation of a person resulting from extended exposure to climatic conditions outside the conventional comfort zone (Fountain, Brager et al. 1996). Thermal comfort, being state of mind of subjects expressing satisfaction with the existing environment (Brager and De Dear 1998; ASHRAE (American Society of Heating Refrigerating and Air-Conditioning Engineers) 2017), is related to subject's physiological and psychological factors and influenced by both occupant's experience and expectation (Humphreys 1996). People can express the thermal environment comfort if temperature changes slowly i.e. seasonal but can feel discomfort at the same thermal condition if the change is rapid i.e. within a day/week. As thermal comfort is situational and context-dependent

(Humphreys 1996) therefore being in the same thermal environment, different occupants can have different thermal sensations. Similarly, different occupants can express same thermal feeling in various thermal environments (Auliciems 1981; De Dear and Brager 2002; Rajasekar and Ramachandraiah 2010). Studies reveal that comfort range is dramatically higher for people in tropical and high temperature regions compared to colder one (Humphreys 1978; Busch 1992; Givoni 1992; Kwok 1998).

ii) Ambient Parameters

Thermoregulatory system of human body is capable to provide heat balance within natural environment. There are some elements of natural environment i.e., temperatures, air velocity and RH etc. changes of which directly affect comfort sensation. Key ambient parameters and temperature indices required for analyzing thermal performance of building envelope is discussed in the following section.

a) Air Temperature/ AT(ºC)

AT (AT) is one of the key environmental factors which measures thermal state of air (i.e. how cool or hot). It influences the rate of heat lost or gain from the air through convection, hence, critical towards human comfort. Rate of convective heat loss/gain depends on level of clothing insulation and wind speed. AT differs with height variation therefore, average spatial takes account of the ankle, waist and head levels that differ for occupant sitting or standing (International Organization of Standardization (ISO) 1998; ASHRAE (American Society of Heating Refrigerating and Air-Conditioning Engineers) 2017).

Two types of measurements are done: dry-bulb and wet-bulb temperature where dry-bulb temperature is usually referred to ambient AT which indicates heat content of air. Dry-bulb temperature (DBT)/AT is the true thermodynamic temperature which is not affected by the surrounding moisture/radiation and measured by a thermometer exposed to air. Wet-bulb is the temperature of adiabatic saturation shown by a moisturized air flow thermometer bulb. In the thermometer, adiabatic water evaporation and cooling impact is shown to be "WBT" lower than the "DBT" in the air.

b) Radiation and MRT (MRTºC)

Comfort within a space (especially spaces using passive heating or cooling techniques) does not merely depends on AT. Radiant temperature and/or air movements greatly affect comfort condition (Nayak, Hazra et al. 1999). Within a space radiation exchange depends on mean temperature of all the surrounding surfaces. MRT (MRT) expresses the combined effect of all surrounding surface temperature that eventually affects body’s heat loss through radiation process. Irrespective to AT, lower radiant temperature can contribute to heat loss from body and induce comfort. Radiation from the sun influences radiative heat exchange at outdoor. Individuals directly exposed to radiation has a significant instant effect but those who are shaded from direct rays, this effect is comparatively slow and less (Smith 1989). Solar gain is desirable during winter and problematic during summer because of overheating and subsequent thermal discomfort (Santamouris and Asimakopoulos 1996). In calculating the MRT, the heat emitted by each surface is taken into consideration, and the position of the surface refers to how it is measured. MRT involves detailed analysis and sophisticated computations. But it can be measured approximately with globe thermometer which is basically a mat black copper sphere of nearly 150mm in diameter having a thermometer placed at the middle of the sphere. MRT and globe temperature have nearly same value in still air (air movement has influence on MRT). Room AT is lower than globe temperature when radiation is emitted from the surrounding surfaces. Similarly, when surrounding surface temperature is less than AT, lower globe temperature results compared to AT.

c) Relative Humidity (RH%)

Concentration of water vapor present in the air is known as humidity which can be expressed as absolute humidity (AH g/kg), relative humidity (RH%) or vapor pressure (kPa). AH is the amount of water vapor present in air regardless of temperature whereas RH indicates the percentage of total amount of water vapor that could be held at its current temperature. In several studies, thermal comfort (Fanger 1970; Wargocki, Wyon et al. 1999; ASHRAE Standard 55–2004 2004), perception of the air quality (Fang, Clausen et al. 1998), occupants' health (Climent 2000)and energy consumption (Simonson, Salonvaara et al. 2001) is considered to be affected by RH. It involves temperature and human beings experience the heat exchange rate instead of the body temperature itself. Under transient and hot (high operate temperature) environments, RH effect has a major impact on the human body’s heat balance in high metabolic rate (Parsons 2003). RH affects moisture evaporation rate and vapor diffusion through skin which important to regulate deep body temperature. High humidity impairs body’s potential of heat exchange by affecting moisture evaporation from skin. RH indicated by different organization for human thermal comfort is ranges between 30-60% whereas RH above 70% causes thermal discomfort (Goto, Toftum et al. 2002; Goto, Toftum et al. 2006).RH depends on AT and water vapor present in the air and is kept in a range of areas little enough to be comfortable, but sufficiently large, in order to avoid very dry air problems. RH is low when the temperature is high and the evaporation of water is quick. In hot-humid environments high temperature associated with high moisture content creates thermal discomfort by reducing sweat evaporation potential of the body.

d) Air Velocity (m/s)

Air speed is the rate of air movement over time at a particular distance. Air flow influences convective heat exchanges as well as moisture evaporation rates from the surface of the body. This varies with the atmospheric temperature and humidity. Air movement is especially important in tropical climates since it cools the body when AT is high, through the evaporation of perspiration. Some studies investigated the possibility to provide indoor thermal comfort due to wind-driven natural ventilation (Chandra, Fairey Iii et al. 1986; Ernest, Bauman et al. 1991). In addition to successfully contributing to thermal comfort for the occupants, natural ventilation also reduces total cooling load and therefore saves energy (Ernest 1991; Jóźwiak, Kacprzyk et al. 1996; Aynsley 1999). The comfort zone demonstrates the airflow's impact by improving the relative moisture tolerance (Mallick 1994; Ahmed 1995; Ahmed 2003). But air velocity can lead to a discomfort when it is over 0.2 m/s or combined with cold AT and any air velocity (Chen 2010).

e) Operative Temperature (OT)ºC

AT, MRT and air speed altogether determine operating temperature (OT). It is defined as the consistent temperature of an imaginary black enclosure in which a person exchanges heat in the same quantity through radiation and convection as in the real non-uniform environment (De Dear 1998). OT is frequently regarded as only ATs in structures with a lower thermal mass.

2.7 Thermal Comfort Level

2.7.1. Codes and Standards

ASHRAE Standard 55

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 55-2004 specified thermal comfort limit for residential buildings (Table 2.8). Again, acceptable operative temperature ranges for naturally conditioned spaces are specified in ASHREA 55-2010 taking into account occupants activity level (1-1.3 met) and where the occupants are free to adapt their clothing to the indoor and/or outdoor thermal conditions. But this standard is not applicable if the mean monthly outdoor temperature is less than

10°C or greater than 33.5°C. ASHREA 55-2013 defined acceptable comfort zone on psychometric chart indicating OT and RH for specified clothing (0.5-1 clo.) and activity value (1-1.3 met) (ASHRAE Standard-55 2013). According to ASHRAE Standard 55-2017, thermal environmental conditions for human occupancy, temperature should be between 19.5°C-28°C for thermal comfort, however, it is dependent on relative humidity, season, clothes worn, activity levels and other factors. Though the level is defined for conditioned building but gradually started to be used for performance analysis of naturally ventilated buildings (Givoni 1992; Lam, Yang et al. 2006). People in hot-humid climate living in naturally ventilated buildings feel comfortable if even environmental parameters remain far-off from conventional comfort boundaries because these standard lack consideration for acclimatization, occupants' perception and behavioral adaptation, impact of wind speed towards extended comfort range (Sharma and Ali 1986; Nicol and Roaf 1996; Indraganti 2010).

The ecologically beneficial method of passive cooling building design, with natural ventilation and dynamic indoor environmental conditions, is incompatible with these traditional comfort standards (Milne and Givoni 1979; Szokolay 1985). Therefore prior to evaluate the thermal performance of naturally ventilated traditional timber, it is important to know the thermal comfort boundaries for rural occupants in Bangladesh. Literature survey shows that unfortunately, there is no specific standard regarding indoor thermal comfort in naturally ventilated houses in the Bangladesh National Building Code (BNBC) 2008.

Table 2.8: thermal comfort level specified by ASHRAE 55-2004

Season	Temperature Range(°C)	Humidity (%)	Ventilation rate
Summer	22.5 ~ 26	60	low enough to avoid drafts
Winter	20 ~ 23.5		

National Building Code of India (NBCI)

Our neighboring country India specifies a narrow comfort range for all types of buildings for summer and winter condition in NBCI 2005 which is 23°C-26°C and 21°C-23°C respectively. Again, in NBCI 2016 Part-8, Section -1, Part-5 (Ventilation) it is specified that the thermal comfort of a person lies between tropical summer index (TSI) values of 25°C and 30°C with optimum condition at 27.5°C where TSI is defined as the temperature of calm air at 50 percent relative humidity which imparts the same thermal sensation as the given environment. Air movement is necessary in hot and humid weather for body cooling. The minimum desirable wind speed needed for achieving thermal comfort at different temperatures and relative humidity are also specified in the code. The warmth of the environment was found tolerable between 30°C and 34°C (TSI), and too hot above this limit. On the lower side, the coolness of the environment was found tolerable between 19°C and 25°C (TSI) and below 19°C (TSI), it was found too cold. As per Adaptive Thermal Comfort Model Air Conditioning Systems NBCI 2013, for interior spaces intended for human occupancy shall be sized for not more than 26°C for cooling and for not less than 18°C for heating at occupied level. It is recommended to practice sector specific adaptive thermal comfort model. More accurate design conditions can be derived using following equations. These equations are not applicable for outdoor running mean temperatures below 15°C. For naturally ventilated (NV) buildings an equation (equation (i)) is provided to calculate comfort temperature. The 90% acceptability range for the India specific adaptive models for naturally ventilated buildings is ±2.38°C.

$$\textbf{Indoor (OT)} = (0.54 \times \textbf{outdoor temperature}) + 12.83 \quad \text{-----------------(i)}$$

where, indoor OT (°C) is neutral temp and outdoor temp. is 30 days outdoor running mean AT (°C).

Bangladesh National Building Code (BNBC)

In BNBC 2008, part-8, section 2.7.2.1, acceptable comfort range, RH and ventilation rate for indoor design condition for air conditioning during summer is provided (Table 2.9). Velocity of air in an air-conditioned space, in the zone between the floor level and the 1.5m 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 2.9: Guidelines for indoor design condition (air conditioning) during summer in BNBC 2008

Type of application	DBT(C°)	RH (%)	Air Velocity
Hotel guest room	23 ~26	50 ~ 60	--
Kitchen	28 ~31	--	--

In Section 2.11.3. guidance (AT, RH and ventilation rate) on mechanical ventilation is provided for the occupiable room where natural ventilation is not possible (Table 2.10). Again, in section2.11.2. guidelines for only source and ventilation area is specified for naturally ventilated buildings but AT, RH, ventilation rate etc. are not specified (Table 2.11).

Table 2.10: Thermal comfort guidelines for mechanically ventilated building in BNBC 2008

Type of application	DBT(C°)	RH (%)	Minimum air circulation rate (air change/hour)
Any occupiable space	**More than 40**	70	2-4 (bedroom)
			6-10 (bathroom)

Table 2.11: Thermal comfort guidelines for naturally ventilated building in BNBC 2008

Type of application	DBT(C°)	RH (%)	Required ventilated air (l/s per person)
Residential Comfort	**Not mentioned**	**Not mentioned**	**Not mentioned**

2.7.2. Thermal Comfort in Hot-humid Climate

Table 2.12 illustrates a summery on the comfort researches conducted in the 70 years in sequential order. From the table it is observed that comfort surveys were field survey based and conducted for naturally ventilated house. Summer comfort temperature ranges between 24°C-30°C and for winter it ranges between 15°C-24°C. Though all the researches have taken naturally ventilated buildings for field data collection but only few researches consider rural areas and subjects for comfort survey.

Table 2.12: Thermal comfort in the hot-humid region

Title	Author/ Year	Country	Study and Building Type	Comfort Temperature
Thermal comfort of rural residents in a hot–humid area	(Zhang, Zhang et al. 2017)	China	--	Thermal **neutral standard effective temperature (SET)** is **26.8°C**. 90% thermal acceptable SET range was **22.9–30.7°C** for rural subjects.

The India Model for Adaptive Comfort (IMAC) developed by CEPT University indicates that Indians' thermal comfort range is even wider for Naturally Ventilated (NV) and Mixed Mode (MM) buildings	(Manu, Shukla et al. 2016)	India	--	The thermal comfort range for people in **NV buildings** is **19.6-28.5°C, Mixed Mode buildings** is **21.5-28.7°C** and **air-conditioned buildings** is **23.5-25.5°C.**
Comfortable indoor temperatures and the climate: An adaptive model for Japanese dwellings	(Rijal, Humphreys et al. 2015)	Japan	Field survey Japanese houses	Comfort Temperature Winter: 17.6°C, and Summer: 27°C
Thermal Comfort and Acceptability in Offices in Japan and India: A Comparative Analysis	(Indraganti M., Ooka R. et al. 2014)	Japan	--	Close to 80% of occupants are comfortable with indoor operating temperatures of **24-30°C and at 27-28°C** of indoor temperature in Japan and India respectively.
Investigation of comfort temperature, adaptive model and the window-opening behavior in Japanese house	(Rijal, Honjo et al. 2013)	Japan	Field survey Japanese houses	Comfort Temperature Winter: 15.6°C, and Summer: 26.1°C
Thermal comfort for naturally ventilated residential buildings in Harbin	(Wang, Zhang et al. 2010)	China	--	Neutral temperature is 23.7 °C, with clothing insulation of 0.54 clo. 80% of the occupants accept AT range of 21.5–31.0 °C where the preferred temperature range is 24-28°C.
Thermal comfort in naturally ventilated buildings in hot-humid area of China	(Zhang, Wang et al. 2010)	China	Field survey Naturally ventilated	90% (80%) acceptable range of 23.5–27.4 °C (22.1–28.7 °C).
Seasonal and regional differences in neutral temperatures in Nepalese traditional vernacular houses	(Rijal, Yoshida et al. 2010)	Nepal	Field survey Traditional vernacular (NV)	Comfort Temperature Winter: 13.4~24.2°C and Summer: 21.1~30.0°C
Thermal performance study and evaluation of comfort temperatures in vernacular buildings of North-East India	(Singh, Mahapatra et al. 2010)	India	Field survey Naturally ventilated	Neutral temperature: 27.10°C (To), Comfort range (summer): NA 29.1°C
Thermal comfort in naturally ventilated apartments in summer: Findings from a field study in Hyderabad, India	(Indraganti 2010)	India	Field survey Naturally ventilated	Neutral temperature: 29.23°C (To) Comfort range: 26-32.45°C
Thermal environmental conditions for human occupancy	(ASHRAE Standard 55–2004 2004)	Singapore	Field survey Naturally ventilated	80% acceptability: 23.30°C-30.20°C
Thermal comfort for naturally ventilated houses in Indonesia	(Feriadi and Wong 2004)	Indonesia	Field survey NV	neutral point is found at 29.2°C Effective Temperature (ET) whereas preferable temperature is 26°C.
Thermal comfort in classrooms in the tropics	(Wong and Khoo 2003)	Singapore	Field survey NV	Neutral temperature: 28.8°C (OT)
Thermal comfort evaluation of naturally ventilated public housing in Singapore	(Wong, Feriadi et al. 2002)	Singapore	Field survey Public housing (NV)	Higher thermal acceptability measured by Bedford scale compared to ASHRAE scale

Pioneering new indoor temperature standards: the Pakistan project	(Nicol and Roaf 1996)	Pakistan	Field survey Naturally ventilated house	Comfort Temperature Winter: 19.8~25.1°C and Summer: 26.7~29.9°C
A tale of two populations: thermal comfort in air-conditioned and naturally ventilated offices in Thailand	(Busch 1992)	Thailand	Field survey Naturally ventilated and Air-Conditioned	For NV: neutral temperature was found at 27.4°C (ET) but the upper bound of acceptable level, defined by ASHRAE 55-81, was 31°C (ET). For AC building ET is 24.5°C.
Thermal comfort in the humid tropics: Field experiments in air conditioned and naturally ventilated buildings in Singapore	(de Dear, Leow et al. 1991)	Singapore	Field survey Naturally ventilated and Air-Conditioned	For NV: thermal neutrality (comfort) at 28.5^0C (Operative Temperature) 24.2°C (AC)
Tropical summer index - a study of thermal comfort of Indian subjects	(Sharma and Ali 1986)	India	Naturally ventilated building	Specified comfortable at 28°C (Thermal Summer Index) with successive thermal sensations change at interval of 4.5°C
The diurnal variation of warmth and discomfort in some buildings in Singapore	(Webb 1961)	Singapore	Field survey Naturally ventilated building	Most comfortable temperature was found at 25.9°C (SI)
Thermal Discomfort in an Equatorial Climate. A Nomogram for the Equatorial Comfort Index	(Webb 1960)			
An analysis of some observations of thermal comfort in equatorial climate	(Webb 1959)			
Thermal comfort in warm and humid atmospheres: observations on groups and individuals in Singapore	(Ellis 1953)	Singapore	Field survey Naturally ventilated	Effective Temperature: 22–25.5°C
On some observation of indoor climate in Malaya	(Webb 1952)	Singapore	Field survey	26.2°C ET

2.7.3. Thermal Comfort in Bangladesh

Table 2.13 sequentially summarized the researches on thermal comfort of Bangladesh. From the table it is clear that existing thermal comfort studies in Bangladesh are primarily urban-centric, with little attention paid to thermal comfort in rural regions (Ahmed 1994; Mallick 1994; Ahmed 1995). For people wearing basic summer clothing and engaged in light/sedentary actions, limited studies in the rural perspective of Bangladesh indicates that people feel comfortable between the ranges of 17–32°C in winter (Ahmad and Rashid 2010) and 24–32°C with RH ranges of 50–90% almost no airflow in summer (Sharma and Ali 1986; Mallick 1996). For this research, the aforementioned ranges were used as the baseline.

Table 2.13: Thermal comfort in Bangladesh

Title	Author/ Year	Country	Findings	Remarks
Indoor thermal comfort evaluation of naturally ventilated rural houses in Dhaka region, Bangladesh	(Shajahan and Ahmed 2016)	Dhaka, Bangladesh	**Thermal comfort band 29-34ºC with neutral temperature 31.5ºC**	

Thermal Comfort of Bangladesh Traditional House In A High Density Environment with the Worst Surroundings Condition in Dhaka City	(Ahmad and Rashid 2010)	Dhaka, Bangladesh	**Comfort zone** analysis for **winter season** is **17°C to 32°C** (Sharma and Ali, 1986; Mallick, 1994;) and for **summer** is **24°C to 32°C**	Dhaka region based research and much higher than the thermal comfort range defined for air-conditioned buildings by ASHRAE 55–2010
Comfort in urban spaces: defining the boundaries of outdoor thermal comfort for the tropical urban environments	(Ahmed 2003)	Dhaka, Bangladesh	Average **relative humidity of 70%,** the boundaries of average **AT** for **outdoor comfort** vary between **28.5 -32.842ºC** **Airflow in urban spaces** increases the number of people thermally satisfied at temperatures **below 34.8°C.**	
The Effects of Climate on the Design and Location of Windows for Buildings in Bangladesh	(Ahmed 1987)	Dhaka, Bangladesh	23.1ºC-28.6ºC	
Thermal comfort and building design in the tropical climates	(Mallick 1996)	Dhaka, Bangladesh	People feel **comfortable** at AT **24-32ºC**, RH – 50-90%without or in little air movement	

2.8 Thermal Performance of Timber House: Overview

Table 2.14 presents the study conducted in the past 20 years on thermal performance analysis of timber houses. The study results are obtained from field survey or parametric simulation studies. From the table it is observed that most of the study selected urban environmental condition and deals with the wall envelope materials only. Again, study on traditional timber houses of Bangladesh is limited to marginal. Even design strategies for future development lacks consideration of local insulation materials. Therefore, the current study aims to evaluate the thermal performance of traditional timber house envelope (wall, floor and roof) through field observation and parametric studies have been conducted towards improvement of indoor thermal environment of these houses in the future.

Table 2.14: Thermal performance of timber house envelope

Title & Year	Author/ Year	Country	Building Type	Findings
Improving thermal response of lightweight timber building envelopes during cooling season in three European locations	(Pajek, Hudobivnik et al. 2017)	Finland, Austria, Spain	Passive cooling mode	Using wood-based insulation in external wall improve thermal performance. Again, application of high intensity ventilation is necessary, which additionally lowered the internal surface temperature up to 8C.
Assessment of bamboo application in building envelope by comparison with reference timber	(Huang, Sun et al. 2017)	--	Model analysis enclosed space	Bamboo had better heat storage and vapor resistance but worse heat transport properties.
Thermal comfort of wood-wall house in coastal and mountainous region in tropical area	(Prianto and Setyowati 2015)	Indonesia	--	Occupants in the coastal houses are more comfortable than occupants in the mountainous houses
Thermal Performance of Low-carbon Prefabricated Timber Housing in the UK	(Adekunle 2015)	United Kingdom	Passive building	Occupants with small floor area adapts better compared to larger one and they are less satisfied with little control over indoor condition.

The difference of thermal performance between houses with wooden walls and exposed brick walls in tropical coasts	(Prianto and Setyowati 2015)	Indonesia	Passive house	Average temperature of solar radiation (Tmrt) for wooden houses ranged from 2 4.0 º C to 32.3 º C. Temperature of brick houses ranged from 25.4 º C to 31 º C. Occupants in houses with wooden walls feel more comfortable than occupants in houses with exposed brick walls.
Thermal Performance Evaluation of a Dynamic Insulation Technology Applied to a Timber Framework House in a Real Environment	(Yaegashi, Hiyama et al. 2015)	Japan	Mechanical ventilation	Dynamic insulation (wood-fiber) technology can significantly reduce heat loss through the building envelope
Experimental Measurements and Numerical Simulations of Dynamic Thermal Performance of External Timber Frame Wall	(Skotnicova, Galda et al. 2014)	Czech Republic, Europe	Passive building	The dynamic thermal performance of the exterior walls of a timber house indicates a positive impact of insulation layer (wood-fiber) with a greater specific heat capacity to remove summertime heat load.
Temperature and humidity profiles in passive-house building blocks	(Mlakar and Å trancar 2013)	Slovenia, Europe	Passive house	Ventilated wooden facades, in comparison with classical façade plaster, protect the building blocks from high thermal loads. Vapor retarders and moisture-buffering materials maintain indoor comfort.
Indoor Air Quality in a Wooden House	(Salonvaara, Ojanen et al. 2004)	Finland, Belgium, Germany and Italy	Passive method	Wood and wood-based materials have hygroscopic properties that are favorable for producing good indoor climate. Hygroscopic buffering may also result in energy savings.
Contribution of indoor exposed massive wood to a good indoor climate: in situ measurement campaign	(Hameury 2004)	Sweden	--	A large area of exposed massive wood contributes to buffer the indoor temperature variations. It's not clear that a large area of exposed massive wood is able to damp the daily fluctuations in relative humidity.

2.9 Conclusion

In this chapter understanding from the previous research has been presented. First of all, location of traditional timber house and climatic condition of the areas have been reviewed to identify the best season to perform field monitoring. Then literature have been reviewed regarding thermal comfort code and standard for rural areas of Bangladesh and other countries to identify thermal comfort limit to assess the thermal performance of the tradition houses concerning indoor thermal comfort. Finally, previous study on thermal performance of timber house has been reviewed to authenticate what has not yet been done and establish the significance of the research.

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CHAPTER THREE: METHODOLOGY

Introduction

Research Methods

Qualitative Data Collection

Quantitative Data Collection

Simulation and Parametric Study

Data Analysis and Synthesis Process

Conclusion/Summary

References

3.1 Introduction:

The study, aims to investigate the indoor thermal performance of traditional timber houses in Bangladesh. As thermal performance of building depends on several factors this study focuses on thermal performance of envelope material. To achieve this aim, the research conducted a range of different methods including literature review, field observation, climatic data monitoring, questionnaire survey and parametric simulations studies. Literature review was performed to find out location of houses, local climate and standard thermal comfort limit for rural areas of Bangladesh etc. Evaluation of envelope's thermal performance requires understanding existing thermal environment and occupant's perception of comfort within the house. Hence, field study is essential. But due to time limitation filed survey for a longer period was difficult. Parametric study helps to visualize thermal performance scenario for entire year. Therefore, for comprehensive and more accurate assessment of envelope's indoor thermal performance simulation study was conducted for entire year. From the findings design strategies were made, assessed and finally design developments were recommended for enhanced indoor thermal comfort in the future. In this chapter, research methods have been presented through the following sections:

- Qualitative data monitoring
- Quantitative data monitoring
- Parametric study
- Data analysis and synthesis

3.2 Research Methods

This research applied mixed method. Fig. 3.1 illustrates the structure of the research. For this study, identification of specific location, typology of timber houses, local climatic condition and particular climatic period to conduct field data monitoring is necessary before conducting detailed field survey. In addition, to evaluate the indoor thermal performance of traditional timber houses, it is essential to identify standard indoor thermal comfort range for the rural areas of Bangladesh. Therefore, data from books, journals, articles and other established sources have been studied to collect relevant literature on local climate, house typology and house location as well as indoor thermal comfort standard for rural areas of Bangladesh.

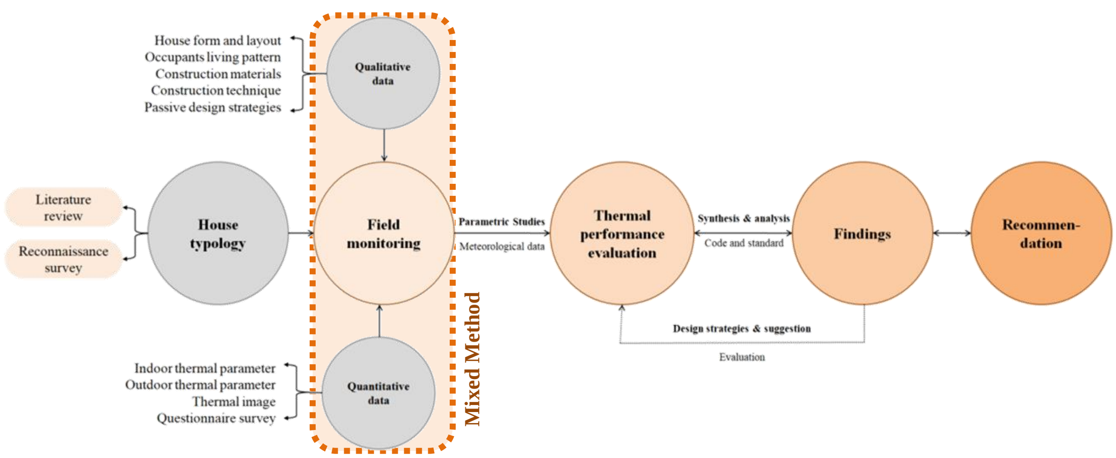


Figure 3.1 Structure of the research.

Study period and house locations have been selected from literature review. Study on traditional timber houses of Bangladesh is marginal, thus, a reconnaissance survey was conducted to classify typologies of the houses to be surveyed. A traditional timber house is a product of time long trial and error process and lacks necessary architectural documentation. Hence, initial drawings and information on local construction materials and techniques were documented at this stage. The research was conducted in two phases: Phase-I mainly involve field work. Recent studies identified that field study is a widely used method for environmental evaluation of naturally ventilated houses (Nicol and Humphreys 2002; Wong, Feriadi et al. 2002; Feriadi and Wong 2004; Wang, Zhang et al. 2010). Therefore, field study aims to collect qualitative and quantitative data regarding existing indoor thermal environment and applied design strategies related to thermal comfort, occupant's perception and subsequent adaptation within the house. Phase-II aims to investigate thermal performance of envelope materials of both existing and proposed design strategies/suggestions concerning indoor thermal comfort. Based on existing codes and standards, the simulation outcomes are analyzed and synthesized towards design developed for enhanced indoor thermal comfort in the future. The following section presents the methodological framework applied for this research work.

3.3 Qualitative Data Collection

Representative sample for study were selected based on two criteria: (a) construction period and (b) existing condition of the houses. From reconnaissance survey three (03) typologies of traditional timber houses were identified. Then, ten (10) cases from each typology and a total of 30 cases were selected for field observation. Later excluding the most similar one five (05) cases from each typology and a total of fifteen (15) cases were selected for detailed observation. Timber houses which are constructed mainly with timber and those essentially gone through less change over time, having north-south orientation and built over at least forty (40) years ago were selected as case study samples.

Because of its extensive use of timber traditional timber houses have unique construction technique compared to other traditional houses in Bangladesh. Again, these houses are naturally ventilated and local people adopted different local techniques to make it comfortable for its occupants. Therefore, qualitative data collection which includes information on building materials and local construction technology used as well as passive features, construction and architectural details related to indoor thermal comfort have been identified. Traditional houses are observed carefully and rough drafts of the architectural and construction details, materials used are made and photographs are taken for documentation and interpretation afterward.

3.4 Quantitative Data Collection

Evaluation of thermal performance of envelope material makes it essential to understand the existing condition of indoor thermal environment of the traditional timber houses. Therefore, quantitative data monitoring has to address the following objectives:

(a) Investigating existing indoor thermal environment regarding thermal comfort.
(b) Exploring occupant's perception of indoor thermal comfort and living pattern within house.

For achieving these objectives, two quantitative methods were adopted. First method was in-situ climatic data monitoring with instruments to explore existing indoor thermal environment. Exploring subjective responses in real environment for understanding occupant's thermal comfort needed in existing indoor thermal environment is considered as one of the recommended methods (Nicol, Humphreys et al. 2012). Therefore, the second method is to conduct questionnaire survey to study occupant's indoor thermal perception and living pattern within traditional timber house. These research methods were developed from literature review of previous similar studies. The findings of quantitative data monitoring were used for reliable occupancy scheduling and validation to conduct parametric study. The overall findings of qualitative data monitoring is presented in the next chapter (Chapter 4).

3.4.1 Environmental Monitoring

Quantitative data on thermal parameters, i.e., AT°C, RH%, wind speed, etc. was collected through in-situ physical measurement. Simultaneously, thermal images were collected to find out surface temperatures of different materials used for construction. For qualitative observation three traditional timber houses from each typology (one single-storied, one double-storied and one stilt house) have been selected for whole day in-situ measurement. For comparative analysis of thermal performance, another timber-framed plain sheet house (all features are similar to that of the traditional double-storied timber house except wall material and floor height) has been selected for whole day data monitoring. The room with at least two exterior walls having direct contact with the outdoor has been selected for whole day data monitoring.

(a) Instruments

The instruments used are listed in Table 3.1. Surface temperature (Laser Non-Contact Thermometer: MT4) and thermal images (Thermal Digital Camera: FLIR Z-CAMERA) were collected for different times to get a deep insight about the thermal performance of different envelopes of the house.

Table 3.1 Instruments used and their properties

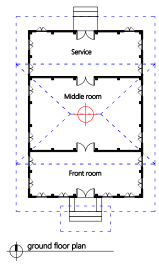
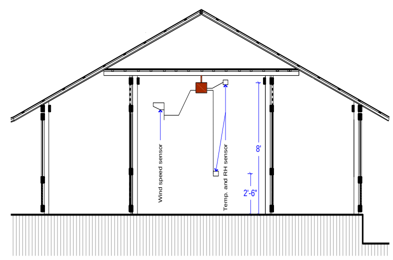
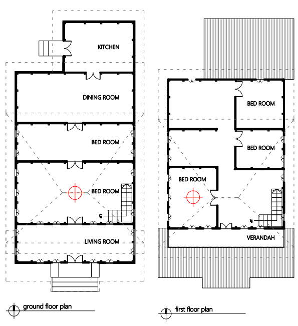
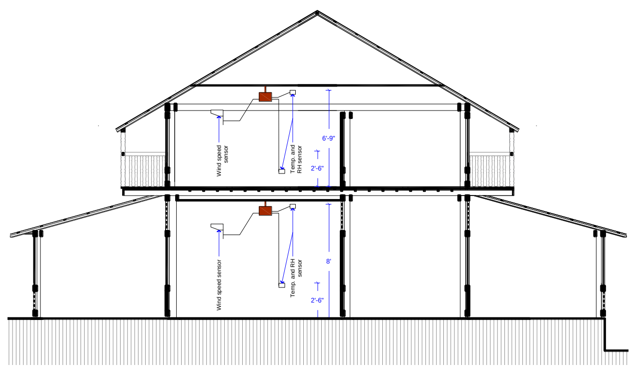
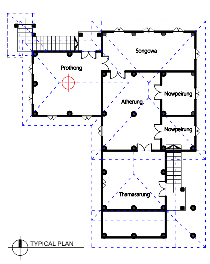
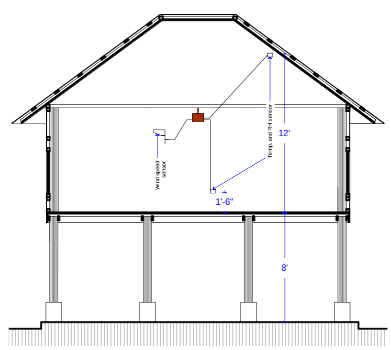
Instrument	Environmental indicator	Accuracy	Image
HOBO U30 with Smart sensor	Environmental/ Energy Monitoring System: ▪ Temperature & RH ▪ Solar Radiation ▪ Wind Sensor/ Anemometer	± 0.25% of FSR from 50mV to FSV (Range -40 to 60°C)	
FLIR Z-CAMERA	Thermal Digital Camera: forms an image using infrared radiation	±2°C (±3.6°F) or ±2% of reading for ambient temperature 15°C to 35°C (59°F to 95°F) and object temp. above 0°C (32°F)	
MT4 Laser Non-Contact Thermometer	Surface temperature	98% (range 0-750°C)	
Environmental Quality Meter	▪ AT ▪ Humidity ▪ Air speed ▪ Light ▪ Sound ▪ Thermocouple	±5%@calibrated wavelength 633 nm / 1 mW (range: 0 ~ 40°C, 80% non-condensing, maximum)	

Data logger (HOBO ware Pro. U30) have been installed in the middle of the room. Both indoor and outdoor thermal and climatic data (AT (AT °C), relative humidity (RH %)), wind and gust speed, solar radiation) for each second for a whole day have been recorded with the smart sensors and thermal monitoring tools of the data logger. Environmental quality meter was used to monitor AT, RH and wind speed during questionnaire survey.

(b) Data Logger Installation

Climatic data has been collected at two different heights: human occupancy zone which is the head level of a sitting person (1.1m and 0.9m from the floor for single/double and stilt house respectively) as recommended by ISO 7726 (1998) and near the ceiling (2.4m for single/double storied and 3.6m for stilt house). Table 3.2 shows the instrument position in plan and section. Fig. 3.2 shows the installation of HOBO U-30 data logger in the traditional timber houses.

Table 3.2 Instrument position in plan and section.

Type	Instrument Position in Plan	Instrument Height in Section
Single-storied		
Double storied		
Stilt house		

Weather station HOBO U30 has smart sensors and connection between logger and sensors being digital requires no calibration or programming. For this study six (06) sensors were used: three (03) AT and RH sensors for collecting data at two different heights of the indoor and outdoor respectively, one solar radiation sensor at outdoor and two (02) wind and gust speed sensors one at indoor and other at outdoor. After running the HOBO ware, sensors are needed to be plugged in with the logger and configured. Then device is launched to record data automatically. After logging, device is needed to be readout for viewing and analysis of recorded data. Findings of climatic data monitoring is presented in the next chapter (Chapter 4).

Figure 3.2 Data logger installation at traditional timber houses

3.4.2 Questionnaire Survey

To understand occupant's living pattern and perception of indoor thermal comfort a questionnaire survey was conducted followed by personal observations, interviews and discussions with local people during in-situ climatic data monitoring.

(a) Survey Form

The questionnaire has been developed based on information ASHRAE 55-2004 (Appendix C) (ASHRAE 2017) and from similar previous studies (Wong et al., 2002; Feriadi and Wong, 2004; Wang et al., 2010). Questionnaire has 03 major parts: general and personal information (date, age, gender, height, weight, etc.); thermal perception (thermal sensation, airflow feeling, sweating feeling, clothing, activity level, etc.) and personal micro-climate control (adaptive control). The ASHRAE 7-point scale was used for measuring thermal sensation and feelings. In this study instead of numbering -3, -2, -1, 0, +1, +2, +3 written annotations: cold, slightly cool, cool, neutral, warm, slightly warm and hot was used respectively (Fig. 3.3), so that respondent can easily respond towards sensation and perception. Considering better understanding of respondents, questionnaire was prepared using native language (Bengali) but English translation was provided as well.

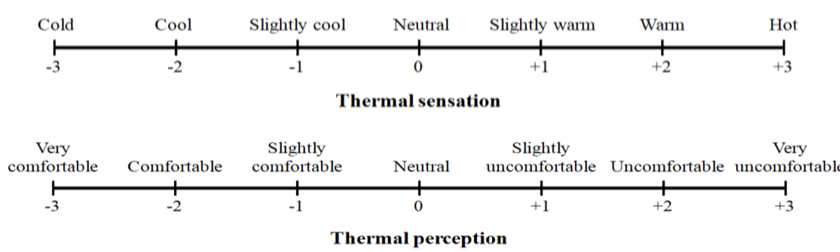


Figure 3.3 ASHRAE 7-point scale used for questionnaire survey

(b) Questionnaire Survey Process

At least three participants were asked to participate in the questionnaire survey from each case study house. This survey was repeated at two hours' interval i.e., 4:00 am, 6:00 am, 8:00 am and so on.

Respondents were engaged with sedentary activities for at least 30mins. Metabolic rate ranges ≤3 where height value corresponds for cooking activity (3 met) (Mallick 1994). They were allowed to wear traditional dress they typically wear in the house and for which clo. values remain within 0.5clo. (Mallick 1994; Engineering ToolBox 2004). As the houses are naturally ventilated the occupants were allowed to operate the openings for adapting with the outdoor conditions. Participants were demonstrated about the questionnaire survey and verbal consent was taken before conducting questionnaire survey. For each question, respondents simply asked to mark proper scale with their own condition. For an enhanced insight of occupants' thermal experience, they were asked to respond for their perception of comfort feeling for different times of the day for a typical summer day other than their present feelings. In case of participants who had little or no capability to understand the questionnaire, the questionnaires were filled by the researcher as per respective answer. For analysis of occupants' thermal perception of indoor thermal environment, their experience was emphasized over their present situation. Other necessary details i.e., occupants' adaptive behavior, door-window operation, occupancy schedule etc. were collected during questionnaire survey. Results of the questionnaire survey are explained in detail in Chapter 4.

3.5 Parametric Study

For examination of building's thermal performance simulation tools are widely used nowadays. In practical situation it is not possible to examine buildings considering different scenarios and design factors. However, simulation tools offer opportunity to study buildings allowing for different factors and scenarios (Almhafdy, Ibrahim et al. 2013; Bahar, Pere et al. 2013). Parametric study also helps to analyze building thermal performance for different envelope composition and for any period of the year. From the field survey thermal condition and envelope's performance for a certain period were obtained, therefore, parametric simulation study was carried out to study year-round performance of existing building envelope regarding indoor thermal comfort. From the result of existing envelope's thermal performance other envelope design strategies were evaluated for enhanced thermal performance. As there can be variety of envelope design strategies and evaluating all the options are difficult and time-consuming task, therefore, options were narrowed down for most effective result. Envelope combination considering local materials was therefore considered as design strategies among wide variety of alternatives. Output from parametric study have been discussed and presented in Chapter 6.

3.5.1 Simulation tools

In this study Google sketch-up with OpenStudio plug-in is used to build envelope model and EnergyPlus simulation engine is used to analyze envelope's thermal performance. This program can simulate heat transmission through envelope from outdoor considering thermal properties of materials for long period. Besides that this program also allows studying impact of specific physical aspect while keeping other aspects constant which are not possible to evaluate in practical condition due to impact of different aspects simultaneously. A brief description of the simulation tools used is illustrated below:

(i) Google sketch-up with OpenStudio plug-in

OpenStudio is free and open-source software applications used in building information modeling for building energy analysis. OpenStudio is designed to work with SketchUp. Many concerned professionals use SketchUp for building designs. OpenStudio plug-in for SketchUp allows users to use standard SketchUp tools to create and edit building geometry (i.e., zones and surface etc.) quickly. The plug-in allows SketchUp to view EnergyPlus input files in 3D and adds building energy simulation capabilities of EnergyPlus to the SketchUp environment. Performing an

EnergyPlussimulation of building model and analyzing results without leaving SketchUp is possible. Therefore, integration with SketchUp allows professionals to study building's energy performance before construction.

(ii) EnergyPlus

EnergyPlus is DOE's open-source and stand-alone whole-building energy modeling engine which is extensively tested before release. With this engine it is possible to model heating, cooling, lighting, ventilation, water use and other energy flows. This simulation engine reads input and writes output in text files. EnergyPlus implements in-depth air, moisture and heat transfer mechanics to calculate heating and cooling loads necessary to maintain thermal control set points, energy consumption of primary plant equipment etc. EnergyPlus has several inventive simulation abilities i.e., heat balance-based zone simulation, thermal comfort, natural ventilation, sub-hourly time steps (less than an hour) etc. For location specific simulation study EnergyPlus readable weather data is available which is provided by U.S. Department of Energy (DOE).

3.5.2 Database for Parametric Study

Parametric study with EnergyPlus requires data input for several compulsory fields for building modeling, simulation and evaluation process. Manufacturer's literature, energy building codes, previous design and technical recommendation issued by the National Clean Energy Laboratory (Leach, Lobato et al. 2010) and the Pacific Northwest Laboratories were used as input criteria (Thornton et al. 2009). Among all database, input in climate and location, internal condition, internal load, building operation and scheduling, building, materials database, construction, simulation run variables are crucial for simulation study. Based on the site parameters and the test zone conditions, the climate, building operation, occupancy schedule and other internal database are prepared. Materials and building construction databases are built in with the program and can be structured in different arrangements. For proper analysis, local construction materials properties and configurations for simulation study were used. Then, construction database was prepared for local construction elements (walls, floor, roof etc.). These construction elements are composed several layers of materials which were assigned from material database. A detail of parametric database is described in chapter-5.

3.5.3 Simulation procedure

This study considered following zone output variables: (a) AT(ºC), (b) mean radiant temperature (MRT)(ºC), (c) mean AT(ºC), (d) operative temperature(OT) (ºC) and (e) relative humidity (RH) (%) to assess existing traditional timber house envelope's thermal performance.

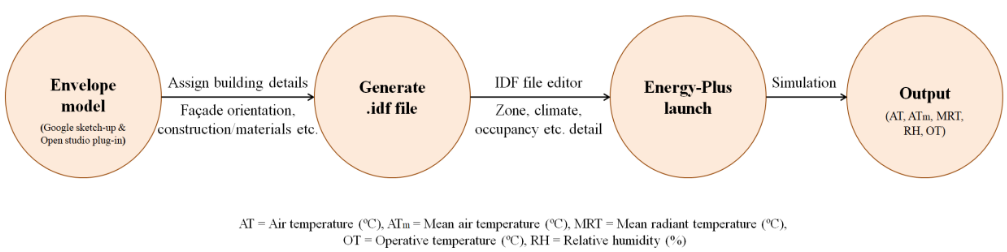


Figure 3.4 Parametric study process with EnergyPlus simulation engine

To carry out the parametric study with EnergyPlus, initially using Google sketch-up with OpenStudio plug-in software, a 3D model of the space was prepared. This plug-in software allows editing building geometry (i.e., façade orientation, construction and materials etc.) and to generate. idf file. Importing. idf file in IDF-Editor allows editing zone surface boundary conditions and surface details, climatic information, occupancy schedule and internal gains details etc. Using plug-in software allows launching EnergyPlus simulation. Therefore, simulation studies were carried out through EP-Launch (EnergyPlus launch). Simulation experiment procedure is further explained in detail in 'Simulations and Parametric Study' chapter (Chapter-5). Fig. 3.4 illustrates the performed parametric study procedure with EnergyPlus simulation engine.

3.6 Data Analysis and Synthesis

First of all, qualitative and quantitative data obtained from field monitoring were set against time and interpretational graph was developed showing existing relationship between indoor thermal environment and occupant's living patterns within traditional timber houses. Fig. 3.5 shows the data interpretation strategy adopted for the current study. Outputs obtained from parametric study for whole year are compared with local codes and standard of thermal comfort to identify annual uncomfortable hours. Then design strategies studied has been studied for this uncomfortable period and obtained results are assessed based on local thermal comfort standard. From the obtained result, design insights and strategies for development of timber house envelope were proposed. Prior to recommendation, options have been assessed regarding occupants' experience and occupancy schedule as well as indoor thermal comfort. There were two aims for doing this comparative analysis: (a) to find out existing envelope's thermal performance regarding indoor thermal comfort and (b) to study and develop design improvement strategies for timber house's envelopes design for enhanced indoor thermal environment concerning occupant's comfort in the future. Finally, recommendations were made for traditional timber houses envelope for enhanced indoor thermal comfort in the future. Data analysis, synthesis, final findings and recommendation is presented in detail in Chapter 7.

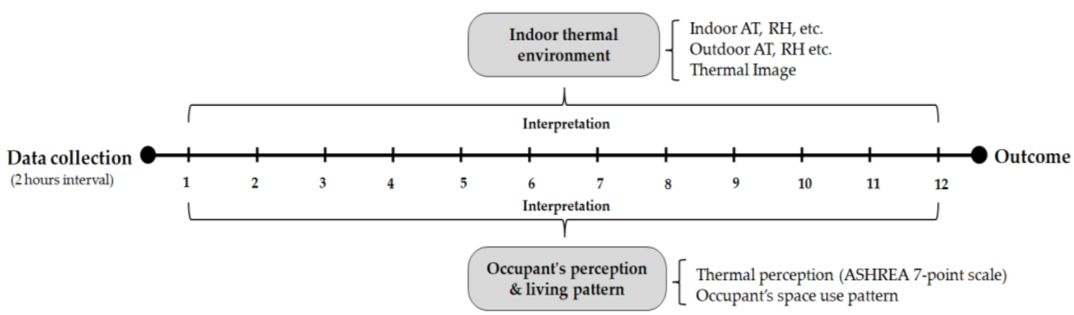


Figure 3.5 Interpretation strategy of monitored field data

3.7 Conclusion

This chapter presents the research methodology implemented to study indoor thermal performance of traditional timber houses with special focus on envelope materials in Bangladesh. Initially, this study evaluated the existing envelope's thermal performance regarding indoor thermal comfort. From the findings later some envelope design strategies have been assessed regarding indoor thermal comfort and finally recommendations have been made to improve indoor thermal condition within the house in future. Evaluation of existing envelope's thermal performance requires understanding prevailing indoor thermal environment and occupant's perception of comfort within the house. Therefore, a detailed field survey was conducted which involves collection of qualitative and quantitative data. Qualitative data collection includes materials and local construction techniques used as well as passive strategies adapted concerning indoor thermal comfort, whereas quantitative data comprises in-situ climatic data (AT, RH, wind speed etc.) monitoring and questionnaire survey for collection of subjective responses. From the findings of field survey parametric model was developed using Google SketchUp with OpenStudio plug-in and necessary data input have been done to perform parametric study with EnergyPlus simulation engine. Then parametric study was performed to visualize whole year thermal condition within the house. Finally, results have been compared with codes and standard regarding indoor thermal comfort that was specified earlier through intensive literature review. From these annual thermally uncomfortable hours have been identified. Then prior to propose design strategies, options have been assessed towards improved indoor thermal environment.

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CHAPTER FOUR: FIELD SURVEY

4.1 Introduction

This study deals with the thermal performance of traditional timber houses of Bangladesh focusing on the envelope’s performance concerning thermal comfort; hence a field study has become important to assess the condition. The field study has three major parts: Qualitative and quantitative observation of indoor thermal environment and Occupant's perception of the indoor environment of the house. For quantitative observation, day-long data monitoring, and at the same time, architectural features related to thermal comfort have been recorded. To understand the subjective thermal perception a structured questionnaire survey has been conducted along with the collection of relevant data on adaptation factors of users followed by in-situ measurements of AT (AT °C) and Relative humidity (%) at the middle point of the room.

The present chapter deals with the analysis of the common architectural features related to the thermal behavior of 15 different exemplary case studies and the occupant's thermal perception. Again day-long measurement of indoor thermal parameters and effect of internal heat gains is evaluated for 3 different exemplary houses. The comparative analysis between the houses as well as outdoor condition is performed as a part of the study. These findings provide an overview of the existing thermal environment of the houses. Again, qualitative observation of the architectural details further helps to prepare 3D model for parametric simulation. Design parameters considered for simulation modeling are based on the analysis of this chapter. The recorded field data has been compared later with the obtained parametric study results.

4.2 Field Survey

The fieldwork and the subsequent field results review have been focused on the following goals:

a. To study the thermal performance of envelope materials and the construction details related to the indoor thermal performance of timber house.

b. To assess the indoor thermal environment (Air Temp./AT, Relative Humidity/RH, Surface Temp, etc.) concerning the requirement of indoor comfort related to the performance of traditional timber house building envelope.

4.2.1. Selection of Study Area

In Bangladesh, different traditional houses evolved in different regions in response to socio-economic and climatic demands. Traditional timber houses are one such commodity that is emerged near the southern part of the country. As discussed earlier (Chapter-2) the single and double-storied houses are found at Barisal and south part of Khulna and the stilt timber house is mostly found in some areas of Chittagong (Cox's Bazar municipality, Khuruskul, Chowfaldandi, RamuSadar, Panerchhara, Ashkor Kata, TeknafSadar, Kharangkhali, Hneela, Harbang of Chokoria, Gorokhghata of Maheskhali) and Patuakhali (Khepupara and Kuakata).

For studying single and double-storied timber house two random villages (Atghor-Kuriana and Joyjogotpur) near river Shondha, Swarupkathiupazila, Pirojpur have been selected. The reasons behind selecting of this area are: firstly, south-eastern part of the country is mainly coast. Being located on the heart of Ganges Delta, this region has a great network of river connected to the whole country and traditional timber house has created a spontaneous dialogue with the settings. As selected villages have grown up near river, this will help understand the extent of adaptation of these houses in such climatic conditions. Secondly, country’s largest wood market is grown on this river and that’s why this region has the highest number of households made of wood and this, in turn, will help collect more information regarding availability of different wood, current situation of timber house and other details. Again, for stilt timber house, village of Rakhain community near Bakhali River, Ramu and Maheshkhali, Cox's Bazar has been selected for same reason.

4.2.2. Selection Criteria of Houses

Though the indoor thermal performance of houses has bearing on a multitude of factors: the context, orientation, size and geometry, color, envelope materials, etc. (Watson and Labs, 1992; Nieuwolt, 1984; Evans, 1980; Saini, 1973), but envelope material and construction technique have a direct bearing on indoor thermal performance as it is directly exposed to the sun and weather. Therefore, this study focused on the envelope's thermal performance of traditional timber houses in Bangladesh.

For selecting the case study houses, construction period and length of residing of occupants are given priority. Houses having at least five (05) years construction period are selected to observe if the house needs any kind of repair work/modification within this time. Though a residing period of at least six months was fixed for occupants, so that they have got acclimatized with the environment, but in all the cases studied the period is over 2/3 years.

4.2.3. Case Studies

Table 4.1 shows the description of the 16 case studies selected for detailed observation and the discussions below are the upshot of a detailed survey of these 15 houses, 5 from each typology. Table 4.2 presents types of materials used in traditional timber houses. Excluding the more identical examples, further details of the studied cases have been presented in Appendix A.

Table 4.1 General information of the Case study houses.

Case	Location	Cons. Period (approx.)	Architectural style	Plan/ Shape	Orientation	Number of Occup.	Construction Method
1.	Aakalam, Atghar-Kuriana, Swarupkathi, Pirojpur	50+	Traditional single-storied		Facing South, elongated towards N-S	Num. – 5 Age: 10-50	Mostly owner and skilled local carpenter having undocumented traditional knowledge from ancestors
2.	South-East Heulikunra, Barguna	60+	Traditional single-storied		Facing South, elongated towards N-S	Num. – 6 Age: 05-60	Local skilled carpenter having undocumented traditional knowledge
3.	Aakalam, Atghar-Kuriana, Swarupkathi, Pirojpur	45+	Traditional single-storied		Facing South, elongated towards N-S	Num. – 7 Age: 10-60	The owner (having undocumented traditional knowledge from ancestors) with the help of skilled workers
4.	Aakalam, Atghar-Kuriana, Swarupkathi, Pirojpur	40+	Traditional single-storied		Facing South, elongated towards N-S	Num. – 5 Age: 08-55	The owner (having undocumented traditional knowledge) with the help of skilled local carpenters
5.	Aakalam, Atghar-Kuriana, Swarupkathi, Pirojpur	60+	Traditional single-storied		Facing South, elongated towards N-S	Num. – 6 Age: 05-60	Owner with the help of the local worker
6.	Aakalam, Atghar-Kuriana, Swarupkathi, Pirojpur	65+	Traditional double-storied		Facing East, square plan	Num. – 7 Age: 05-75	Traditional carpenters and laborers using the traditional method.
7.	Aakalam, Atghar-Kuriana, Swarupkathi, Pirojpur	75+	Traditional double-storied		Facing South, elongated towards N-S	Num. – 7 Age: 04-65	Traditional carpenters and laborers using the traditional method.

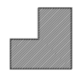
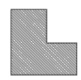
8.	Aakalam, Atghar-Kuriana, Swarupkathi, Pirojpur	70+	Traditional double-storied		Facing South, elongated towards N-S	Num. – 7 Age: 07-65	Traditional carpenters and laborers using the traditional method.
9.	Aakalam, Atghar-Kuriana, Swarupkathi, Pirojpur	65+	Traditional double-storied		Facing South, elongated towards N-S	Num. – 6 Age: 10-60	Traditional carpenters and laborers using the traditional method.
10.	Joyjogotpur, Swarupkathi, Pirojpur	75+	Traditional double-storied		Facing South, elongated towards N-S	Num. – 5 Age: 12-85	Traditional carpenters and laborers using the traditional method.
11.	Aakalam, Atghar-Kuriana, Swarupkathi, Pirojpur	60+	Traditional double-storied		Facing East, square plan	Num. – 6 Age: 15-65	Traditional carpenters and laborers using the traditional method.
12.	RamuSadar, Cox's Bazaar	100 +	Traditional stilt		North facing, L-shaped with larger arm elongated towards N-S	Num. – 5 Age: 8-65	Rakhain architectural style: Group of skilled carpenter and laborers from Myanmar (former Burma)
13.	U-Chit San Buddhist Temple, Ramu, Cox's Bazaar	100 +	Traditional stilt		South facing, L-shape plan with longer arm elongated towards N-S	Num. – 5 Age: 16-70	Rakhain architectural style: Group of skilled carpenter and laborers from Myanmar (former Burma)
14.	Adinath, Rakhain Para, Moheskhali, Cox's Bazaar	78	Traditional stilt		South facing, elongated towards N-S	Num. – 6 Age: 10-65	Mostly owner and skilled local carpenter having undocumented traditional knowledge from ancestors
15.	Adinath, Rakhain Para, Moheskhali, Cox's Bazaar	87	Traditional stilt		South facing, elongated towards N-S	Num. – 8 Age: 15-70	Mostly owner and skilled local carpenter having undocumented traditional knowledge from ancestors
16.	BoroRakhain Para, Moheskhali, Cox's Bazaar	100+	Traditional stilt		South facing, L-shape plan with longer arm elongated towards N-S	Num. – 5 Age: 10-55	Rakhain architectural style: Group of skilled carpenter and laborers from Myanmar (former Burma)

Table 4.2 Types of materials used in the investigated houses.

Case	Plinth	Structure	Floor	Wall	Roof	Veranda	Opening
1.	Earthen (stepped)	Hard timber	Earthen	Timber frame with 12.5mm thick wooden shingle	C.I. sheet on a timber frame with wooden false ceiling and 'Chadoa'* beneath it.	('Paschati') C.I. sheet on timber frame	Wooden panel with wooden grill
2.	Brick with plastered outside	Hard timber	Earthen	Timber frame with 12.5mm thick wooden shingle	C.I. sheet on a timber frame with wooden false ceiling and 'Chadoa'* beneath it	('Paschati') C.I. sheet on timber frame	Wooden panel with iron grill
3.	Earthen	Hard timber	Earthen	Timber frame with 12.5mm thick wooden shingle	C.I. sheet on a timber frame with wooden false ceiling and 'Chadoa'* beneath it	('Paschati') C.I. sheet on timber frame	Wooden panel with wooden grill
4.	Brick with plastered outside	Hard timber	CC (cement concrete) flooring	Timber frame with 12.5mm thick wooden shingle	C.I. sheet on a timber frame with wooden false ceiling and 'Chadoa'* beneath it	('Paschati') C.I. sheet on timber frame	Wooden panel with wooden grill
5.	Earthen	Hard timber	Earthen	Timber frame with 12.5mm thick wooden shingle	C.I. sheet on a timber frame with wooden false ceiling and 'Chadoa'* beneath it	No 'paschati'	Wooden panel with wooden grill
6.	Brick with plastered outside	Hard timber	Lower: CC flooring Upper: Wooden	Timber frame with 12.5mm thick wooden shingle	C.I. sheet on a timber frame with wooden false ceiling and 'Chadoa'* beneath it.	('Paschati') C.I. sheet on timber frame with wooden shingle below	Wooden panel

7.	Brick with plastered outside	Hard timber	Lower: Earthen Upper: Wooden	Timber frame with 12.5mm thick wooden shingle	C.I. sheet on a timber frame with wooden false ceiling and 'Chadoa'* beneath it.	('Paschati') C.I. sheet on a timber frame with partial wooden shingle underneath and 'chadoa'	Wooden panel
8.	Brick with plastered outside	Hard timber	Lower: Earthen Upper: Wooden	Timber frame with 12.5mm thick wooden shingle	C.I. sheet on a timber frame with wooden false ceiling and 'Chadoa'* beneath it.	('Paschati') C.I. sheet on a timber frame with wooden shingle underneath	Wooden panel
9.	Brick with plastered outside	Hard timber	Lower: Earthen Upper: Wooden	Timber frame with 12.5mm thick wooden shingle	C.I. sheet on a timber frame with wooden false ceiling and 'Chadoa'* beneath it.	('Paschati') C.I. sheet on a timber frame with the bamboo knitted mat underneath and chadoa	Wooden panel
10.	Brick with plastered outside	Hard timber	Lower: Earthen Upper: Wooden	Timber frame with 12.5mm thick wooden shingle	C.I. sheet on a timber frame with wooden false ceiling and 'Chadoa'* beneath it.	('Paschati') C.I. sheet on a timber frame with wooden shingle below	Wooden panel
11.	CC plinth	Traditionally hard timber but now the lower part is replaced with concrete beam-column structure though the upper structure is kept as it was (hard timber post & joists)	Lower: CC flooring Upper: Wooden	Timber frame with 12.5mm thick wooden shingle	C.I. sheet roofing with 25mm wooden shingle underneath	No veranda	Wooden panel with operable wooden louver and iron grill
12.	CC plinth	Hard timber	Lower: CC floorin Upper: Wooden	Timber frame with 12.5mm thick wooden shingle	C.I. sheet roofing with bamboo knitted mat/wooden shingle beneath	No veranda	Wooden panel with operable wooden louver and wooden grill
13.	No plinth	Same as case 11	Lower: Earthen with brick lining at the outer periphery Upper: Wooden	Timber frame with 12.5mm thick wooden shingle	C.I. sheet roofing with bamboo knitted mat underneath	C.I. sheet on timber frame	Wooden panel and iron grill
14.	No plinth	Hard timber	Lower: Earthen Upper: Wooden	Timber frame with 12.5mm thick wooden shingle	C.I. sheet roofing with bamboo knitted mat underneath	No veranda	Wooden panel and wooden grill
15.	CC plinth	Same as case 11	Lower: CC flooring Upper: Wooden	Timber frame with 12.5mm thick wooden shingle	C.I. sheet roofing with 25mm wooden shingle underneath	C.I. sheet on timber frame having 25mm wooden shingle underneath	Wooden panel with operable wooden louver/ Wooden panel and wooden grill

*a light fabric used over bed just beneath the ceiling (traditional artifact)

QUALITATIVE ASSESSMENT

4.3 Qualitative Assessment

Though this study has emphasized the performance of building envelope, qualitative observation has brought into account the features that impact the indoor thermal environment. Again, findings regarding occupants' perception and experience regarding indoor thermal environment has been presented under this section. The overview of this observation will help analyze the thermal data monitored with the help of data monitoring tools.

4.3.1 Architectural Features

i) Site and Surroundings:

The context of the house, the presence of natural features i.e., trees, water-bodies, etc. and physical attributes impact the indoor environment (Givoni, 1993; Geiger, 1975).

a) Context of the House:

As discussed earlier, single and double-storied houses are detached house forms having separated kitchen and toilet from the main block. But recently houses with adjacent kitchen are a new trend. Again, the whole house is surrounded by large evergreen trees for climatic reasons. Though the prime reason for planting trees around house is to protect it from high-pressure wind during storm but at the same time give shade from direct sun. Again, proximity of the river/canal also contributes to comparatively comfortable outdoor. During the field survey, local people acknowledged that prevailing cool breezes from the river/canal provide a comparatively comfortable outdoor environment most of the time.

Stilt timber is also a detached house constructed on an elevated platform usually having no boundary wall. Usually, toilet block is kept outside the main house block. House has a huge plantation of coconut and other evergreen trees that keeps cooler outdoor as well as provides shading. Again, proximity of Bay of Bengal contributes ample cool breezes in these areas. The lifestyle of the people is such that they are used to spend much of their day-time in the airy shaded area beneath the elevated platform to perform their domestic chores. During field survey, occupants of these houses reported the airy shaded space is more comfortable compared to indoor at noon.

b) Vegetation:

Both traditional single/double-storied and stilt timber houses are surrounded by trees (Fig. 4.1) that help to keep a comfortable outdoor. At the same time shade from the trees also contribute to lower indoor temperature. During the survey, it is observed that the shaded houses or a particular portion of the house having shade from nearer trees are cooler than the non-shaded one/part.

c) Air Movement:

The settlement pattern of the single and double-storied traditional timber house is linear with the separate house which allows unobstructed airflow through the entire area. During the field survey, maximum outdoor wind speed has been recorded as 3.52 m/s. But spot measurement inside the house pointed towards nearly no air movement (zero to .01/0.02m/s). The upper floor has slightly higher airspeed than the ground floor. With a typical height of the ground floor 2.6m (6 hath/8-8.5ft) and the first floor nearly 2.4m (5hath/7.5-8ft), the traditional timber houses have been constructed as a naturally ventilated one. During the day all the windows both ground and first floor are kept open while at night these are kept closed for privacy and security purpose. During night, gap between floor and wall helps enter cool outdoor air inside the house and gap between roof and wall helps evacuate the indoor warm air. But, from field survey, it is observed that nowadays ceiling-mounted/pedestal fan is a common element in all houses for enhanced indoor thermal environment.

Figure 4.1 Context of timber house: traditional double-storied (left) and stilt timber (right)

In contrast, the elevated single-storied houses are typically elevated at a height of 2.4m (8 ft.) from the ground level. These houses with its elevated ground floor allow obstacle-free airflow through the entire area. The elevated platform while protecting the house from floodwater and ground moisture also contributes to keeping the house off from the radiant heat gain from the hotter ground. Again, the raised platform has cracks between the wood joints allowing air penetration through it inside the house. During the field survey, maximum outdoor wind speed has been recorded as 2.5 m/s. But spot measurement inside the house slows nearly zero value of air movement in the middle of the room while a speed of .02/.03m/s has been recorded near the window. The wind speed at the shaded outdoor space beneath the platform has been recorded at 1.02m/s. And during the field survey, it has been found that people spend most of their day-time at this space. These houses with an average height of 2.4m and 3.8m near the wall and middle of the room respectively have been constructed as a naturally ventilated one. But today most of the houses own ceiling fans for having comfortable indoor. From the field survey, it has been observed that people of Rakhain community are used to sleep/seat directly on the floor. That's why the window is positioned in such a way that it allows airflow at the occupancy level. The sill height of the window is typically 0.5m (1.5 ft.) from the floor level. As the windows are kept closed during night for security and privacy, windows are provided with operable louvers to allow night-time natural ventilation inside the house.

ii) Building Design

a) Orientation, Plan, and Layout

All the timber houses selected (both single, double-storied, and stilt timber) for the study are facing-south. The reason is that almost all the houses in this area have similar N-S orientation. The traditional single and double-storied houses are rectangular in plan and elongated along the N-S direction while the stilt timber house has a nearly square shape plan. The typical builders demonstrate their talent to put the house in an atmosphere that avoids the harsh consequences of disasters. Since the cyclones mostly proceed from the south and south-west directions that are why placing a house having the short-side towards this direction is more logical. Moreover, the south wall receives direct solar radiation, and the short-side towards this direction contributes to minimizing direct solar gain. Again, the west side with low sun angle is also vulnerable for indoor thermal comfort. Large trees in this direction provide shade to the house and hence contribute to comfortable indoor with ample wind for natural ventilation. Fig. 4.2 shows the June and December solstice, and Equinox (March to September) and wind direction for both Pirojpur and Cox's Bazaar district of Bangladesh and considerations made for orienting the traditional timber houses. The figure is self-descriptive.

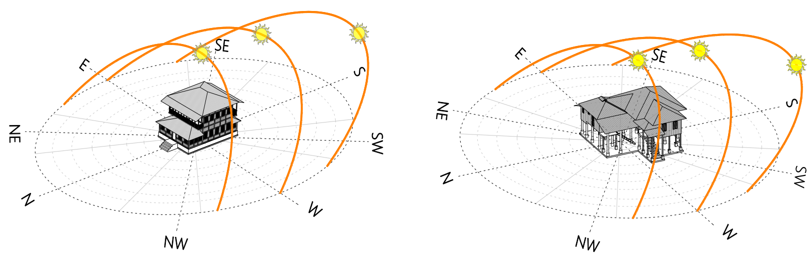


Figure4.2 Orientation of houses following the sun

b) Shade and Porosity

The 'pashchati'/upper veranda acts as solar shading for the main block. Instead of high thermal mass or insulation these houses use natural ventilation and solar shading strategies by introducing side corridor in the front/back/around the house (though the main purpose is protection from storm). Again, gap between wall and roof/floor and wood carving in wall (nearly 15%) provides indoor night-time ventilation.

c) Construction Material: Thermal Mass

From the field survey, it is seen that the indoor temperature is low at night and early morning and started rising with the time during the day. During noon the indoor temperature becomes higher than the outdoor temperature and occupants like to stay at airy outdoor than indoor. The ground floor of the traditional double-storied house is more comfortable compared to the first floor and single-storied house. The wooden floor of the upper story act as insulation for the ground floor and a thin cloth is stretched just beneath the wooden ceiling. The cantilever veranda also provides shade to the room beneath it and thus contribute to comfortable indoor on the ground floor. Again, houses with earthen ground floor also contribute to comfortable indoor than houses with CC (cement-concrete) flooring. First floor with its C.I. sheet roof becomes warmer than outdoor.

The stilt timber house usually has no false ceiling. Instead of a ceiling bamboo mat or wooden shingles are placed directly under the roof covering. Similar to that of the single and double-storied timber house, this house becomes uncomfortable with the time during the day (11-12 pm) and the indoor temperature starts falling in the afternoon. But during this time people usually stay at the space below the elevated platform to perform their daily chores. The ground with mud finishing is reported as much comfortable by the occupants than one having CC finish during the survey.

d) Internal Heat sources

Though there is no such heat-generating equipment inside the house and in most of the cases the kitchen is kept as a separate block. In cases with the internal kitchen, it is the only source of internal heat gain except the heat emitted from the human body and a few electric lights and fans. During the field survey, it is seen that all the case houses have tube/energy-saving light and ceiling/pedestal fan.

4.3.2 Construction Technique

4.3.2.1 Traditional Single and Double-storied House

i) Settlement Pattern & House Form and Layout

The house form of traditional timber houses is the result of a practice that has been transformed from generation to generation, which has been influenced by the trend of industrialization over time. House pattern is of single house form with separate kitchen and toilet at the back. The main house is kept as a single entity aligned with the river/road with adequate set-back from the river/road. This space works as a front yard with a lot of large trees at the boundaries. The house is south or east-facing. The traditional houses in these areas are mostly rectangular with length and width ratio within 2:1 constructed on a high plinth with a huge opening at all sides. A ratio of a maximum of 3:1 is found during the survey. The main house is protected by low height veranda at the front and back locally called '*Pashchati*'– a unique feature of coastal house form (Fig. 4.3). It is an additional covered or semi-covered space around the main house for climatic protection and so on.

Figure4.3 '*Pashchati style'* veranda

The house form starts from the basic one-room unit and then attains a complex shape with the addition of space in 'pashchati' style. The final size of the house varies with the economic solvency of the owner. House is most of the time double-storied but with time single-storied are also seen among the poor to accommodate the nucleated family. The whole structural frame is constructed with locally available wood and the wall envelope is entirely built with thin wooden planks. The whole house stands untied on the plinth. As the double-storied large house has considerable self-weight, though they are used to be displaced during storms, the damage to them is less than that of the single-storied one. Single-storied with its smaller size and less self-weight is severely damaged by strong wind and storm surges. As a local solution sometimes, the outer post is provided with a concrete footing. The roof is a pitched roof with a timber frame. Once as a roof covering 'Golpata' was very popular but nowadays in almost all houses, it has been replaced by the C.I. sheet. Even the industrial metal product (locally known as the plain sheet), brick, etc. have growingly replaced the wood as wall envelope material. Thus, traditional timber house is in continuous process of being lost.

ii) Measurement System

For traditional/local construction 'hath' (hand) is the popular measuring system, where 1hath is approximately equal to 450mm (1.5ft.). The traditional timber house size typically varies between 6hath x 10 hath, 10hath x 17hath, or 16hath x 21hath. The number of posts is calculated based on this measurement. Typically, the front façade (width of the house) is provided with 6, 8 0r 10 posts @ 1-1.5m (3.5-5ft.) c/c. span between two consecutive posts. Typically, the outer comparatively low height wall is generally 6hath with 3 horizontal beams and the inner wall is 10hath with 7 horizontal beams. For detail measurement and wood thickness, the width of 'angul' (width of a single finger) is used where 1angul approximates 12mm (½").

iii) Construction Elements and Materials

Throughout rural Bangladesh, people use ready-to-use construction materials in the respective region. The local craftsman develops different construction techniques and details to sustain the house in different climatic conditions which is a long and evolutionary process where changes take place over time influenced by socio-economic, climatic, technological, and other factors. One such example is the traditional timber house. As discussed above, the type of house is found near Bangladesh's coastal areas, which are essentially cyclone susceptible and where wood is a readily available resource. Through natural disaster encounters, here, people developed a remarkably resilient construction technique with wood to survive and protect their homes and other property. The traditional timber house has the following elements: Plinth, floor, frame structure, wall and fenestration, roof, and other special features i.e., 'pashchati' veranda and others (Fig. 4.4 and 4.5).

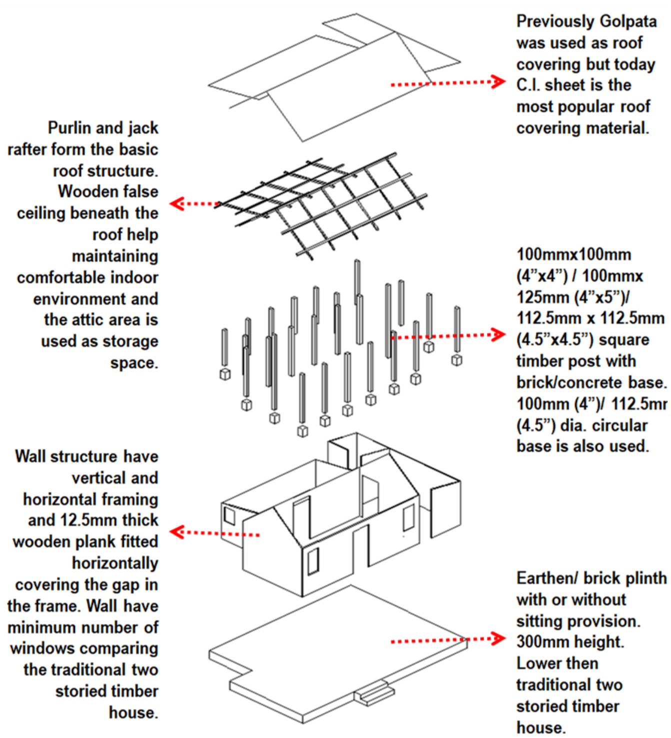


Figure 4.4 Single-storied Timber house elements and construction technique

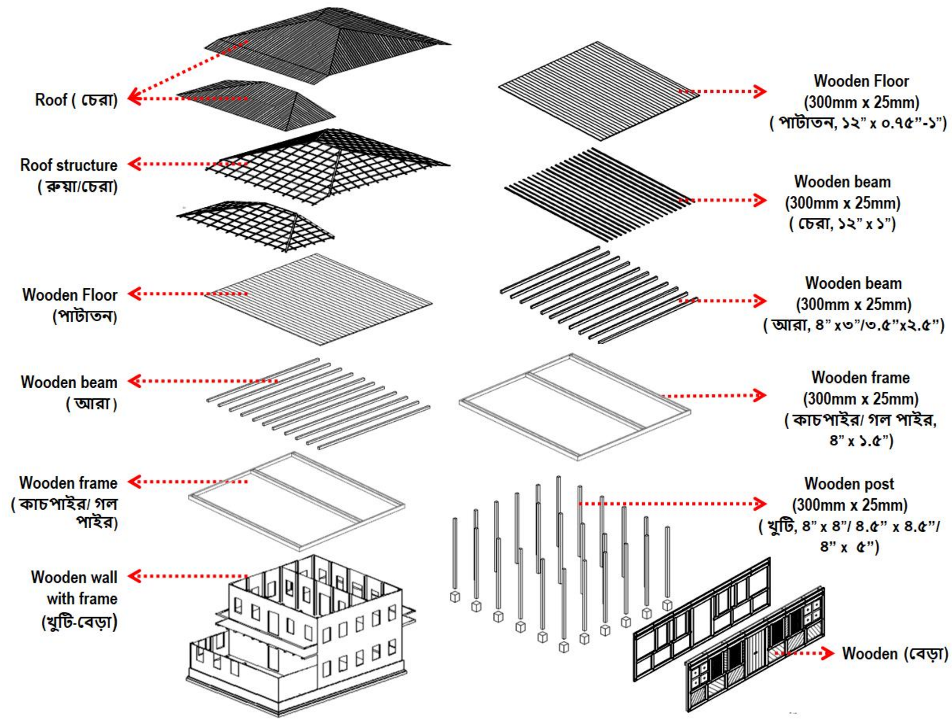


Figure 4.5 Elements and construction technique of traditional single/double-storied timber house

(a) Plinth

As the house is rectangular in plan (generally length-width ratio 2:1 or maximum 3:1) and so is the plinth. Generally, it is 450-600mm (1.5-2 ft.) high above the ground level to protect the house from the rainwater and surface drain out. Sometimes it is as high as 900mm (3ft.) also found during the field survey. Lower portion of earthen plinth is wider than upper portion so that damage due to rainwater is less (Fig 3.6).

Figure 4.6 Different types of plinths of traditional single/double-storied timber house

Traditionally mud plinth is provided with clay plate/brick base at an interval of usually 1.0-1.5m (3.5-5ft.) c/c which is the usual post to post distance. Usually, it is constructed after the construction of the frame structure of the house so that the post rests vertically on the center of the clay plate/brick base. This local technique prevents the wooden post from decay as wood with regular contact with moist soil decay readily. Nowadays plinth is provided with a peripheral brick wall plastered on the outer face and then the whole area inside is filled and compacted with the earth/sand. The interior posts are provided with a continuous brick lining. Currently, instead of mud floor, the affluent class prefers cement concrete (CC) floor and as a modern solution to the problem of house lifting during the cyclone, the wooden post is instilled inside the base.

(b) Frame/Structure

The frame structure of the traditional timber house consists of the vertical upright post ('*khuti'*) with a horizontal beam pinned to it. The number of horizontal beams varies with the height of the post. As a thumb rule, a post having a length of 4.5m (15'/ 10 hath) requires seven horizontal beam whereas 2.75m (9'/6 hath) long post requires three horizontal beam. For a post of 2.75m long one horizontal beam is installed near the bottom of the post (locally called '*choukath*'), another two as sill ('*peti*') and lintel ('*choukath*') and two at the top on the two opposite of the post, where the member towards the outdoor forms the frame locally called '*kachpair'* and opposite to it is the beam along with the partition locally called '*kolpair/kolda'*. The wall frame and internal beam (*ara*) are attached to form the skeleton of the house (Fig. 4.7).

Figure 4.7 Frame structure of traditional single/double-storied timber house

The posts are generally square-shaped measuring 100mm x 100mm/ 112.5mm x 112.5mm (4"x4"/4.5" x 4.5"). Square-shape helps secure a better joint. Sometimes the size of the posts is larger near the joints. The end beam ('*kachpair'* and '*kolpair/kolda*') generally has a size of 100/125mm wide and 37.5mm(4/5"x1.5"), thick, while the internal beam('*ara'*) has a dimension of 87.5-100mm (3.5-4") wide and 62.5-75mm (2.5-3") thick. Usually, for the construction of the post, Raintree (*Samaneasaman*) and Lohakath (*Xyliaxylocarpa*) are used but Poshur (*Xylocarpusmekongensis*), Shaal (*Shorearobusta*), Teak/Shegun (*Tectonagrandis*) are also common. For the end ('*kachpair*' and '*kolpair'*/'*kolda'*) and internal beam ('*ara*') Lohakatha is most popular but Chambal (*Artocarpuslacucha*), Coconut (*Cocos nucifera*), Bain (*Avicenniaofficinalis*) are also used.

As a sequential construction process frame structure is the next to construct. After the treatment and preparation of the wooden post and other horizontal beams, the wall frame for the four sides of the house is prepared separately. Then they are tied together with rope and placed on the clay-plate/brick base to form the primary frame structure of the house. The joints are then provided with iron bolts locally called 'Gojal'- a large size pin to tie the wood. Then the internal beams are installed to make it more stable.

(c) Floor

As mentioned above the ground floor is usually mud floor but the current trend is cement concrete colored floor. But the upper storey floor and ceiling above are always constructed with wood. On the internal beam/ 'ara' number of wooden purlin (locally known as 'Chera') measuring 50mm (2") wide and 25mm (1") thick is placed orthogonally at a distance of 300mm c/c. On this frame wooden plank ('pataton') is placed to form the floor. The planks usually have a dimension of 300mm wide and 18-25mm (¾"-1") thick (Fig. 4.4 and 3.5). 'Chera' is placed in such a way that it covers the joint between two consecutive wooden planks ('pataton'). It restricts the dust-like particles from falling, through the joints. Again, a piece of fabric (locally called 'Chadoa') (Fig. 4.8) is stretched over the bed/resting area, to protect the area from dust falling from the upper level. Raintree (Samanea saman), Coconut (Cocos nucifera), and Chambal (Artocarpus lacucha) trees are commonly used for the construction of the floor.

Figure 4.8 Use of fabric ('*Chadoa*') just beneath the ceiling above the resting area

(d) Roof

The houses have a two-level roofing system. The main block has the hipped roof with a slope 30-45°, where the 'pashchati' around the main block has a separate roof. The shape of the roof is important as it can also be captured by the storm wind. According to the long-standing experiences of the local craftsman they prefer hip roof with little overhang as it has less cyclone hit damage record. As the hip roof is well protected by storm wind, this shape is selected for the main house block. A separate roof is installed for the 'pashchati' so that it doesn't pull the main roof with it during storm.

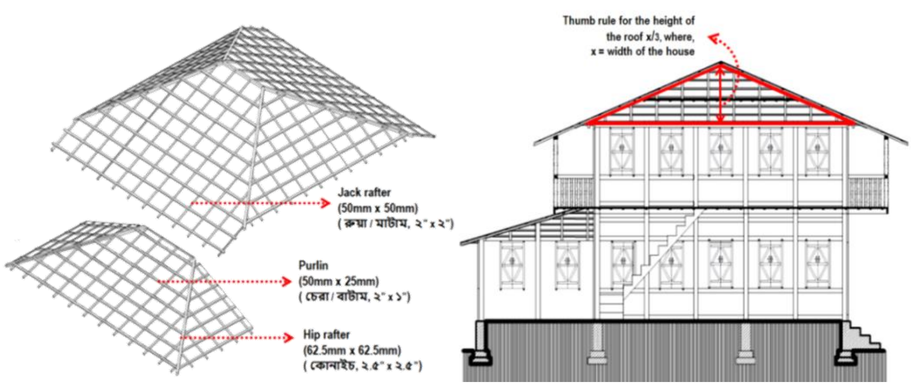


Fig. 4.9 Roof details of traditional single/double-storied timber house

After the construction of the floor, the roof is the next element to be constructed. The different elements of the roof are shown in Fig. 4.9. The height of the main roof depends on the width of the main block of the house. The thumb rule is that the height is one-third of the width of the main block (Fig.

4.9). A wooden ceiling is provided below the main roof forming an attic and this attic area is used as storage and acts as a buffer zone for heat insulation (Fig. 4.10). This ceiling protects the house from being overheated during the day. Sometimes gap is provided at attic area which helps to evacuate hot air from indoor. Hip rafter at four corners is locally called ‘konaich’, which has an area of 62.5mm x 62.5mm. The inclined jack rafter (‘rua’/ ‘madaam’) has a cross-sectional area of 50mm x 50mm. Purlin (‘chera’) is placed over jack rafter. It has a cross-sectional area of 50mm x 25mm. The wood used for the roof structure is the same as used for the floor.

Figure 4.10 Ventilated attic as storage space

(e) Wall Envelop and Fenestration

After the construction of the roof the door, window, and wall envelope is installed with the frame. The roof helps protect the elements from the sun and rain. The door and window frame are fixed first with the wall frame. The position of the window is another important matter to consider. Placing window at the corner of the house façade makes the house more vulnerable to storm wind. That is why the corner window is avoided most of the time. The symmetrical and limited window is preferred on the windward façade. The window is installed in the ‘pashchati’ and the adjacent interior wall. The window height is approximately 1m (3.5 ft.). The windows’ opening system is a swing window with two wooden sashes and a wooden grill attached to a frame which is then fixed with the main wall frame. Most of the time the window sashes open indoor but when the house is provided with cantilever veranda at the top a reverse case is also found during the field survey. Sometimes folded slashes are used so that the slash doesn’t hinder the indoor area. To fix the slashes with the frame traditionally no pin is used. To install the window, slash the local craftsman exercises the local technique of window cleat wooden joints (Fig. 4.11) as the use of the iron pin is problematic. The high moisture in the air causes rapid damage to the iron and thus collapses to the structure. The local technique is used to lock the window for the same reason.

Figure 4.11 Construction details of the door and window

For the construction of window frame and slashes Chambal, Raintree, Bain, Jackfruit, Lohakath, and Shegun (চাম্বর, রেইনট্রি, বাইন, কাঁঠাল, লোহাকাঠ, সেগুন) trees, while for grill Koroi, Mehogoni, Battlenut, and Sundori (করই, মেহগনি, সুপারি, সুন্দরী) are used.

The main entry door is usually folded system but the rest of the doors are swing. It is never fixed with the post. A wood beam is used to install the door. Instead of a steel/aluminum door lock, the local technique is used to lock the door. Shal, Chambal, Raintree, Berry, Lohakath, and Shegun (শাল, রেইনট্রি, জাম, লোহাকাঠ, সেগুন) are used for the construction of door frame and slashes.

Attached wall frame is finally filled with small prefabricated parts (Fig. 4.12). Wall frame is kept elevated from the ground as wood with moist soil gets rotten fast. That is why a gap of 25/50mm is kept between the frame and the floor. Again, at the corner of the house where two walls meet together, it is not possible to install both walls at the same level to the post for structural stability of it (Fig. 4.13). For the same reason, the front part of the plinth is kept slightly low. This allows cool air to enter the house.

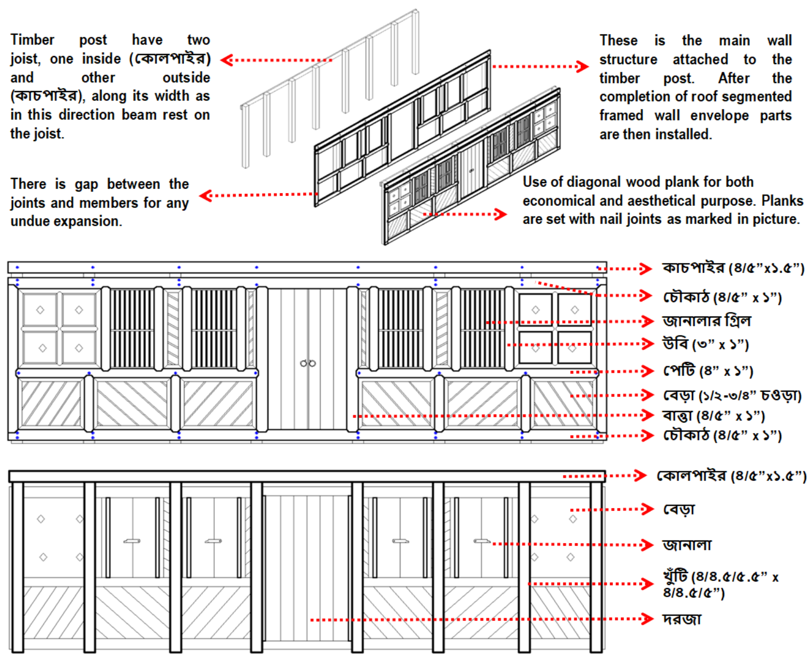


Figure 4.12 Different parts of the prefrabricated wall.

Figure 4.13 Joints of prefraricated wall of traditional single/double-storied timber house

A similar gap is provided at the top of the wall between the end beam (‘*kolda*’) and wall frame (‘*choukath*’), which helps inside warm air to evacuate. The gap of the frame is then filled with prefabricated small parts (Fig. 4.12 and 4.13), having numbers of shingles of 75-100mm (3-4") wide and 12.5-19mm (½-¾") thick, arranged inside a 50mm (2") wooden frame. Firstly, these small parts are prepared on-site and installed to the final position. This prefabricated construction system of wall envelope is essentially economical as it allows changing/repairing small parts of wall instead of changing the whole when part of the wall gets damaged. The planks are placed either diagonally or orthogonally having pinned with one another (Fig. 4.12 and 4.13). Diagonal arrangement acts as bracing for frame and at the same time economical as in a sense it allows small pieces of wood to use.

Envelope has perforated wood carvings at the upper and lower parts of the wall envelope (Fig. 4.14) which enhances night-time ventilation. It allows cool air to enter inside and hot warm air to evacuate outside through it while the doors and windows are closed at night. Moreover, these perforated wood carvings are also present in internal wall that also helps enter prevailing air inside.

Figure 4.14 Wood carvings for night-time ventilation while windows are kept close

iv) Local Technique of Wood Treatment

There are many types of wood which are long-lasting and resistant to insect in hot-humid climate (Johan van Lengen, 2008). Wood construction requires the seasoning of wood before use. Traditionally people do natural seasoning of wood. It increases dimensional stability, reduces or eliminates attack by decay or stain, reduces the weight, and increases the strength of the wood. Before using the wood for construction, it is soaked underwater for at least 15days. Local people believe that soaking help getting out the sap from inside the wood, and the sap is the main reason for insect attack of wood as the sap contains starch. Then the wood is first kept for drying in an upright position and then piled horizontally for at least 10 days. For drying the pieces are kept in such a way that every piece is fully exposed to air. Sometimes an extra load is kept on piled wood to prevent it from bending. After 10 days of drying in the natural condition, the preparation of wood is done. Then the finished part is given a coat of Mobil/coal tar/ kerosene to protect it from insects. Sometimes several coats are applied on the wood. After drying finally, it is used for construction.

v) Traditional Wood Joints

For wood beam and post joints, the local craftsman uses a traditional joint technique (Fig. 4.15). For the post, half-lap joint is usually used. For long beam length, traditional beveled and half-blind tenoned, dadoed, and rabbeted scarf joints are used. For railing and door-window 'tenon and mortise' joint is used. For floor, joints are placed according to the position of joists and purlins below.

Figure 4.15 Traditional wood joining technique

4.3.2.2 Traditional Stilt Timber House

i) Settlement Pattern

The settlement pattern is of scattered type and the house pattern is of single house form with separate kitchen and toilet at the back. There is ample space between the houses and therefore nearly no obstacle for prevailing wind. Again, the whole houses are elevated off to the ground supported by stilts which further ensures prevailing air to pass through the entire area/village without impediment. The whole house is surrounded by trees i.e., betel nut, coconut, and other strong medium height evergreen barky trees, etc. (Fig. 4.16) which act as a windbreaker for the house and at the same time provide shade and cooler surroundings. But a distance of nearly 10-20 ft. is kept between the house and plant as a safeguard from the damage that may be caused by uplifting trees.

Figure 4.16 Vegetation around the traditional stilt timber house

Layout of the house is exclusively regulated by religious faith and custom and is based on gender and age hierarchy. During the field survey, the local craftsmen stated that the houses are mimicry of heaven and they create a sense of harmony, lightness, and floating following the philosophy of Buddhism. Therefore, the form emphasizes linearity, straight line, and simplicity wherepeace is represented in the square shape and the rectangular structure of the house.

Figure 4.17 Basic zoning of the traditional stilt timber house

Architecturally the elevated timber houses are typically L-shaped in plan with small squarish blocks. According to their religious belief, the front part of the house should be faced towards the east but where east-facing is not possible usually a south-facing one is constructed. During the field survey, it has been found that typically houses are facing towards the south. This orientation has a climatic benefit with square block planning (Fig. 4.17). House is positioned according to local wind direction which helps to reduce effective wind pressure on the house. Again, in coastal areas simple, compact, symmetrical shapes are best for resisting high wind pressure and square shape is best to resist high wind (Bhandari et al., 2005). Stilt house with its small and squarish block-planning, has wider depth towards wind direction and this helps to anchor off house against the strong wind.

ii) Measurement System

The measurement system is similar to the traditional measurement system in rural areas of the country – 'hath'. But the size and height of the house are different from those of the traditional single and double-storied timber house.

iii) Construction Elements and Materials

Builders make pre-assembled wooden pieces to build these houses and put them together. They generally make all the pre-fabricated parts of the house (Fig. 4.18): wall and roof frame, wall envelope, posts, and most often tests them before assembling to make it flawless. Then on an auspicious moment, they first erect the largest post of the house which is the central post of the house and supported the partition wall of the prayer room locally known as 'AlichengBera'. During the field survey, local builders stated that during 'Aashari Purnima' to 'Ashwini Purnima' (June-September, three months of the rainy season) they do not start construction work because of possibilities of natural disasters.

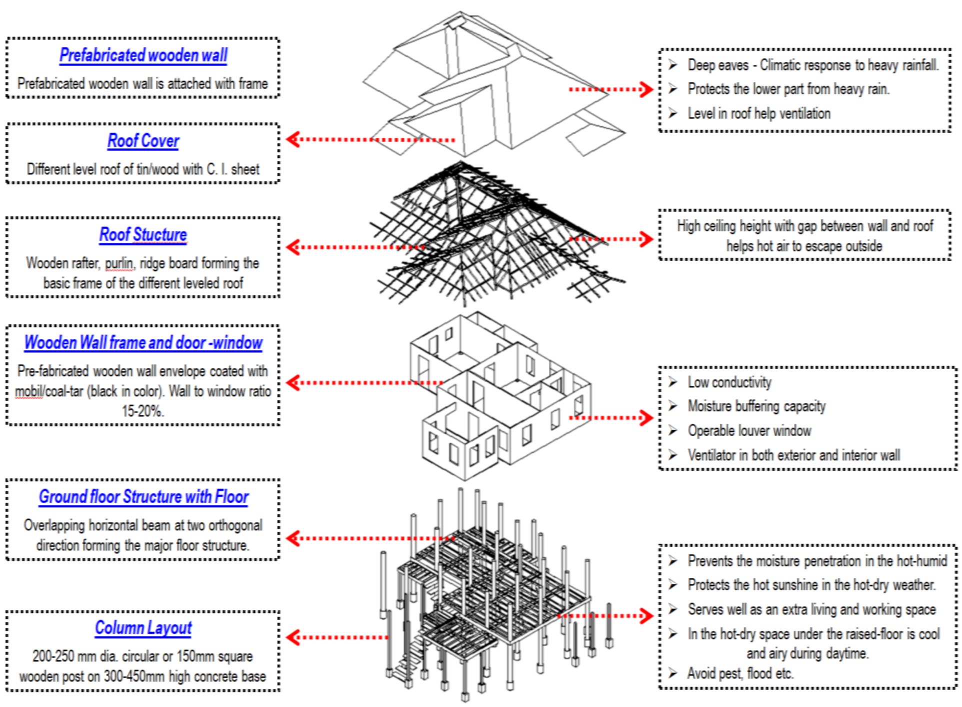


Figure 4.18 Elements and construction technique of traditional stilt timber house

During the month of October-November after the festival of 'Pronomi Purnima' (a festival of self-purification and renunciation of evil) on an auspicious day, they start their house construction work with the erection of the central column. The process of construction is fast because of the pre-fabricated construction system. Traditionally instead of nails and bolts wooden peg/cramp are used for wood joints. This system has fewer possibilities to decay and the structure remains intact as forces automatically press one another on either side of the structure. But with time many traditional techniques of the construction have been modified.

(a) Stilts/Posts and Elevated Platform

Instead of a raised plinth, the whole house is elevated on a platform at the height of 2.5m (8-8.5ft.) from the ground supported by 38 stilts/posts. Usually, these posts are circular with a dia. of 200-250mm (8-10"). The posts are directly ponded into the ground at a depth of 1-2 elbows. With the technological advent and industrialization, the structural system has gone through some modifications for adaptation with the climate. During the field survey, it is found that the post is anchored with a 300mm dia. circular/300mm (12") wide square concrete base having an average height of 200-300mm (8-12") to protect it from ground moisture and floodwater which prevents the wooden post from decay by weather effect (Fig. 4.19). The wooden post is anchored with a steel angle to secure the house from twisting/sliding due to strong storm wind. This system of wood pier foundation elevates the timber structure above the ground level. Therefore, minimal excavation is required and natural features as well as existing drainage patterns of the site is preserved. As the area is subjected to frequent floor, tidal water, and high wind, hence, stilt post protects the house during this time. Traditionally shaded space between mud ground surface (though now the mud floor is sometimes provided with a cement concrete layer) and elevated platform is used for daily work.

Functionally the house has three major parts: the public shaded space on the ground floor, both semi-public guest and prayer space and restroom and service space on the upper floor. These functions are accommodated in different small square blocks having separate roofing on them. A total of 38 posts 38 according to the rules for a beatific life (Moe 2019) are used to elevate the whole structure where different functions have variation in height. Studies shows that square shape is perfect for cyclone-prone areas where houses are most often subjected to strong wind. Fig 4.20 shows functional zoning, post and roof variation.

Figure 4.19 Concrete base under the stilts for protection from ground moisture and flood-water

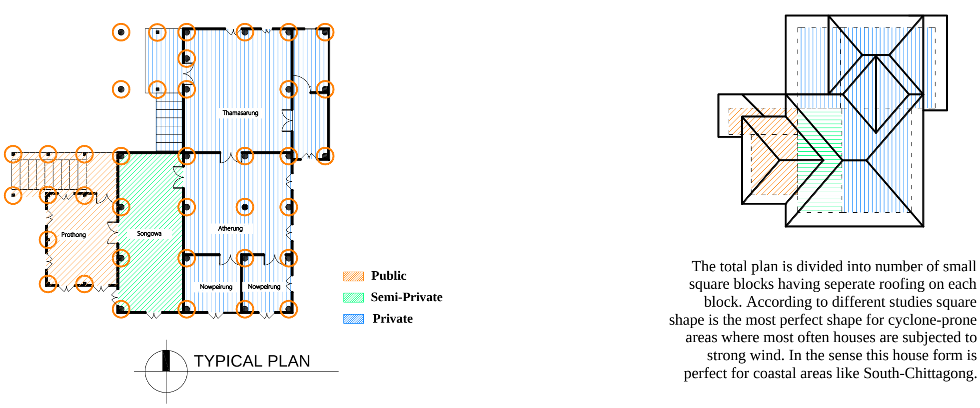


Figure 4.20 Zoning and roof variation of stilt timber house

The structure of the elevated platform has similarities with the structure of the traditional double-storied timber house. The structure of the stilted timber is shown in Fig. 4.21 and the figure is self-explanatory. Each separate form has an outer peripheral floor joist ('Choukath') fixed with the posts with pin locally known as 'Gojal'. Inside the joist, the posts are connected with the horizontal internal beam ('Ara'). Each post is provided with two 'ara' on the opposite side of the post. Again, orthogonally another internal beam 'Chera' is placed at a distance of 250-300mm (10-12") c/c. The size of the members is shown in Fig. 4.21. The wood shingle of 150-200mm (6-8") wide and 25mm (1") is then placed over the structure to form the upper floor.

The wood species used for the construction of post is 'Protiumserratum' locally known as 'Gutia/Gutgutia' tree. Once this tree was available in a large quantity in the forest area of Chittagong, but now it is almost one of the extinct species (Huq, Hasan et al. 1987; Hasnat and Hossain 2018). Nowadays Lohakath (Barma iron wood) is commonly used for the post. For other elements (joist, beam, floor, etc.) of the structure use of 'Gorjon' tree is common.

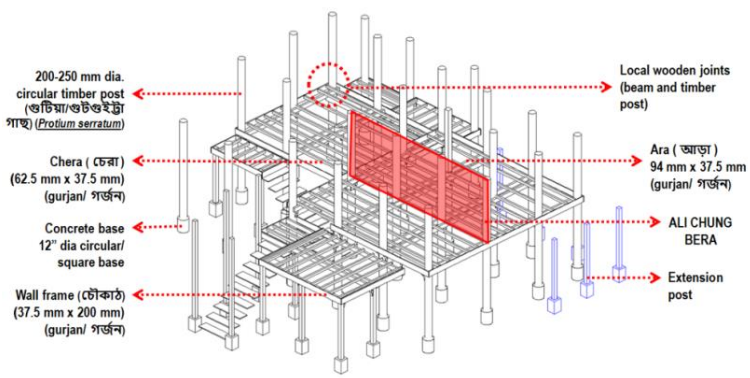


Figure 4.21 Structure of the elevated platform of the Stilt timber Timber house

(b) Frame/Structure

Wall frame is then installed with the posts. From floor to eave, wall has five horizontal members (Fig. 4.22). These are bottom plate, sill trimmer, noggin, head trimmer, and top wall plate from the floor to top plate (roof) respectively to hold the posts in position. Traditionally peg/cramps were used but now bulwarks are used to fix the framing member with the post. At the corner of the wall where two horizontal members of the frame meet together, they are fixed slightly up/down from one another. Inserting bulwarks at the same level from two different sides affects structural stability and strength of the post and may cause the formation of crake at this level. So that frames of both door and window are installed during this stage. Studs are used to fix the frame of the door/window with the frame. For door and window frames mortice and tenon joints are usually used. For the construction of the frame, the 'Gorjon' tree is most popularly used.

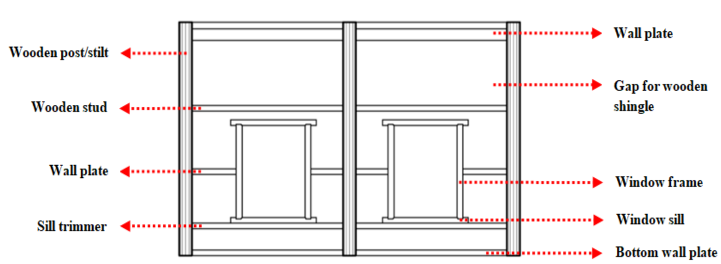


Figure 4.22 Frame structure traditional stilt timber house

(c) Roof

Roof is the next to construct. This house has a multilayer roofing system. Local builders are successful to minimize the mass of roof of a large building by applying multi-layer technique which gives the whole structure a sense of light-weightiness. Separate roof over each different function breaks down the roof into a small unit overlapping with one another. This helps reduce roof size. When the roof is broken, making front and back portion lower than main part, then the structure appears to be light. Usually, prayer space with the restroom has the highest height compared to rest of the functions creating a spiritual sense of connection to heaven. Roof is hipped shape but with a smaller length of the ridge-board, it nearly acts as a pyramidal roof. This roof geometry significantly affects the pressure distribution on roof surface and wall of the building. According to a study by Shreyas Ashok Keote (2015), a pyramidal roof was found with the lowest uplift when compared with the gable and hip roof (Fig. 4.23). Another benefit of this roof is that, deep overhang can be provided to protect the wooden wall underneath without creating extra wind pressure on roof.

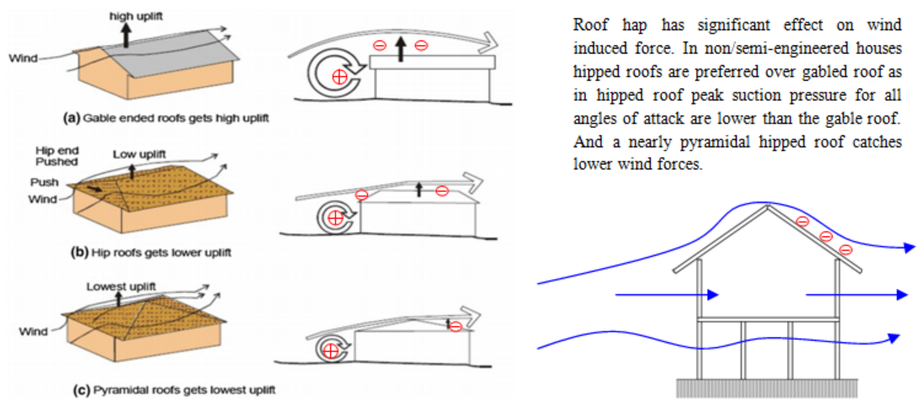


Figure 4.23 Wind flow effect over the gable, hip and pyramidal roof (Shreyas Ashok Keote, 2015)

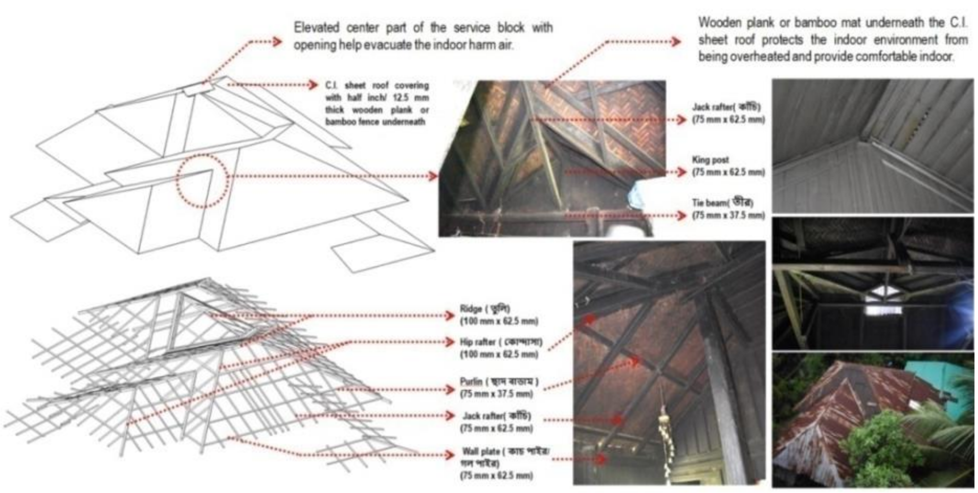


Figure 4.24 Roofing details of traditional stilt timber house

The roof has a complex structure having a connection with each small unit as shown in Fig. 4.24. The dimension of the roof members is shown in the figure and the figure is self-explanatory. The roof has a bamboo mat or wooden shingle just under the roof covering. This protects the indoor from overheating during the day. As per the statement of the local builders, in the past 'chon' was very common as roof covering material. Local people acknowledged that 'Chon' with its high thermal insulation properties combined with the bamboo mat/wood layer performed well. But for a few decades, it is continuously replaced with C.I. sheet roofing because of its durability and availability. There is no gap between the wall and the roof. But sometimes the service area is provided with roof ventilation for hot air, even when the wind is still (Fig. 4.24).

(d) Wall Envelop and Fenestration

After the completion of the roof, the fenestration and the wall envelope are the next to construct. The roof protects the wooden structure from rainwater and direct sunlight. The fenestrations are fixed with the frame first and then the prefabricated wood shingles are fixed with the frame with bulwarks (Fig. 4.25). For window and door installation extra, framing is fixed with the main wall frame to resist any damage caused by the vibration of operating the door (Fig. 4.25). But for joining two adjacent members of the wall (wood shingle) the local craftsman uses traditional joining system as shown in Fig. 4.26. Again, from the outer side, the joints are concealed with a wooden frame (Fig. 4.25).

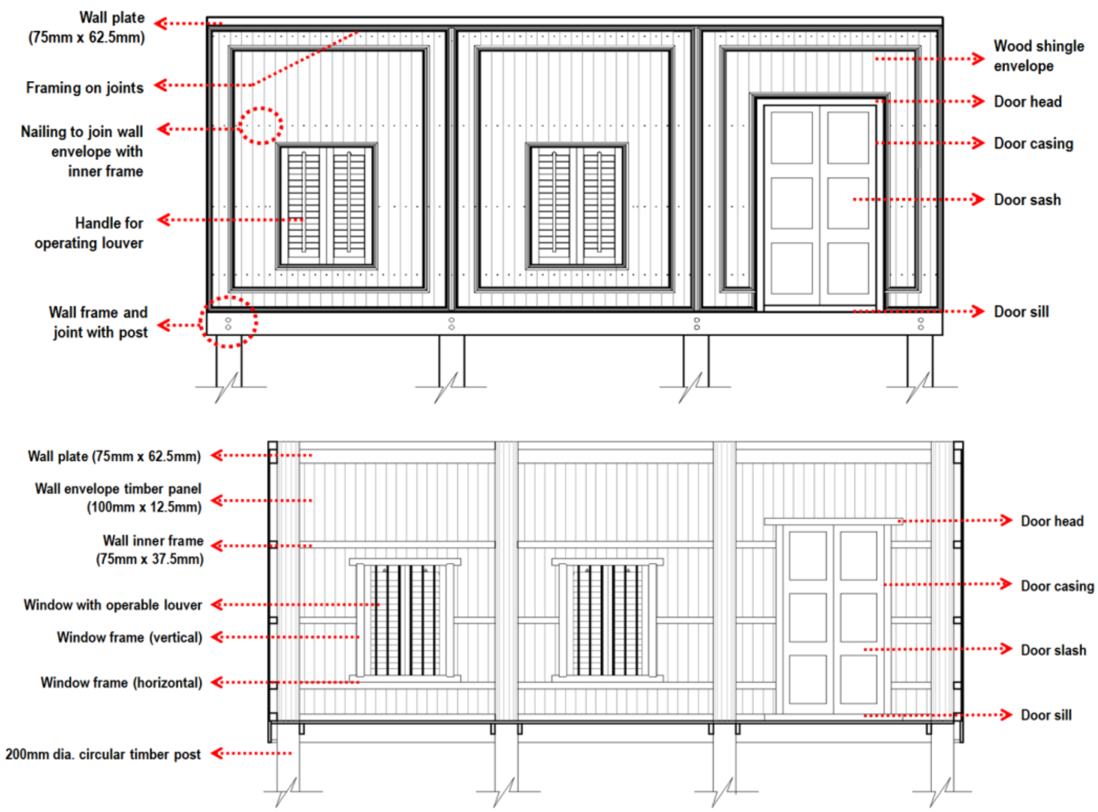


Figure 4.25 Wall and fenestration of Stilt timber house: exterior view (top) and interior view (bottom)

Windows are located on all four sides of the house for ventilation and lit the space. Windows are tall with its sill level near to the floor. This is because traditionally occupants use to sleep/seat on the floor and low sill height allows prevailing air to go directly to the activity level. The internal partition walls are provided with perforated wood carvings which act as hot wind escape from the space. These internal spaces are unlit as the placing of windows is not possible for privacy, and it does not create any problem to their day-to-day life as most traditional livelihood activities are carried on outdoors.

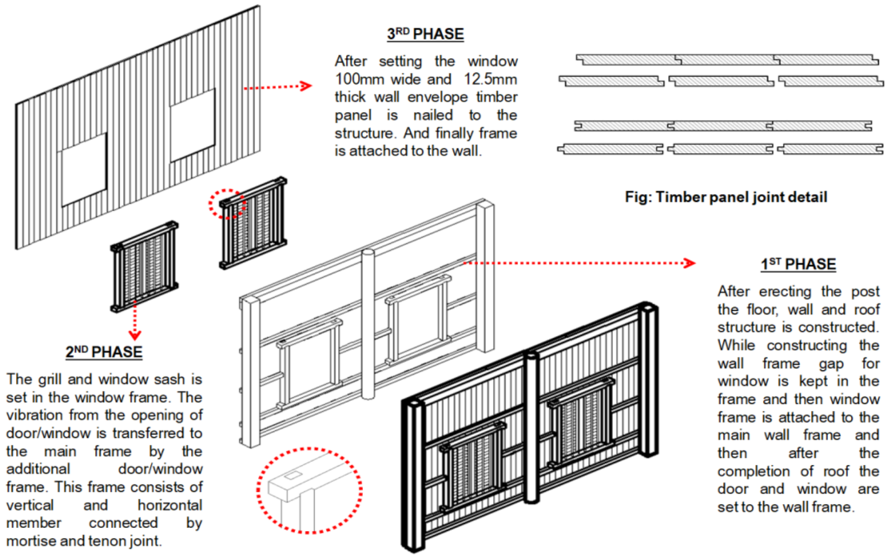


Figure 4.26 Exploded diagram of wooden wall

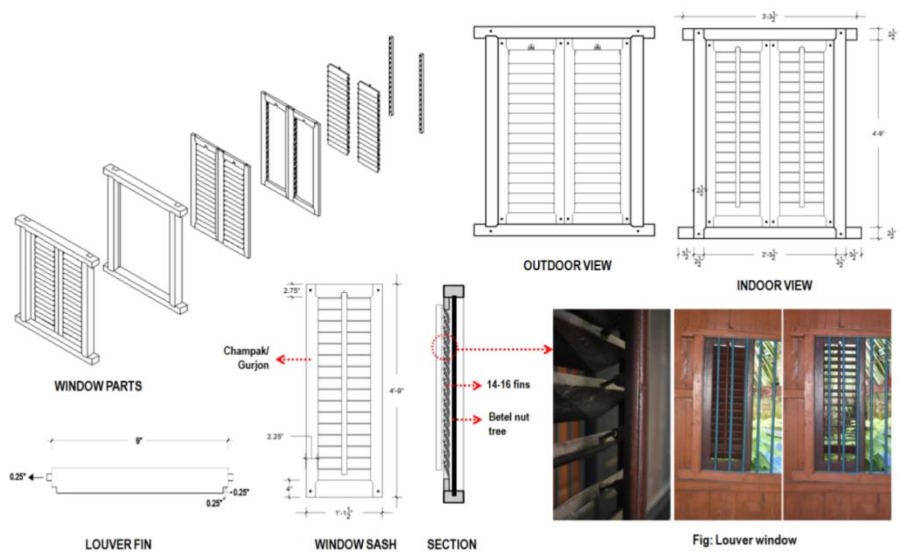


Figure 4.27 Window details of Stilt timber Timber house

Operable louver helps night-time natural ventilation inside the house. For the construction of door and window sashes, Champak (Magnolia champaca) tree is popularly used for its first-class timber, soothing color and texture, and its availability in coastal areas. For door-window frame ‘Gorjon’ tree is popularly used. The door has an average height of 1.8-2m (6-6.5ft.). Traditional windows have an average height of nearly 1.5m (4.5-5 ft.). The window is provided with a wooden window grill. The window sashes have operable wooden louver fixed inside the frame of the sashes. The details of the window are shown in Fig. 4.27 and the figure is self-explanatory.

iv) Local Technique of Wood Treatment

The treatment of wood is the same as the local builders practiced for the traditional single and double storied house. Before using the wood is soaked underwater for 3-4 months. Then it is dried in a shaded airy space for at least 15 days first in an upright position and then horizontally stuck in such a way that every plank is exposed into the air (Fig. 4.28). After the preparation of wood, the finished part is given single/several coats of Mobil/coal tar/ kerosene to protect it from insects' attack.

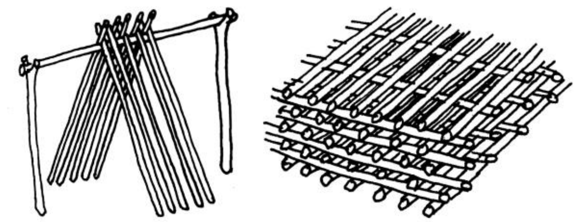


Figure 4.28 Treatment of wood before construction (source: Johan van Lengen, 2008)

v) Traditional Wood Joints

Traditionally different types of scarf joints of wood are popularly used for joining wood together (Fig. 4.29 and 4.30). When post length longer than the wood on hand is required two pieces are joined with the half-pegged bladed scarf joint (Fig. 4.29). This joining technique is a half-lap joint with a tongue or blade that links one post with another. This bladed scarf joint is supported by pins/bolts/peg. As the blades add more surface area the joint becomes strong enough. This type of joinery system works well under light sustained tension and hence suitable for post joinery. For joining beam or similar types of members plain and keyed-hook scarf joints are commonly used (Fig. 4.30). It is formed by lapping two tapered pieces cut at an angle 1:8 to 1:10 in the direction of the grain. The joints are secured with glue and pin/peg/bolts having flush finished surfaces. This joint can resist tension and compression and is suitable for beam.

Figure4.29 Half pegged bladed scarf joints of wooden post

Figure 4.30 Plain and keyed-hook Scarf joints of the wooden beam

4.3.3 Present Condition of Traditional Timber Houses

From the field investigation, it has been observed that the traditional timber houses have gone through several changes. A part or sometimes major parts of the traditional houses are replaced by manufactured materials while repairing the houses. Because of widespread availability and the lower price of manufactured materials i.e. C.I sheet/ plain sheet, wood as a wall envelope material has been continuously replaced by these

materials (Fig. 4.31). The envelope materials of a house have a great bearing on the indoor thermal environment of a house. The higher the thermal conductivity of the envelope material the higher is the heat transfer through wall. Today timber-framed plain sheet wall houses are more popular than the wooden envelope ones among the people. The floor height of this house is higher (ground floor: 3m and first floor: 2.6m) than the traditional one. In many cases, the earthen ground floor is replaced with CC flooring. The traditional roof covering of 'golpata' is now rare, because of its replacement by C.I. sheet.

Figure 4.31 Present condition of traditional single/double-storied timber house

In Cox's Bazar it has been observed that most of the traditional stilt houses have gone through huge changes (Fig. 4.32). Most of the timber posts have been replaced by concrete pillars. In some cases, to accommodate their extended family the space below the raised platform has been occupied while the upper storey is kept as it was. This is because of the changes in their lifestyle and occupation. Traditionally there used to have handloom in every house, but nowadays which is almost extinct (The Daily Star, 28 May 2015). Today as a wall envelope they use C.I. sheet/brick with/without plaster.

Figure 4.32 Present condition of traditional stilt timber house

4.3.4 Summary of Construction and Envelope of Traditional Timber House

From field investigation, it is found that though the construction of traditional single/double-storied and stilt timber houses are different but there are similarities among the envelope materials used for construction. In Fig. 4.33 common envelope materials and dimension of different parts of traditional timber houses are presented.

The ground floor of the traditional single/double-storied house is usually earthen flooring. The plinth is usually 0.5-1.0m high and is sometimes provided with peripheral 250mm brick with outer 12mm plaster lining or CC flooring. For CC flooring 1:2:4 mixes are laid on one layer of 2nd class brick having sand filling below it. Traditional stilt houses usually have an earthen ground or simply one course of 2nd class brick soiling. But in all cases, the first floor is a 25mm wooden floor with a timber structure. The typical floor heights are shown in Fig. 4.33.

Most of the walls are made of a 12mm thick wooden envelope with a timber frame structure. For protection from insect and weather, the wall is coated with Mobil or tarpin oil (locally known as 'maitta-tel') resulting in dark brown to black color. In the case of the traditional single/double-storied house, the wall has a considerable portion of perforation nearly 25-30% as well as the 37.5-50mm gap between floor/roof and wall, while the traditional stilt house has no perforation or such gap in the wall.

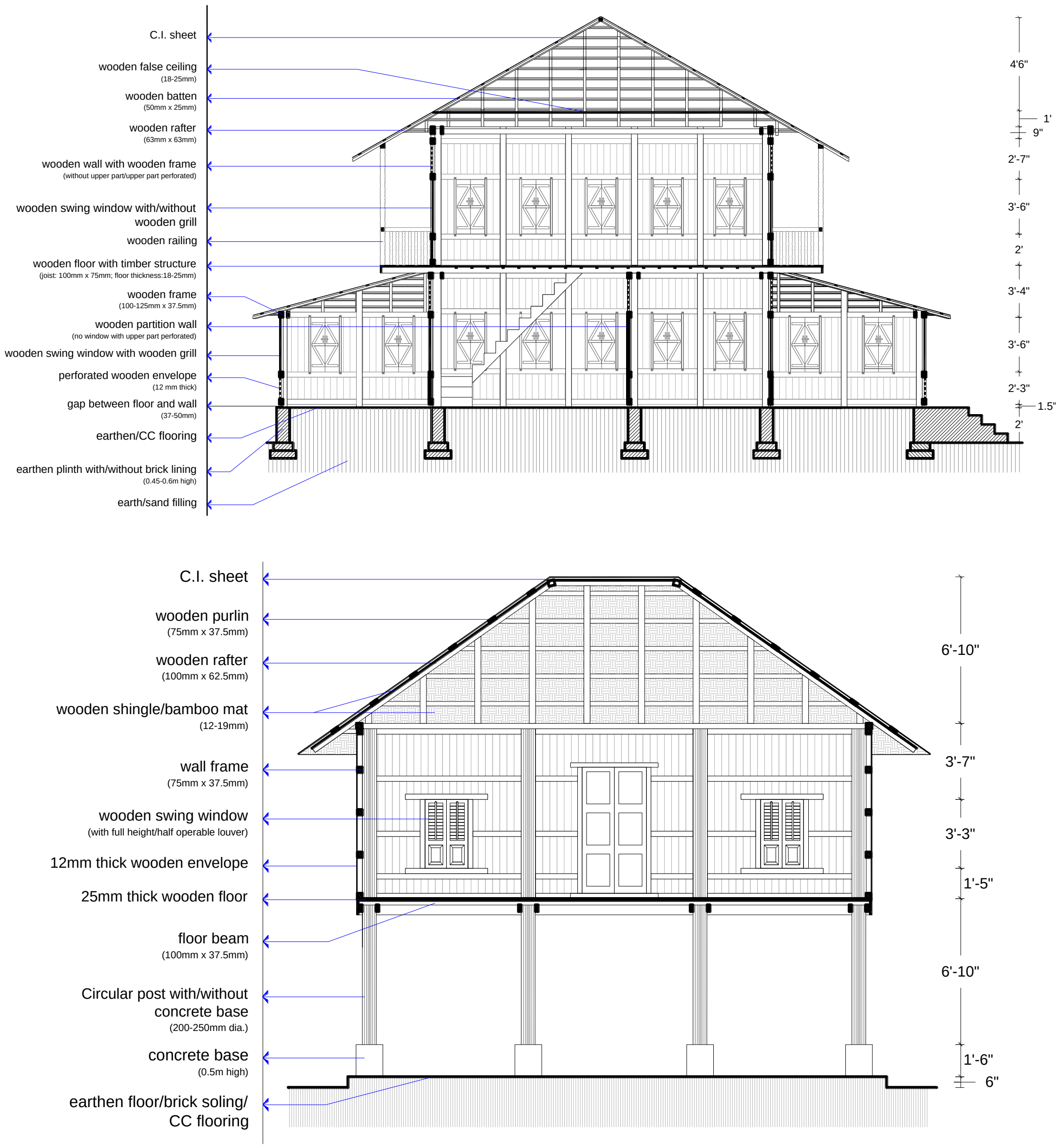


Figure 4.33 Typical section of traditional timber house: single/double-storied (top), stilt house (bottom)

In all cases, roof shape is a hipped roof with a slope ranging 30-40° having 0.12-0.5mm thick C.I. sheet covering over timber frame structure. The main roof of the traditional single/double-storied house is provided with an additional 25-37.5mm thick wooden false ceiling creating ventilated attic space (average height 1.2-1.5m) and the roof over 'veranda'/'pashchati' is provided with 12mm wooden shingle/average 6mm thick bamboo knitted mat just beneath the C.I. sheet covering. The roof of traditional stilt houses is provided with a 12-19mm thick wooden shingle or average 6mm thick bamboo knitted mat attached to the roof structure having no attic.

The window pattern of the traditional single and double-storied houses is similar: a wooden frame swing window with two 12mm thick wooden panel. Average height of the window is 1m with an average sill height of 0.6m from the floor level. On the other hand, average window height of the traditional stilt house is 1.4m with an average sill height of 0.4m from the floor level. The window panels are provided with operable wooden louver (fin is 75mm wide and 12mm thick). Table 4.3 shows envelope details and table. 4.4 presents common construction wood and its uses. Typical dimension of elements is listed in Appendix-4B.

Table 4.3 Various envelope combination of traditional timber house

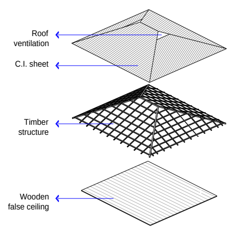
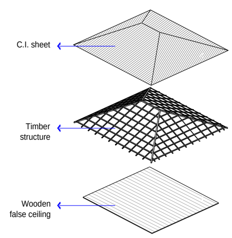
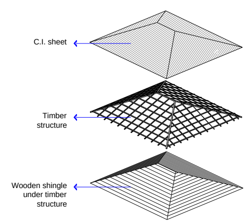
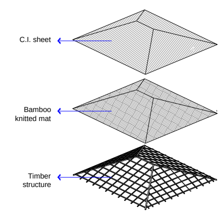
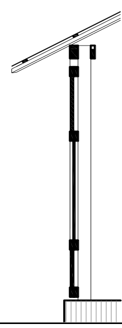
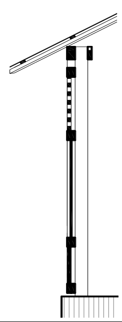
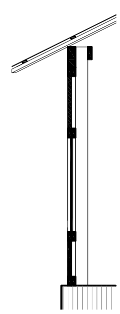
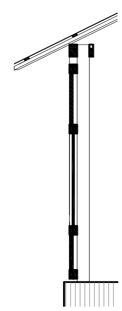
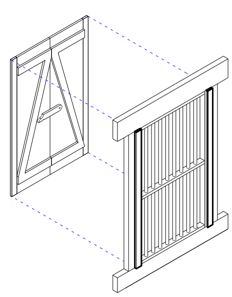
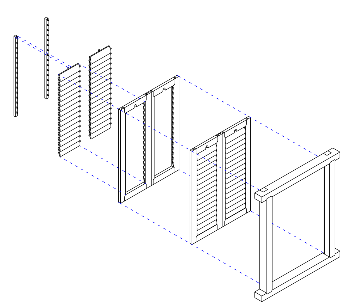
Element	**Different combination**			
Roof	With vented attic having wooden false ceiling beneath 	Without vented attic having wooden false ceiling beneath 	No attic having wooden shingle adjacent to roof covering 	No attic having bamboo knitted mat adjacent to roof covering 
Wall	Timber frame wood envelope with gap between wall and floor/roof 	Timber frame perforated wood envelope with gap between wall and floor/roof 	Timber frame wood envelope having no gap 	Timber frame Plain/C.I. sheet envelope with gap between wall and floor/roof 
Window	Panel wooden without operable louver 		Panel wooden with operable louver 	
Floor	Earthen ground floor and wooden first floor	CC (Cement Concrete) ground floor and wooden first floor	Elevated ground floor and wooden platform	

Table. 4.4 Common construction wood used in traditional timber houses and their uses

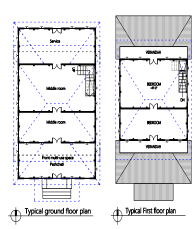
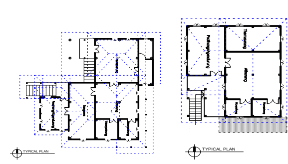
No.	Common name	Botanical name	Construction member	Advantages/ Uses	Reference
1.	Raintree/ Shirish (রেইনট্রি, শিরিষ)	*Samanea saman*	Post, Wall, Joist, Purlin, Floor, Door-window sash	▪ Suitable for carving, paneling, and posts. ▪ It is generally considered a durable wood. ▪ Dry wood has a specific gravity of 0.56. ▪ Resistant to attack by dry-wood termites. ▪ May be subjected to shrinkage and moderate to extreme warp if not carefully dried	(Staples, G. W., and C. R. Elevitch, 2006; Longwood, 1971; Chudnoff 1984; Hossain and Awal, 2012)
2.	Lohakath (লোহাকাঠ)	*Xylia xylocarpa*	Post, Door-Window sash	▪ Colored an attractive red ▪ Hardwood, very strong ▪ Heavy; extremely hard; very strong; very durable, ▪ resistant to the weather as well as termites and other insects ▪ Suitable for heavy-duty uses	(Digital Compendium of Forestry Species of Cambodia, 2008)
3.	Poshur	*Xylocarpus moluccensis*	Post	▪ Colored brown ▪ very hard, strong and durable ▪ Suitable for post	(Uphof, 1959)
4.	Shal/Gajari (শাল/গজারি)	*Shorea robusta*	Post, Wall, Joist, Purlin, Door-Window sash	▪ Colored dark reddish-brown ▪ Hardwood timber ▪ Strong and durable ▪ highly resistant to termite attack and fire ▪ Suitable for construction of structures subject to heavy stress in houses: post, floor, door-window frame	(World Agroforestry Centre; Hossain and Awal, 2012)
5.	Teak/ Shegun (সেগুন)	*Tectona grandis*	Post, Wall, Door-Window sash	▪ Colored yellowish blonde to reddish-brown ▪ Strong and high strength ▪ Suitable for floor, door-window, outdoor use ▪ resistant to the attack of termites and durable if not treated with oil/varnish	(Encyclopædia Britannica, 2019; Hossain and Awal, 2012)
6.	Indian red pear/ Gutguttya (**গুটগুটিয়া**/ গুটগুইট্টা)	*Protium serratum*	Post	▪ Colored brown or reddish-brown ▪ textured, hard ▪ Easy to saw and work ▪ Structural timber, post, door-window frame	(Kyi, 1981; Gardner et al., 2000; Woodcock, 1935)
7.	Chambal (চাম্বল)	*Artocarpus lacucha*	Floor, Door-Window sash	▪ yellowish or brownish wood ▪ Suitable for the door window frame, joinery ▪ non-durable under tropical conditions	(Chancerel, 1920)
8.	Jackfruit (কাঁঠাল)	*Artocarpus heterophyllus*	Wall, Window sash	▪ Golden yellow timber with good grain ▪ Suitable for door-window and roof construction ▪ Termite-proof	(Morton, 2016; Hossain and Awal, 2012)
9.	Sundari (সুন্দরী)	*Heritiera littoralis*	Wall, Joists, Purlin, Grill	▪ reddish-brown or dark brown ▪ hard, strong and resistant to saltwater ▪ Suitable for posts, joists ▪ resistant to marine borers, but not always to termites	(Uphof, 1959)
10.	Coconut (নারিকেল)	*Cocos nucifera*	Purlin, Joists, Floor	▪ hard, high-density timber ▪ Preferred for straightness, strength, and salt resistance ▪ pillars, trusses, rafting, window and door frames, floors, ceiling, and floor joists	(Wikipedia)

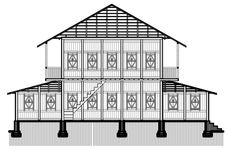
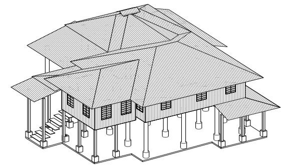
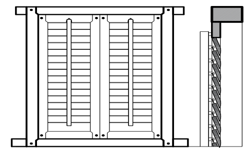
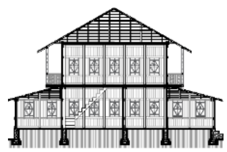
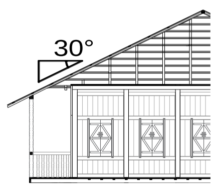
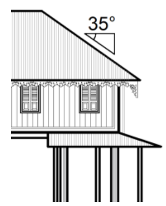
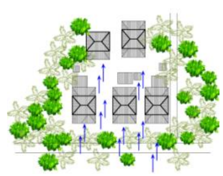
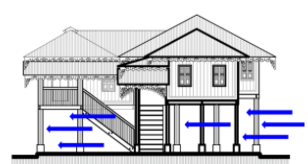
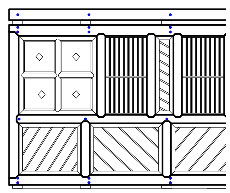
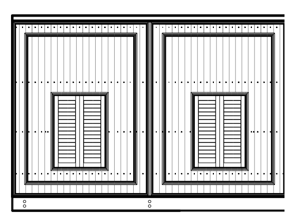
11.	Bain (বাইন)	*Avicennia officinalis*	Purlin, Joists, Window sash	▪ attractive grain and used for house construction	(Duke, 1983)
12.	Koroi (করই)	*Albizia lebbeck/ Albiziaprocera*	Grill	▪ strong, durable ▪ Resistant to insect attack	(Hossain and Awal, 2012)
13.	Mahagoni (মেহগনি)	*Swietenia mahagoni*	Grill	▪ Reddish-brown color ▪ Light, strong, and attractive ▪ Excellent workability, and is very durable ▪ Resists wood rot	(Kumar et al., 2016)
14.	Betel nut (সুপারি)	*Areca catechu*	Grill	▪ strength, and salt resistance ▪ Post, ceiling and floor joists	(Wikipedia)
15.	Tel Gurjan/ Gurjan (গর্জন)	*Dipterocarpus turbinatus Gaertn.) / Dipterocarpus spp.*	Beam, Joist, Purlin	▪ Reddish-brown color ▪ Resistant to termite attack	(Wikipedia)
16.	Black plum (জাম)	*Syzygium spp.*	Door sash	▪ Heavyweight and moderately strong timber ▪ Suitable for construction of door-window	(Hossain and Awal, 2012)
17.	Champak	*Michelia champaca L.*	Door/window sashes	▪ strong, durable, and capable of taking a high polish ▪ suitable for wood carvings	(World Agroforestry Centre)
18.	Bamboo	*Bambusa vulgaris*	Under C.I. sheet as the knitted mat	▪ Light-weight ▪ Resist fire ▪ Suitable for post, wall, floor, fencing, and construction	(Wikipedia)

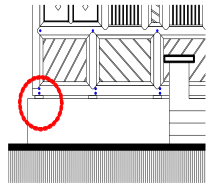
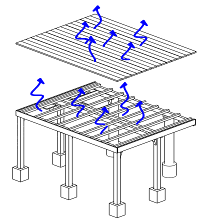
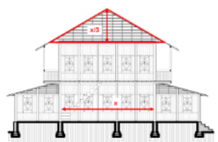
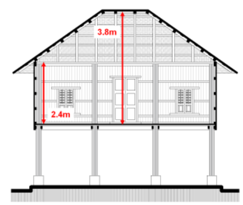
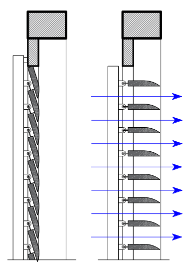
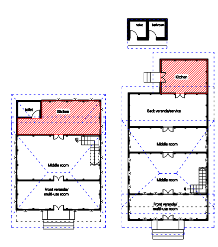
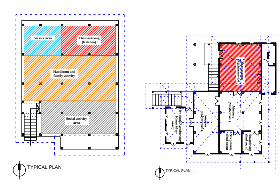
4.3.5 Overview of Architectural Features Related to Indoor Thermal Performance

All design strategies applied in traditional timber houses related to indoor thermal environment were analyzed under some essential climatic aspects: sun-path and solar radiation, temperature, humidity, local wind and seasonal variation. Adopted passive design strategies have been presented in Table 4.5 using 'description and image' approach.

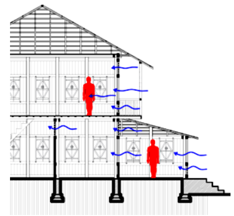
Table 4.5 Summary of architectural featuresrelated to thermal performance

Feature	Single/Double storied timber house		Stilt timber house	
	Design strategies	**Graphical illustration**	**Design strategies**	**Graphical illustration**
Sun-path and Solar radiation	The orientation of smaller arm-side of the house towards the south. Facing south while placing the main block in the middle for protection from direct sun.	 **(a)** **(b)**	The orientation of smaller arm-side of the house towards the south. Facing south or east. The layout of the plan for better solar protection and catching prevailing wind: bedrooms on the south-eastern part, services on north-western part, less used room on the west.	 **(a)** **(b)**

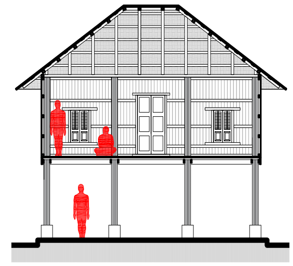
	'Pashchati' veranda (front) with low height roof for effective solar shading.		Veranda and service area with overhang low-height roof on service area/veranda cut the direct sun-ray incident on the wall.	
	The extended fabric just beneath the wooden ceiling acts as insulation for internal radiant heat gain.		Window sashes with wooden louver help natural ventilation while blocking direct sun-ray entering the house	
	Wooden false ceiling acts as insulation against the conduction of external heat through the roof.		Wood shingle/bamboo knitted mat just beneath the roof covering acts as insulation.	
	Shorter side towards the south with hip roof generally having an angle of 30-35°. Sloping roof is less affected by sun rays than a flat roof.		The shorter side towards the south with slope roofing with an angle of 30-40° reduces incident heat on the surface by reflecting the maximum amount of heat.	
	Upper cantilever veranda and Large trees around the house provide shade.	Fig. 4.1	Different level of the roof and Large trees around the house provide shade.	Fig. 4.1
	Day-time activity zone on south/ north. Daytime activity is mostly outdoor oriented and performs in shaded semi-outdoor/outdoor at north/south.	-	Less used space on the west. Day-time activity outdoor-oriented, performed at the airy shaded space beneath the raised platform.	-
Moderate tempe-rature and high humidity	Open planning and free spaces between detached houses help to capture prevailing wind and enhance natural ventilation.		Raising the whole structure on stilts at an average height of 2.4m from the ground allows obstacle-free airflow through the entire area.	
	Lightweight wooden wall (12mm thick) helps night cooling by quickly releasing heat at night. And humility doesn't accumulate on the thin wall.		Lightweight wooden wall (12mm thick wooden shingle) helps night cooling by quickly releasing heat at night and also protection from humidity accumulation.	

	Raised plinth 0.5-0.6m from the ground and again keeping a gap of 25mm between the house and the plinth prevent moisture penetration from the ground.		Raised platform protects the house from ground moisture and flood water.	
	Crack between the wooden shingle of the wall, and wood carving (‘*jali*’) on the lower and upper part of both exterior and interior wall allows prevailing air to penetrate inside.		Raised platform/wooden wall has cracked between the wood joints allowing air penetration inside the house.	
	The attic has a height of one-third of the width of the main block, usually, 1.52m (5ft.), provided contribute evacuation of hot air indoor.		Stilt post keeps the house off from the radiant heat gain from the hotter ground.	
	Perforation in the wall allows night-time ventilation	Fig. 4.14	-	-
	‘Pashchati’/veranda allow constant airflow inside the main block while protecting it from rain.		The average room height is 2.4m and 3.8m near the wall and middle of the room respectively. Thus the formation of a hot air layer far above the human occupancy zone.	
Seasonal variation	Paper/poster is glued in the wall and the gaps between floor /roof and wall are sealed with fabric to cover the perforation during winter for preventing the penetration of cool air.		The flexibility of controlling the indoor environment, during hot, cold, and rainy seasons, is provided with the installation of louvered window sashes.	
The cool breeze from the sea/river	Traditionally separate kitchen is practiced but the new trend is attached kitchen. For both cases, it is placed on the leeward side to avoid heat gain from the kitchen.	 (a) (b)	Traditionally kitchen id kept on the ground floor but nowadays attached one is also found. For both cases, the kitchen is placed on the north-eastern corner (leeward side) to protect the house from heat gain.	 (a) (b)

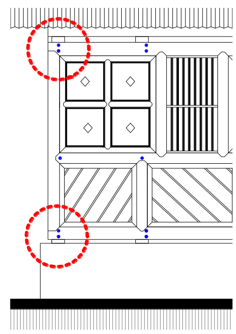
Large opening at a height of 0.75m from the floor level on all sides allows constant air exchange between indoor and outdoor while providing its occupants with flexibility for adaptation while necessary. Folded door/ window sashes also help to control the area of the opening.



Large opening with adjustable louver at a height of o.3m from the floor allows air-flow at occupancy level and control over the indoor environment.



The gap between the wall and plinth allows cool air to enter and the gap between the roof and wall helps hot air to evacuate while the window and the door are closed. This also helps to bring in airflow inside with the stack effect.



Detailed analysis reveals that passive techniques used are harmonized with local building techniques making methods sustainable and easily applicable solutions. Although every house doesn't apply all design strategies, each house adopted at least two-three strategies discussed above. Overview of this observation will help us to analyze the existing indoor thermal environment.

4.3.6 Questionnaire survey

A deep insight into the users' feedback regarding indoor thermal comfort can help analyze the overall performance of this traditional house type. Occupants of a house may have different expectations depending on the way they use it. That's why the users' response towards the thermal performance of the traditional timber house is important. This section discusses findings in detail obtained from questionnaire survey (Appendix C).

4.3.7 Thermal Perception of Occupants

To appraise thermal perception of the users at least three occupants from each house have been selected to participate in a questionnaire survey to evaluate users' thermal perception. A total of 53 responses have been collected, where 41 respondents from traditional single/double-storied and 18 respondents from stilt timber houses have participated in the survey.

4.3.7.1 Occupants Details

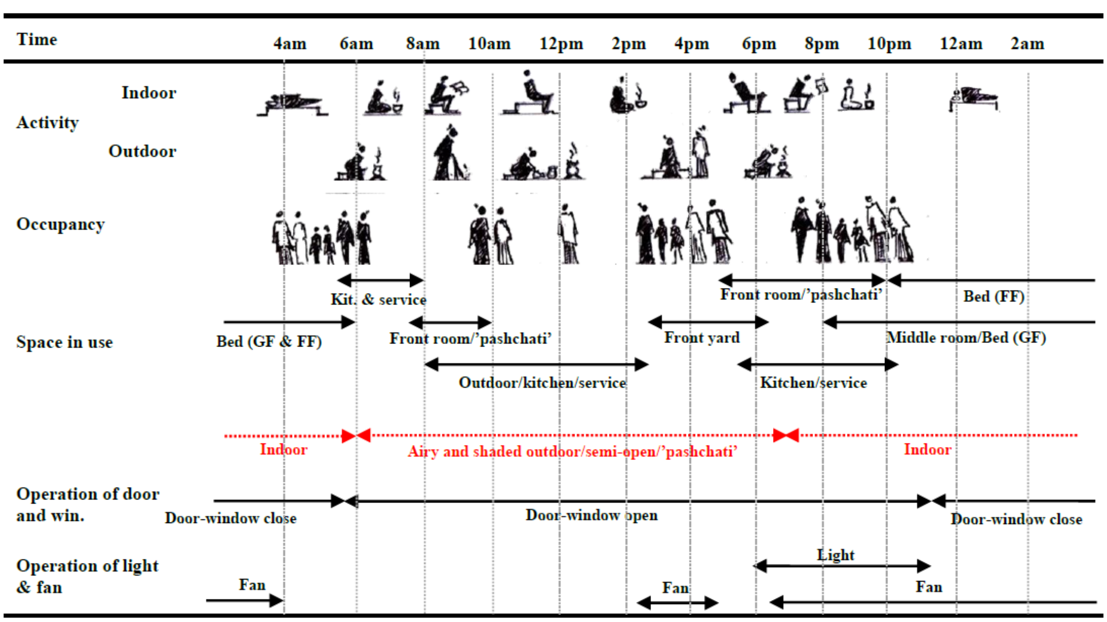
In the rural areas of Bangladesh, the trend of a joint family exists. During the field survey it is found that, almost all the families have 6-7 members: grandparents, parents, and two/three children and the age of the elderly members ranges between 60-80 yrs., parents 24-48 yrs. and the children 4-18 yrs. Respondents' personal parameters are presented in Table 4.6.

Table 4.6 Personal parameters of the respondents

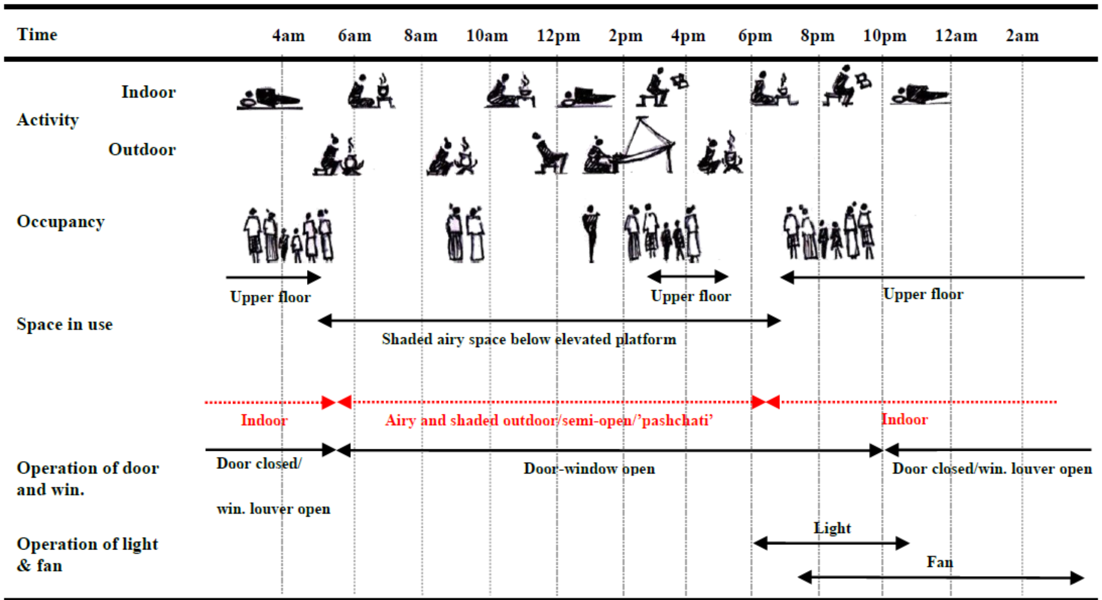
Personal parameters		**Single/Double-storied**	**Stilt**	**Remarks**
		Total respondent: 41	**Total respondent: 18**	
Age	< 20	7.32 %	11.11 %	
	21-30	24.39 %	27.78 %	
	31-40	19.51 %	16.67 %	
	41-50	14.63 %	22.22 %	
	51-60	29.27 %	11.11 %	
	> 60	4.88 %	11.11 %	
Gender	Male	51.22 %	38.89 %	
	Female	48.78 %	61.11 %	
Clothing (clo.) (average)	Male	0.5		(Mallick F. H., 1994)
	Female	0.5		
Metabolism (met) (average)		≤ 3	≤ 3	(Mallick F. H., 1994)

4.3.7.2 Lifestyle and OccupancyMapping

User lifestyle has emerged as reliance on improved thermal performance in traditional buildings. Studies on traditional houses conclude that these houses do not adequately meet users' requirements in their material compositions alone (Pereira et. al, 2017; Evola et. al, 2015). The former statement further strengthens by the study of Kvisgeard and Collet (2015) which shows that lifestyles related to operations on windows and doors improve thermal performance by providing 63%–87% of the air change per hour in a naturally ventilated traditional building. Therefore, it is important to understand the lifestyle and activity pattern of the user to analyze the thermal performance of the traditional timber houses in question.



(a)



(b)

Figure 4.34 Typical activity and space use pattern: (a) Single and Double-storied and (b) Stilt timber house

Main occupation of most of the villagers of Swarupkathi is agriculture and wood related business/labor and their daily activity is simple. The male members remain outside most of the time at day while the female members stay in the house at all the time of the daily cycle. But to do the domestic chores the female members spend most of the time in the backyard of the house. During noon lunch is eaten at the service block of the northern part of the house. Then the female members of the adjacent houses usually use the back/front airy part of the house for their social interaction. By late afternoon when the male members return home, they use to take rest at the southern 'Pashchati' veranda. Main central part generally remains unoccupied during day. At night it is used for sleeping while temperature has already started decreasing from afternoon.

People of Rakhine community are mainly engaged in agriculture and fishing, but business, crafting, boat-making, weaving, etc. are also seen. Like the traditional single and double-storied house, they spend most of their day-time in the airy shaded space under the elevated platform for their daily work. The schedule of activity sequence and space use of the residents of a timber house (both single/double-storied and stilt timber house) for a whole day at a two-hourly interval is illustrated in Fig. 4.41.

4.3.8 Occupant's Thermal Perception and Indoor Thermal Environment

Table 4.12 presents the overall findings of the questionnaire survey regarding the thermal perception of the occupants. From the survey, it is seen that the occupants of traditional single/double-storied timber houses find it comfortable during the night (10:00 pm-6:00 am). During the day with the time, occupants' perception of indoor environment becomes shifted with time from neutral to uncomfortable (Table 4.12-4.13). Most of the respondents found it very uncomfortable during the time 12:00 am-3:00 pm. The Occupants of traditional stilt timber houses responded almost the same perception as the occupants of traditional single/double-storied timber houses. The only difference is that the comfort band for the occupants of this house (majority responded from neutral to comfort for a time range 07:00 pm to 12:00 pm) is broader than that of the occupants of single/double-storied house (neutral to comfort between 10pm to 9 am) (Table 4.12).

There exists a spontaneous relationship between the occupancy schedule and the thermal perception of the occupants of the traditional timber houses. For single/double-storied and stilt timber house, occupants' lifestyle and daily activities on veranda/airy outdoor are compensating for a large time of discomfort during day and night. Fig. 4.42 shows the relationship between occupancy schedule and thermal perception.

Table 4.7 Summary of the questionnaire survey

Time	Single/Double-storied				Stilt			
	Comfort feeling (%)			Adaptive action	Comfort feeling (%)			Adaptive action
	Com.	Neutral	Uncom.		Com.	Neutral	Uncom.	
4 am-6 am	100			Staying at veranda/airy place, going outside, clothing change, taking shower, using ceiling/table fan, opening window at night, etc.	100			Staying at the airy place, opening louver/window at night, clothing change, using ceiling/table fan, etc.
7 am-9 am	90.25	9.75			83.33	16.67		
10am-12pm	9.75	12.2	78.05			61.11	38.89	
1pm-3pm		7.32	92.68			11.11	88.89	
4pm-6pm		19.51	80.49			27.78	72.22	
7pm-9pm	21.95	34.14	43.91		50	50		
10pm-12am	65.85	21.95	12.2		83.33	16.67		
1 am-3 am	100				100			

Comfortable; Neutral; Uncomfortable

Table 4.8 Occupants' responses towards thermal sensation

Time/ Sensation (%)	Single/Double storied Timber House							Stilt Timber House						
	Cold	Cool	Sligh. Cool	Neu.	Sligh. warm	Warm	Hot	Cold	Cool	Sligh. Cool	Neu.	Sligh. warm	Warm	Hot
4 am-6 am		56.1	43.9						83.33	16.67				
7 am-9 am			9.75	78.05	12.2					11.11	61.11	27.78		
10am-12pm					21.95	78.05					11.11	27.78	50	11.11
1pm-3pm						12.2	87.8						61.11	38.89
4pm-6pm					21.95	65.85	12.2					27.78	55.55	16.67
7pm-9pm				21.95	43.9	34.15					50	38.89	11.11	
10pm-12am			12.2	56.1	31.7					38.89	44.44	16.67		
1 am-3 am		21.95	56.1	21.95					27.78	55.55	16.67			

Note: Highlighted values shows the response of participant nearly or above 50%

Very Comfortable ; Comfortable ; Slightly Comfortable ; Neutral ;
Very Uncomfortable ; Uncomfortable ; Slightly Uncomfortable .

From the figure, it is seen that most of the discomfort hours are compensated by staying at veranda/airy outdoor. As an adaptive action to the condition, occupants most frequently prefer staying at veranda/airy outdoor space/going outdoor and using fan (ceiling/pedestal). Hence, veranda plays a vital role in their lifestyle and becomes a way to cope with the discomfort hours of the day. During qualitative observation of traditional stilt house, it has been observed that because of proximity of the sea the area has ample airflow and huge window in all sides with a window position at the occupancy level positively use this climatic resource. Again because of huge height of the room the hot air level is formed far away from the human occupancy level which further benefits the comfortable indoor thermal condition. Discomfort hours are compensated by staying at shaded airy outdoor space beneath elevated platform.

Table 4.9 Occupants' responses towards thermal perception

Time/ Perception (%)	Single/Double storied Timber House							Stilt Timber House						
	Very Com.	Com.	Sligh. Com.	Neu.	Sligh. Uncom.	Uncom.	Very Uncom	Very Com.	Com.	Sligh. Com.	Neutral	Sligh. Uncom.	Uncom	Very Uncom
4am-6am	29.27	70.73						11.11	88.89					
7 am-9 am		68.29	21.95	9.75					83.33		16.67			
10am-12pm			9.75	12.2	39.03	29.27	9.75				61.11	38.89		
1pm-3pm				7.32	14.63	34.15	43.9				11.11	16.66	66.67	5.56
4pm-6pm				19.51	29.27	39.02	12.2				27.78	66.67	5.56	
7pm-9pm			21.95	34.14	43.91				16.66	33.33	50			
10pm-12am		21.95	43.9	21.95	12.2				55.56	27.78	16.66			
1am-3am	12.2	80.49	7.31					11.11	66.67	22.22				

Note: Highlighted values shows the response of participant nearly or above 50%

Very Comfortable ; Comfortable ; Slightly Comfortable ; Neutral ;
Very Uncomfortable ; Uncomfortable ; Slightly Uncomfortable .

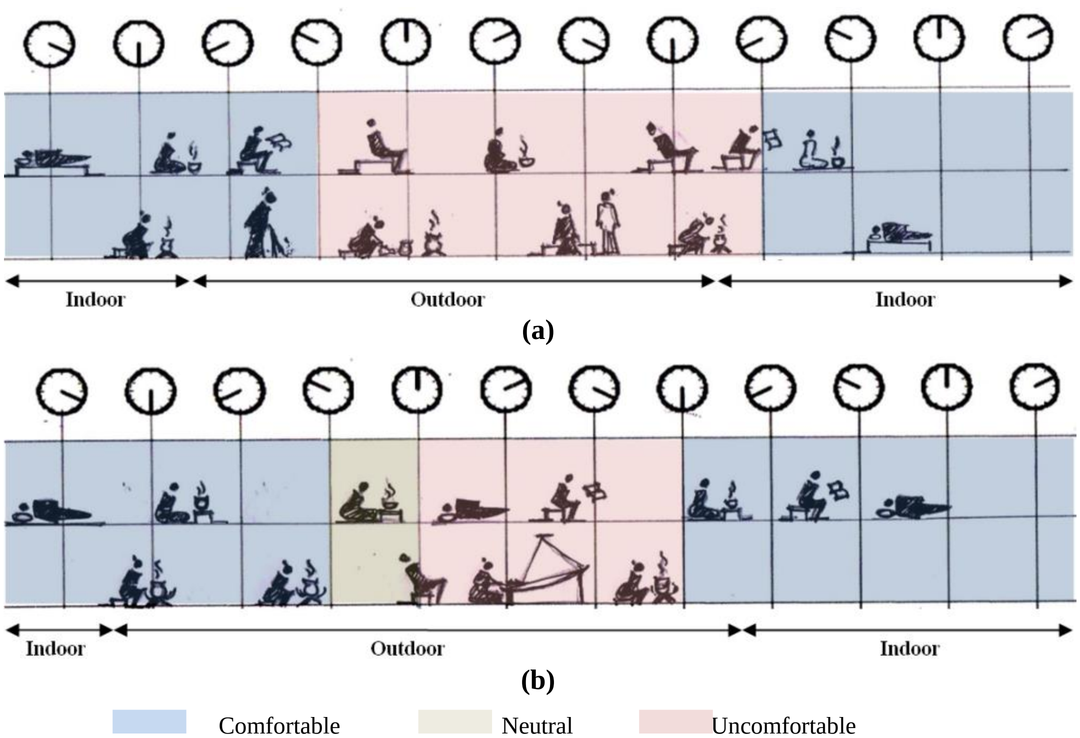


Figure 4.35 Relationship between thermal perception of occupants and lifestyle/occupancy schedule of traditional timber house: (a) single/double-storied and (b) stilt

4.3.9. Thermal Sensation, Adaptation and Performance of Timber Houses

There are relations between the behavior of the occupants and the indoor temperature indoors. From the above analysis, it is seen that indoor temperatures rise penetratingly during the day and reach their peak in the early afternoon as the building has low thermal mass. At night, even with very light winds, it cools down quickly by natural ventilation. In all the investigated cases, residents of all houses have kept the windows open during day which allowed warm air to enter the house resulting in indoor temperature similar to that of the outside temperature during this period.

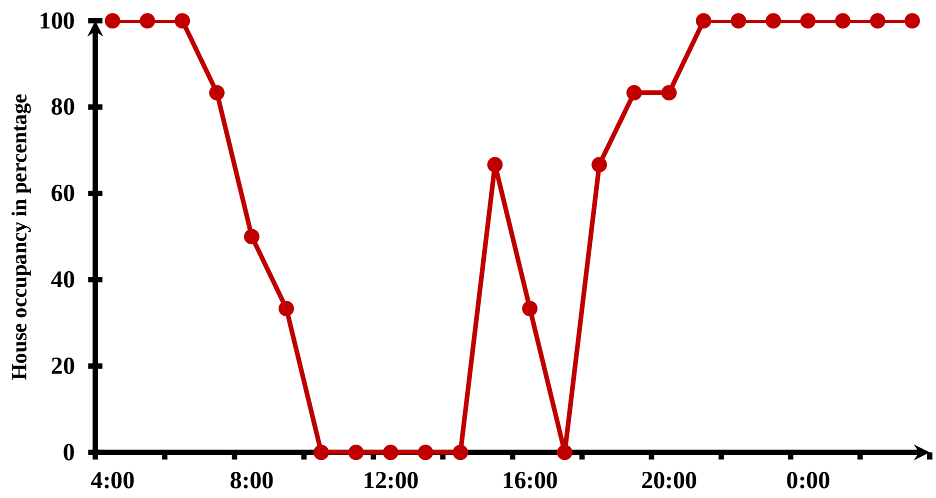


Figure 4.36 Typical occupancy schedule of the traditional timber house

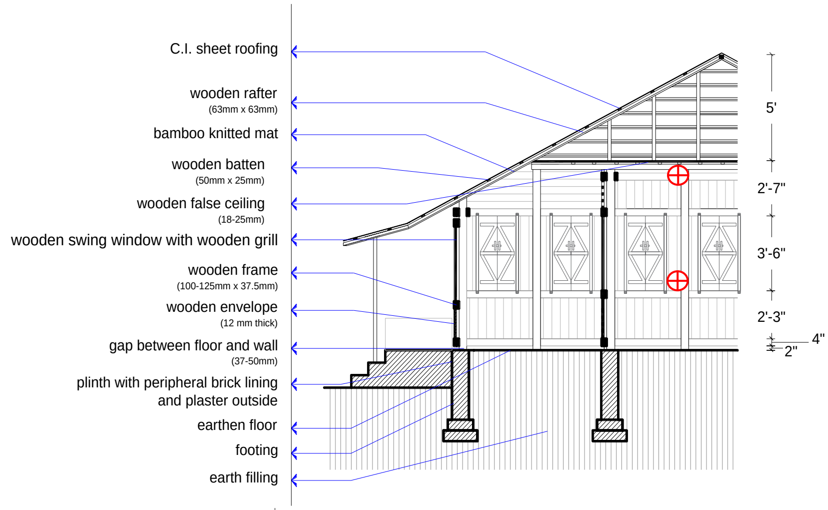
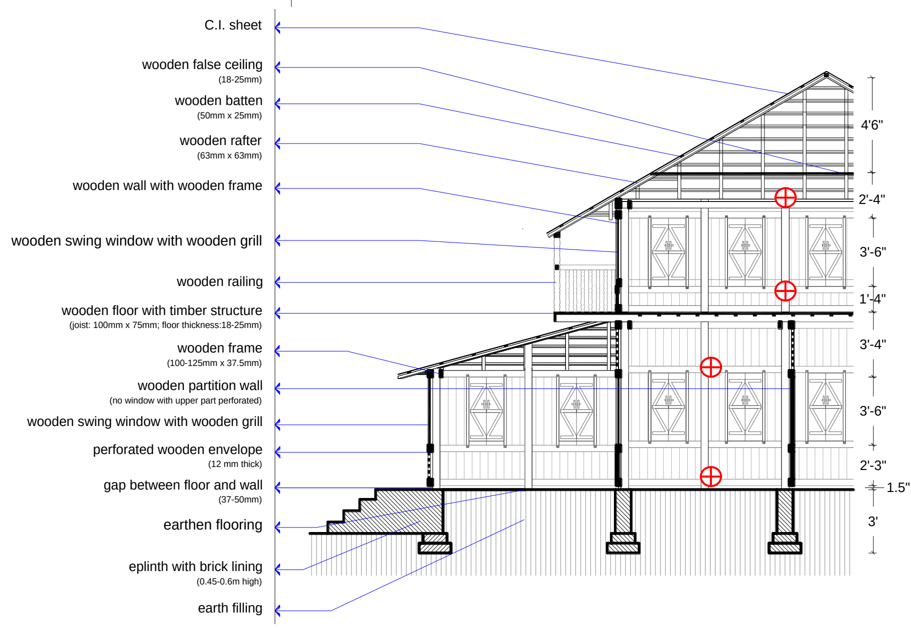
The indoor AT(°C) has been increased exponentially during mid-day between 11 am-4 pm. Again, in double-storied houses, the ground floor AT(°C) is lower than that of the first floor during the day. But the first floor AT(°C) is usually above the comfortable range (32.79-35.99°C were found during the survey) and people hardly use first-floor space during the day. Usually, that space is occupied after 9 pm to 10 pm when it becomes cool. Habitually during the discomfort period, the occupants use to stay at outdoor spaces like veranda and open-air shaded areas have typically been found to help maintain useful lifestyles to deal with this inconvenience throughout the hours. Fig. 4.43 shows the typical occupancy schedule of timber houses. During night-time the outdoor AT(°C) is stable and so is the indoor AT(°C) and it remains within the comfortable range though indoor AT(°C) is slightly higher than that of the outdoor as the occupants close the doors and windows during the night for security.

ENVIRONMENTAL MONITORING

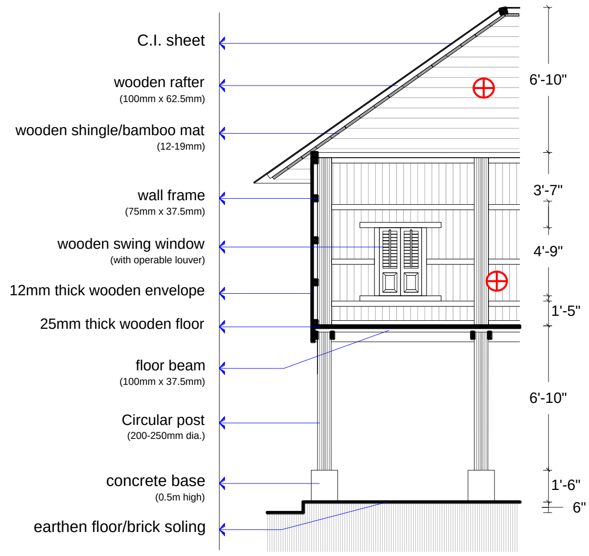
4.4 Environmental Monitoring of Timber Houses

To evaluate the thermal performance of the traditional timber houses this study considers both subjective (occupant's perception of indoor thermal environment) and objective/quantitative data monitoring simultaneously during the field survey. The measurements are carried out at three representative traditional houses and another plain sheet house representative of current trend (Table 4.6). Field data monitoring includes the measurements of AT of both indoor (at two different level: human occupancy and ceiling height) and outdoor relative humidity, wind and gust speed, solar radiation etc. and are discussed in details in the current section.

Table 4.10 Typical section and envelope materials of different traditional timber houses investigated

Type	Name	Graphical illustration
Single-storied	H-1	
Double storied	H-2	

Stilt house H-3



4.4.1 Findings of Field Data Monitoring

Field investigation has been conducted between 2nd July to 8th July at traditional single/double-storied timber houses and 22nd August to 25th August at stilt timber houses. Major findings of the field data monitoring are presented in this section.

The result of the field data monitoring has been analyzed based on the followings:

i) Relationship between envelope materials and indoor thermal environment
ii) Relationship between indoor and outdoor temperature
iii) The thermal sensation of occupants and thermal environment

i) Relationship between Envelope Materials and Indoor Thermal Performance

Building envelope materials (thermal mass), their surface temperature and color have great bearing on the thermo-physical environment of a house in hot-humid climate (Cheng, Ng, & Givoni, 2005; Mridha, 2002; Givoni, 1963). Different envelope combination of traditional timber houses is presented in Table 4.3. From the thermal images of the house, it is observed that the roof with its C.I. sheet covering has the maximum surface temperature (up to 44.8-53.5°C) during the day. But roof with its 19mm thick wooden insulation has a lower surface temperature in the interior (up to 35.1°C). Among all surfaces the earthen floor has the lower surface temperature (maximum 31.7°C has been found during field survey) (Fig. 4.34 and 4.35).

Wall surface temperature is lower than roof surface temperature. Both the indoor and outdoor, wall surface temperature is lower at the lower part than the upper part in all cases. This is because of radiant heat from the low thermal capacity of roof material. In contrast, the earth with its high thermal capacity absorbs more heat and hence wall surface temperature near the earth is lower than the wall surface temperature near the roof. During night-time, the situation is reversed. The surface temperature of the C.I. sheet decreases as soon as the sun sets while the wall and floor surface cools down slowly.

In H-2 it is observed that temperature difference between external and internal wall surfaces is nearly 2°C whereas difference between wooden floors' surfaces is nearly 3.7°C (Fig. 4.34). Shaded surface of both interior and exterior has low surface temperature than the one directly exposed to solar radiation. In H-3, the wooden floor surface temperature (Fig. 4.35) is lower than that of the wooden first-floor surface temperature of the H-2. The reason is that the outer surface of raised platform has a very low temperature being off from radiant heat gain from hotter ground.

Figure 4.37 Indoor and outdoor surface temperature of a traditional double-storied timber house (Top: outdoor; Middle: ground floor front and middle room; bottom: indoor: first floor)

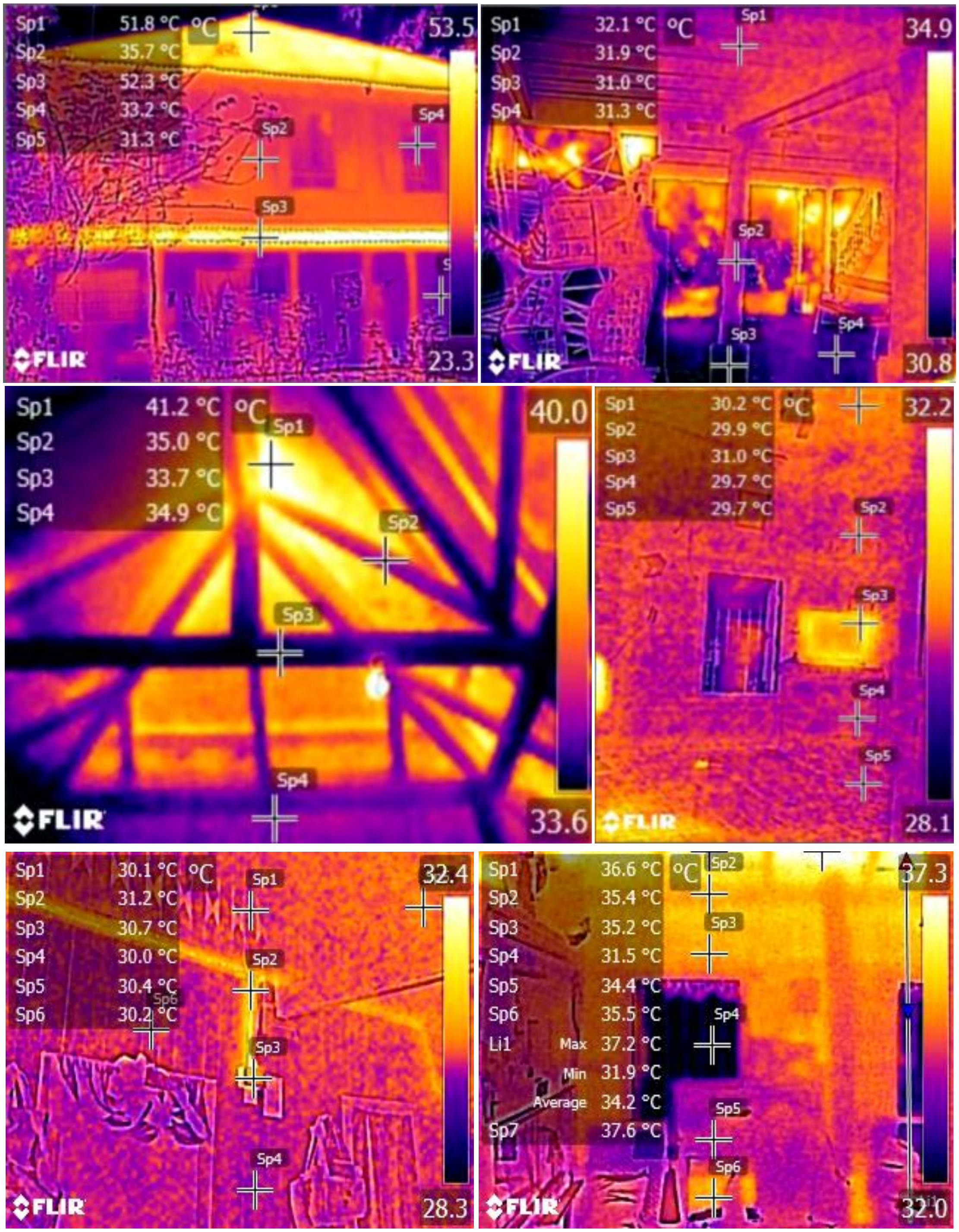


Figure 4.38 Indoor and outdoor surface temperature of the traditional stilt timber house
(From left to right: outdoor, shaded area beneath the elevated platform, indoor roof, room interior)

Again the higher floor height contributes to forming the hot air layer far from the floor level. Roof with an insulation layer of 12-18mm wooden shingle adjacent to the roof covering has a maximum surface temperature difference of 10.6°C. Table 4.7 shows surface temperature of the investigated houses.

Table 4.11 Surface temperature (mid-day) differences of timber house envelope

House no.		Outdoor Air Temp. (°C) (day-time max.)	Floor Interior (°C)(avg.)	Wall (°C) (top to bottom avg.)		Roof/ Ceiling (°C) (avg.)	
				Exterior	Interior	Roof exterior	Ceil. interior
H-1		35.42	35.3	42.2	37.7	58.1	42.0
H-2	Ground Floor	32.3	31.5	35.5	33.5	46.1	33.3
	First Floor		37.0	38.2	37.8		41.6
H-3		31.03	29.9	36.3	30.0	50.1	33.6

ii) Relationship between Indoor and Outdoor Temperature and Thermal Performance

Field data showed that timber houses are cooler than the outdoor AT(°C) early in the morning until the middle of the day. But the situation gets reversed with time. The indoor temperature starts increasing from 7:00 am and reaches its maximum between 12:00 am-4:00 pm in all cases of traditional timber house. Fig. 4.35-4.36 shows the indoor thermal environment and Table 4.8-4.10 shows the maximum, minimum, and average value of the thermal factors of the investigated houses.

Table 4.12 Thermal environmental factors of H-1, (Source: Field experiment)

	Outdoor		Indoor (human height)		Indoor (ceiling height)	
Sample: 8018	Temp °C	RH %	Temp °C	RH %	Temp °C	RH %
Maximum	35.42	98.1	33.52	95.2	32.72	95.4
Minimum	28.22	69.7	28.77	76.6	30.95	81.9
Average	30.64	88.86	30.83	89.82	32.19	91.12
Standard Deviation(σ)	2.42	8.97	1.497	5.02	0.46	3.41
Outdoor wind speed: 1.51m/s (max.) and Solar radiation: 70.6W/m^2 (max.)						

Fig. 4.36 shows the thermal environment of H-1 (single-storied house) for a 24hrs period (from 4Aug-5Aug, 2019). Both indoor and outdoor temperature remains stable during night-time and fluctuates during the day. Diurnal temperature variation of outdoor and indoor is average 7.2°C and 4.76°C respectively. Light wall envelope and large openings in the wall allows natural ventilation, indoor temperature increases with the increase and decreases with the decrease in outdoor temperature without any time-lag. Both the indoor and outdoor temperatures reach their maximum between 12 pm-4 pm. But during this period the indoor temperature is lower (both ceiling and human occupancy height) (avg. 32.5°C) than the outdoor (avg. 34.46°C) because of insulation property of wooden false ceiling with ventilated attic (Ong, 2011; Medina, 2000) and shade from the surrounding trees. At night as openings remain closed, attic become unventilated and hence, ceiling AT(°C) is higher than occupancy level AT(°C). During the stable period (night and early morning) indoor RH is avg. 93.7% while RH of outdoor is avg. 96.58% and shows a reverse order compared to AT(°C).

Fig. 4.37 shows a 49hrs environmental data (02 Aug-04 Aug., 2019) of H-2, where the first 24 hrs. show the thermal environment of the ground floor and the rest 24hrs shows the thermal environment of the first floor. From the ground floor thermal environment, it is observed that night-time indoor (both human and ceiling ht.) AT(°C) is higher (1.56°C and 2.09°C respectively) and day-time indoor AT(°C) is slightly lower than the outdoor AT(°C) (1.31°C and 0.91°C respectively). This is because the upper floor provides insulation for the ground floor and the earthen floor radiates the storage heat slowly during the night while for security purposes the door and windows are kept closed obstructing convective heat loss. Besides that internal gain from the human body and mechanical equipment's (ceiling fan and light) also contributes to higher indoor AT(°C). But in the first-floor radiant heat from the low thermal capacity roof covering material C.I. sheet increases the ceiling height AT(°C) (38.7°C) much higher than the human height (difference 2.8°C max.) and outdoor AT(°C) (max. difference 4.05°C) during both night and day.

Table 4.13 Thermal environmental factors of H-2, (Source: Field experiment)

Ground Floor	Outdoor		Indoor (human height)		Indoor (ceiling height)	
Sample: 8729	Temp °C	RH %	Temp °C	RH %	Temp °C	RH %
Maximum	33.24	97.8	32.02	91.5	32.3	92.1
Minimum	27.06	75.2	28.47	79.3	28.79	80.0
Average	29.1	90.56	29.76	87.46	29.98	87.9
Standard Deviation(σ)	1.91	6.57	1.09	2.99	1.02	2.68
Outdoor wind speed: 1.01m/s (max.) and Solar radiation: 21.9W/m^2 (max.)						
First Floor						
Sample: 8736	Temp °C	RH %	Temp °C	RH %	Temp °C	RH %
Maximum	34.81	96.2	35.99	90.6	38.78	90.0
Minimum	27.48	68.2	28.74	65.1	29.12	61.2
Average	30.07	87.06	31.21	82.32	32.21	80.24
Standard Deviation(σ)	2.15	7.98	2.02	7.08	2.72	7.87
Outdoor wind speed: 1.01m/s (max.) and Solar radiation: 23.1W/m^2 (max.)						

Table 4.14 Thermal environmental factors of H-3,(Source: Field experiment)

	Outdoor		Indoor (human height)		Indoor (ceiling height)	
Sample: 8619	Temp °C	RH %	Temp °C	RH %	Temp °C	RH %
Maximum	31.64	96.5	32.6	90.7	39.77	89.3
Minimum	26.06	76.1	27.7	74.5	27.73	54.4
Average	28.37	88.21	29.5	84.88	30.82	78.9
Standard Deviation(σ)	1.72	6.03	1.53	4.71	3.29	9.98
Outdoor wind speed: 1.01m/s (max.) and Solar radiation: 23.1W/m^2 (max.),						

Indoor thermal environmental data (from 22 Aug-24Aug, 2019) of H-3 for 46hrs has been recorded and presented in Fig. 4.38. From the first 24hrs cycle it has been observed that the outdoor AT(°C) fluctuates between 8am - 6pm and stable at night and so do the indoor AT(°C). During day-time, indoor human occupancy zone has an AT(°C) similar to that of the outdoor AT(°C) while AT(°C) near ceiling has a temperature difference of 8.09°C. In H-3 instead of a false ceiling the roof is provided with 19mm wooden shingles just beneath the C.I. sheet and this causes more radiant heat from the C.I. sheet to enter the house compared to the others provided with attic having 25mm wooden false ceiling underneath. Again, the roof height is huge compared to the H-1 and H-2 having no opening in the roof level which causes warm air to be trapped at that level. It is noticed that because of cloudy weather and rain the outdoor temperature during second day remained almost constant and lower than a typical sunny day. The indoor AT(°C), being slightly higher than that of the outdoor, has an almost constant temperature variation between indoor and outdoor.

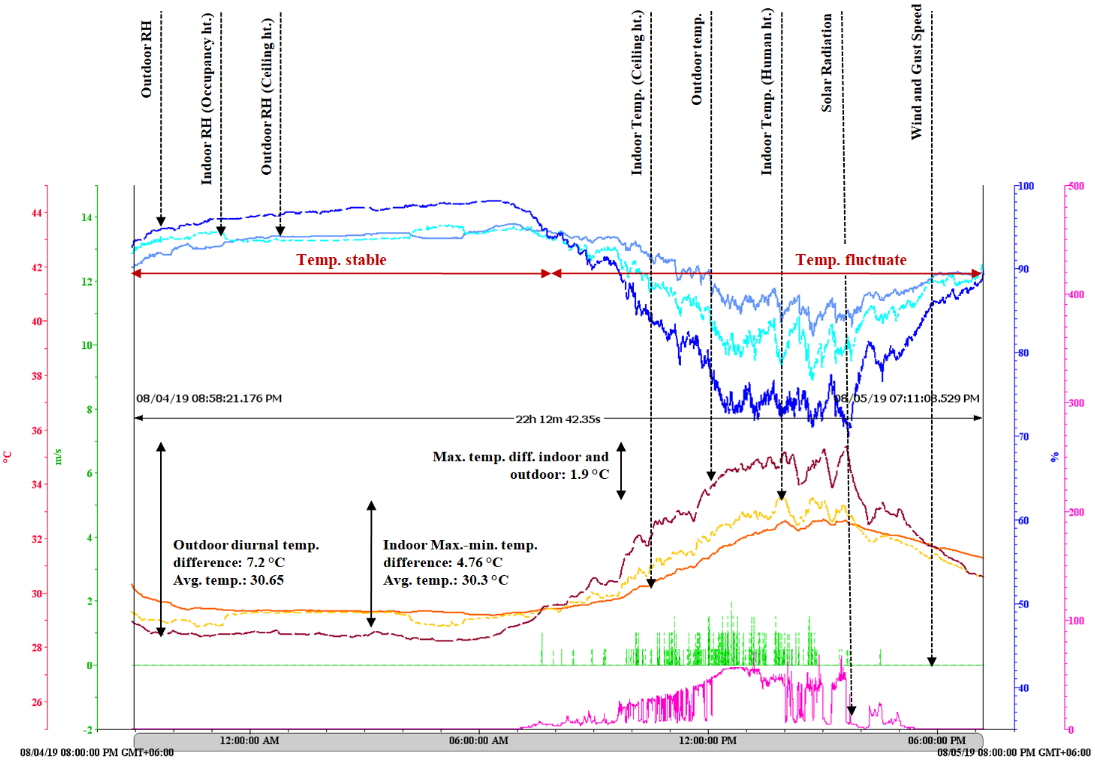


Figure 4.39 Indoor thermal performance of H-1 (Source: data of HOBO data logger from field survey)

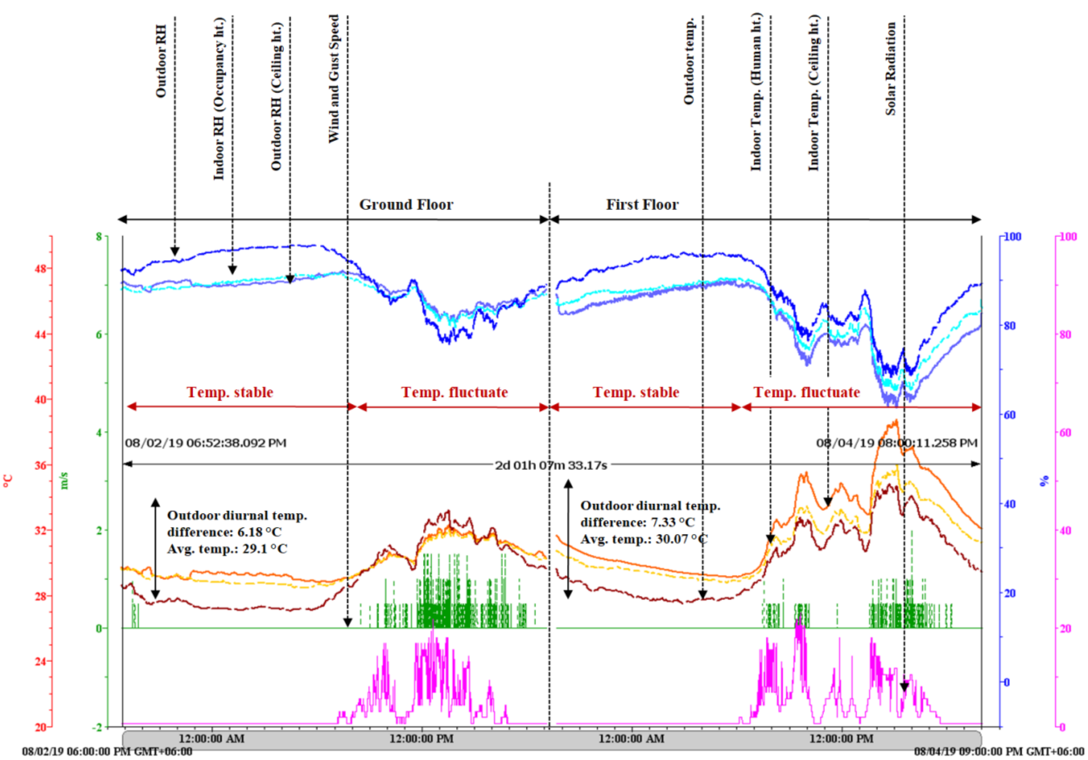


Figure 4.40 Indoor thermal performance of H-2 (Source: data of HOBO data logger from field survey)

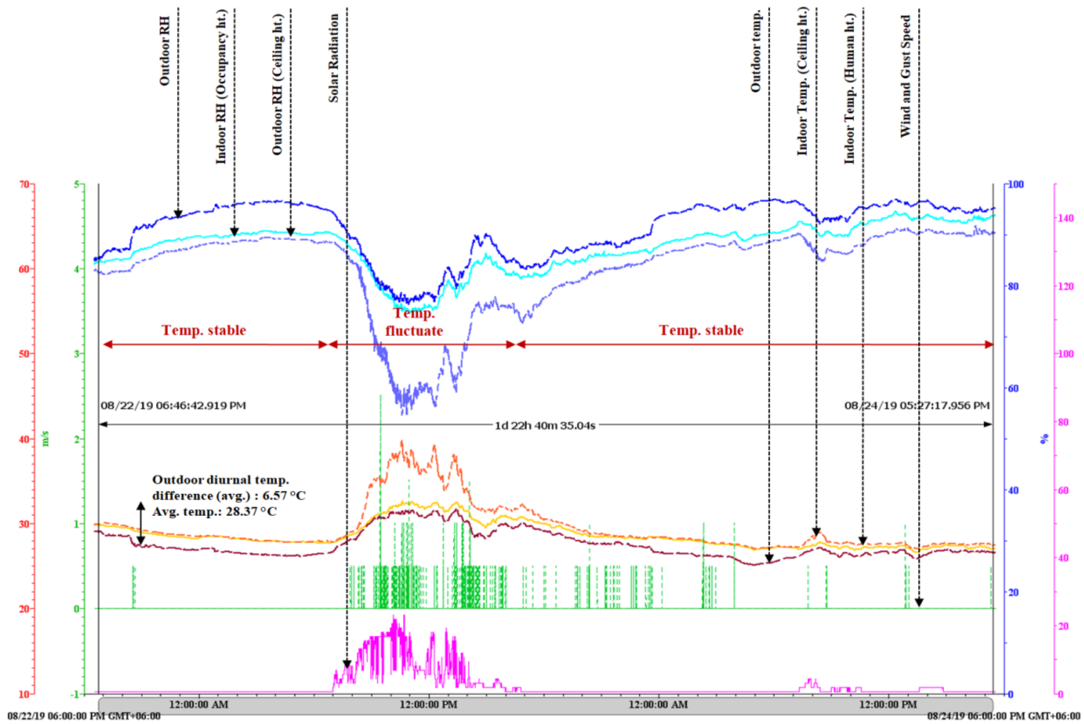


Figure 4.41 Indoor thermal performance of H-3 (Source: data of HOBO data logger from field survey)

In all cases (Fig. 4.36-4.38) there is almost no significant disparity between indoor and outdoor. This confirms the open planning of the house which is preferable for hot-humid climate and also indicates that there is good indoor ventilation. Because of day-time ventilation the indoor AT(°C) is almost similar and sometimes higher than the warm outdoor AT(°C). From the field investigation it has been observed that the occupants tend to open the openings during day and close them in night for security. That is why in all the investigated cases during night indoor AT(°C) is slightly higher than cool outdoor AT(°C) because of occupant's activity and other internal gain factors as well as trapped radiant heat, though the indoor AT(°C) was within comfort range. The perforation in wall and gap between floor/roof and wall allows some night-time natural ventilation. The H-3 with its operable louver allows proper night-time ventilation and cools down early at night. This supports the previous study result that in hot-humid climate night-time ventilation improves indoor thermal comfort reducing operative temperature (Kubota et al., 2009).

iii) Comparative Analysis of Investigated Houses

Fig. 4.42 and 4.43 show a comparative overview of the investigated houses. In all cases, the indoor AT(°C) at the human occupancy level starts increasing from 8 am and decreases between 8 pm to 9 pm while reaching its maximum between 12 pm to 4 pm. The indoor AT(°C) at human occupancy zone is higher during day-time and remains slightly lower/ similar to that of the outdoor AT(°C) indicating well ventilated indoor environment, while night-time indoor AT is higher than the outdoor AT(°C). From Fig. 4.40 it is seen that in all the investigated houses, AT(°C) at ground floor level of H-2 remains low. This is because shade from upper floor and front room as well as middle position of the room. AT(°C) of H-2 first is highest amongst all because of its low floor height and radiant heat from the roof having no shade. On the other hand, H-1(2.6m) and H-3 (avg. 3.5m) with their moderately high floor height have relatively lower AT(°C) than H-2 first floor (2.1m).

H-3 cools down as soon as the outdoor AT(°C) falls down and has lower night-time AT(°C) amongst all. In all cases though the occupants keep the opening closed late at night the indoor AT(°C) becomes higher than outdoor AT(°C). That is why radiant heat from the floor and other internal gain factors (i.e. human body, mechanical equipment etc.) gets trapped inside the house. H-3 with its night-time ventilation through operable louver has the cooler indoor amongst all. The others with their perforated wall and gap between wall and roof/floor with ventilated attic at upper floor allow certain night-time ventilation.

From the ceiling level AT(°C) it is clear that ground floor with another floor above has a lower AT(°C) during both day and night while upper floor with no or unvented attic has a higher AT(°C) during both day and night. Again, houses with vented attic have a lower indoor AT(°C). Night-time ventilation has greater impact on cooler indoor during night while day-time ventilation results in higher indoor AT(°C). In all cases, humidity is high when the temperature is low.

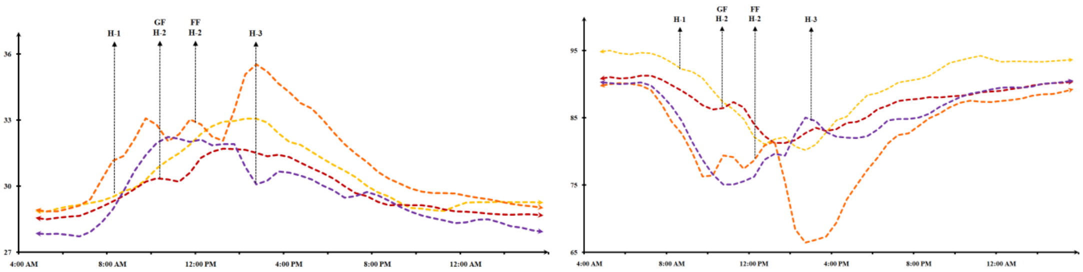


Figure 4.42 Comparison of occupancy zone thermal environment of H-1, H-2 and H-3 (AT°C (right) and relative humidity (left)) (Source: field survey)

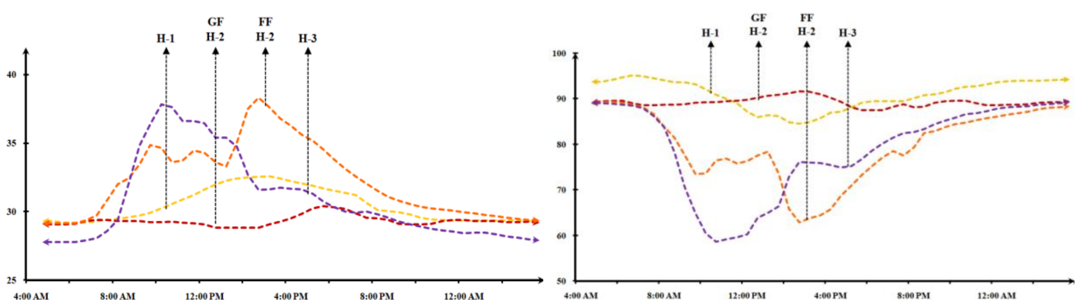
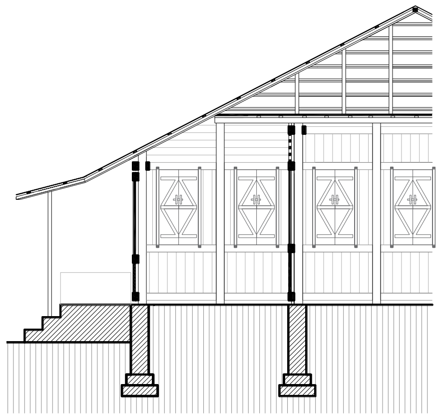
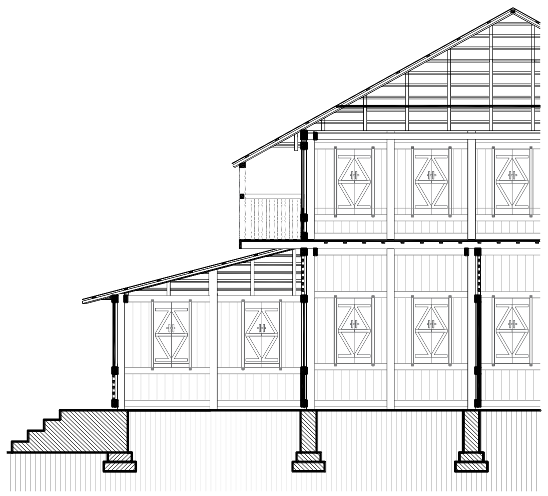
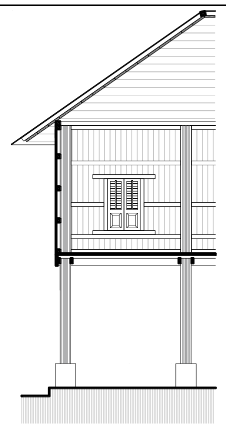


Figure 4.43 Comparison of ceiling level thermal environment of H-1, H-2 and H-3 (AT°C (right) and relative humidity (left))(Source: field survey)

4.5 Conclusion

This chapter, within some limitations, presented the overall study on the construction technique, envelope material, occupants' lifestyle and perception of thermal environment of the traditional timber houses of Bangladesh. Here, the relationship among the different factors i.e. lifestyle and thermal sensation, envelope and thermal performance and relationship among outdoor-indoor AT(°C) etc. are discussed based on the observed field data. From the field study it is seen that the indoor thermal environment is influenced by the different envelope conditions and there is a strong relationship among the thermal performance of the houses and occupant's frequency of the use of the house. The result achieved from the field study will be considered for the parametric simulation study presented in the next chapter. The overall result of field survey is presented in Table 4.15.

Table 4.15 Comparative analysis of indoor thermal performance of different traditional timber house in Bangladesh

House	Annotated Section of different cases studied	Passive Features used	Level	Out-door Temp. (°C)	Surface Temperature (°C) (Mid-day 11pm-4pm) Floor (indoor) Max.	Floor (indoor) Min.	Wall (indoor) Max.	Wall (indoor) Min.	Ceiling (indoor) Max.	Ceiling (indoor) Min.	Roof (outdoor) Max.	Roof (outdoor) Min.	Indoor AT (°C) and RH (%) Day-time Max. Occu. ht.	Day-time Max. Ceil. ht.	Night-time Max. Occu. ht.	Night-time Max. Ceil. ht.	Max. AT(°C) Diff. with Com. Rang. (°C)	Occupants perception of indoor thermal environment
Single storied		'Pashchati Veranda Gap between wall and floor and roof allows night-time ventilation when the window is kept close for security purpose Perforation/wood carving in upper part of wall allows ventilation indoor Wooden ceiling with vented attic		Max. **35.42** Min. **28.22** Avg. **30.64** Std. Dev. **2.42**	31.9	31.0	34.1	32.3	34.2	33.5	58.9	36.4	33.52	32.72	29.32	30.2	+ 1.52	
					Floor: Earthen floor having Brick peripheral wall with plastered outside **Wall:** Timber frame with 12.5mm thick wooden shingle **Roof:** C.I. sheet on a timber frame with wooden false ceiling and 'Chadoa' (a piece of fabric) beneath it. Attic height is 1.07m at the center. **Opening:** Wooden panel with iron grill								**Lifestyle & Adaptive Action** Clo. Value: 0.5 Most of the day-time stay at outdoor space. Other adaptive action includes staying at veranda/airy place, going outside, clothing change, taking shower, using ceiling/table fan, opening window at night, etc.					**Day-time thermal sensation** vote has maximum share of **+1 to +3** votes while **night-time thermal sensation vote** has maximum share of **0 to -3** thermal sensation votes. (Uncomfortable between 10am to till 6pm. Comfortable/Neutral for rest of the time.)
Double storied		'Pashchati'/ hanging (upper) Veranda Gap between wall and floor and roof allows night-time ventilation when the window is kept close for security purpose Perforation/wood carving in upper part of wall allows ventilation indoor Wooden ceiling with vented attic	**FF**	Max. **34.81** Min. **27.48** Avg. **30.07** Std. Dev. **2.15**	37.4	36.3	40.5	36.3	42.2	39.5	52.8	38.7	35.98	38.78	30.7	31.56	+6.78	
			GF		32.3	31.0	35.0	32.5	34.2	32.7	43.3	37.1	32.02	32.3	29.6	29.8	+ 0.3	
					First Floor **Floor:** Timber frame with 12.5mm thick wooden shingle **Wall:** Timber frame with 12.5mm thick wooden shingle **Roof:** C.I. sheet on a timber frame having wooden false ceiling beneath. Attic height 1.4m at the center. **Opening:** Wooden panel with wooden grill **Ground Floor** **Floor:** Earthen floor having Brick peripheral wall plastered outside **Wall:** Timber frame with 12.5mm thick wooden shingle **Ceiling:** 25mm thick wooden shingle on hard-timber beam and 'Chadoa' (a piece of fabric) under the ceiling. **Opening:** Wooden panel with wooden grill								**Lifestyle and Adaptive Action:** Clo. Value: 0.5 Most of the day-time stay at outdoor space. And the upper story is never occupied during day-time. It is occupied after 10 pm at night while it becomes cool. Other adaptive action includes staying at veranda/airy place, going outside, clothing change, taking shower, using ceiling/table fan, opening window at night, etc.					
Stilt		Elevated ground: convective cooling and keep the house off to radiation from the ground Operable louver for night-time ventilation Low window sill level High room height		Max. **31.64** Min. **26.06** Avg. **28.37** Std. Dev. **1.72**	31.1	29.5	30.3	28.0	30.6	29.4	53.3	41.2	32.61	39.77	29.86	30.09	+ 7.77	
					Elevated Floor: Wooden floor, 25-37mm thick with hard-timber structure **Wall:** Timber frame with 12.5mm thick wooden shingle **Roof:** C.I. sheet roofing with 25mm wooden shingle underneath. No attic. **Opening:** Wooden panel with operable wooden louver and iron grill								**Lifestyle and Adaptive Action:** Clo. Value: 0.5 Most of the day-time stay at outdoor space to perform domestic chores. Other adaptive action includes staying at the airy place, opening louver/window at night, clothing change, using ceiling/table fan, etc.					**Mid-day to afternoon (12pm-6pm)** has maximum share of **+1 to +3** votes while the **rest of the time** respondent feel comfortable with maximum votes for the scale **0 to -3**.

Temperature slightly above comfort level   Temperature considerably above comfort level

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CHAPTER FIVE: PARAMETRIC DATABASE AND VALIDATION

5.1 Introduction

Building envelopes being the interface between indoor and outdoor directly interacts with the climate. Hence, these envelopes are responsible for creating a desirable indoor thermal environment. In real field situations, different factors along with envelope materials contribute towards indoor thermal environment. This makes it difficult to evaluate thermal performance of envelope materials separately. But many efficient simulation tools make it possible to identify performance and effects of changes in one factor (i.e. building envelope) while keeping other factors constant. As discussed in chapter-3,3 EnergyPlus program is one such simulation tool that is capable of identifying heat transmission through building envelope from outdoor for a longer period considering thermal properties of materials. Therefore, this study conducted several parametric studies to evaluate performance of traditional timber house's envelope through identifying quality of indoor thermal environment within the house.

It is possible to evaluate thermal performance of building envelope for different periods of the year from parametric study simply by assigning parameters (i.e. AT (ATºC), relative humidity (RH%), wind speed, radiation). But for EnergyPlus simulation study, preparation of database and validation of prepared model is crucial. Several databases have been used for current parametric studies. Therefore, database for material, construction, different schedules (occupancy, lighting, electrical equipment etc.) etc. have been prepared based on the findings of field monitoring. After database preparation, several simulations have been conducted towards validation of prepared 3D model. Data obtained from the parametric simulation have been plotted against the field environmental data of the same day and validation has been done. Detail rationalization of how the database for current parametric study is prepared and validation process of prepared 3D model is presented in this chapter.

5.2 Parametric Database Preparation

As discussed in 'Methodology' chapter (Chapter-3) OpenStudio plug-in with SketchUp has been used for preparing house model. Then EnergyPlus input file (. idf) has been created. For running simulation work basically, two types of input are required: (a) data input within. idf file that cannot be programmed through EnergyPlus and (b) data that can be easily modified through EnergyPlus.

EnergyPlus database includes inputs that are mandatory for model preparation, parametric simulation study and assessment process. EnergyPlus has various types of databases but for the current study, the followings are critical for performing the parametric study.

a) Climate and Location
b) Building Operation and Scheduling
c) Building Materials database
d) Construction
e) Internal Condition
f) Internal Load
g) Zone Airflow

According to site parameters (i.e. location, local climate, etc.) and test zone state climate, internal condition and loads database have been prepared. Materials and construction are built with the program that is editable and different arrangements are possible. These databases are prepared according to local construction types and necessary data on materials are collected from previous related studies.

a) Climate and Location

EnergyPlus weather data is a text-based format that contains data related to site and seven weather variables hourly values. Weather data file for parametric study can be downloaded from EnergyPlus website where weather data for more than 2100 locations are available in EnergyPlus weather format arranged by World Meteorological Organization region and country. Each location has name prefixed with specific region identifier. Each weather file is named having local region identifier, i.e., BGD_Coxs.Bazar.419920_SWERA, where first part represents country name is Bangladesh (BGD) and second part illustrates the local region name Cox's Bazaar. United Nations Environment Program funded SWERA (Solar and Wind Energy Resource Assessment) for developing quality data on solar and wind energy resources for 14 developing countries over the world. Weather file of different formats can be downloaded from the EnergyPlus official website (http://www.energyplus.gov).

b) Building Operation and Scheduling

Parametric study requires to input information on building operation and different schedules, i.e., occupancy, lighting, electric equipment operations, door-window etc. EnergyPlus has default schedule information based on building category. But EnergyPlus has options to modify schedules for buildings' parametric studies. Building occupancy schedule includes information on occupants' space use data when it begins and ends regarding times, weekdays, weekends/holidays and seasonal variations (office, school, house etc.). Similarly, lighting, electric equipment operations, door-window and other necessary schedules are needed to be modified as per requirement of specific parametric study.

c) Building Materials Database

Thermal properties (thickness, conductivity, density and specific heat) of material are important for analysis of buildings. For construction detail of different part of the model house, input in material database is mandatory. Table 5.1 illustrates the input field for material database preparations.

Table 5.1 Input for material database

Field	Units	Description	Input type
Name		Material name	Mandatory
Roughness		Roughness index	Mandatory
Thickness	m	Thickness of material	Mandatory
Conductivity	W/m-K	Conductivity of material	Mandatory
Density	kg/m^3	Density of material	Mandatory
Specific Heat	J/kg-K	Specific Heat of material	Mandatory
Thermal Absorptance		Thermal Absorptance of material	Default
Solar Absorptance		Solar Absorptance of material	Default
Visible Absorptance		Visible Absorptance of material	Default

The field 'Roughness' represents the relative roughness of a specific material layer. This parameter only influences the convection coefficients, more specifically the exterior convection coefficient and keyword to be used for this field ranges in order of roughest to smoothest options: "Very Rough", "Rough", "Medium Rough", "Medium Smooth", "Smooth", and "Very Smooth" (EnergyPlus 2003). Thickness, conductivity, density and specific heat of materials are mandatory input field. Thermal, solar and visible absorptances characterize the fraction of incident long wavelength radiation, incident solar radiation, incident visible wavelength radiation that is absorbed by the material respectively. The value of these three files must ranges from 0 to 1. For materials, whose thermal, solar and visible absorptances are unknown, EnergyPlus uses default values for necessary calculation.

d) *Construction*

Walls, roof, floor and door-windows are composed of different layers of materials. Construction database requires input of construction materials for different elements (interior/exterior wall, floor, roof etc.) of the model house. This field requires data input of different layers sequentially from outside to inside from material database prepared.

e) *Internal Condition*

Non-conditioned houses are designed to provide its occupants with necessary comfort within its naturally ventilated condition. In such case, air movement and ventilation between different zones, transfer heat from outside to inside. Besides that depending on surface properties of envelope materials, incident solar radiation is absorbed, reflected and transmitted to indoor space. All these changes indoor air's heat capacity. For generating output results (i.e., air, surface temperature, etc.), EnergyPlus itself solves functional heat balance equations for each hour of simulation. Fig. 5.1 shows internal properties of EnergyPlus.

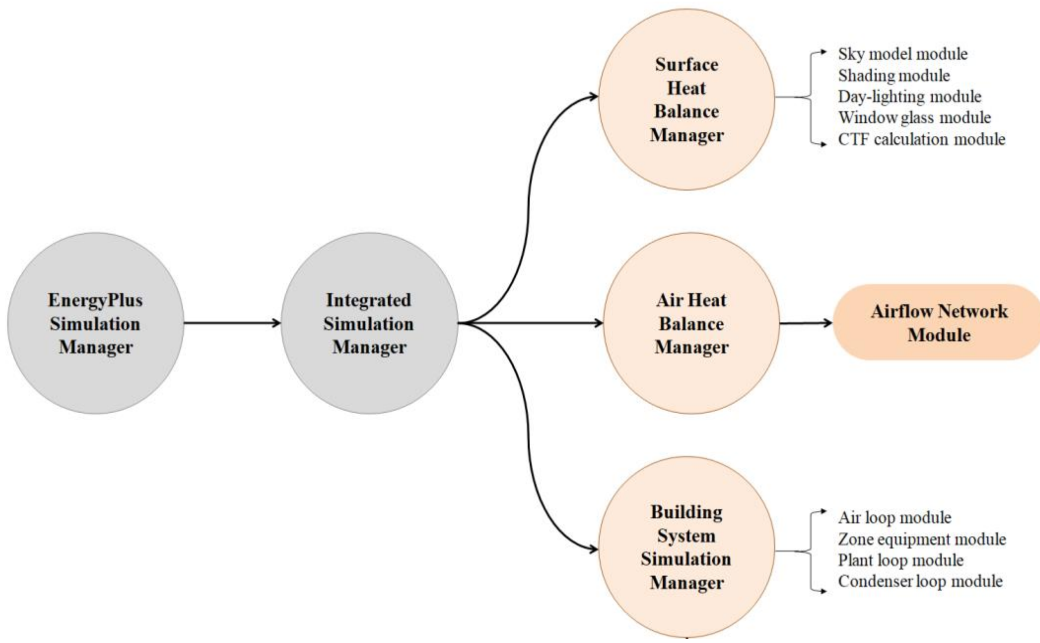


Figure 5.1 Internal properties of EnergyPlus(*Source: US department of energy, USA.gov, 2013*)

f) *Internal Gains*

Energy consumption within a building is not only due to ambient conditions and envelope properties, but internal gains from people, light and different equipments also play a vital role on internal heat gain. EnergyPlus requires data input for these different internal gain factors. Data input for the field 'People' is used to model the occupant's effect on the space conditions. Input in "*Lights*' requires information about electric lighting system, design power-level and operation schedule within a zone and how the heat from lights is distributed thermally (EnergyPlus 2003). Similarly, if a zone has different electric equipment, informationis needed to be inserted for internal gains from them.

g) Zone Airflow

Airflow between zones and airflow due to natural ventilation/ open door-windows or mechanical ventilation is another critical factor of buildings' overall energy consumption. The field 'Zone Airflow' of EnergyPlus simulation engine describes these elements. As the current study deals with naturally ventilated houses, therefore, data has been inserted in the field named '*Zone Ventilation: Wind and Stack Open Area*' which model is used for simplified ventilation calculations of naturally ventilated houses. For this model, the ventilation air flow rate is a function of wind speed and thermal stack effect, along with the area of the opening being modeled (EnergyPlus 2003).

The equation used to calculate the ventilation rate driven by wind is:

$$Q_w = C_w A_{opening} F_{schedule} V \quad (1)$$

where,

Q_w= Volumetric air flow rate driven by wind [m3/s]
C_w= Opening effectiveness [dimensionless]
$A_{opening}$= Opening area [m2]
$F_{schedule}$= Open area fraction [user-defined schedule value, dimensionless]
V = Local wind speed [m/s]

The equation used to calculate the ventilation rate due to stack effect is:

$$Q_s = C_D A_{opening} F_{schedule} \sqrt{2g\Delta H_{NPL}\left(\frac{|T_{zone} - T_{odb}|}{T_{zone}}\right)} \quad (2)$$

where,

Q_s = Volumetric air flow rate due to stack effect [m3/s]
C_D = Discharge coefficient for opening [dimensionless]
$A_{opening}$ = Opening area [m2]
$F_{schedule}$ = Open area fraction [user-defined schedule value, dimensionless]
ΔH_{NPL}= Height from midpoint of lower opening to the neutral pressure level [m].
Estimation of this value is difficult; refer to Chapter 16 of the 2009 ASHRAE Handbook of Fundamentals for guidance.
T_{zone}= Zone air dry-bulb temperature [K]
T_{odb}= Local outdoor air dry-bulb temperature [K]

The total ventilation rate calculated by this model is the quadrature sum of the wind (Equation 1) and stack (Equation 2) air flow components:

$$Ventilation_{windandstack} = \sqrt{Q_w^2 + Q_s^2} \quad (3)$$

5.3 Simulation Parameters

For identifying the thermal performance of envelope materials of traditional timber houses due to heat gain factor from the outdoor the current study has intended to conduct a number of parametric studies. But before performing parametric studies proper validation of EnergyPlus model for reliable result is important. For validation, simulation has been conducted for the months of July and August (two months) as field survey was carried out during these months. Table 5.2 illustrates the simulation engine detail parameters considered for current parametric study. In section 5.2 the critical parameters for the current study is discussed in brief. In the following section the simulation parameters considered are presented in detail.

Table 5.2 Simulation engine detail parameters considered for current parametric study

Field	Specification
Simulation engine	EnergyPlus
Version	8.0.0
Run simulation for weather file run period	Yes
Simulation for sizing period	Yes
Terrain	Country
Loads convergence tolerance value	0.04
Temperature convergence tolerance value	0.4
Solar distribution	Full interior and exterior
Calculation method	Average over days in frequency
Calculation frequency	20
Surface conduction algorithm: Inside	TARP (Thermal Analysis Research Program)
Surface conduction algorithm: Outside	DOE-2 (Department of Energy)
Heat balance algorithm	Conduction transfer function
Number of time step per hour	4

5.3.1 Study Model Details

As discussed in the previous chapter (Chapter 4), the traditional timber house size typically varies between 6hath x 10 hath, 10hath x 17hath, or 16hath x 21hath, where 1hath is approximately equal to 450mm (1.5ft.). But the study model for parametric study has been prepared similar to that of the traditional single-storied timber house (10hath x 17hath) selected for day long in-situ environmental data monitoring. Environmental data were collected at the middle room of the house (Fig. 2).

The single-storied test model has a total dimension of 5.5m x 8m (approx. 43.64 sqm) oriented towards true North having all facades facing the cardinal directions (Fig. 5.2). Traditional timber houses have three parts: front room, middle room and service space at back. Similarly, prepared test model has three different zones: Zone-1, Zone-2 and Zone-3. Zone-1 has an area of 19.1 sqm and Zone-2 and 3 has an area of 12.1 sqm. Zone-1, Zone-2 and Zone-3 have an average height of 3.2m, 2.65m and 2.65m respectively (Fig. 5.3). Zone-1 is the test zone which represents middle room of the monitored traditional single-storied house. Therefore, East and West walls are exterior whereas the South and North walls are blocked by Zone-2 and Zone-3 (Fig. 5.4). Table 5.3 shows the zone details of the test model.

Table 5.3 Zone details of test model

Name	Area (m^2)	Conditioned (Y/N)	Volume (m^3)	Gross wall area (m^2)	Window area (m^2)
Zone-1	19.28	N	54.2	14.89	2.38
Zone-2	12.35	N	30.21	21.04	4.77
Zone-3	12.35	N	8.29	21.04	4.77
Total	43.97		92.70	56.98	11.92
Unconditioned	43.97		92.70	56.98	11.92

The reason behind the selection of this space is that it is the main block that is frequently used for sleeping and other major purposes. Zone-1 has windows on East and West and considerable percentage of perforation on North and South wall as well as 25mm gap at roof and floor level with the wall (Chapter 4). According to a research of University of California, Berkeley, Environment and Energy Division cross-ventilation is effective upto 12/13m depth or five times the height of a room having windows on opposite walls (eslee@lbl.gov). Therefore, it can be assumed that with 20-30% perforation on north and south walls and windows on East-West walls of middle room and 35-40% on the south and north walls of front and service space wall respectively, Zone-1 has effect of cross ventilation. Table 5.4 illustrates the window-wall ratio.

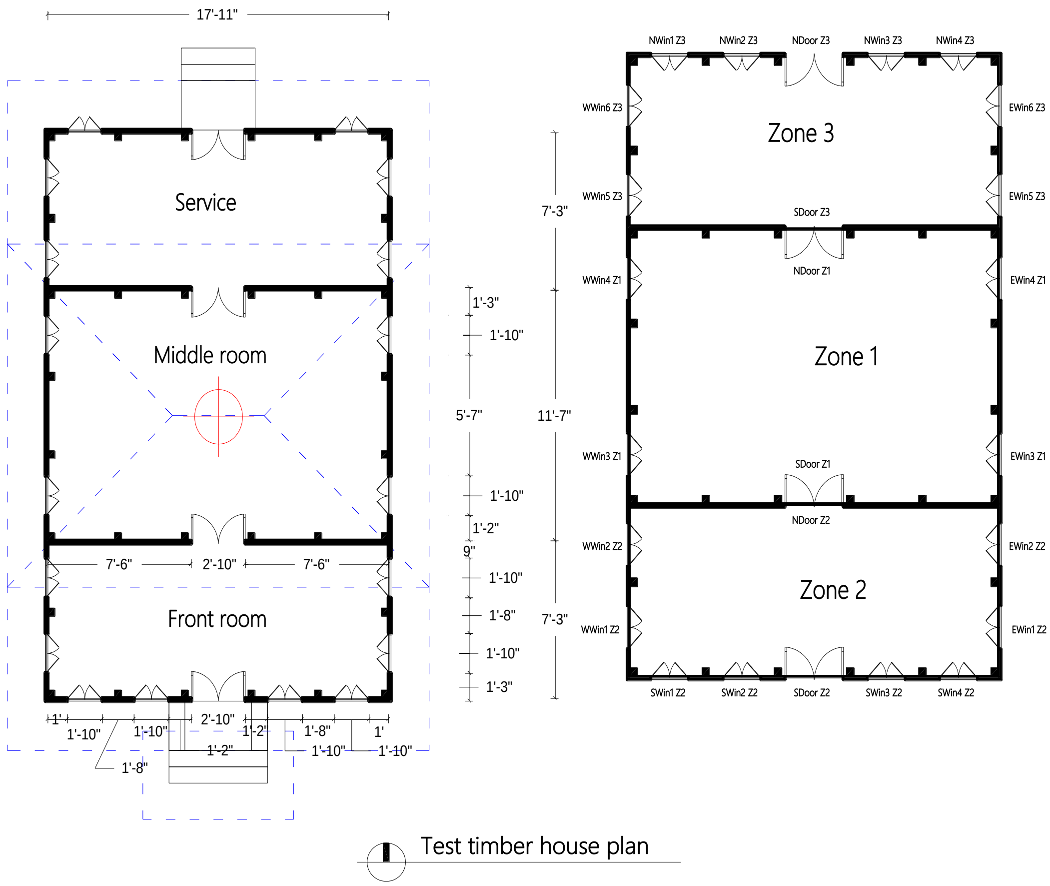


Figure 5.2 Plan (left) and Zone/surface detail (right) of single-storied traditional timber house test zone for EnergyPlus simulation modeling (1ft. = 0.3048m)

Table 5.4 Window-Wall ratio

Name	Total	North	South	East	West
Gross wall area (m^2)	56.98	11.51	11.51	16.97	16.97
Window opening area (m^2)	11.92	2.38	2.38	3.58	3.58
Windoe-wall ratio (%)	20.71	20.71	20.71	21.07	21.07

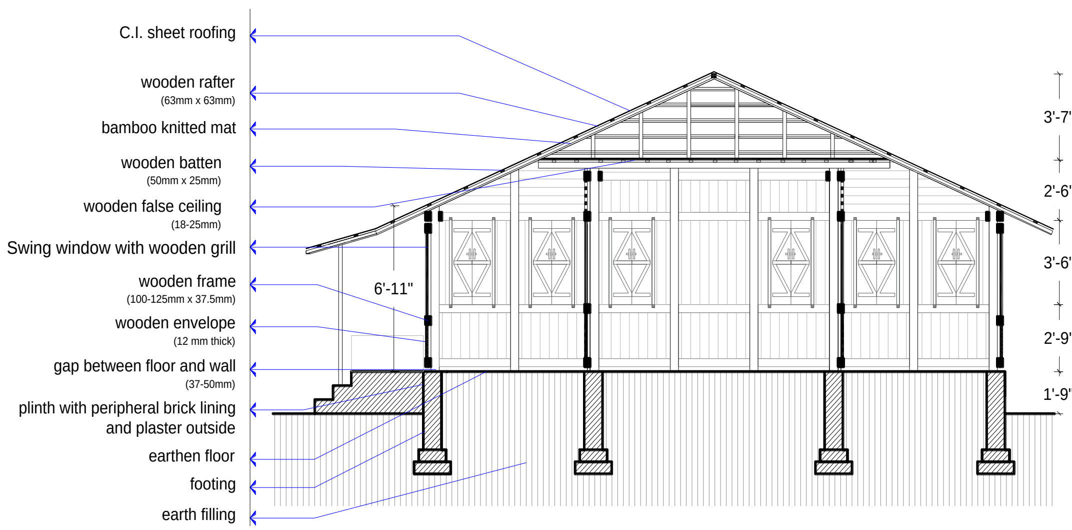
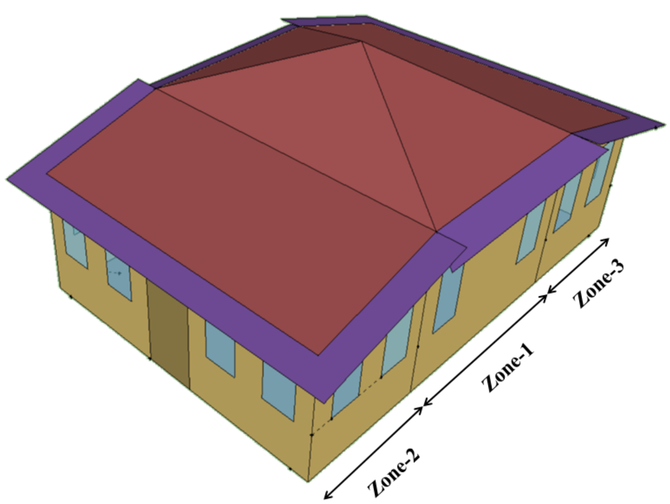


Figure 5.3 Detail section of single-storied traditional timber house envelope test zone for EnergyPlus simulation modeling and parametric study(1ft. = 0.3048m)



- Residential building
- True north orientation
- Location: Barisal, Bangladesh
- Plan: rectangular shape
- Roof: C.I. sheet with wooden false ceiling
- Total floor area: 43.64 sqm
- Zone-1 floor area: 19.1 sqm
- Zone-1 floor height: 3.2m
- Z-1 window: 20-25% of the gross wall area on four sides
- Roof shape: hipped roof
- Floor: earthen floor
- Wall: wooden envelope

Figure 5.4 EnergyPlus simulation model for test zone parametric study

5.3.2 Parametric Database Considered for Test Zone

a) Study location and climate

Field survey was conducted in two different locations: Barisal and Cox's Bazar. From literature review it is found that Barisal and Cox's Bazar remains in the same climatic zone of Bangladesh. In the EnergyPlus website weather data for Bangladesh has been provided for eight specific locations: Bogra, Chittagong-Patenga, Cox's Bazar, Dhaka, Ishurdi, Jessore, Rangpur and Sylhet. Therefore, weather data file of Cox's Bazar has been used for parametric study. Table 5.5 illustrates the climate and location used for validation of EnergyPlus simulation engine towards conducting parametric studies.

Table 5.5 Weather profile and location used for validation of EnergyPlus simulation engine

Fields	Specifications
Weather file	BGD_Coxs.Bazar.419920_SWERA
Site: Location	BARISAL – BGD
Latitude	{N 21° 25'}
Longitude	{E 91° 58'}
Time Zone	{GMT +6.0 Hours}
Elevation (m) above sea level	4
Standard Pressure at Elevation	101277Pa
Data Source	SWERA
WMO Station	419920
Weather File Design Conditions	Calculated from the weather file
Maximum Dry Bulb Temperature (C)	56.0°
Maximum Dry Bulb Occurs on	Jan 10
Minimum Dry Bulb Temperature (C)	1.9°
Minimum Dry Bulb Occurs on	Dec 13
Maximum Dew Point Temperature (C)	29.4°
Maximum Dew Point Occurs on	Aug 9
Minimum Dew Point Temperature (C)	0.8°
Minimum Dew Point Occurs on	Jan 26
Standard Heating Degree-Days (base 10°C)	not found
Weather File Heating Degree-Days (base 10°C)	0
Standard Cooling Degree-Days (base 18.3°C)	not found
Weather File Cooling Degree-Days (base 18°C)	2930
Köppen Classification	Aw
Köppen Description	Tropical savanna (pronounced wet and dry seasons, lat. 15-20°)
Köppen Recommendation	Unbearably hot dry periods in summer, but passive cooling is possible
ASHRAE Climate Zone	1A
ASHRAE Description	Very Hot-Humid

b) Schedule load

Design load considered for parametric studies of Zone-1 are specified in Table 5.6. For occupancy, lighting, equipment and door-window operation real field schedule specified in Chapter 4 (Section 4.7.1) were used. Table 5.7-5.10 illustrates the occupancy, lighting, electric equipment and door-window schedule considered for parametric study.

Table 5.6 Zone-1 load considered for parametric study

Fields	Parameter
Occupancy schedule	People (Residence occupancy)
Calculation method	Number of people calculation method
Number of people	5

Fields	Parameter
Lighting schedule	Residence lighting schedule
Design level calculation method	Watt/Area
Design level (W)	120
Equipment schedule	Residence equipment schedule
Design level calculation method	Watt/Area
Design level (W)	450

Table 5.7 Zone-1 occupancy schedule for parametric study

Time	Occupancy (%)
Until 10:00 am	0
Until 11:00 am	60
Until 14:00 pm	20
Until 18:00 pm	40
Until 14: 30 pm	80
Until 18:00 pm	60
Until 19:00 pm	20
Until 20:00 pm	80
Until 24:00 am	100

Table 5.8 Zone-1 lighting schedule for parametric study

Time	Parameter (%)
Until 10:00 am	0
Until 11:00 am	60
Until 14:00 pm	20
Until 18:00 pm	60
Until 20:00 pm	100
Until 23:00 pm	40
Until 24:00 am	0

Table 5.9 Zone-1 electric-equipment schedule for parametric study

Time	Parameter (%)
Until 06:00 am	50
Until 11:00 am	0
Until 13:00 pm	100
Until 14:30 pm	30
Until 15: 30 pm	100
Until 20:00 pm	0
Until 24:00 am	50

Table 5.10 Zone-1 door-window operation schedule for parametric study

Time	Opening (%)
Until 05:30 am	0
Until 22:00 pm	100
Until 23:00 pm	80
Until 24:00 am	0

c) *Surface construction elements*

Construction materials similar to that of envelope materials of traditional timber houses are used for model. Construction details and thermal properties of elements are shown in Table 5.11.

Table 5.11 Surface construction and thermal properties considered for parametric study

Name	Construction	Reflectance	U-Factor with Film [W/m2-K]	U-Factor with no Film [W/m2-K]	Gross Area [m2]	Azimuth [deg]	Tilt [deg]	Cardinal Direction
Ewall Z1	Exterior wall	0.30	6.271	102.400	7.44	90.00	90.00	E
Wwall Z1	Exterior wall	0.30	6.271	102.400	7.44	270.00	90.00	W
Floor Z1	Interior floor	0.30	1.489	2.333	19.28	0.00	180.00	
Roof Z1	Exterior roof	0.30	0.048	0.049	19.28	180.00	0.00	
Wwall Z2	Exterior wall	0.30	6.271	102.400	4.77	270.00	90.00	W
Ewall Z2	Exterior wall	0.30	6.271	102.400	4.77	90.00	90.00	E
Swall Z2	Exterior wall	0.30	6.271	102.400	11.51	180.00	90.00	S
Floor Z2	Interior floor	0.30	1.489	2.333	12.35	0.00	180.00	
Roof Z2	Exterior roof	0.30	0.048	0.049	12.35	180.00	0.00	
Nwall Z3	Exterior wall	0.30	6.271	102.400	11.51	0.00	90.00	N
Wwall Z3	Exterior wall	0.30	6.271	102.400	4.77	270.00	90.00	W
Ewall Z3	Exterior wall	0.30	6.271	102.400	4.77	90.00	90.00	E
Floor Z3	Interior floor	0.30	1.489	2.333	12.35	0.00	180.00	
Roof Z3	Exterior roof	0.30	0.048	0.049	12.35	180.00	0.00	
Ewin3 Z1	Exterior window	-	5.894	-	0.60	90.00	90.00	E
Ewin4 Z1	Exterior window	-	5.894	-	0.60	90.00	90.00	E
Wwin3 Z1	Exterior window	-	5.894	-	0.60	270.00	90.00	W
Wwin4 Z1	Exterior window	-	5.894	-	0.60	270.00	90.00	W
Wwin2 Z2	Exterior window	-	5.894		0.60	270.00	90.00	W
Wwin1 Z2	Exterior window	-	5.894	-	0.60	270.00	90.00	W
Ewin2 Z2	Exterior window	-	5.894	-	0.60	90.00	90.00	E
Ewin1 Z2	Exterior window	-	5.894	-	0.60	90.00	90.00	E
Swin4 Z2	Exterior window	-	5.894	-	0.60	180.00	90.00	S
Swin3 Z2	Exterior window	-	5.894		0.60	180.00	90.00	S
Swin2 Z2	Exterior window	-	5.894	-	0.60	180.00	90.00	S
Swin1 Z2	Exterior window	-	5.894	-	0.60	180.00	90.00	S
Nwin1 Z3	Exterior window	-	5.894	-	0.60	0.00	90.00	N
Nwin2 Z3	Exterior window	-	5.894	-	0.60	0.00	90.00	N
Nwin3 Z3	Exterior window	-	5.894	-	0.60	0.00	90.00	N
Nwin4 Z3	Exterior window	-	5.894	-	0.60	0.00	90.00	N
Wwin5 Z3	Exterior window	-	5.894	-	0.60	270.00	90.00	W
Wwin6 Z3	Exterior window	-	5.894	-	0.60	270.00	90.00	W
Ewin5 Z3	Exterior window	-	5.894	-	0.60	90.00	90.00	E
Ewin6 Z3	Exterior window	-	5.894	-	0.60	90.00	90.00	E
SDoor Z2	Exterior door	-	38.4	38.4	1.65	180.00	180.00	S
NDoor Z3	Exterior door	-	38.4	38.4	1.65	0.00	0.00	N

Note: (Here, N= North, S= South, E= East and W=West) and as window has no glass therefore reflectance is considered zero (0)

Test Zone-1 has two interior walls (North and South) which are not sun/wind exposed while other two (East and West) are sun/wind exposed. Both interior and exterior walls are composed of 12.5mm wooden plank (Teak). Roof has 4 layers C.I. sheet covering, 1.1m high attic, wooden false ceiling of 25mm thickness and a layer of cotton fabric from exterior to interior. Floor is earthen and door and windows have operable wooden panels of 25mm thickness (Sal). Material database used for the simulation is presented in Table 5.12.

Table 5.12 Thermal properties of materials of traditional timber house.

Material	Conductivity (W/m-K)	Density (Kg/m^3)	Specific Heat (J/kg-K)	R-Value (m^2-K/ W)	Reference
Earthen floor	0.5~1.4	1460	879	-	(https://www.engineeringtoolbox.com/thermal-conductivity-d_429.html; Clarke, Yaneske et al. 1990)
Concrete (cement:sand:agg=1:2:4)	1.34	2487	670~850	-	(Chowdhury 2014)
Local brick (1st Class)	0.55	1789.102	1171.52	-	(Chowdhury 2014)
Local brick (2nd Class)	0.55	1789.102	1171.52	-	(Chowdhury 2014)
Local brick (3rd Class)	1.34	1081.406	3514.56	-	(Chowdhury 2014)
Plaster (cement:sand = 1:5)	0.43	2375	650~753	-	(Chowdhury 2014)
Timber wall	0.13–0.14	515–650	1200–1600	-	(Hadden, Bartlett et al. 2017; Wade, Spearpoint et al. 2018)
Wood shingle	0.115	512	1256	-	(Clarke, Yaneske et al. 1990)
Timber flooring	0.14	650	1200	-	(Clarke, Yaneske et al. 1990)
Wooden floor	0.14	600	1210	-	(Clarke, Yaneske et al. 1990)
CI sheet/Tin	65	7300	235	-	(Clarke, Yaneske et al. 1990)[48]
Mahogony	0.155	700	1880	-	(Clarke, Yaneske et al. 1990)
Teak	1.28	710	1880	-	(Vasubsbu, Nagaraju et al. 2015)
SilKoroi		696	1880	-	(Hossain and Awal 2012)
Sal	0.96	660	1880	-	(Vasubsbu, Nagaraju et al. 2015)
Rain tree	0.74	480	1880	-	(Vasubsbu, Nagaraju et al. 2015)
Kanthal		615	1880	-	(Hossain and Awal 2012)
Black plum/Jam	0.119	817	1880	-	(Vasubsbu, Nagaraju et al. 2015)
Mango	0.117	596	1880	-	(Vasubsbu, Nagaraju et al. 2015)
Garjan		1300	1880	-	(Hossain, Shuvo et al. 2014)
Kerosene		1120	1880	-	(Hossain, Shuvo et al. 2014)
Gamari		860	1880	-	(Hossain, Shuvo et al. 2014)
Hardwood (std.)	0.23	800	1880	-	(Clarke, Yaneske et al. 1990)
Softwood (std.)	0.17	550	1880	-	(Clarke, Yaneske et al. 1990)
Polythene (Low density)	0.3175	919	2600		(Clarke, Yaneske et al. 1990; Designerdata Accesd on: 29 April, 2021)
Polythene (High density)	0.44	940	1330-2400		(Clarke, Yaneske et al. 1990; Thakare, Vishwakarma et al. 2015)
Terracotta tiles	0.81-1.15	1700-2000	840	-	(Clarke, Yaneske et al. 1990)
Roof tile	0.84	1900	800	-	(Clarke, Yaneske et al. 1990)
Straw thatch	0.07	240	180	-	(Clarke, Yaneske et al. 1990)
Rice husk	0.045-0.051	120-135	1000	-	(Clarke, Yaneske et al. 1990)
Jute fiber	0.067	329	1090	-	(Clarke, Yaneske et al. 1990)

d) Internal gains

Zone load considered are illustrated in Table 5.13. As the house is naturally ventilated therefore there is no conditioned space in test model. Table 5.14 shows internal gain and heat removal from different sources.

Table 5.13 Zone load considered for parametric study

Name	Lighting (W/m^2)	People (m^2 per person)	Electrical Equipment (W/m^2)
Zone-1	6.28	3.86	70.33
Zone-2	10.00	2.47	37.20
Zone-3	4.95	2.47	0.00
Total	6.951	2.93	41.2829
Unconditioned	6.951	2.93	41.2829

Table 5.14 Zone internal gain and heat removal from different sources

Name	People Sensible Heat Addition[GJ]	Lights Sensible Heat Addition[GJ]	Equipment Sensible Heat Addition[GJ]	Equipment Sensible Heat Removal[GJ]	Win. Heat Removal [GJ]	Interzone Air Transfer Heat Removal [GJ]	Infiltratio n Heat Removal[GJ]	Opaque Surface Conduction and Other Heat Removal [GJ]
Zone 1	0.567	0.162	2.170	0.000	-0.234	0.000	-0.192	-2.473
Zone 2	0.622	0.165	0.866	0.000	-0.431	0.000	-0.118	-1.104
Zone 3	0.669	0.082	0.000	0.000	-0.397	0.000	-0.062	-0.292
Total	1.858	0.409	3.036	0.000	-1.062	0.000	-0.372	-3.86

e) Zone airflow

For calculating the effect of natural ventilation, data has been input in EnergyPlus object Zone Ventilation: Wind and Stack Open Area which with simplified equation (Section 5.2 (g)) calculates flows at zone level driven by wind and stack effect considering temperature difference between indoor-outdoor, wind speed, opening area, opening efficiency and height difference. Opening area fraction schedule is considered as per door-window schedule traced from field survey (Chapter 4, Section 4.7.1). Opening effectiveness is calculated automatically by EnergyPlus simulation engine. Maximum indoor outdoor AT difference was found to be 5ºC and wind speed was found to be 3m/s from literature review (Chapter 2). Table 5.15 shows the data input considered for the parametric study.

Table 5.15 Zone-1 airflow calculation input for parametric study

Field	North Cross-vent.	South Cross-vent.	East Cross-vent.	West Cross-vent.
Opening area	1.64	1.64	1.19	1.19
Opening area fraction schedule	Door-window operation schedule	Door-window operation schedule	Door-window operation schedule	Door-window operation schedule
Opening effectiveness	Auto-calculate	Auto-calculate	Auto-calculate	Auto-calculate
Effective angle	0	180	90	270
Delta temperature (ºC)	5	5	5	5
Wind speed	3	3	3	3

5.3.3 Run Period

As field survey was conducted during the high temperature and high humidity months of July and August therefore simulation run period has been scheduled for this period for validation of the simulation engine. The period considered for the parametric study is illustrated in Table 5.16.

Table 5.16 Simulation run-period parameters of Zone-1 for parametric study

Field	Weather File Days
Begin month	July
Begin day of month	1
End month	August
End day of month	31
Day of week for start	Saturday
Use weather file daylight saving period	No
Use weather file rain and snow indicators	Yes
Period selection	Tropical hot

5.4 Simulation Output Variables

For the current study the following output variables were considered:

a) Zone AT (ºC)
b) Zone Mean AT (ºC)
c) Zone MRT (MRT) (ºC)
d) Zone Operative Temperature (ºC)
e) Zone Air Relative Humidity (%)

For accuracy besides the above output other thermal variables like Zone Ventilation Sensible Heat Loss Energy, Zone Ventilation Air Inlet Temperature, Site Outdoor AT and Site Outdoor Air Relative Humidity were measured by EnergyPlus.

5.5 Evaluation Process

Fig. 5.5 illustrates evaluation process. As discussed in Chapter-3 building model for parametric study is developed using Google SketchUp with OpenStudio plug-in software EnergyPlus. But parametric study requires validation of prepared model.

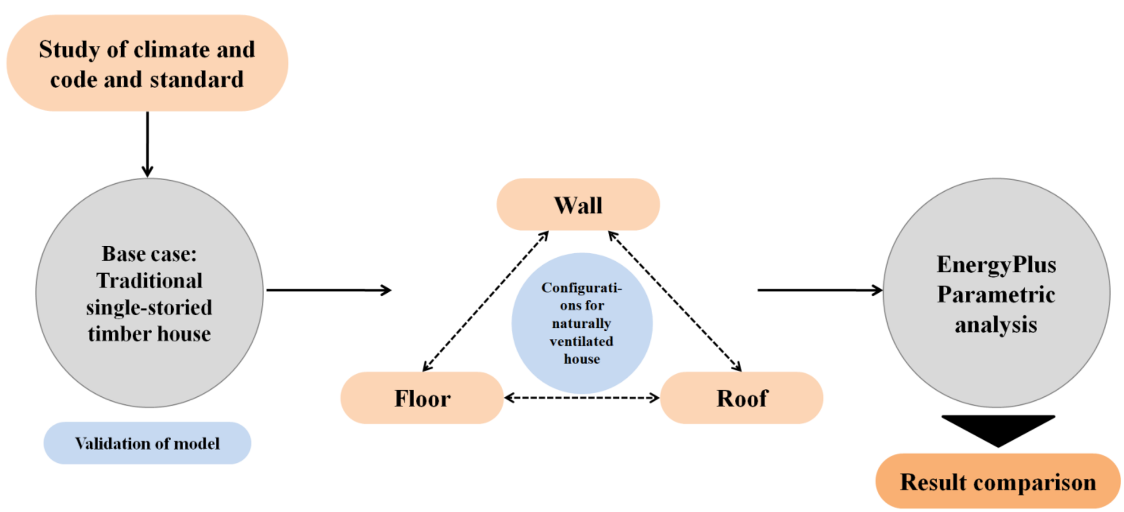


Figure 5.5 Evaluation process of parametric study

Therefore, several parametric simulation studies have been conducted for validation and obtained result is compared with the monitored field environmental data. Detailed validation process is discussed in section 5.6. After proper validation whole year parametric study has been conducted to trace discomfort period of the year. Then several envelope design strategies have been examined through EnergyPlus parametric study. Finally obtained result has been analyzed and synthesized regarding comfort standard. The parametric study and analysis section has been discussed in detail in the Chapter 6.

5.6 Simulation and Validation of Model

For validation the input mentioned above has been considered. But for input of schedule details a broad range of four-five hours has been considered. Output result of Zone-1 AT(ºC) of 4-5th August has been compared with the field environmental data of house H-1 (traditional single-storied house) of the same day. Zone-1 AT varies from the field AT value by -0.98ºC to 2.88ºC during the period of 07:00am to 20:00pm. AT variation is very little (-0.36ºC to 0.1ºC) between late-night to early morning (21:00pm – 05:00am). Fig. 5.6 illustrates initial parametric study conducted for validation of simulation model.

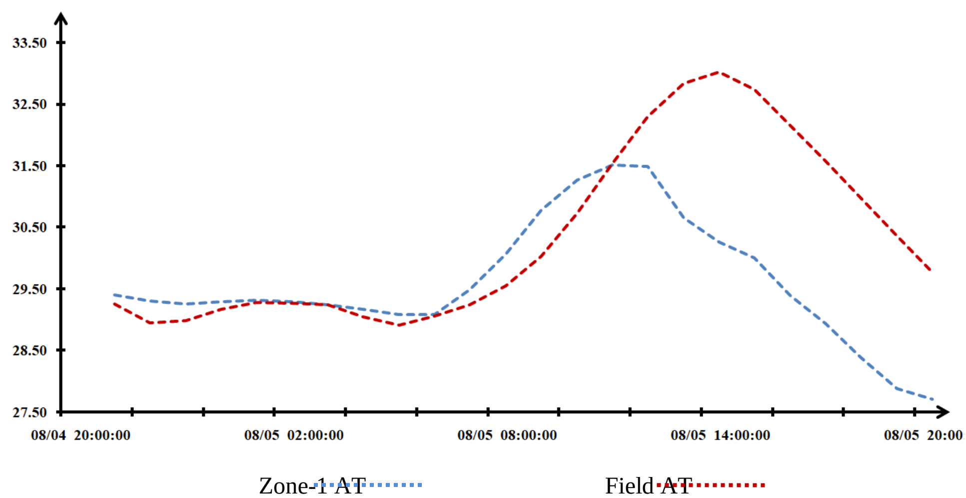


Figure 5.6 EnergyPlus model validation_1: simulation and field data comparison

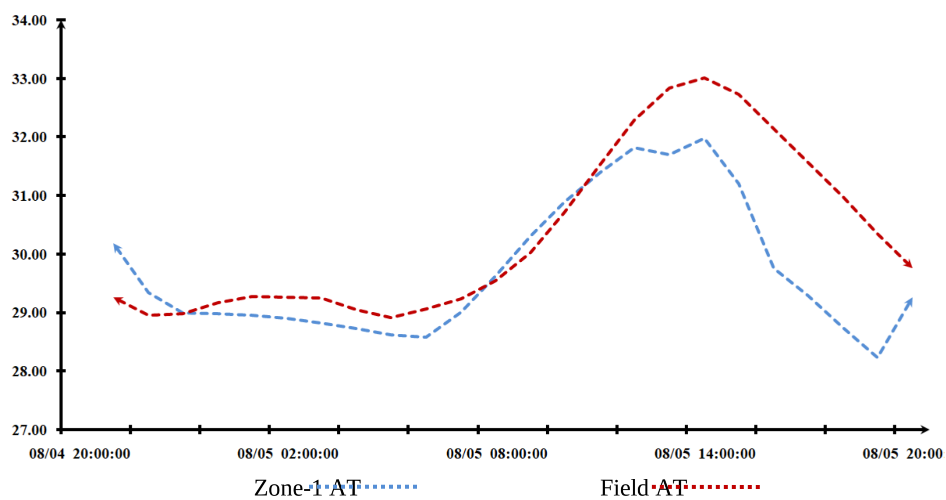


Figure 5.7 EnergyPlus model validation_2: simulation and field data comparison

For the next simulation study, occupancy schedule has been detailed out for an interval of nearly three hours. For lighting, electric equipment schedule has been considered for four-five hours' interval. The result is then compared with field environmental data. Fig. 5.7 shows that further detail out of the different schedules results in considerably lower AT difference between field and simulation output data. Maximum AT difference has been found during the period of 17:00pm-19:00pm which ranges from 1.99 ºC -2.45ºC.

Delta temperature corresponds to indoor and outdoor air (dry-bulb) temperature difference (in ºC) below which no ventilation can take place (EnergyPlus 2003). For first two studies the 'delta temperature' (ºC) was considered as low as 0.5ºC. For delta temperature value of 1.5 ºC, resulting lower AT difference between field data and simulation output for Zone-1 AT (Fig. 5.8). Maximum temperature variation resulted between the period 12:00pm-13:00pm (1.38 ºC and 2.29 ºC respectively). Rest of the period has a value which ranges from -98 ºC to 0.70 ºC.

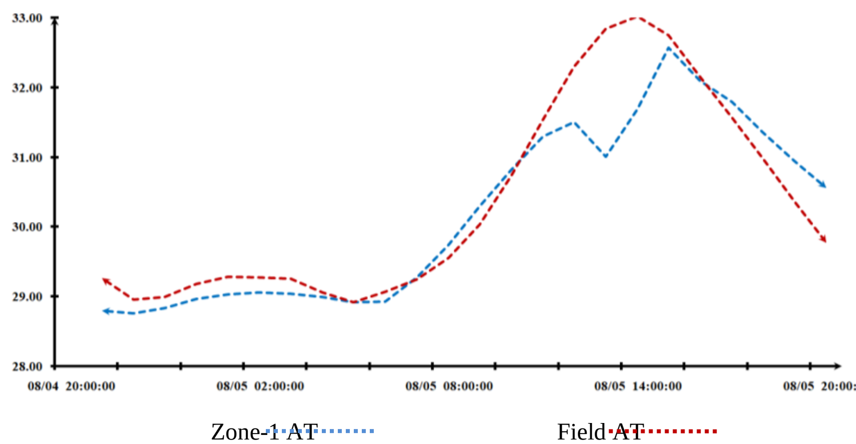


Figure 5.8 EnergyPlus model validation_3: simulation and field data comparison

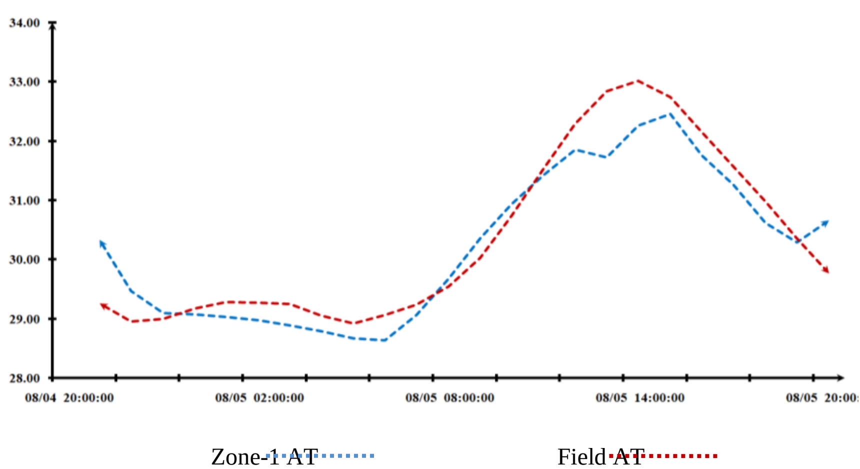


Figure 5.9 EnergyPlus model validation_4: simulation and field data comparison

Initially wind speed was considered 2.0m/s. But from literature review (Chapter-2, section 2.3.3) it is seen that annual minimum and maximum wind speed ranges from 2.5m/s-3.5m/s for Pirojpur (case study region). Therefore, wind speed is considered 3m/s in average for parametric study. Result obtained is presented in Fig. 5.9. From Fig. 5.9 it is observed that though AT variation during the period

12:00pm-13:00pm declines further but for the rest of the period AT difference between field and simulation increases.

Later break-down of lighting, electric and door-window schedules at an interval of one to two hours during day-time period comes out with simulation result with a variation of -0.59ºC to 0.76ºC during the 24hrs period. Fig. 5.10 illustrates the result comparison between Zone-1 and field data for the day of 4-5th August.

Again, further elaboration of occupancy schedule has been elaborated at an interval of one/ two hours, resulted in AT variation ranging from -0.64ºC to 0.69ºC during the selected period. Fig. 5.11 illustrates the result comparison between Zone-1 and field data for the same day (4-5th August).

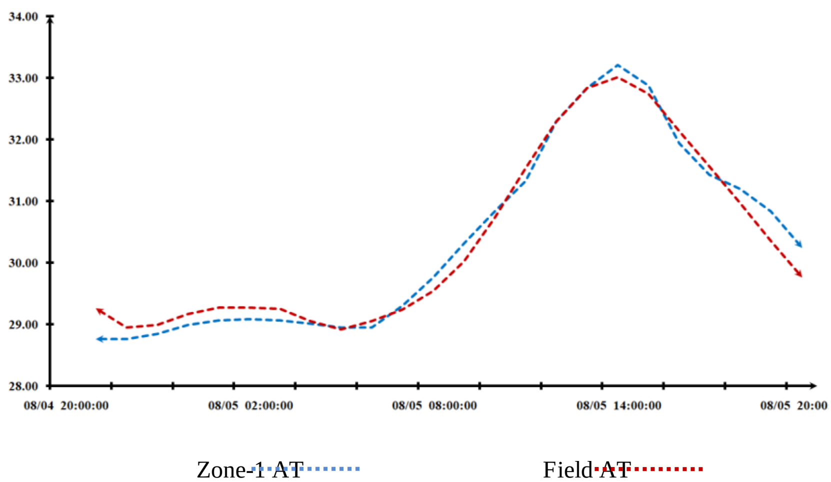


Figure 5.10 EnergyPlus model validation_5: Simulation and field data comparison

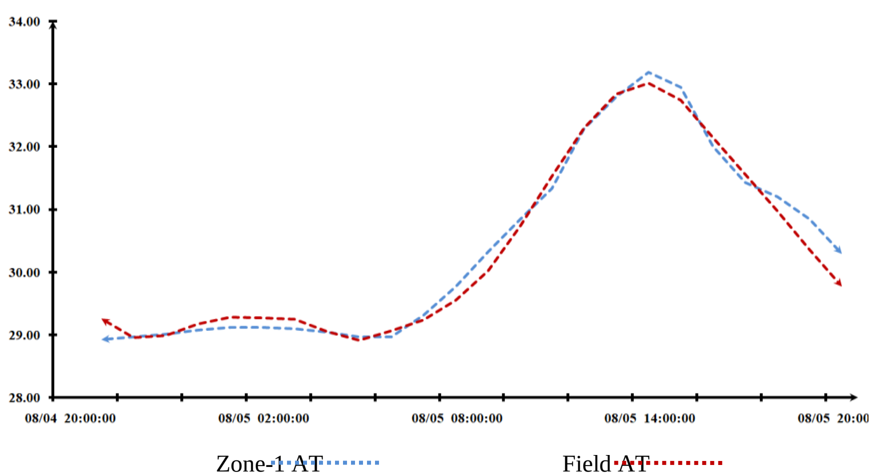


Figure 5.11 EnergyPlus model validation_6: Simulation and field data comparison

5.7 Conclusion

For parametric study this research employed EnergyPlus simulation engine. Though OpenStudio plug-in has been used for building modeling; but, not all the input regarding parametric study was possible with this plug-in software. Therefore, several text file editing using. idf file have been done to run EnergyPlus simulation. This chapter presents the overall factors towards parametric database preparation, validation and evaluation procedure of obtained simulation result. Database for simulation study has been prepared based on the findings from field monitoring. Different schedules (i.e., occupancy, lighting, equipment, door-window schedule) and climatic data related database have been prepared as per information obtained from physical survey. Several parametric studies have been conducted and obtained data have been plotted against field environmental data of the same period. From this comparison validation of prepared model has been done for further parametric studies to identify discomfort periods and check different design strategies towards enhanced indoor thermal comfort. Design strategies considered and details of parametric studies are presented in the next chapter (Chapter 6).

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CHAPTER SIX: PARAMETRIC STUDY RESULT AND ANALYSIS

6.1 Introduction

Preparation of three dimensional EnergyPlus model (EnergyPlus 2013) representing typical traditional single-storied timber house of Bangladesh and detail validation process of the model has been illustrated in the previous chapter (Chapter 5). In this chapter, initially a whole year simulation study has been performed to evaluate annual thermal performance of the existing traditional timber house envelope. Later a few probable envelope design strategies have been studied regarding indoor thermal performance of the proposed envelope towards enhanced indoor thermal comfort. Though there can be several design strategies, however, options have been narrowed down considering local construction materials and technology. For this study design strategies have been considered for wall, roof and floor. Basically, three types of variables have been considered: thickness, material and construction detail. For parametric study a total of thirty-eight (38) wall, six (06) roof and two (02) floor Constructions have been studied.

From literature review (chapter-2) it is seen that climate is categorized as dry winter (December to February), hot and dry pre-monsoon (March to May), hot and wet monsoon (June to September) and post-monsoon (October to November) (Ahmed 1995; Mridha 2002; Ahsan 2009)where winter is cool-dry and rest of all are hot- humid (Ahmed 1995).Among all the hot-humid period 'July' has comparatively high temperature and high humidity and heavy rainfall. Hence, simulation studies for probable envelope Constructions have been conducted for the month of July. Therefore, this chapter illustrates the simulation experiments in detail. Results obtained from simulation studies for each Construction have been presented statistically. Then, for various temperature gradients, regression and co-relational model has been set-up towards understanding thermal performance of different Constructions considered regarding indoor thermal comfort standard (Mallick 1996; ASHRAE 2001; BNBC 2006). From conducted different parametric studies, this study tries to suggest envelop design strategies of traditional timber house for improved indoor thermal environment in the future.

6.2 Whole Year Performance of Existing Envelope

Literature study shows that people in rural areas of Bangladesh express indoor environment comfortable when AT(ºC) remains within the range of 24 -32°C and relative humidity value of 50-90% with or without presence of little air movement (Mallick 1996). Fig. 6.1 shows hourly indoor AT(ºC) and RH (%) for Z-1.

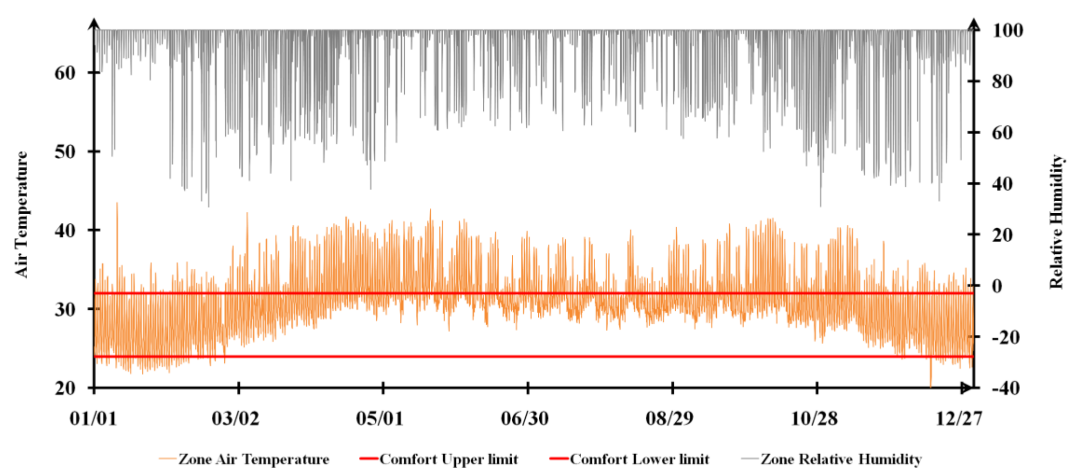
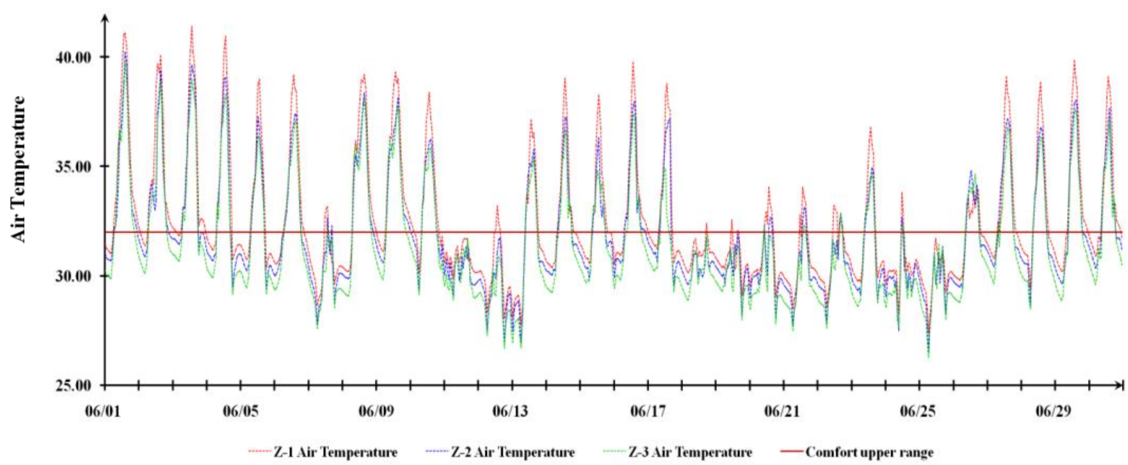


Figure 6.1 Hourly Zone-1 AT(ºC) for a whole year.

Whole year simulation study for traditional timber house shows that indoor AT(ºC) inside house remains within comfort level nearly for the period of November to mid-March. Indoor AT(ºC) remains higher than upper limit of comfort for rest of month mostly during late March to October. In terms of relative humidity, it is seen that it is low during the periods January to April and October to December. But relative humidity remains comparatively high during the period May to September.

Table 6.1 Simulation result summary of existing envelope of traditional timber house for month of June.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	41.39	39.73	40.42	40.23	39.33	39.78	39.78	39.05	39.42
Minimum	23.54	27.38	26.97	27.18	26.50	26.30	26.40	26.26	26.01	26.14
Mean	27.83	32.46	31.73	32.10	31.80	31.37	31.58	31.36	31.04	31.20
Median	27.41	31.62	31.00	31.30	31.02	30.59	30.84	30.63	30.17	30.43
Mode	26.58	31.48	30.61	31.04	31.01	30.22	30.62	30.24	29.58	29.91
Kurtosis	-0.6	0.70	0.02	0.39	0.58	-0.08	0.27	0.27	-0.39	-0.07
Skewness	0.42	1.19	0.91	1.06	1.06	0.86	0.97	0.97	0.76	0.86
Std. Dev.	2.03	2.77	2.61	2.67	2.52	2.66	2.57	2.54	2.76	2.63
Sample Var.	2.11	7.69	6.81	7.15	6.34	7.08	6.61	6.44	7.60	6.92
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439



(a)

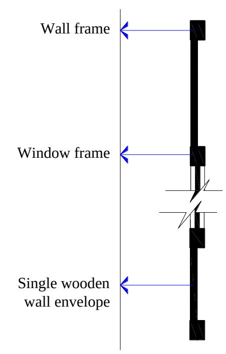
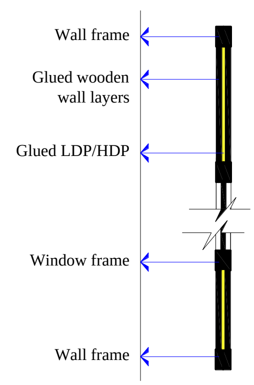
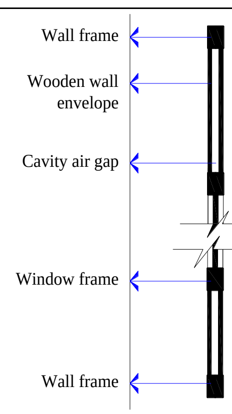
Figure 6.2 Simulation result of hourly temperature gradient for Z-1, Z-2 and Z-3 during study period: (a) AT(ºC), (b) MRT(ºC) and (c) OT(ºC)

From Fig. 6.1 it is observed that from May to August temperature and relative humidity both remain higher. But during the month of June AT(ºC) remains comparatively high with higher RH (%) value (Fig. 6.2). Therefore, experimental parametric studies of different envelope Constructions have been conducted for the period of June. Table 6.1 illustrates the simulation results summary of temperature gradients: AT(ºC), MRT(ºC) and OT(ºC) during the month of June. The figure shows that throughout the study period of June all the temperature gradients remain relatively higher during the first week. Fig. 6.2 shows simulation result of hourly AT(ºC) for Z-1 during study period.

6.3 Constructions Considered for Parametric Studies

Whole year parametric study for traditional timber house shows AT above comfort level for most of the hot-humid period. Therefore, several envelope Constructions have been examined regarding indoor thermal comfort. Constructions include thirty-eight (38) wall, six (06) roof and two (02) floor envelope design strategies. For wall four parameters have been considered: thickness, laminated layer, cavity and cavity insulation with three different locally available materials (i.e., straw, coconut fiber and jute fiber). For roof two covering materials have been considered: roof tile and C.I. sheet combined with presence of attic space. For floor two Constructions: attached with ground and elevated from the ground, have been tested. Window construction is considered similar to the window of traditional timber house found during the field survey. Table 6.2-6.5 illustrates the wall, roof, floor and window Constructions considered. Graphical presentation of each construction is provided within the table.

Table 6.2 Wall Construction considered for parametric studies.

Parameter	Type/ Thickness	Name	Construction	Graphical illustration
Thickness (W-1)	18.75mm	W-1a	Traditional wooden wall: 12.5-37.5mm thick	
	25mm	W-1b		
	31.25mm	W-1c		
	37.5mm	W-1d		
Glued layers timber (W-2)	12.5mm two layer	W-2a	Traditional wooden wall: 25-37.5mm thick with plastic sheet in between layers	
	12.5mm three layer	W-2b		
	2 layer with low density polythene	W-2c		
	3 layer with low density polythene	W-2d		
	2 layer with high density polythene	W-2e		
	3 layer with high density polythene	W-2f		
Cavity Air gap (W-3)	cavity 6.25mm, wall 37.5mm	W-3a	12.5-18.75mm two wooden leaf with cavity. Total wall thickness 37.5-50mm	
	cavity 12.5mm, wall 37.5mm	W-3b		
	cavity 12.5mm, wall 43.8mm	W-3c		
	cavity 18.75mm, wall 43.8mm	W-3d		
	cavity 12.5mm, wall 50mm	W-3e		
	cavity 18.75mm, wall 50mm	W-3f		
	cavity 25mm, wall 50mm	W-3g		

Cavity insulation with straw thatch (W-4)	cavity 6.25mm, wall 37.5mm	W-4a	Wooden wall having cavity thickness ranging between 6.25-25mm with straw thatch/ rice husk/ jute fiber as cavity insulation material	
	cavity 12.5mm, wall 37.5mm	W-4b		
	cavity 12.5mm, wall 43.8mm	W-4c		
	cavity 18.75mm, wall 43.8mm	W-4d		
	cavity 12.5mm, wall 50mm	W-4e		
	cavity 18.75mm, wall 50mm	W-4f		
	cavity 25mm, wall 50mm	W-4g		
Cavity insulation with coconut fiber/coir (W-5)	cavity 6.25mm, wall 37.5mm	W-5a		
	cavity 12.5mm, wall 37.5mm	W-5b		
	cavity 12.5mm, wall 43.8mm	W-5c		
	cavity 18.75mm, wall 43.8mm	W-5d		
	cavity 12.5mm, wall 50mm	W-5e		
	cavity 18.75mm, wall 50mm	W-5f		
	cavity 25mm, wall 50mm	W-5g		
Cavity insulation with jute fiber (W-6)	cavity 6.25mm, wall 37.5mm	W-6a		
	cavity 12.5mm, wall 37.5mm	W-6b		
	cavity 12.5mm, wall 43.8mm	W-6c		
	cavity 18.75mm, wall 43.8mm	W-6d		
	cavity 12.5mm, wall 50mm	W-6e		
	cavity 18.75mm, wall 50mm	W-6f		
	cavity 25mm, wall 50mm	W-6g		

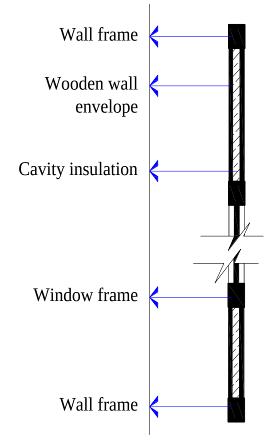
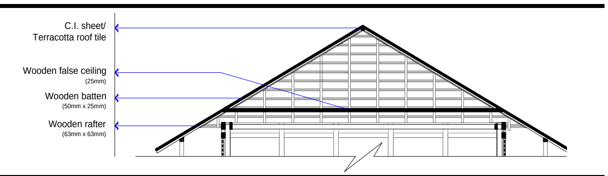


Table 6.3 Roof Construction considered for parametric studies.

Parameter	Name	Construction materials	Graphical illustration
With attic (R-1)	R-1a	C.I. sheet roof covering having wooden false ceiling	
	R-1b	Roof tile with wooden false ceiling	
No attic (R-2)	R-2a	C.I. sheet roof covering with wood panel below	
	R-2b	C.I. sheet roof covering with bamboo knitted mat	
	R-2c	Roof tile with wood panel	
	R-2d	Roof tile with bamboo knitted mat below	



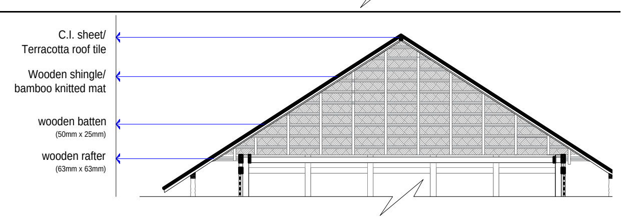


Table 6.4 Floor Construction considered for parametric studies.

Parameters	Type/Thickness	Name	Construction materials	Graphical illustration
Connection with ground	With ground floor	F-1	Earth	
	2.44m (8ft.) Elevated ground floor	F-2	Timber	

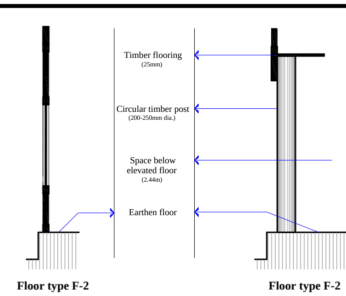
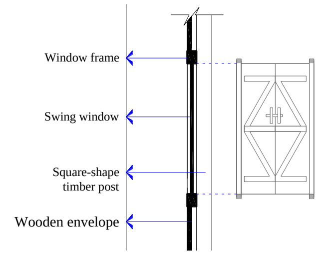


Table 6.5 Window Construction considered for parametric studies.

Parameters	Type/Thickness	Name	Construction materials	Graphical illustration
Window	Existing conventional swing window	Win.-1	Timber	

6.4 Simulation Study Result for Wall

6.4.1 Wall Constructions with Change in Thickness: W-1

For parametric study of wall type W-1, a three-dimensional model of 43.64 sqm is considered having three zones: front zone (Z-1), middle zone (Z-2) and back zone (Z-3). Wall Construction of W-1 basically has four types regarding variation in thickness: W-1a (18.75mm/¾"), W-1b (25mm/1"), W-1c (31.25mm/1¼) and W-1d (37.5mm/1½"). Floor is earthen attached with ground (F-1). Roof has C.I. sheet covering with an attic space of 1.09m high provided with 25mm thick wooden false-ceiling (R-1) below. Fenestrations are considered same as existing swing windows having two wooden shutters of 18.75mm (¾") thickness. Both internal and external doors have two swing wooden panels of 25mm (1") thickness (Win.-1). Cross-sectional view of W-1 is shown in Fig. 6.3. Thermal properties of all envelope materials (roof, floor, wall) considered for wall Construction W-1 are presented in Table 6.6.

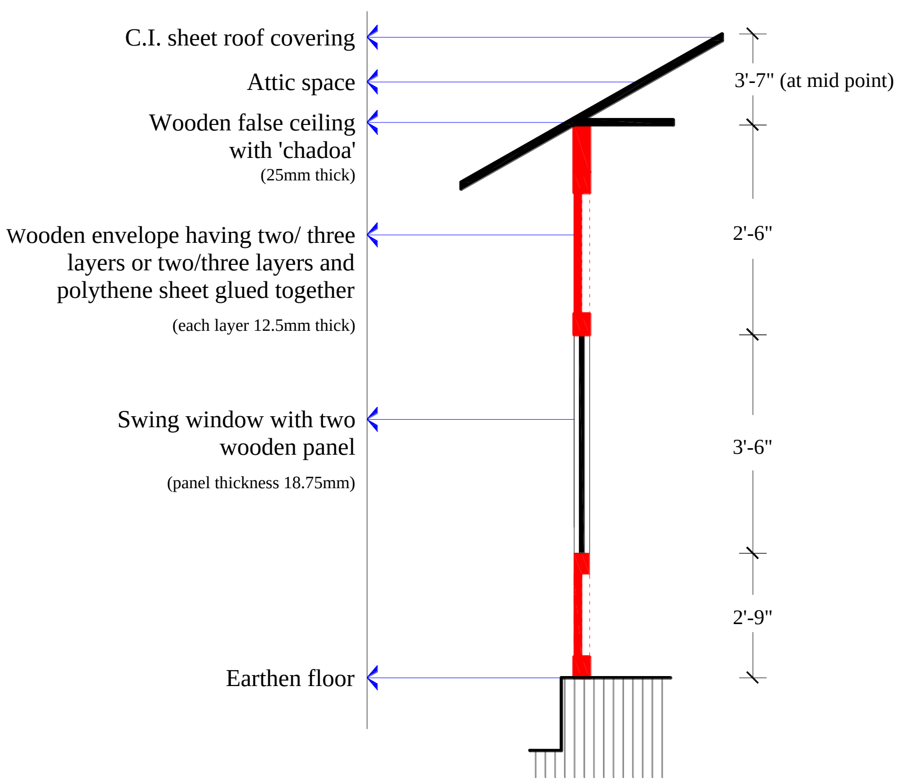


Figure 6.3 Cross sectional view of wall type W-1

Table 6.6 Thermal properties of envelopes considered for wall type W-1.

Envelope Name	Material	Thickness	Conductivity	Density	Specific-Heat
Wall	Teak	18.75mm/25mm/31.25mm/37.5mm	1.28	710	1880
Roof covering	C.I. sheet	0.5mm	65	7300	235
Ceiling	Raintree	25mm	0.74	480	1880
Chadoa	Cotton fabric	0.01	0.04	225	1380.72
Floor	Earthen	-	1.4	1460	879
Window	Sal	18.75mm	0.96	660	1880
Door	Sal	25mm	0.96	660	1880

a) Wall type W-1a

The wall envelope type W-1a considered for simulation study has 18.75mm (¾") thickness. The thickness is considered for all the three zones: Z-1, Z-2 and Z-3. As from field study it is found that teak is commonly used for wall envelope construction, hence, thermal properties of teak wood is considered. Parametric study is conducted for the month of June (1^{st}-30^{th} June) only. Result obtained from the EnergyPlus simulation for wall type W-1a is summarized in Appendix D. Obtained parametric study result for wall type W-1a and a comparison of AT(ºC), MRT(ºC) and OT(ºC) of Z-1, Z-2 and Z-3 for the month of June is presented in Fig. 6.4. All the three-temperature gradient shows similar trend where Z-1, with its position at the middle, shows higher temperature than other two zones. Z-3, being the rear zone regarding wind direction, has the lowest temperature. Also, temperature variation is relatively low at Z-2 compared to Z-1 during study period as standard deviation is comparatively higher for Z-1 whereas Z-2 has lower value. From Fig. 6.4 it is clear that there is a correlation between outdoor AT and indoor temperature. For all the three zones AT(ºC), MRT(ºC) and OT(ºC) fluctuates in the same way with the outdoor AT(ºC). But all temperature gradients remain above standard level of comfort for most of the time though outdoor AT(ºC) remains within comfort range all the time during study period.

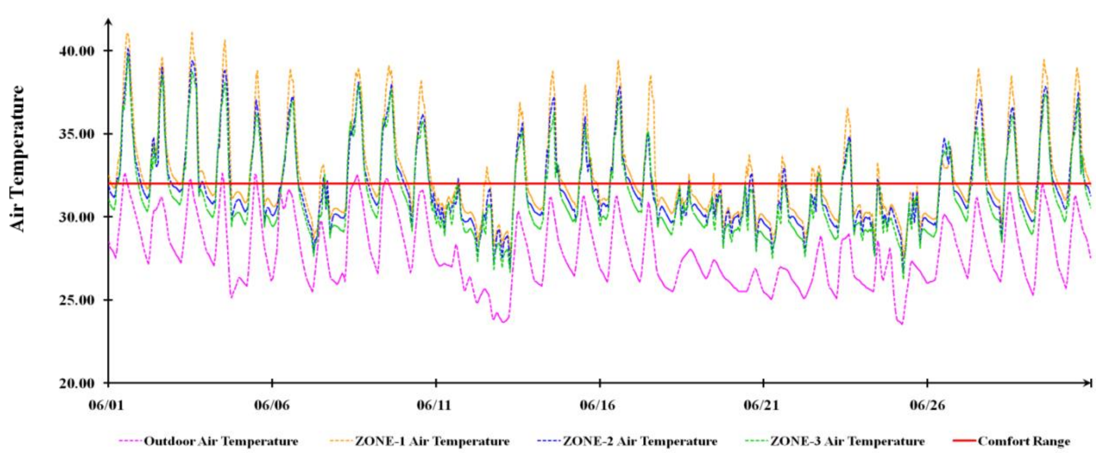


Figure 6.4 Comparison of AT(ºC) of different zones for wall type W-1a

All the temperature gradients have a maximum value during first week of the study period. Appendix- D (Fig. D.2) shows temperature gradient for first week of June for wall type W-1a. It is observed that indoor temperature remains within comfort range for a little period of time particularly during early morning and late night and reaches its peak during the period 15:00pm-16:00pm. During mid-day indoor AT(ºC) reaches as high as 41.02°C and started to fall again after evening. Indoor AT(ºC) reaches its minimum at 5:00am and becomes 31.72°C. After this period AT(ºC) again started to increase gradually. As it is clear that indoor temperature fluctuates with the outdoor temperature, therefore, linear regression analysis of resulted temperature gradients regarding outdoor temperature has been studied. This analysis illustrates how all the temperature gradients change with respect to outdoor temperature during study period. Variability of about 77-80 percent is found for temperature gradients whereas OT(ºC) and MRT(ºC) have maximum variation around its mean. A variation of 77 percent of AT(ºC) is found during study period. Linear regression analysis for wall type W-1a is shown in Appendix D (Fig. D.3).

There remains a positive correlation among different temperature gradients with the outdoor temperature (Appendix D). Best correlation among outdoor temperature and other resulted temperature gradients occurs when AT(ºC), MRT(ºC) and OT(ºC)is 0.88, 0.90 and 0.90 respectively. Similarly, with AT(ºC) standard correlation exists between MRT(ºC) and OT(ºC) with values of 0.97 and 0.99 respectively.

b) Wall type W-1b

Wall type W-1b has thickness of 25mm (1"). All the walls of Z-1, Z-2 and Z-3 have similar thickness and construction materials. For wall envelope thermal properties of teak wood is considered. Parametric study is conducted for June and obtained results for different temperature gradients are summarized in descriptive statistics for three zones: Z-1, Z-2 and Z-3 in Appendix D. Maximum AT(ºC) is 7-8.5°C higher than the upper level of comfort. Mean AT(ºC) of Z-1 is highest among all zones and 0.52°C above the upper comfort level whereas Z-2 and Z-3 have mean temperature gradients within upper level of comfort. In all cases standard deviation remain nearly 2.5. AT(ºC) during the study period of EnergyPlus parametric study for wall type W-1b is illustrated in Fig. 6.5.

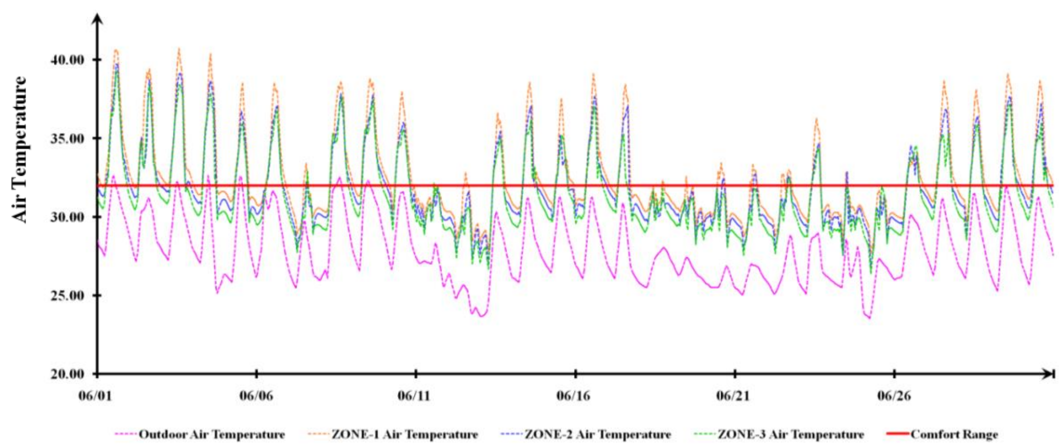


Figure 6.5 Comparison of AT of different zones for wall type W-1b

From the figure it is clear that change in thickness of 6.25mm (¼") has very little impact on the overall indoor thermal environment. Still the indoor AT(ºC) of all the three zones remains above the upper level of comfort. High temperature results during the first week of June. OT(ºC) for all the three zones remain slightly higher compared to AT(ºC) and MRT(ºC) (Appendix D). MRT(ºC) is lowest among all. But in all cases temperature gradients remain within comfort level during early morning and late-night and increases as outdoor temperature started rising.

Correlation of outdoor temperature and other temperature gradients have been analyzed. From the analysis it is found that variation of different temperature with respect to outdoor temperature ranges between 77-79 percent. AT(ºC) has the lowest variation around its mean. Linear regression analysis is presented in Appendix D. There remains a positive correlation among temperature gradients and outdoor temperature. Standard correlation results with outdoor temperature, when AT(ºC), MRT(ºC) and OT(ºC) values are 0.88, 0.89 and 0.89 respectively (Appendix D). AT(ºC) has standard correlation with MRT(ºC) and OT(ºC) when it is 0.98 and 0.99 consecutively.

c) Wall Type: W-1c

Wall type W-1c having 31.25mm (1¼") thickness is considered for EnergyPlus simulation. Parametric study results for wall type W-1c are summarized in descriptive statistics in Appendix D.

Outdoor temperature remains within comfort level except for a little period of time during mid-day of first week, whereas, indoor temperature is higher than comfort level most of the time (Fig. 6.6). All the three zones have a temperature difference ranging between 3.5°C-4.3°C with the outdoor AT(ºC) where Z-1 has a higher temperature compared to Z-2 and Z-3. Z-2 has a temperature difference of average 0.18°C-0.84°C whereas for Z-3 it ranges between 1.1°C-1.38°C. A standard deviation of nearly 2.5 is observed from the table for all the temperature gradients.

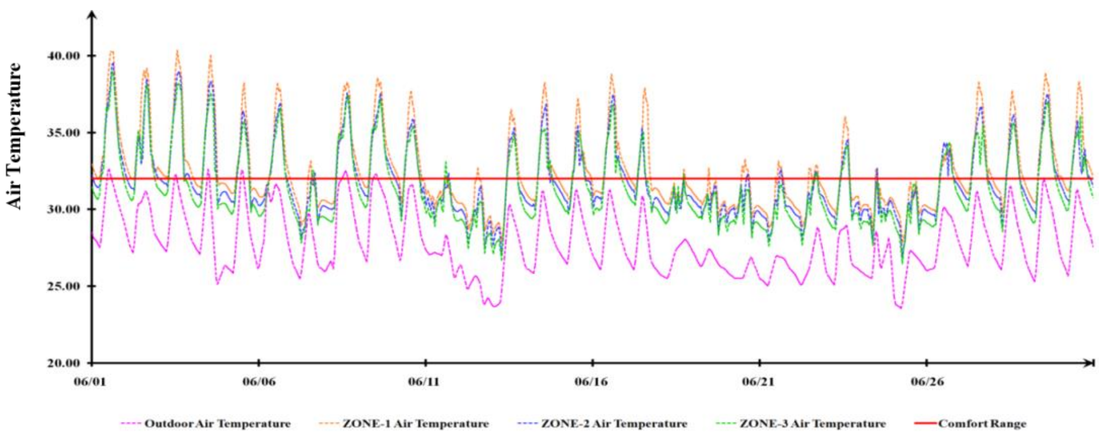


Figure 6.6 Comparison of AT(ºC) of different zones for wall type W-1c

Linear regression analysis (Appendix D) of different temperature gradients with respect to outdoor temperature shows a variation of 77-78.5 percent. Change is higher for MRT(ºC) and OT(ºC) compared to AT(ºC). Best correlation of outdoor and indoor temperature result when indoor AT(ºC) value is 0.88 while other two have same values of 0.89 (Appendix D).

d) Wall Type: W-1d

Thickness of W-1d is 37.5mm (1½"). Simulation results obtained are summarized in descriptive statistics in Appendix D. Temperature gradients of Z-2 and Z-3 has an average difference of 0.5°C. Z-1 AT(ºC) is higher with a temperature difference of 1.5°C with Z-2 and Z-3 whereas MRT (ºC) and OT(ºC) have an average difference of 0.5°C. Fig. 6.7shows the AT(ºC) found during parametric study period.

Linear regression analysis has been studied for wall type W-1d to identify how all the temperature gradients changes with respect to outdoor temperature during the study period (Appendix D). Variability is about 76-77 percent around its mean (Appendix D). OT(ºC) and MRT(ºC) have maximum variation which is nearly 77 percent. For AT(ºC) it is 76 percent. Positive correlation exists among different temperature gradients and outdoor temperature. Best correlation occurs with outdoor temperature when AT(ºC), MRT(ºC) and OT(ºC) have values of 0.87, 0.88 and 0.88 correspondingly. Standard correlation occurs with AT(ºC) and other two when the values of MRT(ºC) and OT(ºC) are 0.97 and 0.99 respectively.

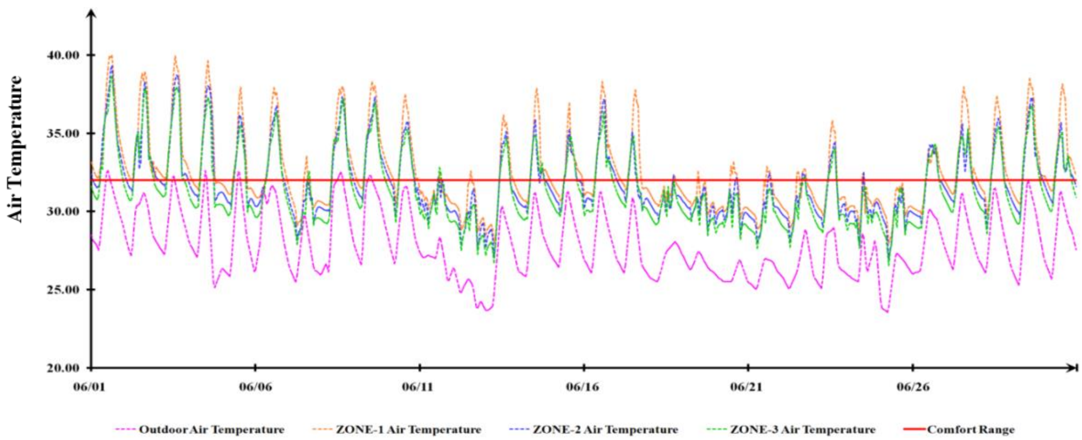


Figure 6.7 Comparison of AT(ºC) of different zones for wall type W-1d

e) Comparative analysis of different wall thickness (wall types W-1):

Existing wall envelope of traditional timber house has thickness of 12.5mm (½"). For wall Construction W-1 four different thicknesses are considered: W-1a (18.75mm/¾"), W-1b (25mm/1"), W-1c (31.25mm/1¼") and W-1d (37.5mm/1½"). For evaluating the performance of all wall types, outdoor temperature has been considered constant with mean AT of 27.83ºC and standard deviation of 2.03.

Changes in thickness impact the overall temperature gradients of the traditional timber house. Fig. 6.8 illustrates the comparison of AT due to changes in thickness of wall envelope for three different zones and comparative analysis of mean, maximum and minimum temperature gradients of the studied four wall types is presented in Table 6.7.

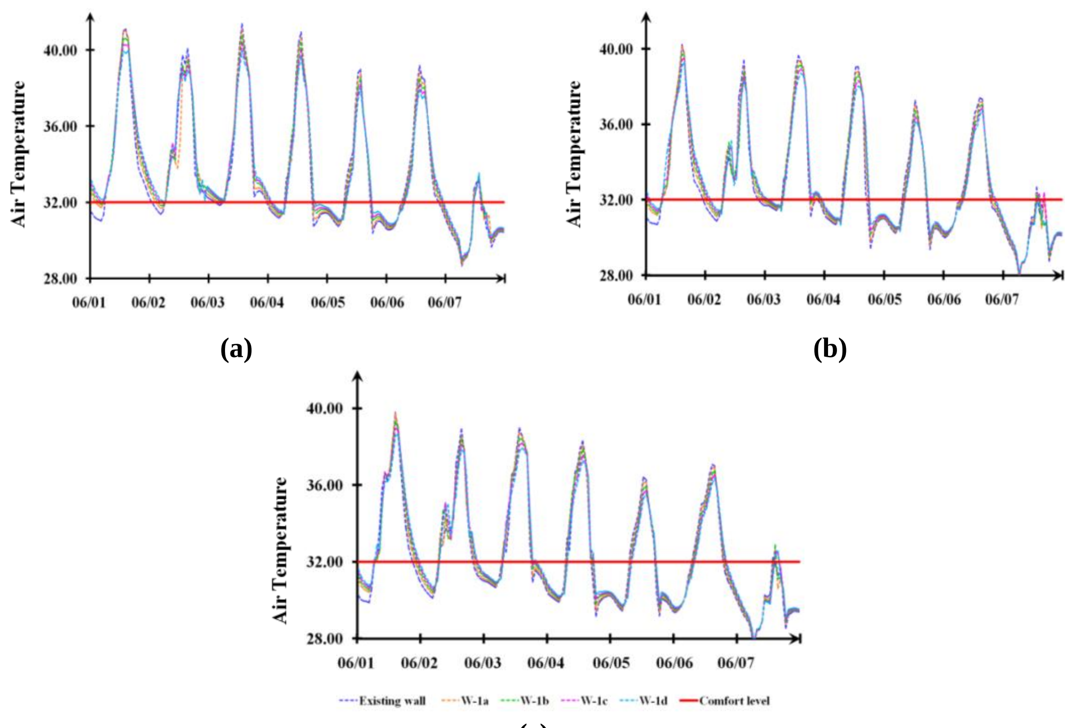
Temperature gradients of all the three zones are much higher (6.0ºC-7.5ºC) than upper level of comfort for the wall type W-1. From the table it is seen that maximum temperature decreases gradually with the increase in wall thickness and decreasing rate is higher at Z-2 and Z-3. An increase in thickness of 25mm (1") results in subsequent decrease in AT(ºC) (max.) nearly 1.5ºC for Z-1 while for Z-2 and Z-3 it is nearly 1ºC. MRT decreases up to 0.8ºC for all three zones. Changes in OT are high at Z-1 and Z-3 (≥1ºC) whereas it is relatively low at Z-2. Minimum AT(ºC) increases with the increase in thickness of wall. Increase in minimum AT compared to existing minimum AT(ºC) ranges from 0.3ºC-0.6ºC for wall type W-1d which is the maximum among all wall types considered.

Comparative analysis of four walls shows that temperature gradients (maximum) resulted for wall type W-1d has lowest value among all. Maximum value of AT(ºC), MRT(ºC) and OT(ºC) of W-1d is 0.89ºC-1.5ºC lower than the existing condition. Mean and minimum value of temperature gradients are nearly same for all the walls which is almost same as existing wall condition. Compared to comfort temperature mean AT(ºC) and OT are marginally higher (0.12ºC-0.5ºC) at Z-1 whereas at Z-2 and Z-3 it remains within comfort level. Overall performance of different wall types shows that W-1d performs better among all wall types considered.

Table 6.7 Mean, maximum and minimum temperature for different wall thickness (W-1).

Temp. (°C)	Wall Type	Maximum (°C) Z-1	Maximum (°C) Z-2	Maximum (°C) Z-3	Mean (°C) Z-1	Mean (°C) Z-2	Mean (°C) Z-3	Minimum (°C) Z-1	Minimum (°C) Z-2	Minimum (°C) Z-3
Air Temp	Existing wall	41.39	40.23	39.78	32.46	31.8	31.36	27.38	26.5	26.26
	W-1a	41.1	40.14	39.72	32.5	31.81	31.38	27.52	26.58	26.29
	W-1b	40.72	39.72	39.3	32.52	31.84	31.41	27.68	26.71	26.38
	W-1c	40.36	39.52	38.98	32.51	31.81	31.41	27.83	26.83	26.46
	W-1d	39.97	39.31	38.63	32.5	31.78	31.38	27.97	26.94	26.54
MRT Temp.	Existing wall	39.73	39.33	39.05	31.73	31.37	31.04	26.97	26.3	26.01
	W-1a	39.1	39.28	39.03	31.75	31.37	31.04	27.12	26.39	26.08
	W-1b	39.32	38.92	38.63	31.77	31.38	31.04	27.32	26.54	26.19
	W-1c	39.12	38.78	38.43	31.75	31.35	31.02	27.44	26.65	26.28
	W-1d	38.84	38.57	38.16	31.74	31.34	30.99	27.51	26.76	26.38
OT Temp.	Existing wall	40.42	39.78	39.42	32.1	31.58	31.2	27.18	26.4	26.14
	W-1a	40.37	39.71	39.38	32.12	31.59	31.21	27.32	26.49	26.19
	W-1b	39.96	39.31	38.96	32.15	31.61	31.22	27.5	26.63	26.29
	W-1c	39.69	39.15	38.67	32.13	31.58	31.21	27.65	26.74	26.37
	W-1d	39.4	38.94	38.39	32.12	31.56	31.19	27.75	26.85	26.46

*Temperature gradients above comfort temperature is highlighted with color



(c)

Figure 6.8 Comparison of changes in AT(ºC) for different wall types of W-1: (a) Zone-1, (b) Zone-2 and (c) Zone-3

Table 6.8 Standard deviation of different wall thickness (W-1).

Wall Type	Outdoor Temp.	Air Temp. Z-1	Air Temp. Z-2	Air Temp. Z-3	MRT Temp. Z-1	MRT Temp. Z-2	MRT Temp. Z-3	OT Temp. Z-1	OT Temp. Z-2	OT Temp. Z-3
Existing wall	2.03	2.77	2.52	2.54	2.61	2.66	2.76	2.67	2.57	2.63
W-1a	2.03	2.71	2.45	2.49	2.55	2.6	2.7	2.61	2.51	2.58
W-1b	2.03	2.65	2.41	2.44	2.49	2.54	2.64	2.55	2.46	2.53
W-1c	2.03	2.57	2.32	2.39	2.41	2.46	2.57	2.47	2.37	2.47
W-1d	2.03	2.47	2.22	2.3	2.33	2.38	2.48	2.38	2.28	2.38

*Color gradient shows comparative changes in standard deviation

Table 6.8 shows that among all the walls W-1d, which is 37.5mm (1½") thick, has the lowest standard deviation. Therefore, temperature gradients for this wall type fluctuates less during the simulation period. Standard deviation of existing wall Construction has the highest deviation around its' mean. Z-2 shows relatively low standard deviation value compared to other two zones.

6.4.2 Wall Constructions having Glued Layers: W-2

For wall Construction W-2, maximum wall thickness of 37.5mm (1½") is considered. W-2 has six wall types: W-2a, W-2b, W-2c, W-2d, W-2e and W-2f. W-2a and W-2b have glued wooden panels whereas W-2c, W-2d, W-2e and W-2f have glued wooden panels having polythene sheet in between them. Cross-sectional details are illustrated in Fig.6.9. Considered properties for wall envelope are presented in Table 6.9.

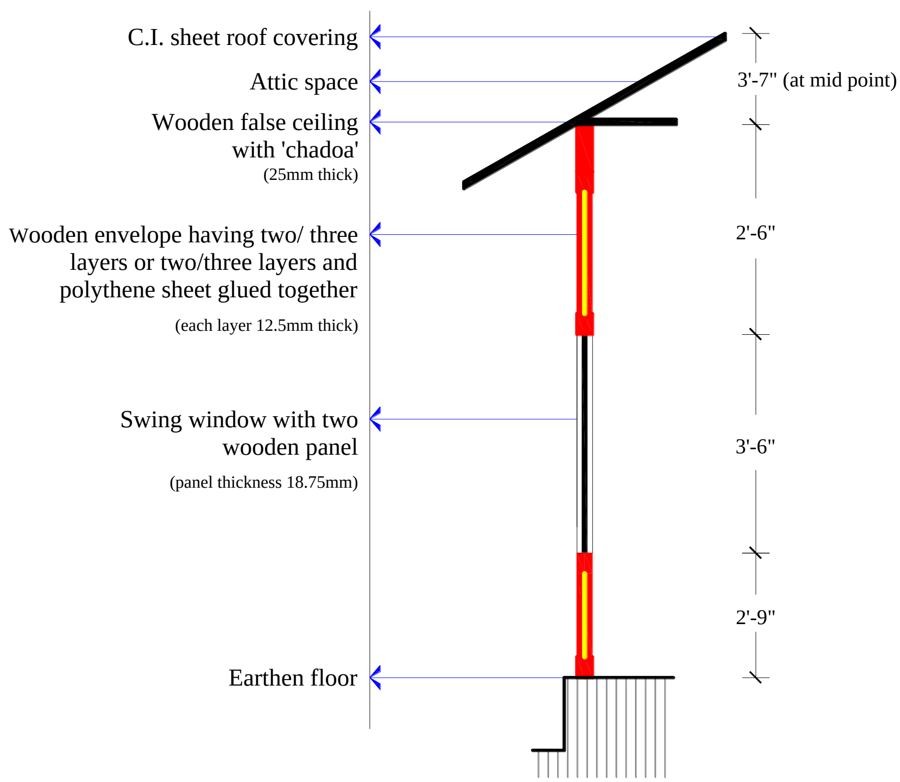


Figure 6.9 Cross sectional view of wall type W-2

Table 6.9 Thermal properties of wall envelope considered for wall type W-2.

Envelope Name	Material	Thickness	Conductivity	Density	Specific-Heat
Wall	Teak	12.5mm	1.28	710	1880
	Polythene	0.5mm	0.96	660	1880
Roof covering	C.I. sheet	0.5mm	65	7300	235
Ceiling	Raintree	25mm	0.74	480	1880
Chadoa	Cotton fabric	0.01	0.04	225	1380.72
Floor	Earthen	-	1.4	1460	879
Window	Sal	18.75mm	0.96	660	1880
Door	Sal	25mm	0.96	660	1880

a) Wall type W-2a

Wall type W-2a considered for parametric study is composed of two 12.5mm thick wooden panels having a total thickness of 25mm (1"). All zone walls have the same wall Construction and thermal properties of teak for wall envelope are considered. Study was conducted for the whole month of June. Simulation result obtained for wall type W-2a is the same as the obtained result obtained for wall type W-1b (single wall panel having thickness of 25mm (1")).

b) Wall Type W-2b

Wall type W-2b has three 12.5mm (½") panels glued together. Thus, ultimate thickness of the wall is 37.5mm (1½"). Simulation result obtained for wall type W-2a is the same as the result of wall type W-1d (single wall panel having thickness of 37.5mm (1½")).

c) Wall Type W-2c

Wall type W-2c is composed of two 12.5mm (½") panels having low density one polythene layer in between two layers. Parametric study result is obtained for the month of June (Appendix D). Variation of temperature gradients during study period is presented in Fig. 6.10.

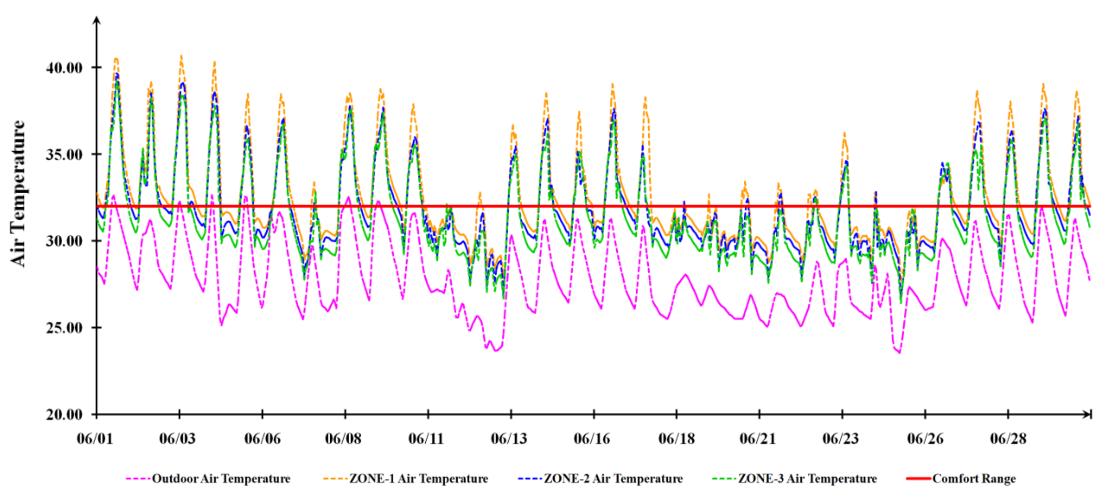


Figure 6.10 Comparison of AT(ºC) of different zones for wall type W-2c

From the analysis it is observed that mean temperature gradients are within upper level of comfort except for Z-1. Z-1 AT is nearly 0.5ºC higher than comfort level. Both AT(ºC) and MRT(ºC)are high for Z-1. Temperature difference with Z-2 and Z-3 is nearly 0.5ºC-1.5ºC. Standard deviation for all temperature gradients ranges nearly 2.5.

From Fig. 6.10 it is observed that AT(ºC) changes in the similar trend with outdoor AT(ºC) and Z-1 has higher temperature compared to other two. Temperature gradient remains higher during first week of the study period for all temperature gradients. Comparative changes of temperature gradients during first seven days of study period is shown in Appendix D. Changes in AT(ºC) is higher whereas it is lower for OT(ºC).

Linear regression analysis shows that all of temperature gradients are positively correlated and variation of MRT(ºC) and OT(ºC) is higher around its mean (Appendix D). Correlation matrix among different temperature indices is presented in Appendix D. Best fitted correlation obtained with AT(ºC) and other two when MRT(ºC) and OT(ºC) are 0.98 and 0.99 respectively.

d) Wall Type W-2d

Wall W-2d has three 12.5mm (½") panels having two low density polythene layers inserted between two panels. From descriptive statistics of simulation results it is seen that though Z-1 has slightly higher mean AT than comfort range but mean temperature gradients of Z-2 and Z-3 are within comfort limit (Appendix D). MRT is nearly similar for Z-1 and Z-2 whereas it is lower for Z-3.

Fig. 6.11 shows that AT(ºC) variation of three zones during study period. From the figure it is observed that AT(ºC) remains higher between late-morning to night. Z-1 has higher temperature than Z-2 and Z-3. OT(ºC) is lower compared to other two for all the zones (Appendix D).

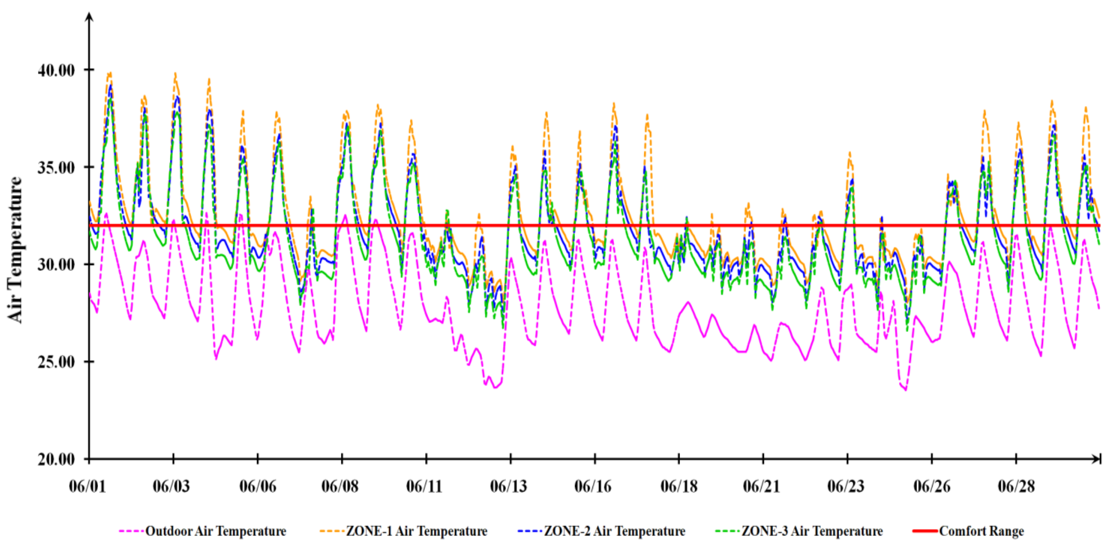


Figure 6.11 Comparison of AT(ºC) of different zones for wall type W-2d

Correlation between AT(ºC), MRT(ºC) and OT(ºC) with outdoor AT is presented in Appendix D. Linear regression analysis shows positive correlation among different temperature gradients and 75-77 percent of variability of different temperature gradients around its mean (Appendix D). Best fitted correlation between outdoor and other temperature gradients is obtained when the values of AT(ºC), MRT(ºC) and OT(ºC) is 0.87, 0.87 and 0.99 respectively.

e) Wall Type W-2e

Wall type W-2e has two 12.5mm (½") panels having high density polythene layer in between two wooden panels. Fig. 6.12 shows the AT(ºC) of Z-1, Z-2 and Z-3 during the study period.

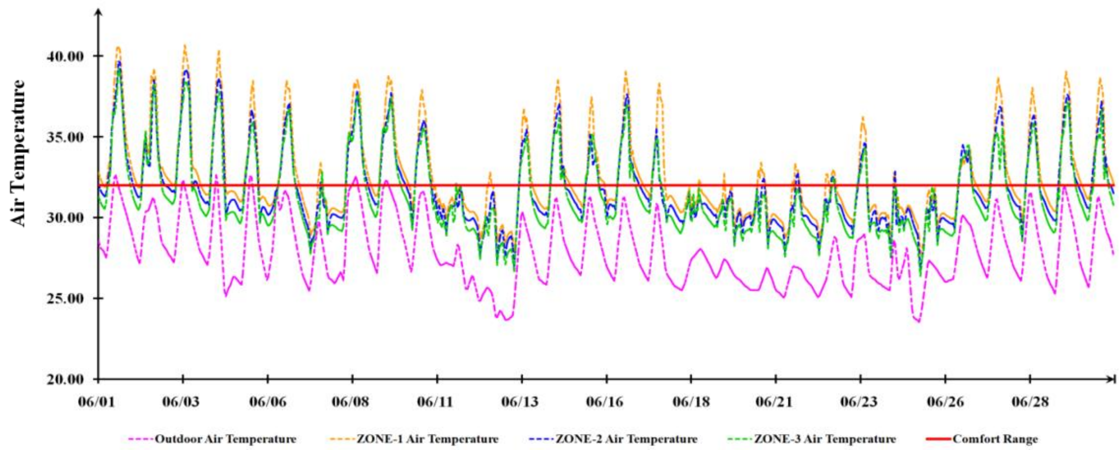


Figure 6.12 Comparison of AT(ºC) of different zones for wall type W-2e.

Mean AT(ºC) is nearly 0.5ºC higher than upper level of comfort for Z-1 whereas it is within comfort level for rest of the zones. But all the temperature gradients remain higher than comfort range for most of the period of a 24hrs cycle (Appendix D). Maximum AT is found for Z-1 which is 40.68ºC and it occurs between 15:00pm-16:00pm. Minimum AT for Z-1 is found to be 27.7ºC which occurs during early morning. Z-3 has lower MRT(ºC) value which is 38.57ºC. Z-1 has the highest MRT(ºC) among all zones. It is 0.7ºC higher than that of Z-3. Standard deviation for all the temperature gradients remains around 2.5.

Linear regression analysis shows positive correlation having 77-79 percent of variability of different temperature gradients around its mean. Best relationship has been found between air and MRT(ºC) with a value of 0.88 which is the lowest value in the correlation matrix (Table 6.23). For OT(ºC) and MRT(ºC) best fitted relationship is obtained when OT(ºC) values are 0.99. Correlation matrix among different temperature indices for wall type W-2e is presented in Appendix D.

f) Wall Type W-2f

Wall type W-2f is composed of three 12.5mm (½") panels having two high density polythene layers inserted between two wooden panels. Obtained parametric study results are presented in Appendix D. From the descriptive statistics of obtained result it is observed that mean temperature gradients remain within comfort for all the three zones. Temperature difference between different zones remains almost between 0.5ºC-1ºC. Standard deviation remains marginally lower than 2.5. Fig. 6.13 shows that AT(ºC) of Z-1, Z-2 and Z-3 during study period. From figure it is found that AT(ºC) remains higher compared to other two gradients at all zones. Comparison of temperature gradient for wall type W-2f during first week of study period is presented in Appendix D.

Correlation of outdoor temperature and other temperature gradients have been analyzed and presented in Appendix D. From the analysis it is found that variation of different temperatures with respect to outdoor temperature ranges between 75-77 percent. AT(ºC) has the lowest variation around its mean. Correlation matrix among outdoor and other temperature gradients for the wall type W-2f shows that there remains a positive correlation among temperature gradients and outdoor temperature (Appendix D). Standard correlation results with outdoor temperature when AT(ºC), MRT(ºC) and OT(ºC) values are 0.87, 0.87 and 0.88 respectively. AT(ºC) has standard correlation with MRT and OT when these are 0.97 and 0.99 consecutively.

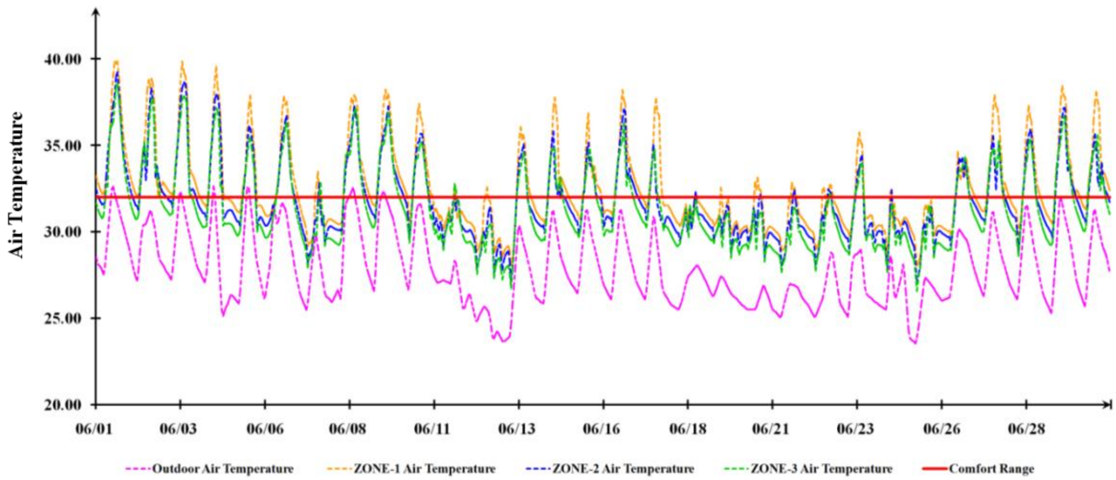


Figure 6.13 Comparison of AT(ºC) of different zones for wall type W-2f

g) Comparative analysis of different W-2 wall types:

For wall Construction W-2, 12.5mm wooden panels are considered. Wooden panels are glued together having maximum wall thickness of 37.5mm (1½"). Six different wall types are considered: W-2a, W-2b, W-2c, W-2d, W-2e and W-2f. W-2a and W-2b have glued wooden panels having total thickness of 25mm and 37.5mm respectively. W-2c and W-2e are composed of 12.5mm two wooden panels with low/high density polythene sheet in between them whereas W-2d and W-2f have three 12.5mm panels having low/high density polythene sheet inserted in between two panels. Therefore, thickness of W-2a, W-2c and W-2e is 25mm while thickness of W-2b, W-2d and W-2f are 37.5mm. Outdoor temperature is constant with mean AT of 27.83ºC and standard deviation of 2.03.

Fig. 6.14 illustrates the comparison of AT for different wall types of W-2. From the figure it is observed that maximum temperature gradient for W-2 is always lower than temperature gradients for existing wall condition. Among all wall envelopes W-2b, W-2d and W-2f have almost similar impact on indoor thermal environment and resulted in low AT (maximum). Z-1 and Z-2/3 AT(ºC) (maximum) is almost 1.15ºC-1.5ºC and 1ºC lower than the existing temperature respectively (Table 6.10). For all wall types, mean AT(ºC) is slightly higher than existing condition which is almost negligible. However, minimum AT(ºC) is 0.3ºC-0.5ºC higher than minimum AT(ºC) of existing indoor situation. For all wall types average and minimum value of MRT(ºC) are almost same as existing situation. But highest decrease in maximum MRT(ºC) resulted for wall types W-2b, W-2d and W-2f which are 0.8ºC-1.0ºC lower than existing maximum MRT(ºC) value.

Table 6.11 shows that among all the walls W-2b, W-2d and W-2f have nearly same standard deviation. Compared to these three walls W-2d (three 12.5mm (½") panels having two low density polythene layers inserted between them) has comparatively lower standard deviation which means that temperature gradients for this wall fluctuates less during the simulation period. Standard deviation of existing wall Construction has the highest deviation around its' mean. AT(ºC) and OT(ºC) of Z-2 have lower standard deviation values whereas MRT(ºC) of Z-1 has a lower standard deviation compared to other two values.

Table 6.10 Comparative performance analysis of different glued wall types (W-2).

Temp. (ºC)	Wall Type	Maximum (ºC) Z-1	Maximum (ºC) Z-2	Maximum (ºC) Z-3	Mean (ºC) Z-1	Mean (ºC) Z-2	Mean (ºC) Z-3	Minimum (ºC) Z-1	Minimum (ºC) Z-2	Minimum (ºC) Z-3
Air Temp	Existing wall	41.39	40.23	39.78	32.46	31.8	31.36	27.38	26.5	26.26
	W-2a	40.72	39.72	39.3	32.52	31.84	31.41	27.68	26.71	26.38
	W-2b	39.97	39.31	38.63	32.5	31.78	31.38	27.97	26.94	26.54
	W-2c	40.67	39.65	39.21	32.52	31.82	31.41	27.7	26.73	26.39
	W-2d	39.85	39.2	38.52	32.49	31.78	31.38	28.04	26.99	26.58
	W-2e	40.68	39.67	39.23	32.52	31.82	31.41	27.7	26.73	26.39
	W-2f	39.89	39.24	38.55	32.5	31.78	31.38	28.02	26.98	26.57
MRT Temp.	Existing wall	39.73	39.33	39.05	31.73	31.37	31.04	26.97	26.3	26.01
	W-2a	39.32	38.92	38.63	31.77	31.38	31.04	27.32	26.54	26.19
	W-2b	38.84	38.57	38.16	31.74	31.34	30.99	27.51	26.76	26.38
	W-2c	39.24	38.89	38.55	31.76	31.37	31.04	27.35	26.56	26.21
	W-2d	38.72	38.47	38.04	31.75	31.34	30.98	27.56	26.81	26.42
	W-2e	39.26	38.9	38.57	31.76	30.7	31.04	27.34	26.56	26.21
	W-2f	38.76	38.5	38.07	31.74	31.34	30.98	27.54	26.8	26.41
OT Temp.	Existing wall	40.42	39.78	39.42	32.1	31.58	31.2	27.18	26.4	26.14
	W-2a	39.96	39.31	38.96	32.15	31.61	31.22	27.5	26.63	26.29
	W-2b	39.4	38.94	38.39	32.12	31.56	31.19	27.75	26.85	26.46
	W-2c	39.88	39.25	38.88	32.14	31.59	31.22	27.53	26.65	26.3
	W-2d	39.28	38.84	38.28	32.12	31.56	31.18	27.8	26.9	26.5
	W-2e	39.9	39.27	38.9	32.14	31.59	31.22	27.52	26.64	26.3
	W-2f	38.31	38.87	38.31	31.18	31.56	31.18	26.49	26.89	26.49

*Temperature gradients above comfort temperature is highlighted with color

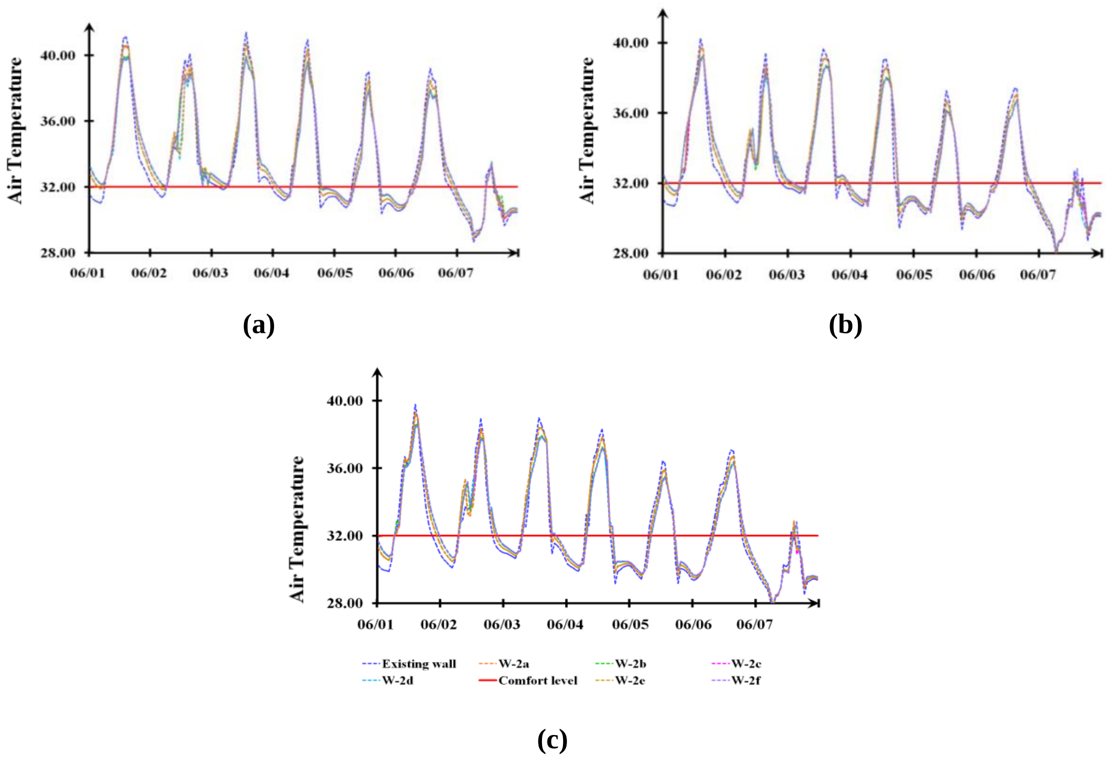


Figure 6.14 Comparison of changes in AT(ºC) for different wall types of W-2:

(a) Zone-1, (b) Zone-2 and (c) Zone-3

Table 6.11 Standard deviation of different glued wall types (W-2).

Wall Type	Outdoor Temp.	Air Temp. Z-1	Air Temp. Z-2	Air Temp. Z-3	MRT Temp. Z-1	MRT Temp. Z-2	MRT Temp. Z-3	OT Temp. Z-1	OT Temp. Z-2	OT Temp. Z-3
Existing wall	2.03	2.77	2.52	2.54	2.61	2.66	2.76	2.67	2.57	2.63
W-2a	2.03	2.65	2.41	2.44	2.49	2.54	2.64	2.55	2.46	2.53
W-2b	2.03	2.47	2.22	2.3	2.33	2.38	2.48	2.38	2.28	2.38
W-2c	2.03	2.62	2.38	2.43	2.47	2.51	2.62	2.53	2.43	2.52
W-2d	2.03	2.42	2.19	2.27	2.29	2.35	2.45	2.34	2.25	2.35
W-2e	2.03	2.62	2.38	2.44	2.47	2.52	2.63	2.53	2.43	2.52
W-2f	2.03	2.44	2.2	2.28	2.3	2.36	2.45	2.36	2.26	2.36

*Color gradient shows comparative changes in standard deviation

6.4.3 Wall Constructions having Cavity Air Gap: W-3

Wall Construction W-3 is composed of two timber wall panels having cavity air gap in between them. Thickness of wall ranges between 37.5mm-50mm (1.5"-2"). Annotated cross-section of W-3 is presented in Fig. 6.15. Thermal properties of envelope materials considered for simulations are presented in Table 6.12.

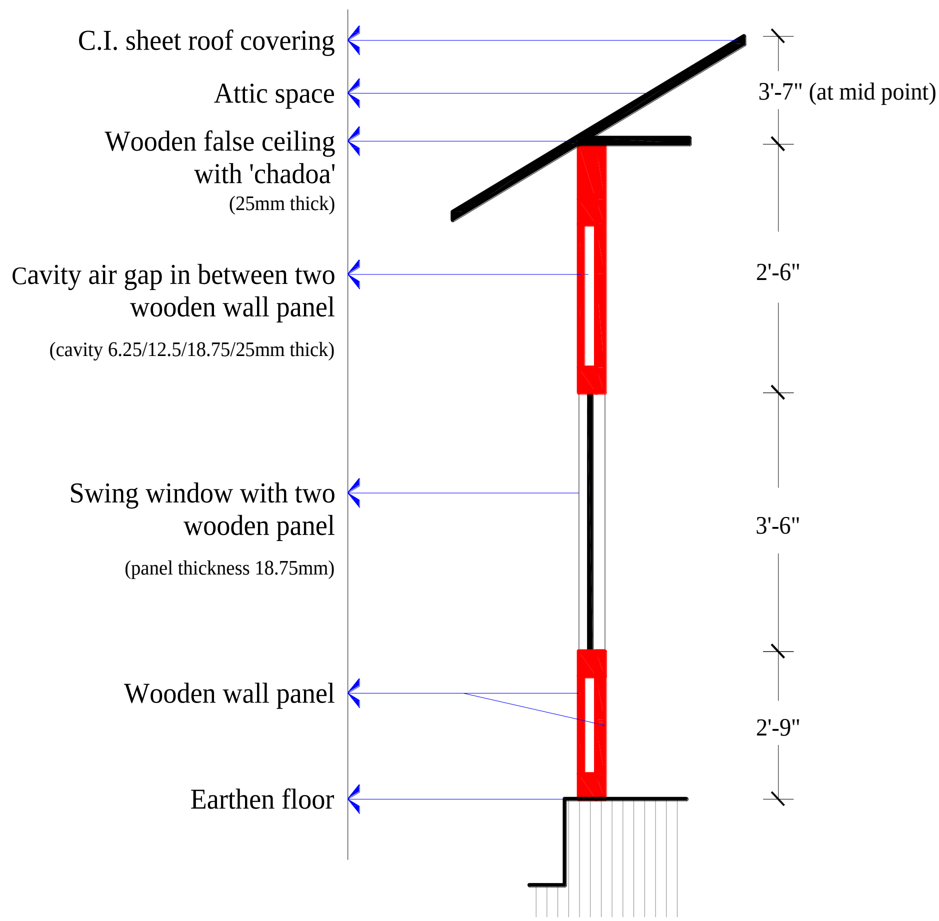


Figure 6.15 Cross sectional view of wall type W-3

Table 6.12 Thermal properties of envelopes considered for wall type W-3.

Envelope	Material	Thickness (mm)	Conductivity (W/m-K)	Density (kg/m^3)	Specific-Heat (J/kg-K)	Resistance (m^2-K/ W)
Wall	Teak	18.75 /25 /31.25 /37.5	1.28	710	1880	-
	Cavity air gap	6.25 /12.5 /18.75 /25	-	-	-	0.14-0.17
Roof	C.I. sheet	0.5	65	7300	235	-
Ceiling	Raintree	25	0.74	480	1880	-
Chadoa	Cotton fabric	0.01	0.04	225	1380.72	-
Floor	Earthen	-	1.4	1460	879	-
Window	Sal	18.75	0.96	660	1880	-
Door	Sal	25	0.96	660	1880	-

a) Wall type W-3a

Wall type W-3a has one 12.5mm (½") and one 18.75mm (¾") wooden panels leaving a cavity air gap of 6.25mm (¼") in between them. Therefore, total thickness of the wall is 37.5mm (1½"). Results obtained from the EnergyPlus simulation for wall type W-3a are analyzed and descriptive statistics of wall type W-3a shows that mean temperature gradients remain within upper level of comfort except in Z-1 which is 0.7ºC higher than the upper value of comfort (Appendix D). AT(ºC) is high compared to other temperature gradients. Z-1 has highest (39.47ºC) and Z-3 has lowest (37.37ºC) AT(ºC) value.

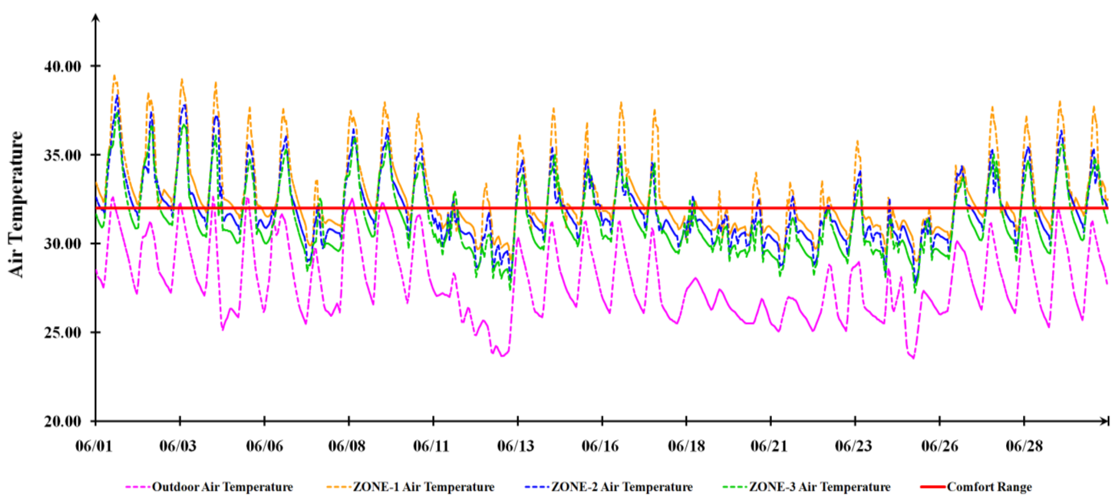


Figure 6.16 Comparison of AT(ºC) of different zones for wall type W-3a.

Temperature difference between maximum and minimum AT(ºC) within a zone is nearly 10ºC. Z-1 has the maximum and Z-3 has the minimum MRT(ºC) values. MRT is nearly 0.3ºC-1.5ºC lower than respective zone AT(ºC). In all cases standard deviation ranges between 1.8-2.1. Fig. 6.16 presents AT(ºC) temperature gradient during study period. During first few days of study period all the temperature gradients remain high. Temperature gradient for first week of the study period for wall type W-3a is presented in Appendix D. From the figure it is observed that temperature gradients of Z-1 remain above the upper range of comfort. However, Z-2 and Z-3 show lower temperature values compared to Z-1 but still temperature remains above the comfort level most of the time.

Indoor temperature fluctuates with the outdoor temperature. Linear regression analysis of resulted temperature gradients regarding outdoor temperature is illustrated in Appendix D. This analysis illustrates how all the temperature gradients change with respect to outdoor temperature during the study period. Variability of about 70-73 percent is found for temperature gradients whereas OT(ºC) and MRT(ºC) have maximum variation around its mean. A variation of 70 percent of AT(ºC) is found during study period.

Correlation matrix among temperature gradients and outdoor temperature is presented in Table 6.30. Positive correlation remains among different temperature gradients. Best fitted correlation among outdoor temperature and resulted temperature gradients occurs when AT(ºC), MRT(ºC) and OT(ºC) are 0.84, 0.85 and 0.85 respectively (Appendix D). Best fitted correlation of MRT(ºC) and OT(ºC) with AT(ºC) exists when the values of MRT(ºC) and OT(ºC) are 0.97 and 0.99 respectively.

b) Wall type W-3b

Wall type W-3b has two 12.5mm (½") wooden panels with 12.5mm (½") cavity air gap in between them. Total thickness of the wall is 37.5mm (1½"). Results obtained from the parametric study are analyzed and descriptive statistics of simulation result shows that Z-1 air and OTs are slightly higher than the upper level of comfort though other zones have temperature gradients within comfort level (Appendix D). Temperature difference ranges nearly 0.4ºC-1.5ºC between different zones whereas Z-1 has high and Z-3 has low temperature gradients. Standard deviation remains between 2.5. AT(ºC) remains higher compared to other two temperature gradients for all zones. During the first few days temperature gradients remain higher compared to rest of the days. Z-1 has highest temperature compared to other two zones and this remains above the upper level of comfort. Fig. 6.17 illustrates AT(ºC) of three zones and Appendix D shows different temperature gradients obtained from the parametric study for wall type W-3b.

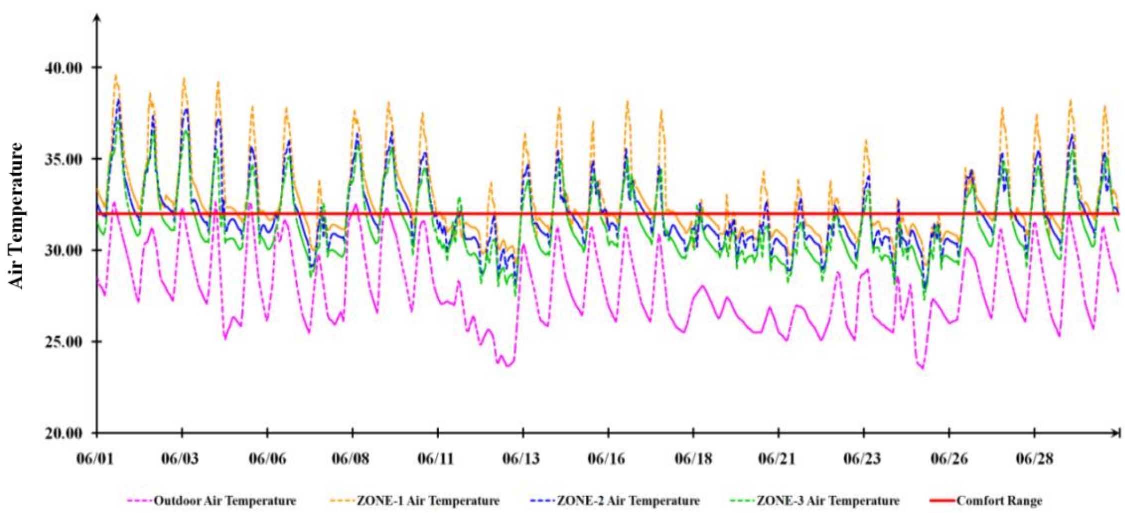


Figure 6.17 Comparison of AT(ºC) of different zones for wall type W-3b

Linear regression analysis of resulted temperature gradients with respect to outdoor temperature during study period is illustrated in Appendix D. Variability of about 70-73.5 percent is noticed for temperature gradients. OT(ºC) and MRT(ºC) have maximum variation around its mean. A variation of nearly 74 percent is found for MRT(ºC) and OT(ºC) (Appendix D).

Positive correlation remains among different temperature gradients. Best fitted correlation occurs among outdoor temperature and resulted temperature gradients when AT(ºC), MRT(ºC) and OT(ºC) are 0.83, 0.86 and 0.85 respectively whereas best fitted correlation of MRT(ºC)andOT(ºC) with AT(ºC) exists when the values of MRT(ºC) and OT(ºC) are 0.96 and 0.99 respectively.

c) Wall type W-3c

Wall type W-3c has outer 12.5mm (½") and inner 18.75mm (¾") wooden walls having 12.5mm (½") cavity air gap in between them. Total thickness of the wall is 43.75mm (1¾"). Obtained result from the parametric study is summarized in descriptive statistics format (Appendix D).

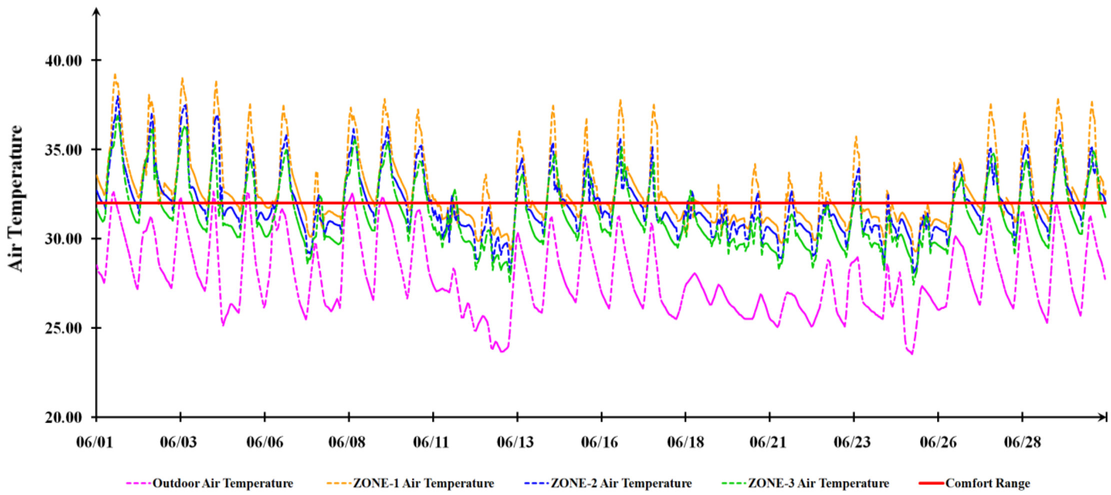


Figure 6.18 Comparison of AT(ºC) of different zones for wall type W-3c

All zones have mean temperature gradients remaining within comfort level except Z-1. Mean air and OT(ºC) of Z-1 are slightly higher than the upper level of comfort which is 32.73ºC and 32.37ºC respectively. Z-1 has high and Z-3 has low temperature gradients. With respect to Z-1, mean AT difference of Z-2 and Z-3 ranges between nearly 1.75ºC-2.5ºC whereas for MRT(ºC) it ranges between 0.5ºC-1ºC. Throughout the study period it is observed that temperature gradients during first few days remain higher than rest of the days. Though maximum outdoor AT(ºC) is marginally higher than the upper level of comfort but maximum temperature gradients remain far above the upper level of comfort for all the three zones. Z-1 has highest and Z-3 has lowest temperature gradients among all. Fig. 6.18 illustrates AT(ºC) of three zones and Appendix D shows different temperature gradients obtained from the parametric study for wall type W-3c.

Linear regression analysis of resulted temperature gradients with respect to outdoor temperature during study period is illustrated in Appendix D. Variability of about 68-71 percent is noticed for temperature gradients. OT(ºC) and MRT(ºC) have maximum variation around its mean. A variation of nearly 71 percent is found for MRT(ºC) and OT(ºC).

Correlation matrix among temperatures resulted for W-3c shows positive correlation with each other (Appendix D). Best fitted correlation occurs among outdoor temperature and resulted temperature gradients when AT(ºC), MRT(ºC) and OT(ºC) are 0.82, 0.84 and 0.84 respectively whereas best fitted correlation of MRT(ºC) and OT(ºC) with AT(ºC) exists when the values of MRT(ºC) and OT(ºC) are 0.95 and 0.99 respectively.

d) Wall type W-3d

W-3d wall type has two 12.5mm (½") wooden walls leaving 18.75mm (¾") cavity air gap in between them. Total thickness of the wall is 43.75mm (1¾"). Descriptive statistics of obtained parametric study result shows that wall type W-3b and W-3d have same effect on indoor thermal environment.

e) Wall type W-3e

The outer wall of Wall type W-3e is 12.5mm (½") and inner wall is 25mm (1") in thickness. Cavity air gap in between walls is 12.5mm (½") and total thickness of W-3e is 50mm (2"). Parametric study result is summarized in descriptive statistics format in Appendix D.

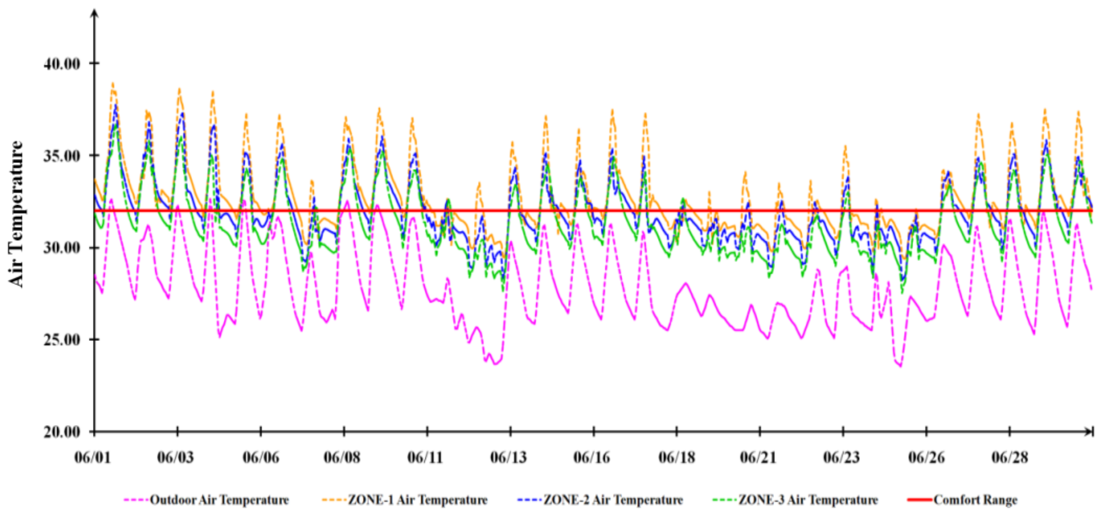


Figure 6.19 Comparison of AT(ºC) of different zones for wall type W-3e

Z-1 mean temperature gradients are 0.4ºC-0.7ºC higher than the upper level of comfort. Other zones have temperature gradients within comfort level. Difference between mean outdoor and zone AT(ºC) ranges nearly 3.5ºC-4.89ºC. Z-1 has high and Z-3 has low temperature gradients. Mean value of MRT(ºC) of all the zones remain within comfort level. But parametric study result for wall type W-3e shows that during first few days when outdoor temperature remains higher (maximum temperature > 32ºC) Z-1 and Z-2 temperature gradients always remains above upper limit of comfort. Z-3 temperature remains below upper comfort temperature during late to early morning. Fig. 6.19 illustrates AT(ºC) of three zones and Appendix D shows different temperature gradients obtained from the parametric study for wall type W-3e.

Linear regression analysis of resulted temperature gradients with respect to outdoor temperature shows variability of about 66-69 percent. OT(ºC) and MRT(ºC) have maximum variation around its mean which is 69 percent. Variation of AT(ºC) is 66 percent around its mean. Linear regression analysis for wall type W-3e is presented in Appendix D.

Positive correlation remains among different temperature gradients. Best fitted correlation occurs among outdoor temperature and resulted temperature gradients when AT(ºC), MRT(ºC) and OT(ºC) are 0.81, 0.83 and 0.83 respectively. MRT(ºC) and OT(ºC) have best fitted correlation with AT(ºC) when the values of these temperatures are 0.94 and 0.99 respectively.

f) Wall type W-3f

Wall W-3f is 50mm (2") thick. Outer and inner walls have thicknesses of 12.5mm (½") and 18.75mm (¾") respectively having 18.75mm (¾") cavity air gap in between them. Analysis of simulation result shows that wall types W-3c and W-3f have similar indoor thermal environment.

g) Wall type W-3g

Wall type W-3g is composed of two 12.5mm (½") wooden walls leaving 25mm (1") cavity air gap in between them. Total thickness of the wall is 50mm (2"). Descriptive statistics of obtained results from the parametric study is illustrated in Appendix D. During parametric study period it is noticed that mean temperature gradients of Z-2 and Z-3 remain within comfort level whereas Z-1 mean temperature gradients are 0.4ºC-0.8ºC higher than upper level of comfort. Difference between mean outdoor and zone AT ranges nearly 3ºC-5ºC. Average value of MRT of all zones remains within comfort level. Z-3 has the lowest MRT which is 30.88ºC. But when maximum outdoor AT remains high, Z-1 temperature gradients remain above comfort temperature. Fig. 6.20 illustrates AT of three zones and Appendix D shows resulted temperature gradients.

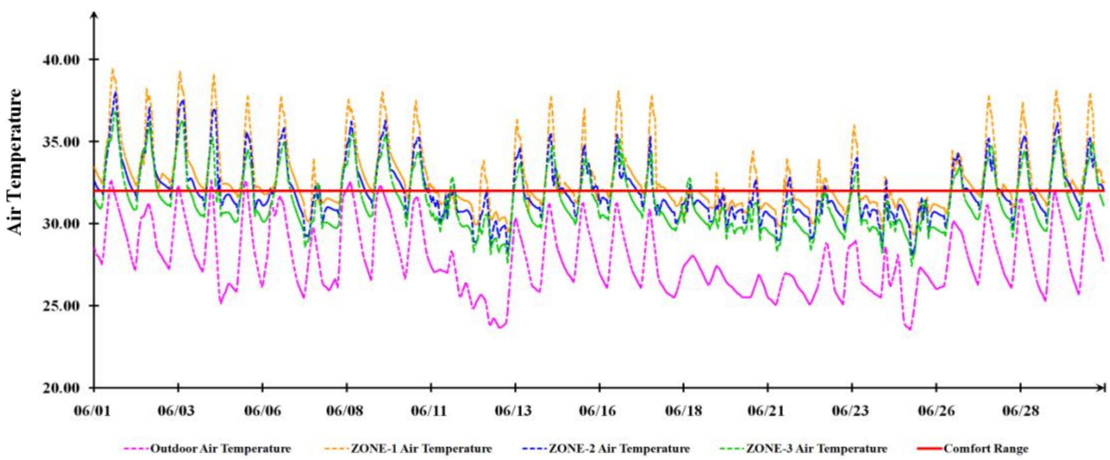


Figure 6.20 Comparison of AT(ºC) of different zones for wall type W-3g

Linear regression analysis of resulted temperature gradients with respect to outdoor temperature shows variability of about 68-72 percent. MRT(ºC) has maximum variation around its mean which is 72 percent. Variation of AT(ºC) and OT(ºC) is 66 and 71.5 percent respectively. Appendix D illustrates the linear regression analysis for wall type W-3g. Positive correlation remains among different temperature gradients. Best fitted correlation occurs among outdoor temperature and resulted temperature gradients when AT(ºC), MRT(ºC) and OT(ºC) are 0.82, 0.85 and 0.85 respectively. MRT(ºC) and OT(ºC) have best fitted correlation with AT(ºC) when the values of these temperatures are 0.95 and 0.99 respectively.

h) Comparative analysis of cavity walls (W-3):

Wall Construction W-3 is composed of two wooden walls leaving a cavity air gap in between them. The outer wall is always 12.5mm (½") in thickness whereas for inner wall three different thicknesses 12.5mm (½"), 18.75mm (¾") and 25mm (1") is considered. Cavity air gap varies between 6.25mm-25mm (¼"-1") in thickness. Total wall thickness ranges between 37.5mm-50mm (1½"-2"). Six different wall types are considered: W-3a, W-3b, W-3c, W-3d, W-3e, W-3f and W-3g. Walls W-3a, W-3c and W-3f have 18.75mm (¾") thick inner wall with cavity thicknesses 6.25mm (½"), 12.5mm (½") and 18.75mm (¾") respectively. Thickness of inner wall of W-3b, W-3d and W-3g is 12.5mm (½") and cavity air gaps are 12.5mm (½"), 18.75mm (¾") and 25mm (1") respectively. Wall type W-3e has cavity thickness of 12.5mm (½") with inner wall 25mm (1") thick. Outdoor temperature is constant with maximum, mean and minimum AT of 32.63ºC, 27.83ºC and 23.54ºC respectively with standard deviation of 2.03. Table 6.13 shows maximum, mean and minimum temperature values resulted for cavity walls considered for parametric study.

Table 6.13 Comparative performance analysis of cavity walls (W-3)

Temp. (°C)	Wall Type	Maximum (°C)			Mean (°C)			Minimum (°C)		
		Z-1	Z-2	Z-3	Z-1	Z-2	Z-3	Z-1	Z-2	Z-3
Air Temp	Existing wall	41.39	40.23	39.78	32.46	31.8	31.36	27.38	26.5	26.26
	W-3a	39.47	38.36	37.37	32.69	31.91	31.38	29.01	27.83	27.22
	W-3b	40.72	39.72	39.3	32.52	31.84	31.41	27.68	26.71	26.38
	W-3c	39.22	38	36.9	32.73	31.95	31.35	29.28	28.08	27.42
	W-3d	40.72	39.72	39.3	32.52	31.84	31.41	27.68	26.71	26.38
	W-3e	38.91	37.75	36.68	32.72	31.96	31.34	29.39	28.22	27.53
	W-3f	39.22	38	36.9	32.73	31.95	31.35	29.28	28.08	27.42
	W-3g	39.42	38.02	36.81	32.77	31.97	31.34	29.34	28.09	27.41
MRT Temp.	Existing wall	39.73	39.33	39.05	31.73	31.37	31.04	26.97	26.3	26.01
	W-3a	38.08	37.78	37.03	31.96	31.47	30.94	28.47	27.61	27.04
	W-3b	39.32	38.92	38.63	31.77	31.38	31.04	27.32	26.54	26.19
	W-3c	37.77	37.45	36.59	32.01	31.49	30.9	28.72	27.87	27.23
	W-3d	39.32	38.92	38.63	31.77	31.38	31.04	27.32	26.54	26.19
	W-3e	37.51	37.21	36.35	32.02	31.5	30.89	28.84	28.01	27.35
	W-3f	37.77	37.45	36.59	32.01	31.49	30.9	28.72	27.87	27.23
	W-3g	37.83	37.5	36.55	32.06	31.51	30.88	28.78	27.86	27.21
OT Temp.	Existing wall	40.42	39.78	39.42	32.1	31.58	31.2	27.18	26.4	26.14
	W-3a	38.57	38.07	37.2	32.33	31.69	31.16	28.74	27.72	27.13
	W-3b	39.96	39.31	38.96	32.15	31.61	31.22	27.5	26.63	26.29
	W-3c	38.25	37.72	36.74	32.37	31.72	31.12	29	27.98	27.32
	W-3d	39.96	39.31	38.96	32.15	31.61	31.22	27.5	26.63	26.29
	W-3e	37.98	37.48	36.51	32.37	31.73	31.12	29.11	28.12	27.44
	W-3f	38.25	37.72	36.74	32.37	31.72	31.12	29	27.98	27.32
	W-3g	38.45	37.76	36.68	32.42	31.74	31.11	29.06	27.97	27.31

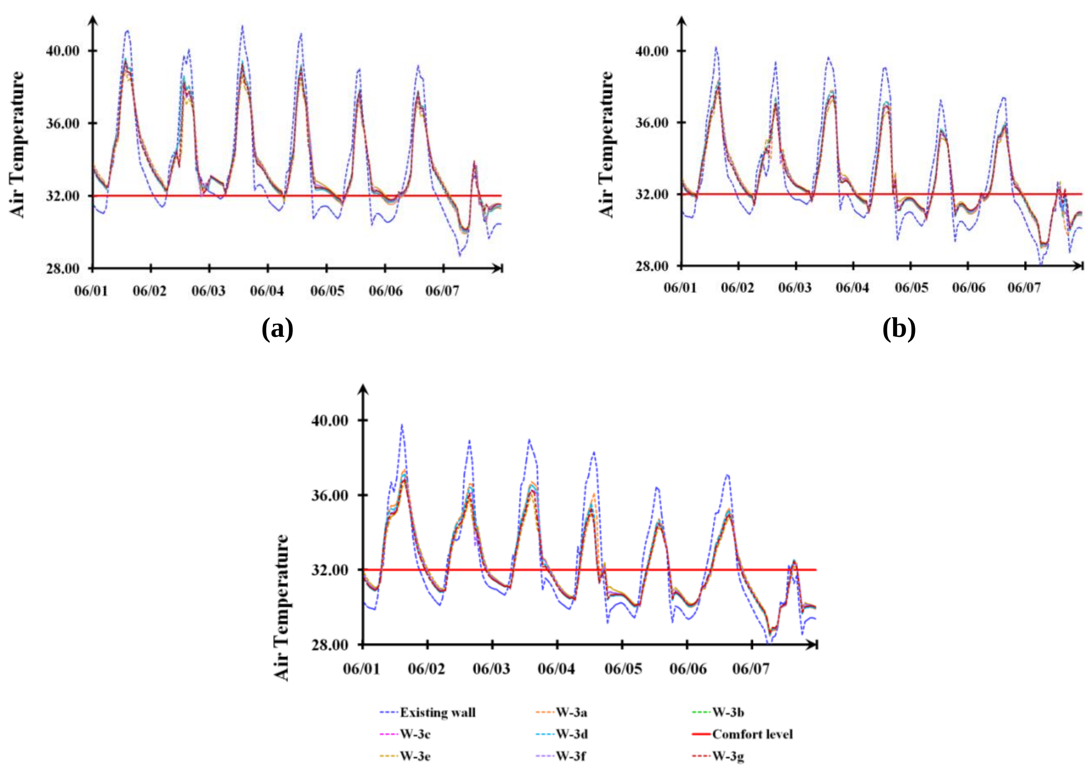
*Temperature gradients above comfort temperature is highlighted with color

Table 6.14 Standard deviation of different cavity wall types (W-3)

Wall Type	Outdoor Temp.	Air Temp.			MRT Temp.			OT Temp.		
		Z-1	Z-2	Z-3	Z-1	Z-2	Z-3	Z-1	Z-2	Z-3
Existing wall	2.03	2.77	2.52	2.54	2.61	2.66	2.76	2.67	2.57	2.63
W-3a	2.03	2.11	1.83	1.91	1.96	1.99	2.08	2.02	1.89	1.99
W-3b	2.03	2.65	2.41	2.44	2.49	2.54	2.64	2.55	2.46	2.53
W-3c	2.03	2	1.73	1.78	1.84	1.87	1.94	1.9	1.78	1.85
W-3d	2.03	2.65	2.41	2.44	2.49	2.54	2.64	2.55	2.46	2.53
W-3e	2.03	1.9	1.67	1.71	1.76	1.8	1.87	1.81	1.72	1.78
W-3f	2.03	2	1.73	1.78	1.84	1.87	1.94	1.9	1.78	1.85
W-3g	2.03	2.01	1.71	1.76	1.85	1.87	1.93	1.9	1.77	1.84

*Color gradient shows comparative changes in standard deviation

In all cases maximum temperature gradients are lower than existing situation. For all wall types, mean and minimum values of temperature gradients are slightly higher than existing condition. Maximum temperature gradients for W-3 are lower than temperature gradients of existing wall condition. Among all wall envelopes Wall Types W-3b and W-3d as well as W-3c and W-3f have similar thermal impact on indoor thermal environment. Compared to all the walls in consideration, mean temperature gradients of W-3b/W-3d is marginally lower (0.0.15ºC-0.25ºC) than that of W-3e. Minimum temperature gradient of W-3b/W-3d is lowest among all though slightly higher than existing condition. W-3e resulted in 0.5ºC-1.5ºC higher minimum temperature gradients compared to W-3b/W-3d; however, W-3e resulted in low maximum AT value. W-3e has nearly 2.5ºC lower temperature (maximum) than existing condition whereas for W-3b/W-3d the difference is 0.67ºC. Fig. 6.21 shows relative changes in AT for different wall types of W-3. Table 6.14 shows that among all the walls W-3ehas the lowest standard deviation which means that temperature gradients for this wall fluctuates less during the simulation period. Standard deviation of existing wall Construction has the highest deviation around its' mean. AT(ºC) and OT(ºC) of Z-2 whereas MRT of Z-1 shows relatively low standard deviation value compared to others.



(c)

Figure 6.21 Comparison of changes in AT(ºC) for different wall types of W-3:
(a) Zone-1 (Z-1), (b) Zone-2 (Z-2) and (c) Zone-3 (Z-3).

6.4.4 Wall Constructions having Cavity Insulated with Straw: W-4

Wall Construction W-4 is composed of two timber wall panels of same/different thickness having cavity space in between them filled with straw as insulation material. Total thickness of wall ranges between 37.5mm-50mm (1½"-2"). Wall panel thickness ranges between 12.5mm-25mm (½"-1") and cavity thickness for insulation material ranges between 6.25mm-25mm (¼"-1"). Outer wall is always considered to have 12.5mm (½") thickness while cavity insulation gap and inner wall vary in thickness. Detailed cross-section of wall type W-4 is presented in Fig. 6.22. Thermal properties of envelope materials considered for simulations are presented in Table 6.15.

Table 6.15 Thermal properties of envelopes considered for wall type W-4.

Envelope	Material	Thickness (mm)	Conductivity (W/m-K)	Density (kg/m^3)	Specific-Heat (J/kg-K)
Wall	Teak	12.5 /18.75 /25	1.28	710	1880
	Cavity insulation (Straw)	6.25 /12.5 /18.75 /25	0.07	240	180
Roof	C.I. sheet	0.5	65	7300	235
Ceiling	Raintree	25	0.74	480	1880
Chadoa	Cotton fabric	0.01	0.04	225	1380.72
Floor	Earthen	-	1.4	1460	879
Window	Sal	18.75	0.96	660	1880
Door	Sal	25	0.96	660	1880

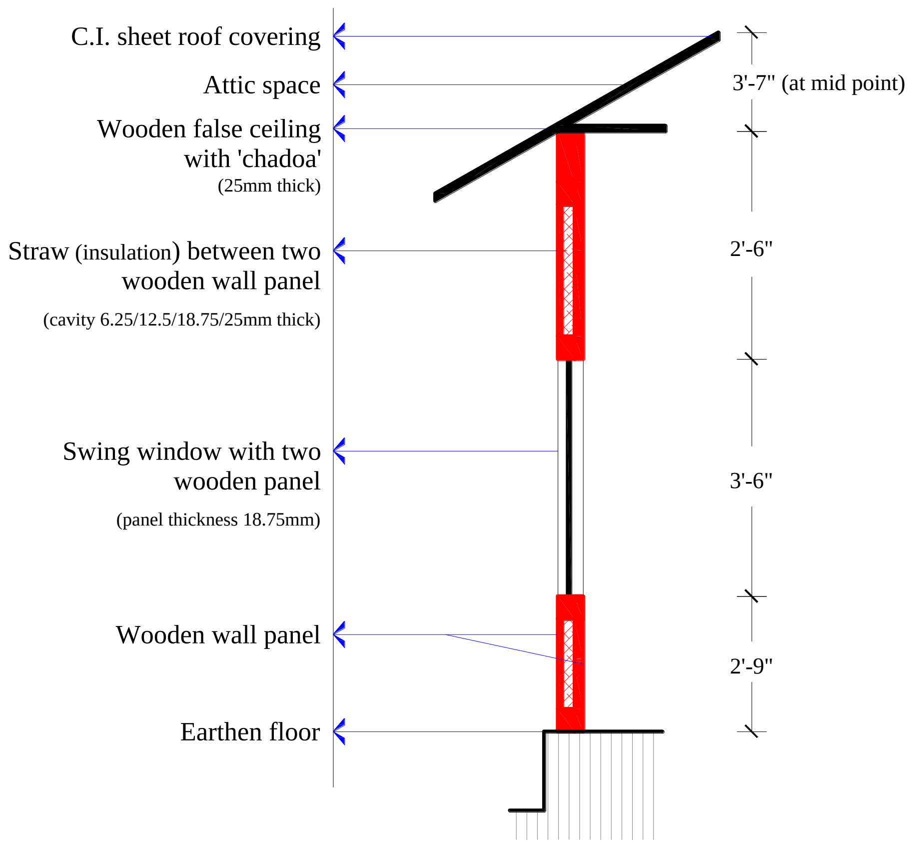


Figure 6.22 Cross sectional view of wall type W-4.

a) Wall type W-4a

Wall type W-4a has one 12.5mm (½") and one 18.75mm (¾") wooden panels having a 6.25mm (¼") cavity in between them which is insulated with straw husk as cavity insulation material. Total thickness of the wall is 37.5mm (1½"). Results obtained from the parametric study are analyzed and presented in descriptive statistics format in Appendix D.

Fig. 6.23 presents the AT(ºC) during study period. From the figure it is noticed that all the temperature gradients remain high during the first few days of the study period. Temperature gradients of Z-1 remain above upper range of comfort when outdoor AT(ºC) remains above 28ºC. However, Z-2 and Z-3 shows lower temperature compared to Z-1 but still temperature remains above comfort level most of the time. Temperature gradients during first seven days of June are illustrated in Fig. 6.23.

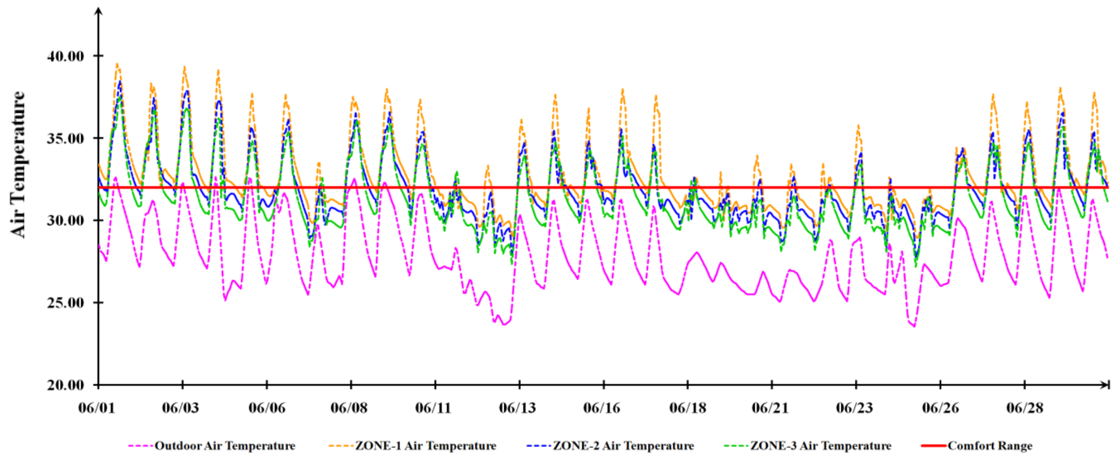


Figure 6.23 Comparison of AT(ºC) of different zones for wall type W-4a.

Compared to other temperature gradients it is seen that AT(ºC) is high among all and Z-1 mean AT(ºC) is 0.67ºC higher than comfort level. Descriptive statistics of wall type W-4a shows that mean temperature gradients of Z-2 and Z-3 remain within upper level of comfort. Z-1 has the highest (39.54ºC) and Z-3 has the lowest (37.16ºC) AT value. Temperature difference between maximum and minimum AT(ºC) within a zone is nearly 10.5ºC. MRT(ºC) is nearly 0.3ºC-1.5ºC lower than respective zone AT(ºC). In all cases standard deviation is around 2.

Linear regression analysis of resulted temperature gradients regarding outdoor temperature is illustrated in Appendix D. This analysis illustrates how all the temperature gradients change with respect to outdoor temperature during study period. Variability of about 71-73.5 percent is noticed for temperature gradients. OT(ºC) and MRT(ºC) have maximum variation around its mean. AT(ºC) variation of about 71 percent is found during study period. Correlation matrix among temperature gradients and outdoor AT(ºC) is presented in Table 6.43. Positive correlation remains among different temperature gradients. Best fitted correlation among outdoor temperature and resulted temperature gradients occurs when AT(ºC), MRT(ºC) and OT(ºC) are 0.84, 0.86 and 0.86 respectively (Appendix D).

b) Wall type W-4b

Wall type W-4b has two 12.5mm (½") wooden panels with 12.5mm (½") cavity insulated with straw in between them. Total thickness of the wall is 37.5mm (1½"). Results obtained are summarized in descriptive statistics format (Appendix D).Mean temperature gradients of Z-1 are higher whereas mean temperature gradients of Z-2 and Z-3 are lower than the upper level of comfort. Z-1 mean AT is 0.8ºC high above comfort level but average MRT is within comfort range. In all cases Z-1 has the highest and Z-3 has the lowest temperature gradients. Z-1, Z-2 and Z-3 maximum AT remains nearly 7.5ºC, 6ºC and 4.5ºC above the upper comfort range. Temperature difference between maximum and minimum AT(ºC) within a zone is nearly 9ºC-10ºC. Maximum MRT(ºC) of Z-1 and Z-2 are nearly 1.5ºC and 0.5ºC lower than respective zone AT(ºC) whereas at Z-3 both temperatures are almost same.

Average MRT(ºC) is almost 0.5ºC lower than respective zone's mean AT(ºC). In all cases standard deviation is below 2.

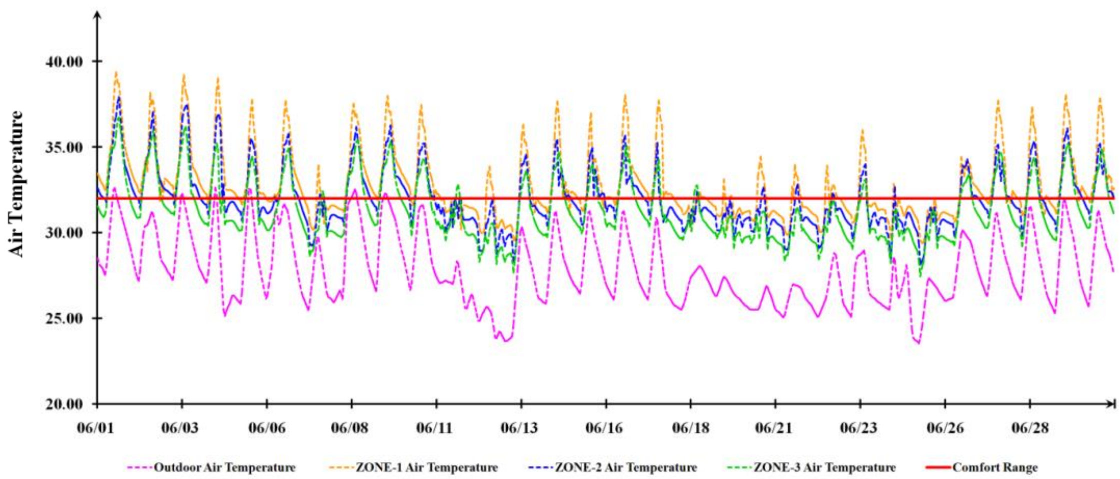


Figure 6.24 Comparison of AT(ºC) of different zones for wall type W-4b.

Fig. 6.24 presents AT of three zones during study period. From the figure it is observed that during first few days of the study period all the temperature gradients remain high. When outdoor AT(ºC) is nearly 28ºC, Z-1 and Z-2 temperatures remain high whereas Z-3 temperature remains below upper comfort range during late-night and early morning. Temperature gradients of three zones for first week of the study period are provided in Appendix D. From the figure it is observed that MRT(ºC) of Z-2 and Z-3 remain within comfort range during late-night to early-morning even if the outdoor AT(ºC) is 28ºC.

Linear regression analysis of temperature gradients with respect to outdoor temperature is illustrated in Appendix D. About 67.5-71.5 percent variability is noticed for different temperature gradients. OT(ºC) and MRT(ºC) have maximum variation around its mean which is nearly 71.5 percent. Positive correlation remains among different temperature gradients. Best fitted correlation of MRT(ºC) and OT(ºC) with AT(ºC) exists when the values of MRT(ºC) and OT(ºC) are 0.95 and 0.99 respectively. Best fitted correlation of AT(ºC) with MRT(ºC) and OT occurs when the value of these two are 0.95 and 0.99 respectively (Appendix D).

c) Wall type W-4c

Wall type W-4c has outer 12.5mm (½") and inner 18.75mm (¾") wooden panels having 12.5mm (½") cavity insulated with straw in between them. Total thickness of the wall is 43.75mm (1¾"). Fig. 6.25 shows the variation in zone AT regarding outdoor temperature during the study period. Maximum value of temperature gradients resulted for parametric study of wall W-4c which is marginally lower (0.3ºC) than the temperature resulted for W-4b. Mean temperature gradients are same for both wall types W-4b and W-4c.

Temperature gradient for first week of the study period is shown in Appendix D. Mean temperature gradients of Z-1 are higher whereas mean temperature gradients of Z-2 and Z-3 are lower than the upper level of comfort. Z-1 mean AT is 0.7ºC high above comfort level but average MRT is within comfort range. In all cases Z-1 has the highest and Z-3 has the lowest temperature gradients. Temperature difference between maximum and minimum AT(ºC) within a zone is nearly 9ºC-10ºC. Maximum MRT(ºC) of Z-1 and Z-2 are nearly 1.3ºC and 0.96ºC lower than respective zone AT whereas at Z-3 both temperatures are nearly same. Average MRT(ºC) is nearly 0.5ºC lower than respective zone's mean AT(ºC). In all cases standard deviation remains 1.5.

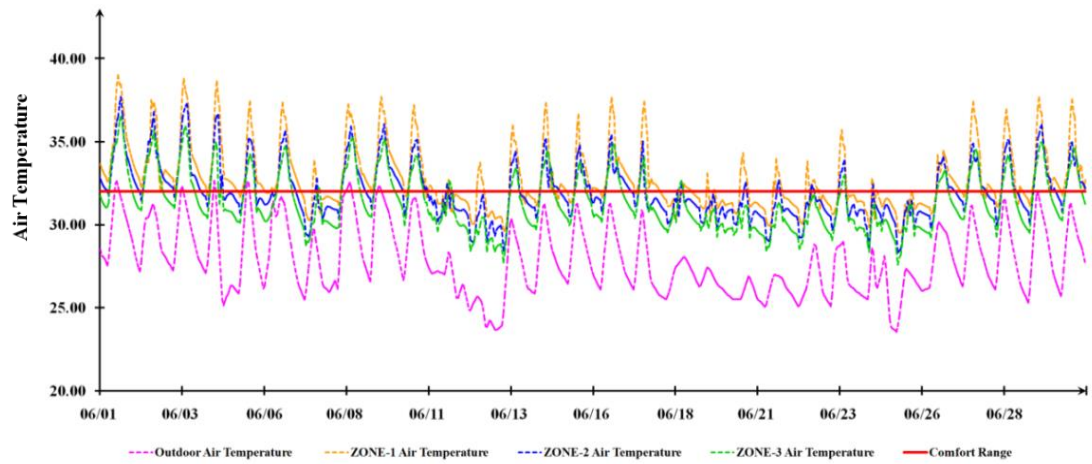


Figure 6.25 Comparison of AT(ºC) of different zones for wall type W-4c.

Linear regression analysis for wall type W-4c with respect to outdoor temperature during study period is illustrated in Appendix D. Variability of about 65.5-69 percent is noticed for different temperature gradients whereas OT(ºC) and MRT(ºC) have maximum (69 percent) variation around its mean. Correlation matrix among temperatures is studied (Appendix D). Positive correlation remains among different temperature gradients. Best fitted correlation results among outdoor temperature and temperature gradients when AT(ºC), MRT(ºC) and OT(ºC) are 0.81, 0.83 and 0.83 respectively.

d) Wall type W-4d

Wall type W-4b has two 12.5mm (½") wooden panels with 12.5mm (½") cavity insulated with straw in between them. Total thickness of the wall is 37.5mm (1½"). Results obtained from the parametric study are summarized in Table 6.48. Fig. 6.26 shows variation of AT(ºC) of three zones during study period.

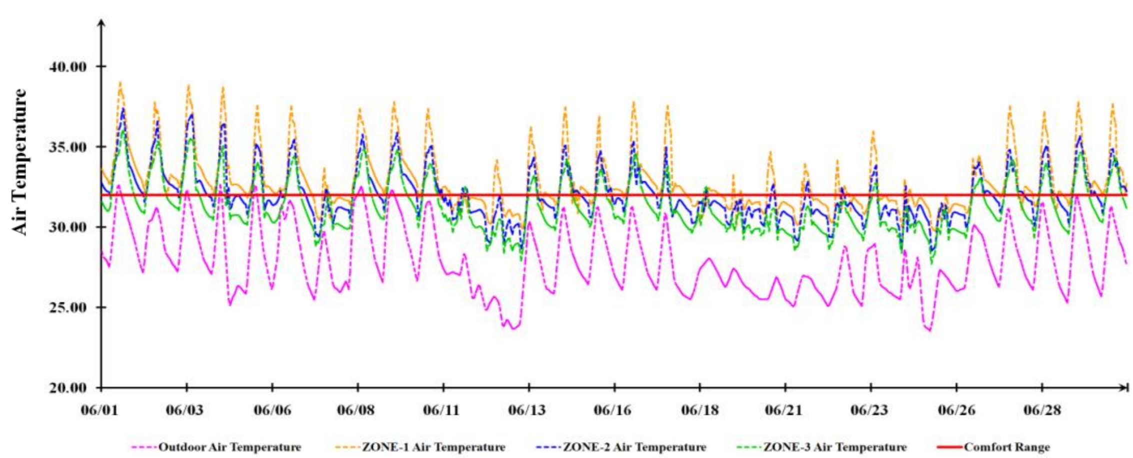


Figure 6.26 Comparison of AT(ºC) of different zones for wall type W-4d.

Mean AT(ºC) and OT(ºC) of Z-1 is 0.2ºC-0.8ºC higher though MRT(ºC) is marginally higher than upper of comfort. Zone AT is 3.5ºC-6.4ºC higher than outdoor AT(ºC). When outdoor temperature remains high (≥28ºC) Z-1 and Z-2 AT(ºC) remain high above comfort level though Z-3 temperature gradients remain within comfort range. Temperature difference between maximum and minimum AT(ºC) within a zone is nearly 8ºC-10.5ºC. Temperature gradients resulted for wall W-4d during study period is shown in Appendix D.

Positive correlation remains among different temperature gradients. Best fitted correlation occurs among outdoor temperature and resulted temperature gradients when AT(ºC), MRT(ºC) and OT(ºC) values are 0.79, 0.82 and 0.82 respectively whereas best fitted correlation of MRT and OT with AT exists when the values of MRT(ºC) and OT(ºC) are 0.94 and 0.99 respectively (Appendix D). Linear regression analysis of temperature gradients with respect to outdoor temperature is provided in Appendix D. About 62.5-67.5 percent variability is noticed for different temperature gradients. OT(ºC) and MRT(ºC) have maximum variation around its mean. A variation of nearly 67.5 percent is found for both MRT(ºC) and OT(ºC).

e) Wall type W-4e

The thicknesses of outer and inner walls of W-4e wall types are 12.5mm (½") and 25mm (1") respectively. Cavity insulation space in between the walls is 12.5mm (½") and total thickness of W-4e is 50mm (2"). Parametric study result is summarized in Appendix D. Mean AT(ºC) of Z-1 is 0.7ºC higher though MRT remains within comfort zone. Mean temperature gradients of other zones remain within comfort level. Difference between mean outdoor and zone AT ranges nearly 3.5ºC-5ºC. Average value of MRT(ºC) of all zones remains within comfort level. But indoor AT for wall type W-4e remains high during first few days when outdoor temperature remains higher. Z-1 and Z-2 temperature gradients remain above while Z-3 temperature remains below upper comfort temperature during late to early morning. Fig. 6.27 illustrates AT(ºC) for w-4e wall type and Appendix D shows different temperature gradients for three zones.

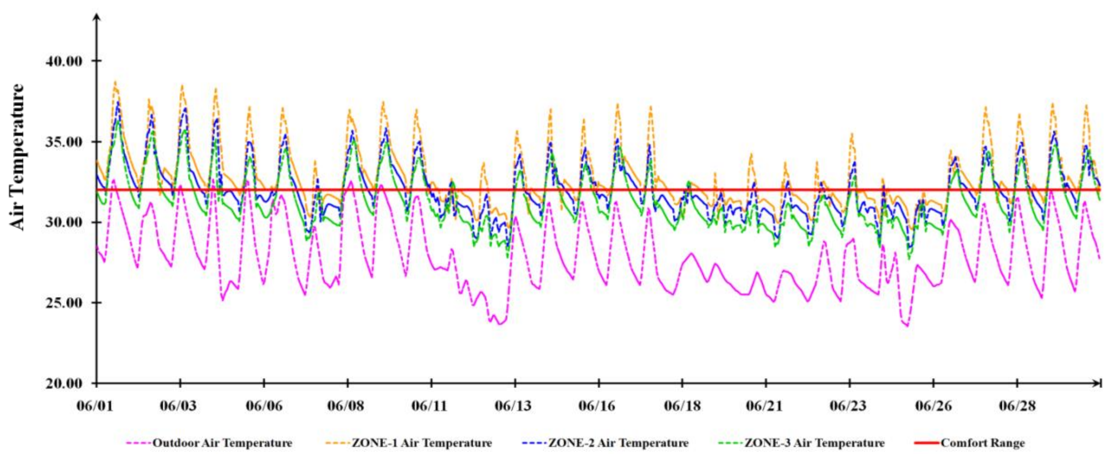


Figure 6.27 Comparison of AT(ºC) of different zones for wall type W-4e.

Linear regression analysis of resulted temperature gradients with respect to outdoor temperature shows variability of about 63.5-67 percent. OT(ºC) has maximum variation around its mean which is 67 percent. Variation air and MRT(ºC) is 63.5 and 66.5 percent around its mean. Linear regression analysis is provided in Appendix D. Correlation matrix for wall W-4e is presented in Table 6.51. Positive correlation remains among different temperature gradients whereas best fitted correlation occurs among outdoor temperature and resulted temperature gradients when AT(ºC), MRT(ºC) and

OT(ºC) are 0.80, 0.82 and 0.82 respectively. MRT(ºC) and OT(ºC)have best fitted correlation with AT when values of these temperatures are 0.93 and 0.98 respectively.

f) Wall type W-4f

Wall W-4f is 50mm (2") thick. Outer and inner wall have thicknesses of 12.5mm (½") and 18.75mm (¾") respectively having 18.75mm (¾") cavity insulated with straw in between them. Parametric study result for wall type W-4f shows that mean temperature gradients of Z-2 and Z-3 remain within upper level of comfort while Z-1 temperature is 0.16ºC-0.7ºC higher than upper value of comfort.

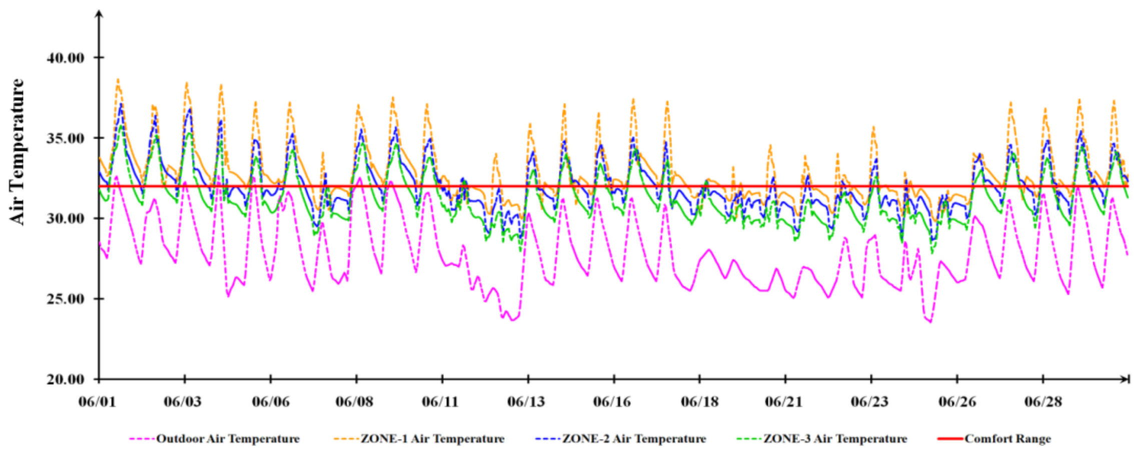


Figure 6.28 Comparison of AT(ºC) of different zones for wall type W-4f.

AT(ºC) is high compared to other temperature gradients. Z-1 has the highest (maximum 38.66ºC) and Z-3 has the lowest (35.78ºC) AT(ºC). Temperature difference between maximum and minimum AT(ºC) within a zone is nearly 8ºC-10ºC. MRT(ºC) is nearly 0.5ºC lower than respective zone AT(ºC). In all cases standard deviation is around 1.5. Analysis of simulation result is summarized in Appendix D. Fig. 6.28 presents temperature gradients during the study period. First few days of the study period show higher temperature gradients and Appendix D shows temperature gradient during this period for wall type W-4f. From the figure it is observed that temperature gradients of Z-1 and Z-2 remain higher than upper range of comfort all the day. However, Z-3 shows lower temperature compared to Z-1 but still temperature remains above comfort level most of the time.

Linear regression analysis of temperature gradients with respect to outdoor temperature is studied and presented in Appendix D. About 61.5-65.5 percent variability is noticed for different temperature gradients. OT(ºC) and MRT(ºC) have maximum variation around its mean. Variation of nearly 65.4 percent is found for both MRT(ºC) and OT(ºC). Positive correlation remains among different temperature gradients. Best fitted correlation occurs among outdoor temperature and resulted temperature gradients when AT(ºC), MRT(ºC) and OT(ºC) are 0.78, 0.81 and 0.81 respectively (Appendix D).

g) Wall type W-4g

Wall type W-4g is composed of two 12.5mm (½") wooden walls having 25mm (1") cavity space in between them. Cavity is insulated with straw as cavity insulation material. Total thickness of the wall is 50mm (2"). Fig. 6.29 illustrates AT(ºC) of three zones and Appendix D shows temperature gradients of three different zones for wall type W-4g.

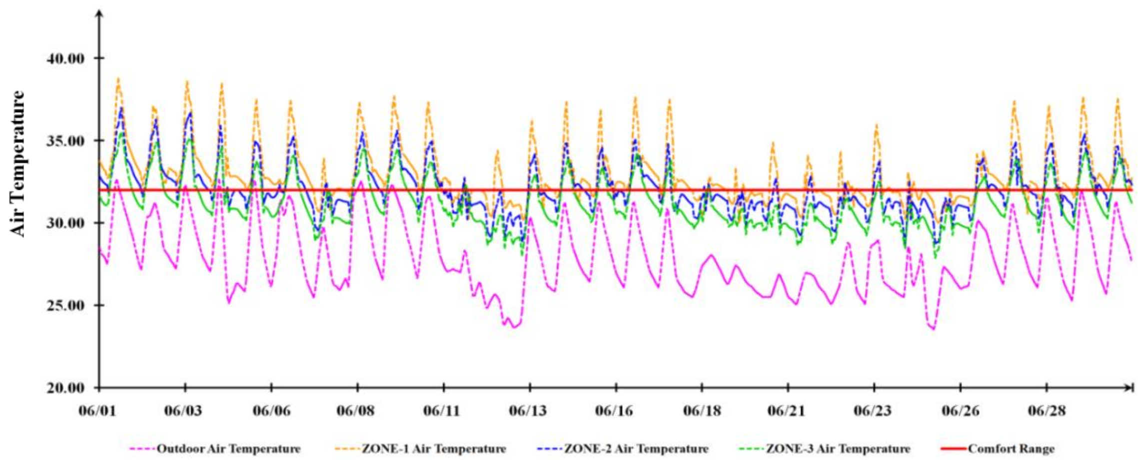


Figure 6.29 Comparison of AT(ºC) of different zones for wall type W-4g.

Temperature gradients of all zones show similar trend whereas Z-1 has higher and Z-3 has lower temperature. During parametric study period it is noticed that mean temperature gradients of Z-2 and Z-3 remain within comfort level while Z-1 mean temperature gradients are 4.5ºC-5ºC and 0.3ºC-0.5ºC higher than outdoor AT(ºC) and comfort level respectively. Average value of MRT(ºC) of all the zones is approximately 0.5ºC lower than respective zone AT(ºC).

Linear regression analysis for wall type W-4g is studied and presented in Appendix D. Linear regression analysis of resulted temperature gradients with respect to outdoor temperature shows variability of about 58-65 percent. OT(ºC) has maximum variation around its mean which is nearly 65 percent. OT variation with respect to outdoor AT(ºC) is similar to that of the MRT. Variation of air and OT(ºC) is 58.5 percent. Different temperature gradients are related to each other positively where best fitted correlation results with indoor temperature gradients and outdoor AT(ºC) when AT(ºC), MRT(ºC) and OT(ºC) are 0.77, 0.81 and 0.80 respectively. AT(ºC) has a best fitted correlation with MRT(ºC) and OT(ºC) when the values of these temperatures are 0.92 and 0.98 respectively. Correlation matrix for wall W-3g is presented in Appendix D.

h) Comparison of Wall Construction W-4

Wall Construction W-4 is composed of two wooden walls with a cavity insulated with straw in between them. 12.5mm (½") thick outer wall is constant whereas inner wall has three different thicknesses 12.5mm (½"), 18.75mm (¾") and 25mm (1"). Cavity thickness for insulation varies within the range 6.25mm-25mm (¼"-1"). Six different wall types W-4a to W-4g is considered and thickness varies within 37.5mm-50mm (1½"-2"). Wall W-4a, W-4c and W-4f have 18.75mm (¾") thick inner wall with insulation thickness of 6.25mm (½"), 12.5mm (½") and 18.75mm (¾") respectively. Thickness of inner wall of W-4b, W-4d and W-4g is 12.5mm (½") and cavity insulations are 12.5mm (½"), 18.75mm (¾") and 25mm (1") respectively. Wall type W-4e has cavity thickness of 12.5mm (½") with inner wall 25mm (1") thick. Fig. 6.30 illustrates zone AT for different wall types of W-4 and Table 6.16 presents the zone-wise temperature gradients for different wall types. Outdoor temperature is constant for all wall types considered. Outdoor maximum, mean and minimum AT(ºC) is 32.63ºC, 27.83ºC and 23.54ºC respectively with standard deviation of 2.03. From the table it is observed that except Z-1, mean and minimum values of temperature gradients of Z-2 and Z-3 remain within upper level of comfort. Z-1 mean AT(ºC) is 0.6ºC-0.9ºC whereas MRT(ºC) and OT(ºC) is 0.07ºC-0.24ºC and 0.3ºC-0.5ºC (respectively) higher than comfort temperature. Maximum temperature gradients remain 5.08ºC-7.54ºC above the comfort range.

Table 6.16 Comparative performance analysis of cavity walls insulated with straw (W-4).

Temp. (°C)	Wall Type	Maximum (°C) Z-1	Z-2	Z-3	Mean (°C) Z-1	Z-2	Z-3	Minimum (°C) Z-1	Z-2	Z-3
Air Temp	Existing wall	41.39	40.23	39.78	32.46	31.8	31.36	27.38	26.5	26.26
	W-4a	39.54	38.47	37.51	32.67	31.9	31.38	28.94	27.75	27.17
	W-4b	39.36	37.95	36.72	32.79	31.98	31.33	29.39	28.13	27.45
	W-4c	39	37.69	36.5	32.77	31.98	31.32	29.49	28.29	27.57
	W-4d	39.02	37.41	36	32.85	32.02	31.27	29.76	28.51	27.71
	W-4e	38.71	37.44	36.28	32.75	31.99	31.32	29.55	28.42	27.68
	W-4f	38.66	37.14	35.78	32.83	32.02	31.26	29.82	28.65	27.83
	W-4g	38.78	37	35.46	32.9	32.04	31.21	30	28.75	27.88
MRT Temp.	Existing wall	39.73	39.33	39.05	31.73	31.37	31.04	26.97	26.3	26.01
	W-4a	38.17	37.87	37.16	31.94	31.46	30.95	28.4	27.54	26.98
	W-4b	37.77	37.43	36.46	32.07	31.52	30.88	28.82	27.91	27.25
	W-4c	37.51	37.17	36.21	32.07	31.52	30.87	28.93	28.08	27.38
	W-4d	37.34	36.94	35.78	32.16	31.55	30.8	29.22	28.29	27.51
	W-4e	37.26	36.93	35.98	32.07	31.52	30.85	29.01	28.2	27.48
	W-4f	37.08	36.67	35.54	32.16	31.55	30.79	29.28	28.44	27.62
	W-4g	37.04	36.57	35.26	32.24	31.58	30.73	29.46	28.54	27.67
OT Temp.	Existing wall	40.42	39.78	39.42	32.1	31.58	31.2	27.18	26.4	26.14
	W-4a	38.67	38.17	37.34	32.31	31.68	31.16	28.67	27.64	27.08
	W-4b	38.39	37.69	36.59	32.43	31.75	31.1	29.11	28.02	27.35
	W-4c	38.04	37.43	36.35	32.42	31.75	31.09	29.22	28.19	27.47
	W-4d	38.05	37.17	35.89	32.5	31.79	31.03	29.49	28.4	27.61
	W-4e	37.75	37.18	36.13	32.41	31.76	31.09	29.28	28.31	27.58
	W-4f	37.71	36.9	35.66	32.5	31.79	31.03	29.55	28.55	27.73
	W-4g	37.82	36.79	35.36	32.57	31.81	30.97	29.73	28.65	27.78

*Temperature gradients above comfort temperature is highlighted with color

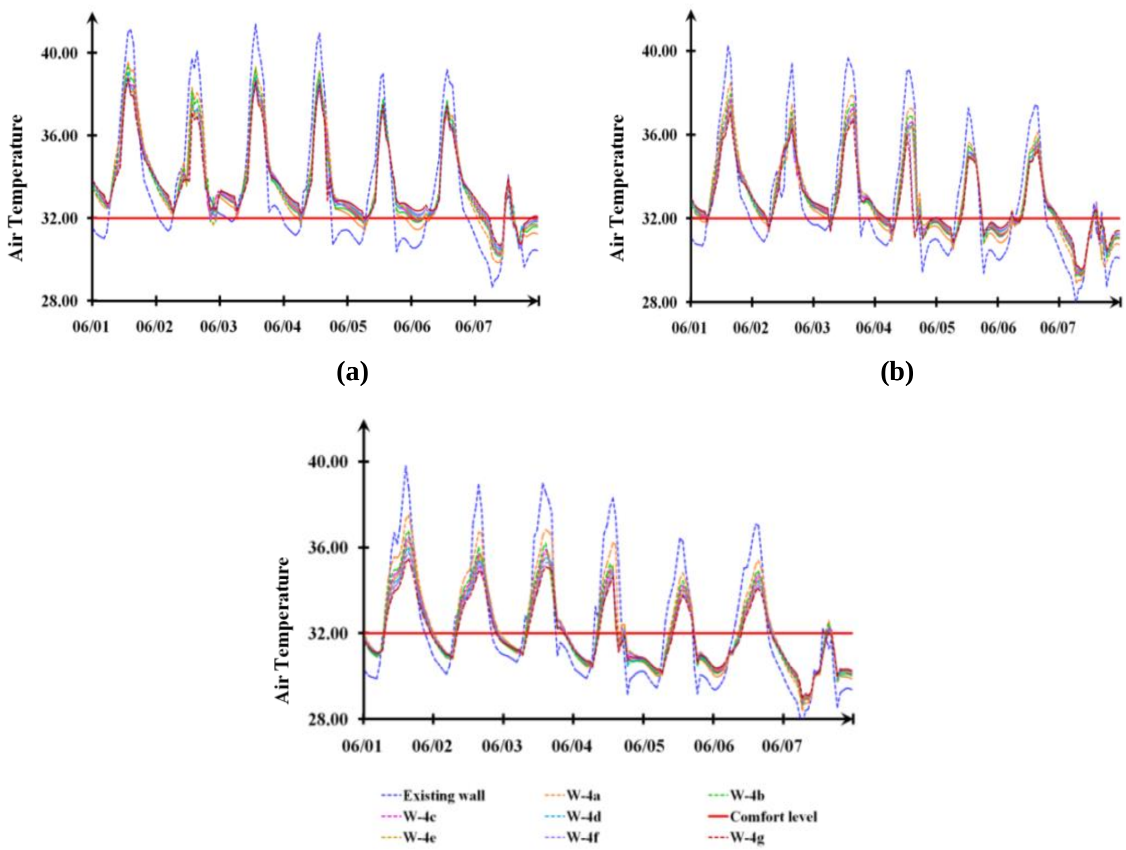
Table 6.17 Standard deviation of different cavity walls insulated with straw (W-4).

Wall Type	Outdoor Temp.	Air Temp. Z-1	Z-2	Z-3	MRT Temp. Z-1	Z-2	Z-3	OT Temp. Z-1	Z-2	Z-3
Existing wall	2.03	2.77	2.52	2.54	2.61	2.66	2.76	2.67	2.57	2.63
W-4a	2.03	2.14	1.86	1.94	1.99	2.03	2.11	2.04	1.93	2.02
W-4b	2.03	1.99	1.7	1.74	1.82	1.84	1.9	1.88	1.75	1.81
W-4c	2.03	1.9	1.64	1.68	1.74	1.77	1.83	1.79	1.69	1.75
W-4d	2.03	1.83	1.55	1.56	1.65	1.67	1.71	1.72	1.59	1.63
W-4e	2.03	1.82	1.59	1.63	1.67	1.71	1.76	1.71	1.64	1.69
W-4f	2.03	1.74	1.49	1.5	1.58	1.6	1.64	1.63	1.53	1.57
W-4g	2.03	1.72	1.43	1.43	1.53	1.54	1.56	1.59	1.47	1.49

*Color gradient shows comparative changes in standard deviation

In existing condition AT(ºC) is 7.78ºC-9.39ºC higher than upper level of comfort. Mean and minimum temperatures remain within comfort temperature; however, at Z-1 mean AT(ºC) is marginally higher (0.46ºC) than comfort range. Considered wall Constructions resulted in lowest maximum whereas highest mean and minimum temperatures compared to existing thermal condition. Difference of maximum temperature between existing and studied wall is the highest at Z-3 and the lowest at Z-1, but for mean and minimum temperature gradients the result shows converse outcome. Comparative analysis of performance of different wall types of W-4 (Fig. 6.30) shows that in all cases W-4g has the lowest maximum and W-4a has the lowest minimum AT. Simulation study for W-4a resulted in 1.75ºC-

2.25ºC lower maximum AT(ºC) compared to existing condition whereas for W-4g the difference is 2.6ºC-4.3ºC. Maximum value of MRT(ºC) and OT(ºC) for W-4g is 2.7ºC-3.8ºC and 2.6ºC-4.0ºC (consecutively) lower than existing condition whereas for W-4a it is 1.5ºC-1.89ºC and 1.75ºC-2.0ºC respectively. Mean and minimum temperature gradients for wall W-4 are higher than existing thermal condition. Resulted mean temperature gradient for W-4g is 0.3ºC higher than W-4a whereas for minimum temperature the difference is 0.6ºC-1ºC.Among all walls, W-4g has lower standard deviation which means that temperature gradients for this wall fluctuates less during simulation period. Standard deviation of existing wall Construction has highest deviation around its mean. AT(ºC) and OT(ºC) of Z-2 have comparatively lower standard deviation whereas MRT(ºC) of Z-1 has relatively standard deviation compared to others. Table 6.17 shows standard deviation of different walls insulated with straw (W-4).



(c)

Figure 6.30 Comparison of changes in AT(ºC) for different wall types of W-4:
(a) Zone-1 (Z-1), (b) Zone-2 (Z-2) and (c) Zone-3 (Z-3).

6.4.5 Wall Constructions having Cavity Insulated with Coconut Fiber: W-5

Wall Construction W-5 is composed of two timber wall panels of same/different thickness having cavity space in between them filled with coconut fiber as insulation material. Total thickness of wall ranges between 37.5mm-50mm (1½"-2"). Detailed cross-section of wall type W-5 is presented in Fig. 6.31. Thermal properties of envelope materials considered for simulations are presented in Table 6.18.

Table 6.18 Thermal properties of envelopes considered for wall type W-5.

Envelope	Material	Thickness (mm)	Conductivity (W/m-K)	Density (kg/m^3)	Specific-Heat (J/kg-K)
Wall	Teak	12.5 /18.75 /25	1.28	710	1880
	Coconut fiber	6.25 /12.5 /18.75 /25	0.038	97	1000
Roof	C.I. sheet	0.5	65	7300	235
Ceiling	Raintree	25	0.74	480	1880
Chadoa	Cotton fabric	0.01	0.04	225	1380.72
Floor	Earthen	-	1.4	1460	879
Window	Sal	18.75	0.96	660	1880
Door	Sal	25	0.96	660	1880

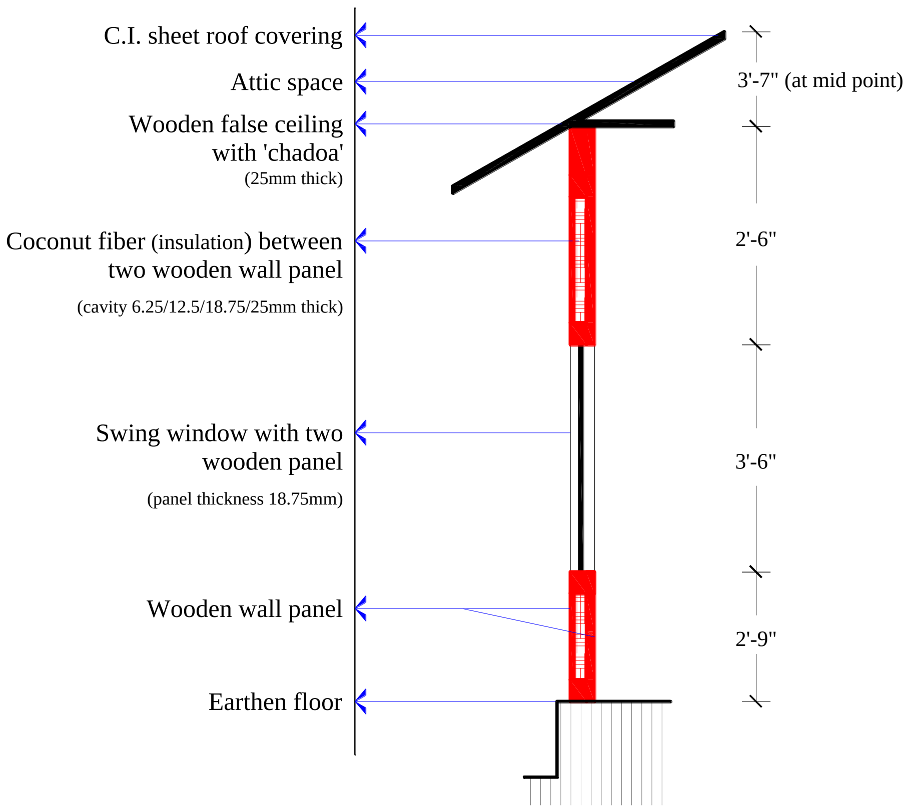


Figure 6.31 Cross sectional view of wall type W-5.

a) Wall type W-5a

Wall type W-5a has 12.5mm (½") thick outer and 18.75mm (¾") thick inner wooden panels having 6.25mm (¼") cavity in between them which is insulated with coconut fiber. Total thickness of the wall is 37.5mm (1½"). Results obtained from the parametric study are summarized (Appendix D) and descriptive statistics of wall type W-5a shows that mean temperature gradient of Z-1 is 0.7ºC higher while those of Z-2 and Z-3 are 0.26ºC-1.12ºC lower than upper level of comfort. Among all temperature gradients AT(ºC) is high for all the three zones. Z-1 has the highest (39.07ºC) and Z-3 has the lowest (36.63ºC) AT(ºC). Maximum and minimum AT(ºC) difference within a zone is nearly 9ºC-9.5ºC. MRT(ºC) is also high at Z-1 and low at Z-3 but at all zones average MRT(ºC) remains within comfort level. MRT(ºC) is nearly 0.5ºC-1.5ºC lower than respective zone AT(ºC). In all cases standard deviation is below 2.

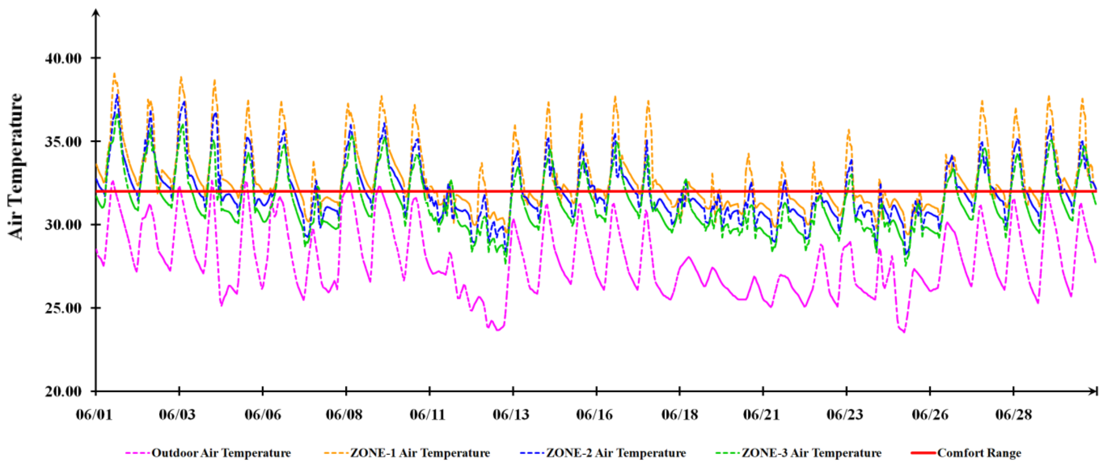


Figure 6.32 Comparison of AT(ºC) of different zones for wall type W-5a.

Fig. 6.32 presents the AT(ºC) gradient during the study period. From the figure it is observed that temperature gradients of Z-1 remain above upper range of comfort. Z-2 and Z-3 show lower temperature compared to Z-1 but still temperature remains above the comfort level most of the time. During first few days when outdoor temperature remains high, Z-1 and Z-2 temperature gradients remain high above the upper level of comfort all the day. Temperature gradient for first week of the study period for W-5a is presented in Appendix D. Linear regression analysis of obtained temperature gradients regarding outdoor temperature shows how all the temperature gradients change with respect to outdoor temperature during the study period. Variability of about 66-70 percent is noticed for temperature gradients. OT(ºC) (69.6 percent) has maximum variation around its mean. AT(ºC) variation of about 66.1 percent is obtained during study period. Positive correlation remains among different temperature gradients. Best fitted correlation among outdoor AT and temperature gradients take place when AT(ºC), MRT(ºC) and OT(ºC) are 0.81, 0.83 and 0.83 respectively while best fitted correlation of MRT(ºC) and OT(ºC) with AT(ºC) occurs when the values of MRT(ºC) and OT(ºC) are 0.94 and 0.99 respectively.

b) Wall type W-5b

Wall type W-5b has total thickness of 37.5mm (1½") considering two 12.5mm (½") wooden leafs with 12.5mm (½") cavity in between them insulated with coconut fiber/coir. Descriptive statistics of obtained result from the parametric study of wall type W-5b shows that maximum temperature of all three zones remain 3.5ºC-6.8ºC higher than comfort temperature. AT(ºC) is high compared to other temperature gradients. Z-1 has the highest (38.84ºC) and Z-3 has the lowest (35.61ºC) AT(ºC). Maximum and minimum AT(ºC) difference within a zone ranges between 7.8ºC-8.9ºC approximately. Z-2 and Z-3 mean temperature gradients remain within upper level of comfort. Z-1 mean temperature gradients are 0.2ºC-0.89ºC higher than upper level of comfort. MRT(ºC) is nearly 0.5ºC-0.6ºC lower than respective zone AT(ºC). In all cases standard deviation remains around 1.5.

Fig. 6.33 shows variation in zone AT(ºC) with respect to outdoor temperature for the study period for wall type W-5b. From the figure it is observed that temperature gradients of Z-1 remain above upper range of comfort during the first few days when the outdoor temperature is above 28ºC. However, Z-2 and Z-3 has low temperatures compared to Z-1 but still temperature remains above the comfort level most of the time. Obtained temperature gradients during the first seven days for wall type W-5b is provided in Appendix D.

Linear regression analysis of temperature gradients with respect to outdoor temperature is studied and provided in Appendix D. About 60-66 percent variability is noticed for different temperature gradients. OT(ºC) and MRT(ºC) have maximum variation around its mean. Variation ranges nearly between 65-66 percent for both MRT(ºC) and OT(ºC). Different temperature gradients have positive correlation with each other. Best fitted correlation of MRT(ºC) and OT with AT(ºC) occurs when they are 0.93 and 0.98 respectively.

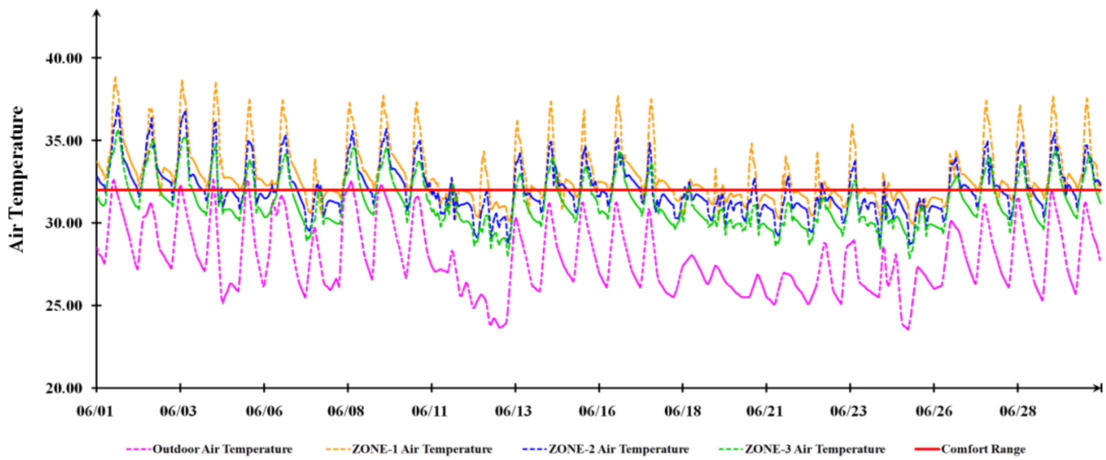


Figure 6.33 Comparison of AT(ºC) of different zones for wall type W-5b.

c) Wall type W-5c

Outer wall and inner wall of W-5c is 12.5mm (½") and 18.75mm (¾") in thickness. Cavity thickness in between them is 12.5mm (½") which is insulated with coconut fiber/coir as cavity insulation material. Descriptive statistics of obtained results from the parametric study shows that most of time of the day temperature remains higher than comfort temperature especially when outdoor temperature is higher than 28ºC. AT(ºC) is high compared to other temperature gradients. Z-1 temperature is 0.2ºC-0.8ºC higher than comfort temperature. Fig. 6.34 illustrates AT(ºC) for wall W-5c.

From figure it is observed that temperature gradients of Z-1and Z-2 remain above upper range of comfort all the day during first few days. Z-3 shows low temperature but remains above comfort level most of the time. Temperature gradients for all the three zones for the period of first seven days are presented in Appendix D.

Linear regression analysis of temperature gradients with respect to outdoor temperature is presented in Appendix D. About 58-63.5 percent variability is noticed for different temperature gradients. OT(ºC) and MRT(ºC) have maximum variation around its mean which ranges nearly 63.5 percent. There remains a positive correlation among different temperature gradients. Correlation matrix among temperatures is presented in Table 6.64. Best fitted correlation of MRT(ºC) and OT(ºC) with AT occurs when they are 0.91 and 0.98 respectively.

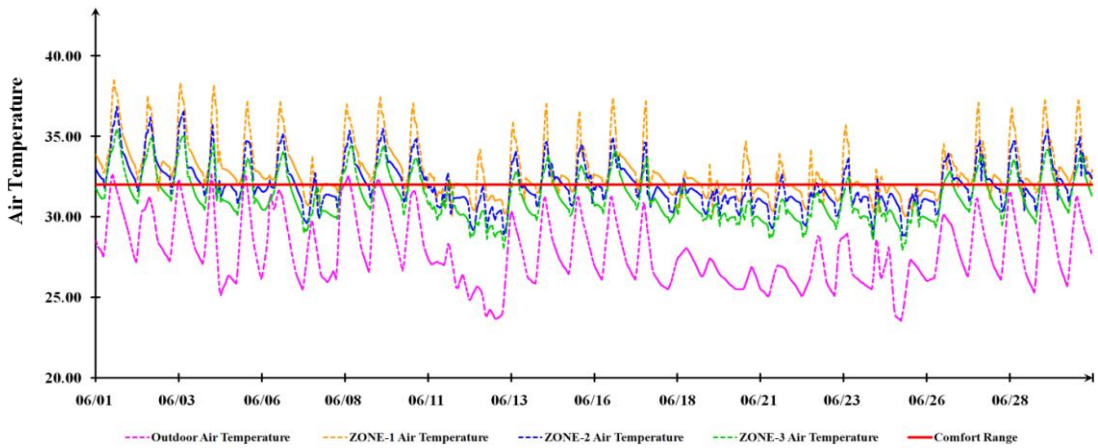


Figure 6.34 Comparison of AT(ºC) of different zones for wall type W-5c.

d) Wall type W-5d

W-5d has two 12.5mm (½") wooden walls with a cavity of 18.75mm (¾") in between them. Cavity is insulated with coconut fiber/coir as cavity insulation material. Descriptive statistics of obtained result from the parametric study shows that mean temperature gradients of Z-1 is higher than upper value of comfort. AT is high compared to other temperature gradients. Z-1 has the highest (38.52ºC) and Z-3 has the lowest (34.92ºC) mean AT(ºC) value. Temperature difference between maximum and minimum AT(ºC) within a zone ranges between nearly 6.5ºC-8.5ºC. MRT(ºC) is nearly 0.23ºC-1.78ºC lower than respective zone AT(ºC). Standard deviation is 1.5.

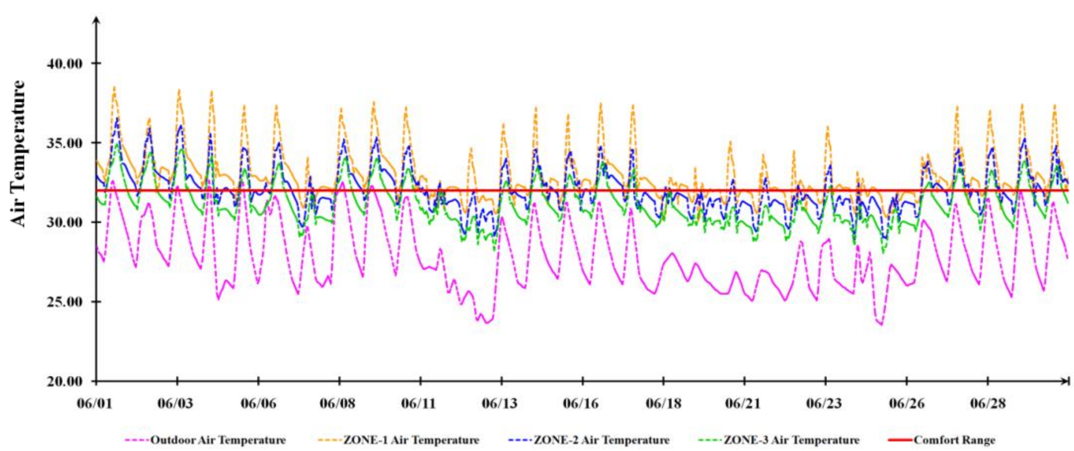


Figure 6.35 Comparison of AT(ºC) of different zones for wall type W-5d.

During first few days of the study period all the temperature gradients remain high. Fig. 6.35 presents the temperature gradients during the study period and Appendix D shows temperature gradient for the first week of the study period for wall type W-5d. From the figure it is observed that temperature gradients of Z-1 remain above upper range of comfort when minimum outdoor AT(ºC) is high (≥28ºC). However, Z-2 and Z-3 show lower temperature compared to Z-1 but still remains above the comfort level most of the time. Z-3 temperature gradients remain within comfort level during late-night to early morning even if minimum outdoor temperature is higher than 28ºC.

Linear regression analysis of temperature gradients with respect to outdoor temperature is studied which shows that different temperature gradients have a variation of about 53-61percent variability around its mean. MRT(ºC) have maximum variation around its mean. A variation of nearly 60.9 percent is found for MRT(ºC). Variation of AT(ºC) is 52.8 percent. Positive correlation remains among different temperature gradients. Best fitted correlation occurs among outdoor temperature and resulted temperature gradients when AT(ºC), MRT(ºC) and OT(ºC) are 0.73, 0.78 and 0.77 respectively. Correlation matrix among temperatures is presented in Table 6.66.

e) Wall type W-5e

The thicknesses of outer and inner walls of W-4e wall type are 12.5mm (½") and 25mm (1") respectively having a cavity space of 12.5mm (½") thick in between them. Cavity is filled with coconut fiber. Total thickness of W-4e is 50mm (2"). Parametric study result is summarized in Table 6.67.

Mean temperature gradients of Z-1 are 0.2ºC-0.8ºC higher than the upper level of comfort. Other zones have temperature gradients within comfort level. Difference between mean outdoor and zone AT remain nearly between 3ºC-5ºC. Average value of MRT(ºC) of all the zones remain within comfort level (Fig. 6.36). But parametric study result for wall type W-5e shows that during first few days when outdoor temperature remains comparatively high. Z-1 and Z-2 temperature gradients always remain above while Z-3 temperature remains below upper comfort during late to early morning. Fig. 6.36 illustrates AT(ºC) of three zones while different temperature gradients during first seven days of study period is presented in Appendix D.

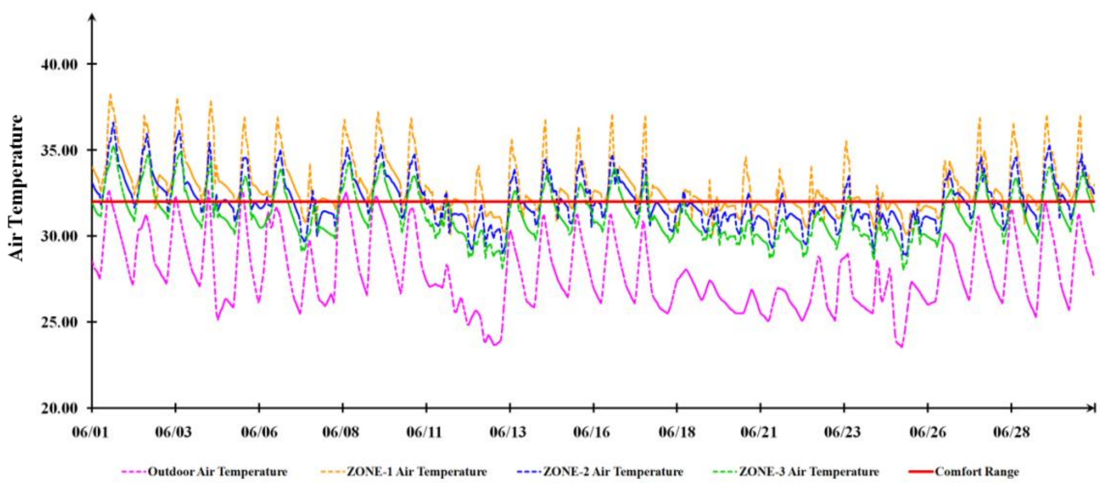


Figure 6.36 Comparison of AT(ºC) of different zones for wall type W-5e.

With respect to outdoor temperature linear regression analysis of temperature gradients shows variability of about 56-61.5 percent. OT(ºC) has maximum variation around its mean which is 61.6 percent. Variation of air and MRT(ºC) is 55.9 and 61.2 percent around its mean. Linear regression analysis for wall type W-5e is presented in Appendix D. Correlation matrix for wall typesW-5e shows positive correlation among different temperature gradients whereas best fitted correlation occurs among outdoor temperature and resulted temperature gradients when AT(ºC), MRT(ºC) and OT(ºC) are 0.75, 0.78 and 0.78 respectively (Appendix D). MRT(ºC) and OT(ºC) have best fitted correlation with AT(ºC) when the values of these temperatures are 0.90 and 0.98 respectively.

f) Wall type W-5f

Wall W-4f is 50mm (2") thick. Outer and inner walls have thicknesses of 12.5mm (½") and 18.75mm (¾") respectively having 18.75mm (¾") cavity insulated with coconut fiber in between them. Analysis of simulation result is summarized and observed that mean temperature gradients of Z-1 are 0.3ºC-0.9ºC higher than comfort temperature. Other zones have temperature gradients within comfort level. Mean outdoor and mean zone AT(ºC) difference ranges between 2.8ºC-5ºC. Average value of MRT(ºC) of Z-2 and Z-3 remain within comfort level whereas Z-1 has marginally higher (0.34ºC) MRT(ºC) compared to comfort temperature. But parametric study result for wall type W-5f shows that during first few days when outdoor temperature remains comparatively high (≥28ºC), Z-1 and Z-2 temperature gradients remain above comfort temperature all the day while Z-3 temperature remains below upper comfort during late to early morning. Fig. 6.37 illustrates AT(ºC) of three zones while different temperature gradients during the first seven days of study period are shown in Appendix D.

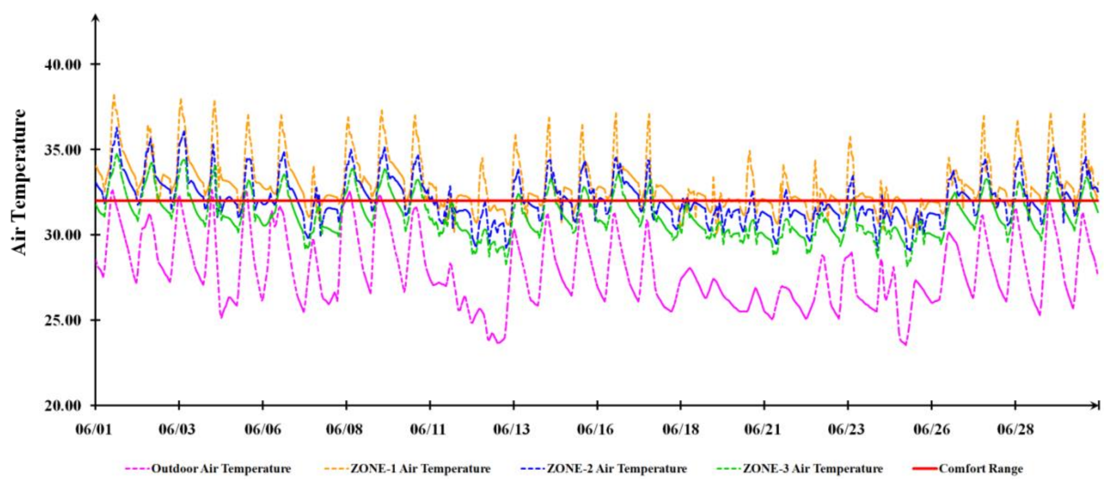


Figure 6.37 Comparison of AT(ºC) of different zones for wall type W-5f.

Linear regression analysis of temperature gradients with respect to outdoor temperature is studied. About 50.5-57.5 percent variability is noticed for different temperature gradients. OT(ºC) has maximum variation around its mean which is 57.7 percent. Variation of nearly 50.6 percent is found for AT. Positive correlation remains among different temperature gradients. Best fitted correlation occurs among outdoor temperature and resulted temperature gradients when AT(ºC), MRT(ºC) and OT(ºC) are 0.71, 0.77 and 0.76 respectively (Appendix D) whereas best fitted correlation of MRT(ºC) and OT(ºC) with AT(ºC) exists when the values of MRT(ºC) and OT(ºC) are 0.88 and 0.97 respectively.

g) Wall type W-5g

Wall type W-5g is composed of two 12.5mm (½") wooden walls having 25mm (1") cavity space in between them. Cavity is insulated with coir as cavity insulation material. Total thickness of the wall is 50mm (2"). Descriptive statistics of obtained result from the parametric study shows that Z-1 mean temperature gradients are 0.5ºC-1ºC higher while other zones' temperature gradients are within comfort level (Appendix D). MRT(ºC) is 0.5ºC higher than respective zone AT(ºC). Maximum and minimum temperature difference within a zone ranges between 6ºC-8.5ºC, 0.5ºC-6.8ºC and 6.25ºC-7ºC for air, MRT(ºC) and OT(ºC) respectively. Standard deviation is below 1.5 for all temperature gradients.

Z-1 has higher and Z-3 has lower temperature gradients. Mean temperature gradients of Z-2 and Z-3 remain within comfort zone whereas Z-1 mean temperature gradients are higher than comfort level. During first few days Z-1 and Z-2 temperature gradients remain above comfort temperature all the day while at Z-3 it is within comfort zone during late-night to early morning. Temperature gradients and linear regression analysis for wall type W-5g is provided in Appendix D. Linear regression analysis of resulted temperature gradients with respect to outdoor temperature shows variability of about 47.5-57 percent. MRT has maximum variation around its mean which is nearly 57 percent. OT(ºC) variation with respect to outdoor AT(ºC) is about 55 percent whereas variation of AT(ºC) is 47.4 percent around its' mean.

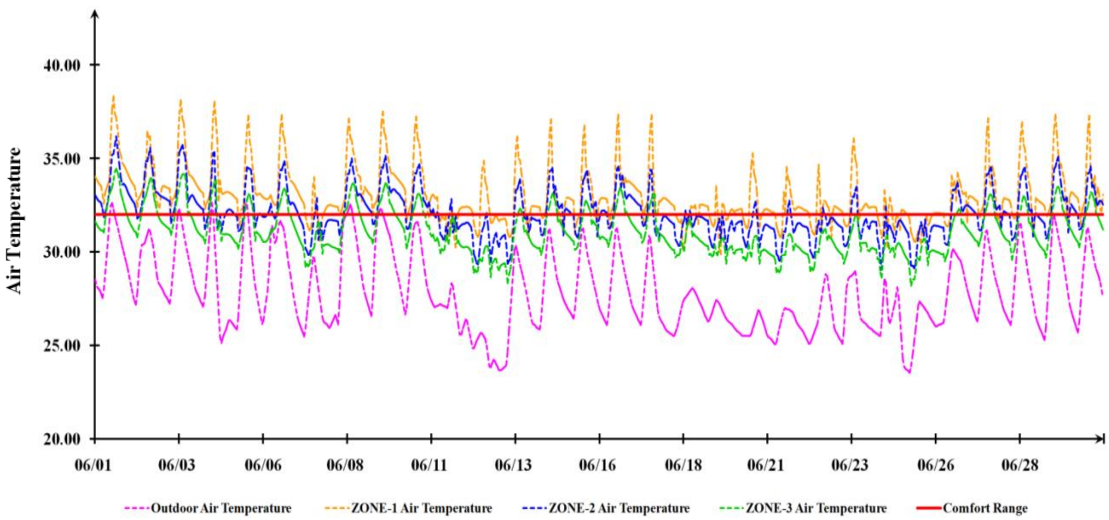


Figure 6.38 Comparison of AT(ºC) of different zones for wall type W-5g.

Different temperature gradients are related with each other positively where best fitted correlation results with indoor temperature gradients and outdoor AT(ºC) when AT(ºC), MRT(ºC) and OT(ºC) are 0.79, 0.76 and 0.74 respectively. AT(ºC) has a best fitted correlation with MRT(ºC) and OT(ºC) when the values of these temperatures are 0.88 and 0.97 respectively. Correlation matrix for wall W-5g is presented in Table 6.72.

h) Comparison of Wall Construction W-5

Wall Construction W-5 has two wooden walls with a cavity insulated with coconut fiber/coir in between them. Thickness of outer wall is 12.5mm (½") thick which is fixed for all walls whereas inner wall has three different thicknesses 12.5mm (½"), 18.75mm (¾") and 25mm (1"). Cavity thickness for insulation varies from 6.25mm-25mm (¼"-1"). Thickness of six different wall types: W-5a to W-5g varies between 37.5mm-50mm (1½"-2").

Wall W-5a, W-5c and W-5f have 18.75mm (¾") thick inner wall with coconut fiber insulation thicknesses of 6.25mm (½"), 12.5mm (½") and 18.75mm (¾") respectively. Thickness of inner wall of W-5b, W-5d and W-5g is 12.5mm (½") while insulation thicknesses are 12.5mm (½"), 18.75mm (¾") and 25mm (1") respectively. Wall type W-5e has cavity thickness of 12.5mm (½") with inner wall of thickness 25mm (1"). Outdoor temperature is constant for all wall types considered whereas maximum, mean and minimum AT(ºC) are 32.63ºC, 27.83ºC and 23.54ºC respectively with standard deviation of 2.03. Fig. 6.39 illustrates zone AT for different wall types of W-5 and Table 6.19 presents zone-wise temperature gradients for different wall types. From the table it is observed that except Z-1, mean and minimum value of temperature gradients of the other zones remain within upper level of comfort. Z-1 mean AT(ºC) is 0.75ºC-1ºC whereas MRT(ºC) and OT(ºC) are 0.05ºC-0.42ºC and 0.4ºC-0.7ºC (respectively) higher than comfort temperature. Maximum temperature gradients of all zones remain 2.2ºC-7ºC above the comfort range.AT(ºC) is 7.78ºC-9.39ºC higher than upper level of comfort in existing condition. With respect to comfort temperature, mean and minimum temperatures remain within acceptable range; however, at Z-1 mean AT(ºC) is marginally higher (0.46ºC) than comfort level. Compared to existing thermal condition, considered wall Constructions resulted in low maximum but high mean and minimum temperature gradients. Difference between existing and studied wall maximum temperature is highest at Z-3 and lowest at Z-1, but for mean and minimum temperature gradients the result shows reverse effect. Relative performance analysis of different wall types of W-5 illustrates that in all cases W-5g has the lowest maximum and W-5a has the lowest minimum AT(ºC). Simulation study for W-5a resulted in 2.32ºC-3.15ºC lower maximum AT compared to existing condition whereas for W-5g the difference is 3.1ºC-5.3ºC.

Table 6.19 Comparative performance analysis of cavity walls insulated with coconut fiber/coir (W-5)

Temp. (°C)	Wall Type	Maximum (°C)			Mean (°C)			Minimum (°C)		
		Z-1	Z-2	Z-3	Z-1	Z-2	Z-3	Z-1	Z-2	Z-3
Air Temp	Existing wall	41.39	40.23	39.78	32.46	31.8	31.36	27.38	26.5	26.26
	W-5a	39.07	37.79	36.63	32.75	31.97	31.33	29.42	28.22	27.52
	W-5b	38.84	37.11	35.61	32.89	32.04	31.23	29.93	28.69	27.83
	W-5c	38.49	36.84	35.41	32.87	32.03	31.22	30.02	28.83	27.96
	W-5d	38.52	36.55	34.92	32.96	32.07	31.14	30.1	28.92	28.06
	W-5e	38.22	36.6	35.23	32.85	32.04	31.22	30.07	28.88	28.05
	W-5f	38.19	36.28	34.73	32.95	32.08	31.14	30.08	29.05	28.17
	W-5g	38.34	36.18	34.45	33.02	32.1	31.07	29.87	29.04	28.19
MRT Temp.	Existing wall	39.73	39.33	39.05	31.73	31.37	31.04	26.97	26.3	26.01
	W-5a	37.59	37.26	36.34	32.05	31.51	30.88	28.86	28.01	27.33
	W-5b	37.12	36.67	35.41	32.22	31.57	30.74	29.39	28.47	27.62
	W-5c	36.87	36.4	35.18	32.21	31.58	30.74	29.48	28.61	27.75
	W-5d	36.74	36.14	34.69	32.32	31.61	30.63	29.76	28.79	27.85
	W-5e	36.63	36.16	34.97	32.22	31.59	30.74	29.55	28.7	27.82
	W-5f	36.48	35.88	34.48	32.34	31.62	30.63	29.86	28.92	27.96
	W-5g	36.52	35.79	34.2	32.42	31.64	30.55	30.01	28.99	27.98
OT Temp.	Existing wall	40.42	39.78	39.42	32.1	31.58	31.2	27.18	26.4	26.14
	W-5a	38.11	37.53	36.49	32.4	31.74	31.11	29.14	28.12	27.42
	W-5b	37.87	36.89	35.51	32.55	31.8	30.99	29.66	28.58	27.73
	W-5c	37.53	36.62	35.29	32.54	31.81	30.98	29.75	28.74	27.85
	W-5d	37.56	36.34	34.81	32.64	31.84	30.88	30.03	28.92	27.96
	W-5e	37.26	36.38	35.1	32.54	31.82	30.98	29.82	28.82	27.94
	W-5f	37.23	36.08	34.61	32.64	31.85	30.89	30.13	29	28.07
	W-5g	37.37	35.99	34.33	32.72	31.87	30.81	30.27	29.05	28.08

*Temperature gradients above comfort temperature is highlighted with color

Maximum values of MRT(ºC) and OT(ºC) for W-5g are 3.21ºC-4.85ºC and 3.05ºC-5.09ºC (consecutively) lower than existing condition whereas for W-5a these differences are 2.07ºC-2.71ºC and 2.31ºC-2.93ºC respectively. Mean and minimum temperature gradients for wall W-4 are higher than existing thermal condition. Resulted mean temperature gradient for W-5g is 0.13ºC-0.3ºC higher than that of the W-5a whereas for minimum temperature the difference is 0.45ºC-1.15ºC.

Standard deviation of existing wall construction has the highest value. AT(ºC) and OT(ºC) of Z-2 have lower standard deviation but MRT(ºC) of Z-1 has a relatively lower standard deviation compared to others. Among all the walls W-5ghas lower standard deviation meaning temperature gradients fluctuate less during the simulation period. Table 6.20 shows standard deviation of different cavity walls insulated with coir (W-5).

Table 6.20 Standard deviation of different cavity walls insulated with coconut fiber/coir (W-5)

Wall Type	Outdoor Temp.	Air Temp.			MRT Temp.			OT Temp.		
		Z-1	Z-2	Z-3	Z-1	Z-2	Z-3	Z-1	Z-2	Z-3
Existing wall	2.03	2.77	2.52	2.54	2.61	2.66	2.76	2.67	2.57	2.63
W-5a	2.03	1.92	1.67	1.71	1.77	1.8	1.86	1.82	1.72	1.78
W-5b	2.03	1.75	1.46	1.47	1.57	1.58	1.6	1.63	1.5	1.53
W-5c	2.03	1.65	1.41	1.41	1.48	1.51	1.54	1.53	1.44	1.47
W-5d	2.03	1.59	1.32	1.28	1.4	1.41	1.4	1.46	1.35	1.33
W-5e	2.03	1.57	1.37	1.36	1.42	1.46	1.48	1.45	1.39	1.42
W-5f	2.03	1.51	1.29	1.24	1.32	1.35	1.34	1.37	1.3	1.28
W-5g	2.03	1.52	1.25	1.17	1.29	1.3	1.27	1.36	1.25	1.21

*Color gradient shows comparative changes in standard deviation

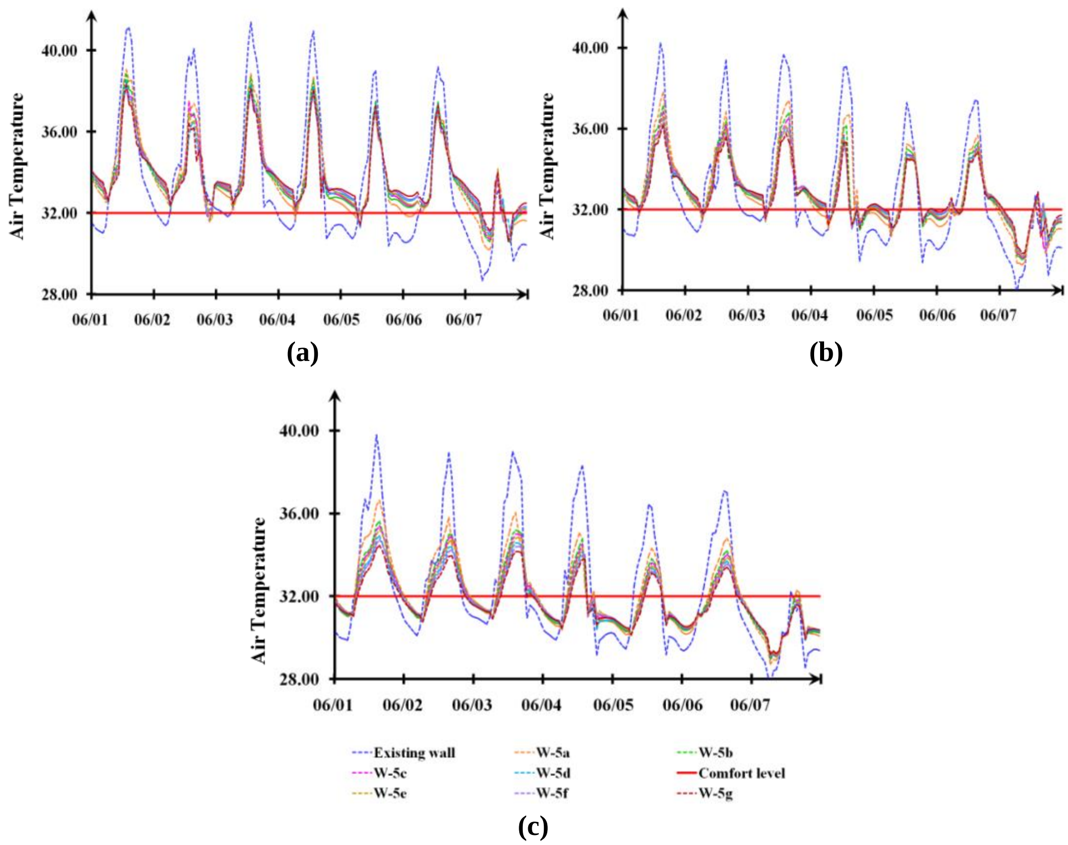


Figure 6.39 Comparison of changes in AT(ºC) for different wall types of W-5:
(a) Zone-1 (Z-1), (b) Zone-2 (Z-2) and (c) Zone-3 (Z-3).

6.4.6 Wall Constructions having Cavity Insulated with Jute Fiber: W-6

Wall construction W-6 has two timber walls of same/different thickness having cavity space in between them filled with jute fiber as insulation material. Total thickness of wall ranges between

37.5mm-50mm (1½"-2"). Cross-section of wall type W-6 is presented in Fig. 6.40. Thermal properties of envelope materials considered for simulations are presented in Table 6.21.

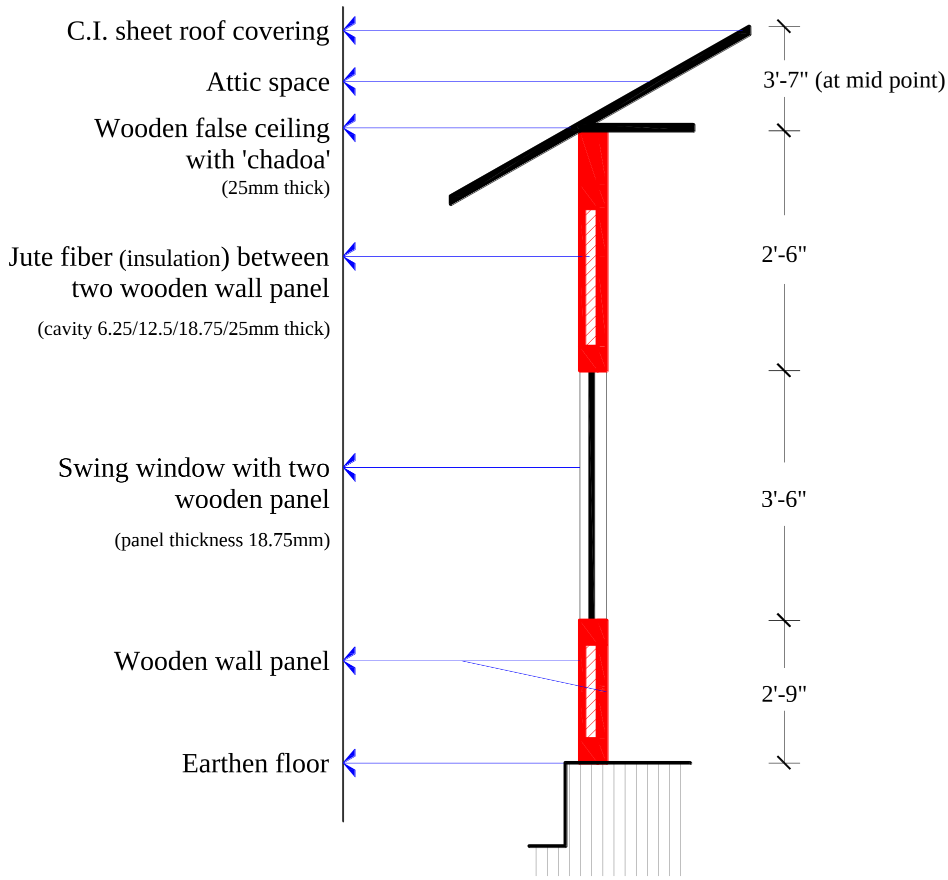


Figure 6.40 Cross sectional view of wall type W-6.

Table 6.21 Thermal properties of envelopes considered for wall type W-6.

Envelope	Material	Thickness (mm)	Conductivity (W/m-K)	Density (kg/m^3)	Specific-Heat (J/kg-K)
Wall	Teak	12.5 /18.75 /25	1.28	710	1880
	Jute fiber	6.25 /12.5 /18.75 /25			
Roof	C.I. sheet	0.5	65	7300	235
Ceiling	Raintree	25	0.74	480	1880
Chadoa	Cotton fabric	0.01	0.04	225	1380.72
Floor	Earthen	-	1.4	1460	879
Window	Sal	18.75	0.96	660	1880
Door	Sal	25	0.96	660	1880

a) Wall type W-6a

Wall type W-6a has outer 12.5mm (½") and inner 18.75mm (¾") thick wooden walls having 6.25mm (¼") cavity in between them which is insulated with jute fiber. Total thickness of the wall is 37.5mm (1½"). Result obtained from the parametric study is summarized in Table 6.76. Descriptive statistics of W-6a shows that among all temperature gradients AT(ºC) is high for all the three zones. Z-1 has the highest (39.44ºC) and Z-3 has the lowest (37.43ºC) AT(ºC). Mean AT(ºC) of Z-1 is 0.67ºC higher while MRT(ºC) is within comfort level. Z-2 and Z-3 mean temperature gradients are lower than upper level of comfort. Maximum and minimum AT difference within a zone is nearly 10.5ºC and difference between zones mean air and MRT(ºC) ranges between 0.4ºC-1.4ºC. In all cases standard deviations remain around 2.

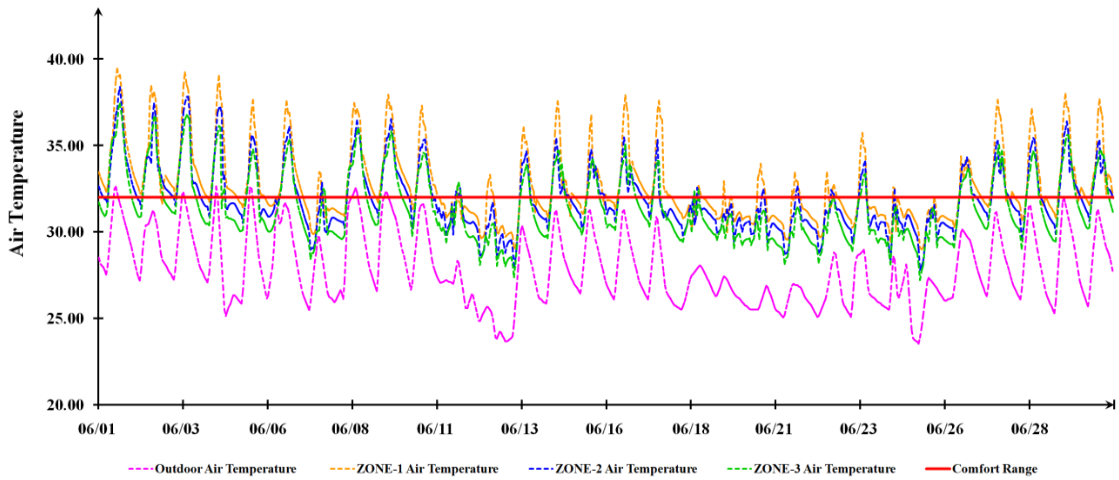


Figure 6.41 Comparison of AT(ºC) of different zones for wall type W-6a.

Fig. 6.41 presents the comparative variation in zone AT(ºC) with respect to outdoor temperature during the study period. From the figure it is observed that AT(ºC) of Z-1 and Z-2 remains above upper range of comfort when outdoor AT(ºC) is higher than 28ºC. Z-3 shows lower temperature compared to Z-1 but still temperature remains above the comfort level most of the time. Z-2 and Z-3 MRT(ºC) and OT(ºC) remain within comfort level during late-night to early-morning for first few days of study period. Temperature gradient for first seven days of the study period for wall type W-6a is provided in Appendix D.

Linear regression analysis of zone temperature gradients shows how all the temperature gradients change with respect to outdoor temperature during study period. Temperature gradients' variation of about 70-73 percent is observed. OT(ºC) has the maximum variation around its mean which is 72.8 percent. AT(ºC) variation of about 70.3 percent is obtained from regression analysis.

Table 6.77 presents correlation matrix of temperature gradients. Positive correlation remains among different temperature gradients. Best fitted correlation among outdoor temperature and temperature gradients occur when AT(ºC), MRT(ºC) and OT(ºC) is 0.84, 0.85 and 0.85 respectively. When MRT(ºC) and OT(ºC) are 0.96 and 0.99 respectively best fitted correlation occurs between them and AT(ºC).

b) Wall type W-6b

Wall type W-6b has total thickness of 37.5mm (1½"). Considered wall type have two 12.5mm (½") wooden leafs with 12.5mm (½") cavity in between them insulated with jute fiber. Descriptive statistics of obtained result from the parametric study is presented in descriptive statistics format (Appendix D). Maximum temperature of all three zones remains 4.3ºC-7.2ºC higher than comfort temperature. Z-1 has the highest (39.18ºC) and Z-3 has the lowest (36.60ºC) AT(ºC). Maximum and minimum AT(ºC) difference within a zone ranges between 9ºC-9.7ºC approximately. MRT(ºC) is nearly 0.5ºC-0.7ºC lower than respective zone AT(ºC). In all cases standard deviations remain below 2.

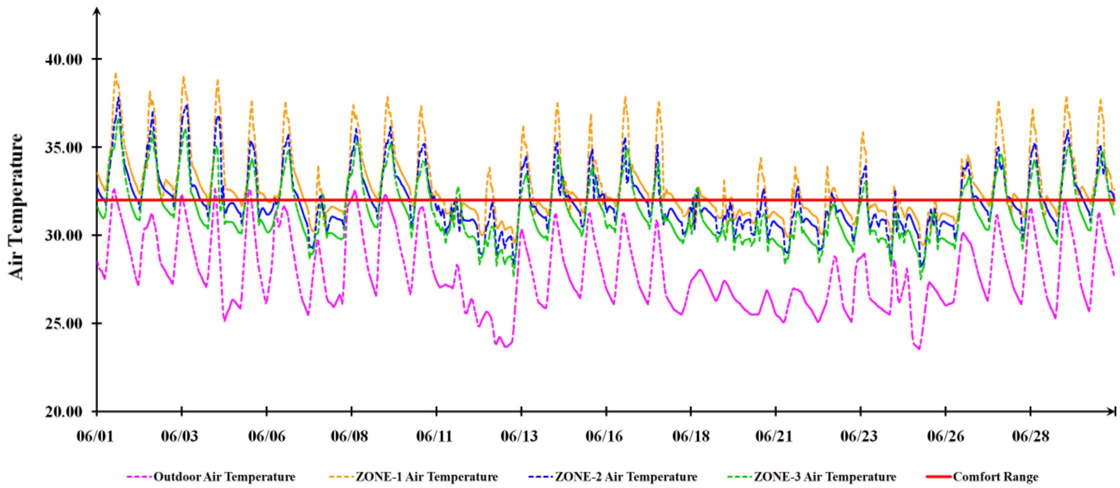


Figure 6.42 Comparison of AT(ºC) of different zones for wall type W-6b.

Temperature gradients of Z-1 remain above upper range of comfort during the first few days when the outdoor temperature is high. However, Z-2 and Z-3 have low temperatures compared to Z-1 but still temperature gradients remain above comfort level most of the time. Fig. 6.42 shows variation in zone AT(ºC) with respect to outdoor and Appendix D shows obtained temperature gradients during first seven days.

Linear regression analysis of temperature gradients with respect to outdoor temperature is studied and provided in Appendix D. About 66-70 percent variability is noticed for different temperature gradients. OT(ºC) and MRT(ºC) have maximum variation around its mean. Variation ranges nearly 70 percent for both MRT(ºC) and OT. Different temperature gradients have positive correlation with each other. Best fitted correlation of MRT(ºC) and OT(ºC) with AT(ºC) occurs when they are 0.95 and 0.95 respectively (Appendix D).

c) Wall type W-6c

Outer walls and inner wall of W-6c are 12.5mm (½") and 18.75mm (¾") in thickness. Cavity thickness in between them is 12.5mm (½") which is insulated with jute fiber as cavity insulation. Descriptive statistics of obtained result from the parametric study shows that zone temperature gradients remain higher than comfort temperature most of the time especially when outdoor temperature is high (≥28ºC). AT(ºC) is high compared to other temperature gradients. Z-1 temperature is 0.07ºC-0.7ºC higher than comfort temperature. Fig. 6.43 illustrates AT(ºC) for wall W-6c. From figure it is observed that temperature gradients of Z-1and Z-2 remain above upper range of comfort all the day during first few days. Compared to other two zones, Z-3 shows low temperature gradients but remains above comfort level most of the time. Temperature gradients for all the three zones for the period of first seven days are provided in Appendix D.

Linear regression analysis of temperature gradients with respect to outdoor temperature is presented in Appendix D. About 64-67.5 percent variability is noticed for different temperature gradients. OT(ºC) and MRT(ºC) have maximum variation around its mean which ranges around 67.5 percent. There remains a positive correlation among different temperature gradients. Correlation matrix among temperatures is presented in Table 6.81. Best fitted correlation of MRT(ºC) and OT(ºC) with AT(ºC) occurs when they are 0.94 and 0.99 respectively (Appendix D).

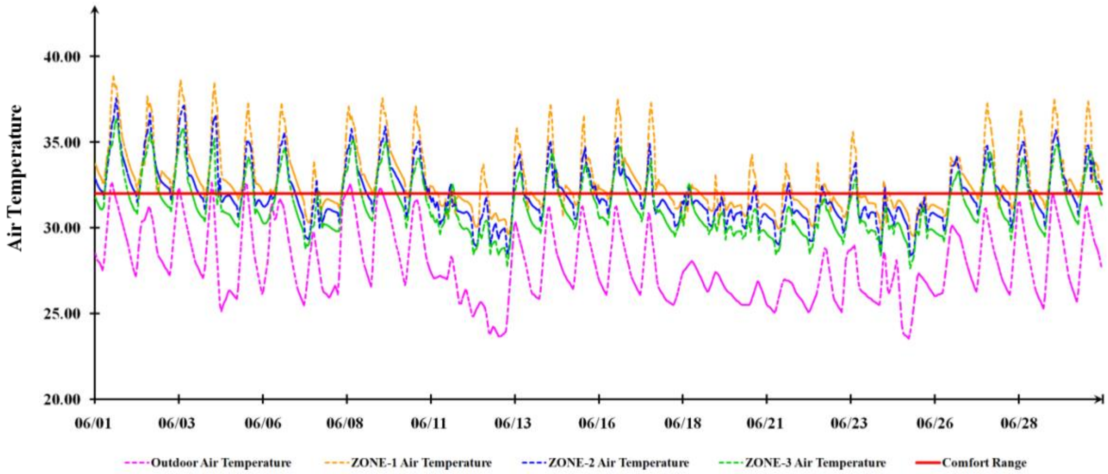


Figure 6.43 Comparison of AT(ºC) of different zones for wall type W-6c.

d) Wall type W-6d

Wall type W-6d has two 12.5mm (½") wooden walls with a cavity of 18.75mm (¾") in between them. Cavity is insulated with jute fiber. Descriptive statistics of parametric study result shows that mean temperature gradients of Z-1 are higher compared to other zones and remain above the upper value of comfort (Appendix D). AT is high compared to other temperature gradients. Z-1 has the highest (38.77ºC) and Z-3 has the lowest (35.84ºC) mean AT(ºC) value. Difference between maximum and minimum AT(ºC) within a zone ranges between 8.1ºC-8.9ºC. Average value of MRT is nearly 0.5ºC-0.6ºC lower than respective zone average AT(ºC) whereas for maximum temperature gradient the difference is 0.3ºC-1.5ºC. In all cases standard deviation is 1.5.

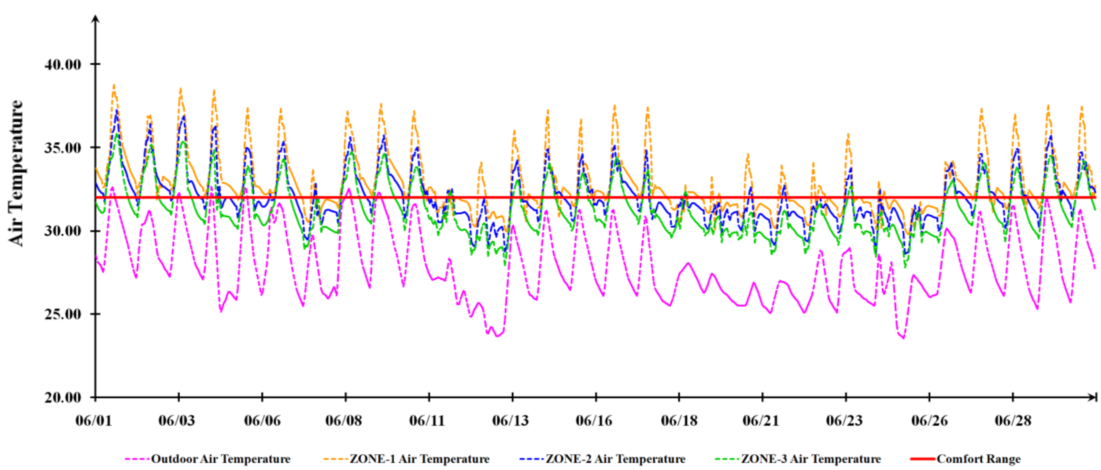


Figure 6.44 Comparison of AT(ºC) of different zones for wall type W-6d.

During first few days of the study period all the temperature gradients remain high. Fig. 6.44 presents the comparative variation in zone AT(ºC) during the study period and temperature gradients for first week of the study period for wall type W-6d is provided in Appendix D. From the figure it is observed that temperature gradients of Z-1 remain above upper range of comfort when minimum value of outdoor AT(ºC) remains high (≥28ºC). However, Z-2 and Z-3 show lower temperatures compared to

Z-1, but remain above the comfort level most of the time. Z-3 temperature gradients remain within comfort level during late-night to early morning even if minimum outdoor temperature is higher than 28ºC.

Linear regression analysis of temperature gradients with respect to outdoor temperature is presented in Appendix d. Different temperature gradients show a variation of about 61-65.5 percent variability around its mean. MRT(ºC) have maximum variation around its mean. A variation of nearly 65.8 percent is found for MRT(ºC). Variation of AT(ºC) is 60.8 percent. Positive correlation remains among different temperature gradients. Best fitted correlation occurs among outdoor temperature and resulted temperature gradients when AT(ºC), MRT(ºC) and OT(ºC) are 0.78, 0.81 and 0.81 respectively (Appendix D).

e) Wall type W-6e

Thicknesses of outer and inner walls of W-6e wall type are 12.5mm (½") and 25mm (1") respectively with a cavity of 12.5mm (½") thickness in between them which is filled with jute fiber. Total thickness of W-6e is 50mm (2"). Mean temperature gradients of Z-1 are 0.1ºC-0.75ºC higher than upper level of comfort. Other zones have mean temperature gradients within comfort level. Difference between mean outdoor and zone AT(ºC) is around 3.5ºC-4.9ºC. Average and maximum values of MRT(ºC) are nearly 0.5C 0.67C and 0.3ºC-1.44ºC lower than the relevant zone mean and maximum AT(ºC) respectively.

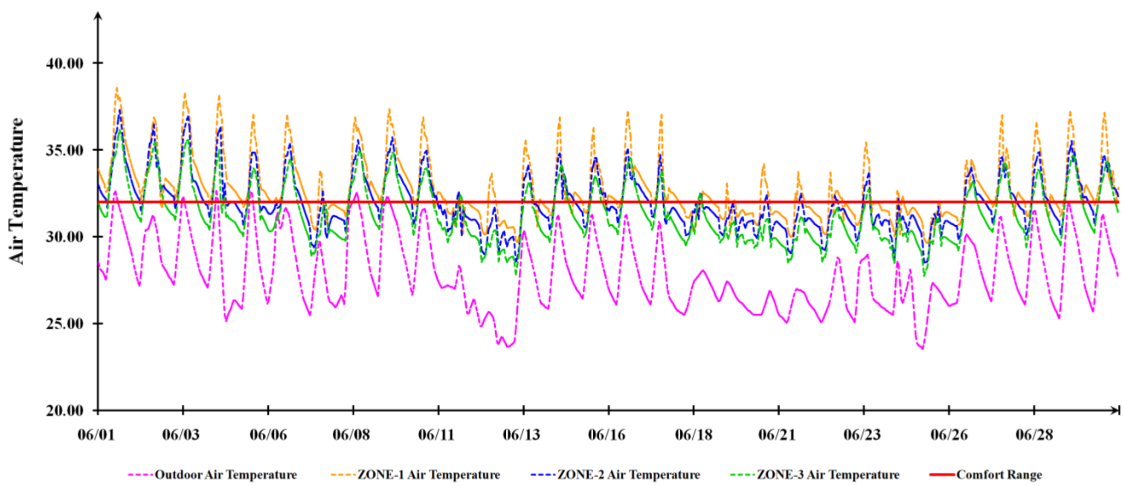


Figure 6.45 Comparison of AT(ºC) of different zones for wall type W-6e.

Parametric study results for wall type W-6e show that during first few days when outdoor temperature remains comparatively high, Z-1 and Z-2 AT(ºC) and OT(ºC) remain above comfort temperature all the day (Appendix D), however, Z-2 MRT(ºC) still remains below comfort upper limit. All through the study period, Z-3 temperature remains below upper comfort level during late to early morning. Different temperature gradients during first seven days of study period are presented in Appendix D.

With respect to outdoor temperature, linear regression analysis of temperature gradients shows variability of about 62.5-66.5 percent. OT(ºC) has maximum variation around its mean which is 66.3 percent. Variation of AT(ºC) and MRT(ºC) are 62.4 and 65.4 percent around its mean. Correlation matrix for wall type W-6e shows positive correlation among different temperature gradients whereas best fitted correlation occurs among outdoor temperature and resulted temperature gradients when AT(ºC), MRT(ºC) and OT(ºC) are 0.79, 0.81 and 0.81 respectively (Appendix D). MRT(ºC) and OT(ºC) have the best correlation with AT(ºC) when the values of these temperatures are 0.91 and 0.98 respectively.

f) Wall type W-6f

Wall W-6f is 50mm (2") thick. Outer and inner walls have thicknesses of 12.5mm (½") and 18.75mm (¾") respectively having 18.75mm (¾") cavity insulated with jute fiber in between them. Analysis of simulation result shows that mean outdoor and mean zone AT(ºC) difference ranges between 3.5ºC-5ºC (Appendix D). Mean temperature gradients of Z-1 are 0.16ºC-0.82ºC higher while other zones have temperature gradients within comfort level. Average value of MRT(ºC) of Z-2 and Z-3 remain within comfort level whereas Z-1 has marginally higher (0.16ºC) MRT(ºC). But parametric study shows that during first few days' outdoor temperature remains comparatively high (≥28ºC) and during this period Z-1 and Z-2 temperature gradients remain above comfort temperature all the day. Z-3 temperature remains below upper comfort from late to early morning. Fig. 6.46 illustrates AT(ºC) of three zones while different temperature gradients during first seven days of study period are presented in Appendix D.

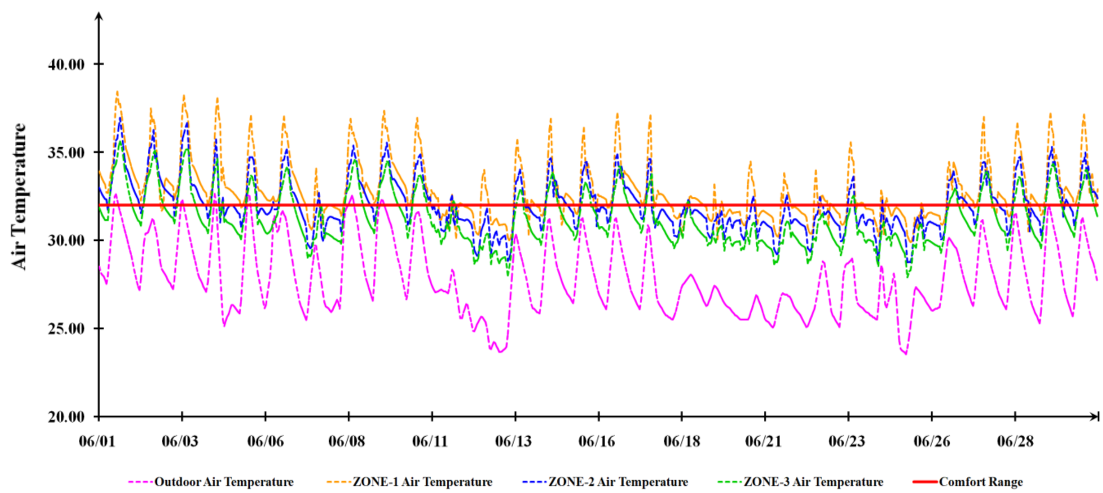


Figure 6.46 Comparison of AT(ºC) of different zones for wall type W-6f.

Linear regression analysis of temperature gradients with respect to outdoor temperature is studied. About 59-64 percent variability is noticed for different temperature gradients. OT(ºC) has maximum variation around its mean which is 63.9 percent. Variation of nearly 59.2 percent is observed for AT(ºC). Different temperature gradients have positive correlation with each other. Best correlation occurs among outdoor temperature and zone temperature gradients when air, MRT(ºC) and OT(ºC) are 0.77, 0.80 and 0.80 respectively whereas best correlation of MRT(ºC) and OT(ºC) with AT(ºC) exists when values of MRT(ºC) and OT(ºC) are 0.92 and 0.98 respectively (Appendix D).

g) Wall type W-6g

Wall type W-6g is composed of two 12.5mm (½") wooden walls having 25mm (1") cavity in between them. Cavity is insulated with jute fiber as cavity insulation material. Total thickness of the wall is 50mm (2"). Descriptive statistics of obtained results for wall W-6g shows that Z-1 mean temperature gradients are 0.2ºC-8ºC higher than comfort temperature while other zones' temperature gradients are within comfort level. Average MRT(ºC) is 0.5ºC-0.6ºC higher than respective zone mean AT(ºC) whereas difference between maximum MRT(ºC) and respective zone mean AT(ºC) is 0.3ºC-

1.5ºC. Difference between maximum and minimum temperature within a zone ranges between 7.5ºC-8.5ºC. Standard deviation is around 1.5 for all temperature gradients.During parametric study period it is noticed that Z-1 has higher and Z-3 has lower temperature gradients. Mean temperature gradients of Z-2 and Z-3 remain within comfort level whereas Z-1 mean temperature gradients are higher than upper level of comfort. Fig. 6.47 illustrates AT(ºC) of three zones during study period. During first few days Z-1 and Z-2 temperature gradients remain above comfort temperature all the day while Z-3 temperature gradients remain within comfort zone during late-night to early morning. Temperature gradients of three different zones for wall type W-6g are presented in Appendix D.

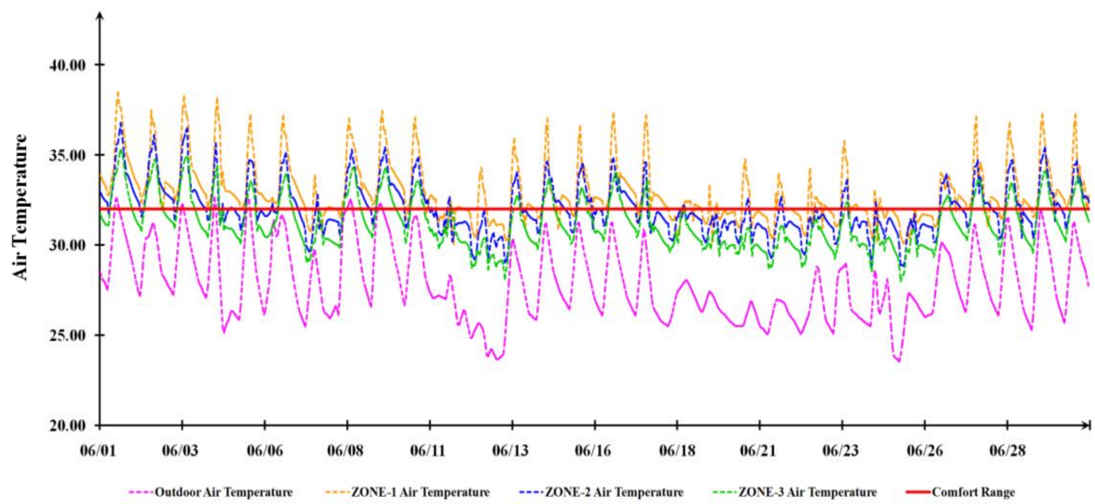


Figure 6.47 Comparison of AT(ºC) of different zones for wall type W-6g.

Linear regression analysis of resulted temperature gradients with respect to outdoor temperature shows variability of about 56-62 percent. MRT(ºC) has maximum variation around its mean which is nearly 62.2 percent. AT(ºC) variation with respect to outdoor AT(ºC) is about 55.9 percent whereas variation of MRT(ºC) is 61.5 percent around its' mean. Different temperature gradients are related with each other positively where best fitted correlation results with indoor temperature gradients and outdoor AT(ºC) when AT(ºC), MRT(ºC) and OT(ºC) are 0.75, 0.79 and 0.78 respectively. AT(ºC) has a best correlation with MRT(ºC) and OT(ºC) when the values of these temperatures are 0.91 and 0.98 (Appendix D).

h) Comparison of Wall Types W-6

Wall Construction W-6 has two wooden walls with a cavity insulated with jute fiber in between them. 12.5mm (½") thick outer wall is fixed for all walls whereas inner walls have three different thicknesses 12.5mm (½"), 18.75mm (¾") and 25mm (1"). Cavity thickness for insulation varies between 6.25mm-25mm (¼"-1"). Thicknesses of six different wall types (W-5a to W-5g) vary between 37.5mm-50mm (1½"-2").

Wall types W-6a, W-6c and W-6f have 18.75mm (¾") thick inner wall with jute fiber insulation thicknesses of 6.25mm (½"), 12.5mm (½") and 18.75mm (¾") respectively. Thickness of inner wall of W-6b, W-6d and W-6g is 12.5mm (½") while insulation thicknesses are 12.5mm (½"), 18.75mm (¾") and 25mm (1") respectively. Wall type W-6e has cavity thickness of 12.5mm (½") with inner wall of 25mm (1") thick. Outdoor temperature is constant for all cases considered where mean AT(ºC) is 27.83ºC with standard deviation of 2.03. Fig. 6.48 illustrates zone AT(ºC) and Table 6.22 presents zone-wise temperature gradients for W-6.

Maximum temperature gradients remain 3ºC-7.5ºC above the comfort range. At different zones mean and minimum values of temperature gradients remain within comfort level except Z-1 mean temperature, which is 0.07ºC-0.89ºC higher than comfort temperature. Resulted mean AT(ºC) of Z-1 is 0.67ºC-0.89ºC higher than upper level of comfort. Average MRT(ºC) is marginally (0.07ºC-0.24ºC) and OT(ºC) is 0.56ºC (maximum) higher than comfort temperature.

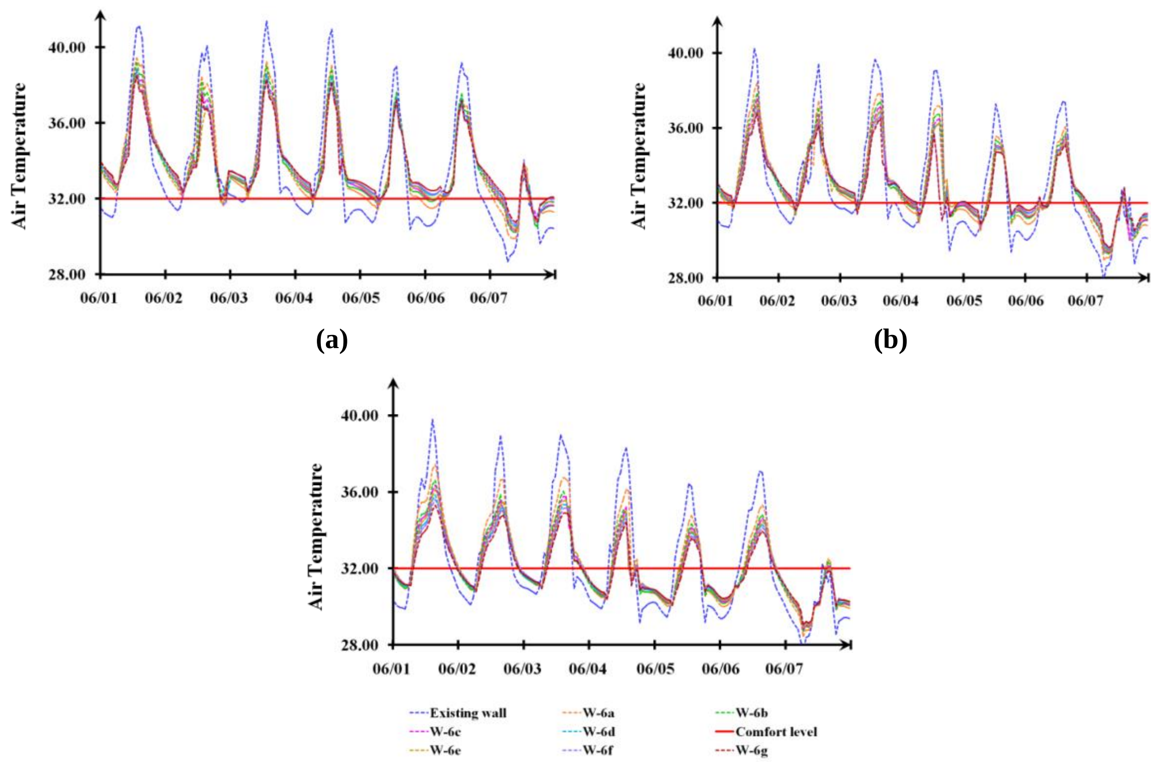
Table 6.22 Comparative performance analysis of cavity walls insulated with jute fiber (W-6)

Name	Wall Type	Maximum (°C)			Mean (°C)			Minimum (°C)		
		Z-1	Z-2	Z-3	Z-1	Z-2	Z-3	Z-1	Z-2	Z-3
Air Temp	Existing wall	41.39	40.23	39.78	32.46	31.8	31.36	27.38	26.5	26.26
	W-6a	39.44	38.39	37.43	32.67	31.91	31.38	28.98	27.8	27.21
	W-6b	39.18	37.82	36.6	32.79	31.98	31.32	29.45	28.21	27.51
	W-6c	38.84	37.55	36.36	32.77	31.99	31.31	29.53	28.37	27.63
	W-6d	38.77	37.23	35.84	32.84	32.03	31.26	29.8	28.6	27.78
	W-6e	38.56	37.3	36.14	32.74	31.99	31.31	29.61	28.5	27.74
	W-6f	38.45	36.96	35.61	32.82	32.02	31.25	29.88	28.74	27.9
	W-6g	38.48	36.78	35.29	32.89	32.04	31.19	30.02	28.83	27.97
MRT Temp.	Existing wall	39.73	39.33	39.05	31.73	31.37	31.04	26.97	26.3	26.01
	W-6a	38.08	37.8	37.07	31.94	31.46	30.94	28.44	27.59	27.02
	W-6b	37.64	37.3	36.32	32.08	31.52	30.87	28.88	27.99	27.31
	W-6c	37.37	37.04	36.07	32.07	31.52	30.85	28.99	28.15	27.43
	W-6d	37.16	36.76	35.6	32.17	31.55	30.78	29.26	28.39	27.58
	W-6e	37.12	36.79	35.84	32.07	31.53	30.85	29.07	28.27	27.52
	W-6f	36.9	36.49	35.36	32.16	31.56	30.77	29.34	28.5	27.69
	W-6g	36.82	36.34	35.05	32.24	31.58	30.7	29.53	28.62	27.77
OT Temp.	Existing wall	40.42	39.78	39.42	32.1	31.58	31.2	27.18	26.4	26.14
	W-6a	38.58	38.09	37.25	32.31	31.68	31.16	28.71	27.69	27.11
	W-6b	38.22	37.56	36.46	32.43	31.75	31.09	29.17	28.1	27.41
	W-6c	37.88	37.3	36.22	32.42	31.76	31.08	29.26	28.26	27.53
	W-6d	37.81	37	35.72	32.5	31.79	31.02	29.53	28.49	27.68
	W-6e	37.61	37.05	35.99	32.41	31.76	31.08	29.35	28.39	27.65
	W-6f	37.49	36.72	35.48	32.49	31.79	31.01	29.61	28.63	27.8
	W-6g	37.52	36.56	35.17	32.56	31.81	30.95	29.8	28.75	27.87

*Temperature gradients above comfort temperature is highlighted with color

AT(ºC) of existing condition is 7.78ºC-9.39ºC higher than upper level of comfort. Z-1 mean AT is slightly higher (0.46ºC) than comfort range while mean and minimum temperature remain within comfort level for existing envelope condition. Obtained result for considered wall constructions shows low maximum but high mean and minimum temperature values compared to existing thermal condition. Difference of maximum temperature gradients between existing and studied walls is highest at Z-3 and lowest at Z-1, but for mean and minimum temperature gradients shows opposite effect.

Comparative performance analysis of different W-6 wall types shows that in all cases W-6g has the lowest maximum and W-6a has the lowest minimum AT(ºC) (Fig. 6.48). Again, regarding mean and minimum temperature gradients W-6a has lowest and W-6g has the highest temperature values. Maximum AT(ºC) of W-6g is 2.9ºC-4.5ºC lower compared to existing condition where at Z-1 difference is small and at Z-3 it is high. Difference between resulted AT(ºC) (maximum) for existing and W-6a wall is 1.95ºC-2.35ºC. Maximum value of MRT(ºC) of W-6a and W-6g are 1.65ºC-1.98ºC and 2.1ºC-4.0ºC whereas resulted OT(ºC) are 1.84ºC-2.17ºC and 2.9ºC-4.25ºC lower than existing condition respectively. Mean temperature gradients of wall W-6g is 0.13ºC-0.3ºC higher than W-6a whereas for minimum temperature the difference is 0.75ºC-1.1ºC.



(c)

Figure 6.48 Comparison of changes in AT(ºC) for different wall types of W-6:
(a) Zone-1 (Z-1), (b) Zone-2 (Z-2) and (c) Zone-3 (Z-3).

Table 6.23 Standard deviation of different cavity walls insulated with jute fiber (W-6).

Wall Type	Outdoor Temp.	Air Temp.			MRT Temp.			OT Temp.		
		Z-1	Z-2	Z-3	Z-1	Z-2	Z-3	Z-1	Z-2	Z-3
Existing wall	2.03	2.77	2.52	2.54	2.61	2.66	2.76	2.67	2.57	2.63
W-6a	2.03	2.12	1.84	1.93	1.97	2	2.09	2.02	1.9	2
W-6b	2.03	1.95	1.67	1.7	1.78	1.8	1.86	1.84	1.72	1.78
W-6c	2.03	1.85	1.61	1.65	1.7	1.74	1.79	1.75	1.66	1.71
W-6d	2.03	1.77	1.51	1.52	1.6	1.63	1.66	1.65	1.55	1.58
W-6e	2.03	1.75	1.56	1.59	1.62	1.67	1.72	1.65	1.6	1.65
W-6f	2.03	1.67	1.45	1.47	1.52	1.55	1.59	1.56	1.48	1.52
W-6g	2.03	1.63	1.39	1.38	1.46	1.49	1.5	1.52	1.42	1.44

*Color gradient shows comparative changes in standard deviation

Existing wall Construction has highest standard deviation. Among all walls, W-6ghas lower standard deviation meaning temperature gradients for this wall fluctuates less during the simulation period. AT(ºC) and OT(ºC) of Z-2 have lower standard deviation values while MRT(ºC) of Z-1 has a lower standard deviation value compared to other zones. Table 6.23 shows standard deviation of different cavity walls insulated with jute fiber (W-6).

6.5 Comparative Performance Analysis of Different Wall Constructions

A total of thirty-eight wall types under six different parameters: thickness, glued layer, cavity and cavity insulation with three locally available materials (i.e., straw, coconut fiber and jute fiber) have been considered for parametric study. From each wall Construction one comparatively best performed wall type has been selected. Among all thicknesses considered 37.5mm (1½") wall performs comparatively well. Similarly, wall having three 12.5mm (total thickness 37.5mm) glued panel performed better. Among all considered cavity and insulated Construction's wall with 12.5mm wooden panels with 25mm cavity/insulation in between them shows comparatively better performance. In this section these selected wall types have been analyzed to figure out the best possible wall type towards traditional timber house wall design strategy. For all parametric study same outdoor condition was considered. Maximum, mean and minimum outdoor AT(ºC) is 32.63ºC, 27.83ºC and 23.54ºC respectively with standard deviation of 2.03.

Table 6.24 Temperature gradients of relatively best performed walls from considered Constructions.

Name	Wall Type	Maximum (°C)			Mean (°C)			Minimum (°C)		
		Z-1	Z-2	Z-3	Z-1	Z-2	Z-3	Z-1	Z-2	Z-3
Air Temp	W-1d	39.97	39.31	38.63	32.5	31.78	31.38	27.97	26.94	26.54
	W-2d	39.85	39.2	38.52	32.49	31.78	31.38	28.04	26.99	26.58
	W-3e	38.91	37.75	36.68	32.72	31.96	31.34	29.39	28.22	27.53
	W-4g	38.78	37	35.46	32.9	32.04	31.21	30	28.75	27.88
	W-5g	38.34	36.18	34.45	33.02	32.1	31.07	29.87	29.04	28.19
	W-6g	38.48	36.78	35.29	32.89	32.04	31.19	30.02	28.83	27.97
MRT Temp.	W-1d	38.84	38.57	38.16	31.74	31.34	30.99	27.51	26.76	26.38
	W-2d	38.72	38.47	38.04	31.75	31.34	30.98	27.56	26.81	26.42
	W-3e	37.51	37.21	36.35	32.02	31.5	30.89	28.84	28.01	27.35
	W-4g	37.04	36.57	35.26	32.24	31.58	30.73	29.46	28.54	27.67
	W-5g	36.52	35.79	34.2	32.42	31.64	30.55	30.01	28.99	27.98
	W-6g	36.82	36.34	35.05	32.24	31.58	30.7	29.53	28.62	27.77
OT Temp.	W-1d	39.4	38.94	38.39	32.12	31.56	31.19	27.75	26.85	26.46
	W-2d	39.28	38.84	38.28	32.12	31.56	31.18	27.8	26.9	26.5
	W-3e	37.98	37.48	36.51	32.37	31.73	31.12	29.11	28.12	27.44
	W-4g	37.82	36.79	35.36	32.57	31.81	30.97	29.73	28.65	27.78
	W-5g	37.37	35.99	34.33	32.72	31.87	30.81	30.27	29.05	28.08
	W-6g	37.52	36.56	35.17	32.56	31.81	30.95	29.8	28.75	27.87

*Temperature gradients above comfort temperature is highlighted with color

Fig. 6.49 shows variation of AT(ºC) at different zones whereas Table 6.24 illustrates temperature gradients of relatively best performed walls from considered Constructions. Statistical summary shows that all walls have maximum temperature gradients higher than comfort level. Among all, W-5g has comparatively lowest temperature gradients whereas W-6g has slightly higher than those of W-5g. Maximum temperature gradients of W-5g is 3ºC-3.3ºC lower than existing and 0.5ºC-2.32ºC lower than other wall types considered. This result reflects that wall types having only wooden panels are relatively less resistant against outdoor temperature compared to cavity/insulated one. Again among all considered insulation materials, coconut fiber shows better insulation quality. For this reason, minimum temperature gradients are 1.5ºC (maximum) higher than other walls considered, though these remain below upper level comfort. Similarly, though mean temperature is slightly higher for W-5g compared to other walls but it remains within upper level of comfort.

Temperature gradient for MRT(ºC) is lower compared to OT(ºC) whereas AT(ºC) has the highest temperature values within a zone. This situation is similar for all considered wall types. Among the three zones, Z-1, being the middle space of the house, has relatively higher temperature gradients and Z-3 (rear and north room) has the lowest temperature whereas Z-2 (south) being the front room has slightly high temperature compared to Z-3. AT(ºC) of Z-1 is higher than that of the Z-2. For AT(ºC) it is about 0.6ºC-1.7ºC high, whereas, for MRT(ºC) and OT(ºC) they are 0.3ºC-1ºC and 0.5ºC-1.4ºC high respectively. However, temperature decreased from Z-1 to Z-3 about a range of 1ºC-3.9ºC, 0.7ºC-2.3ºC and 1ºC-3ºC for AT(ºC), MRT(ºC) and OT(ºC) respectively.

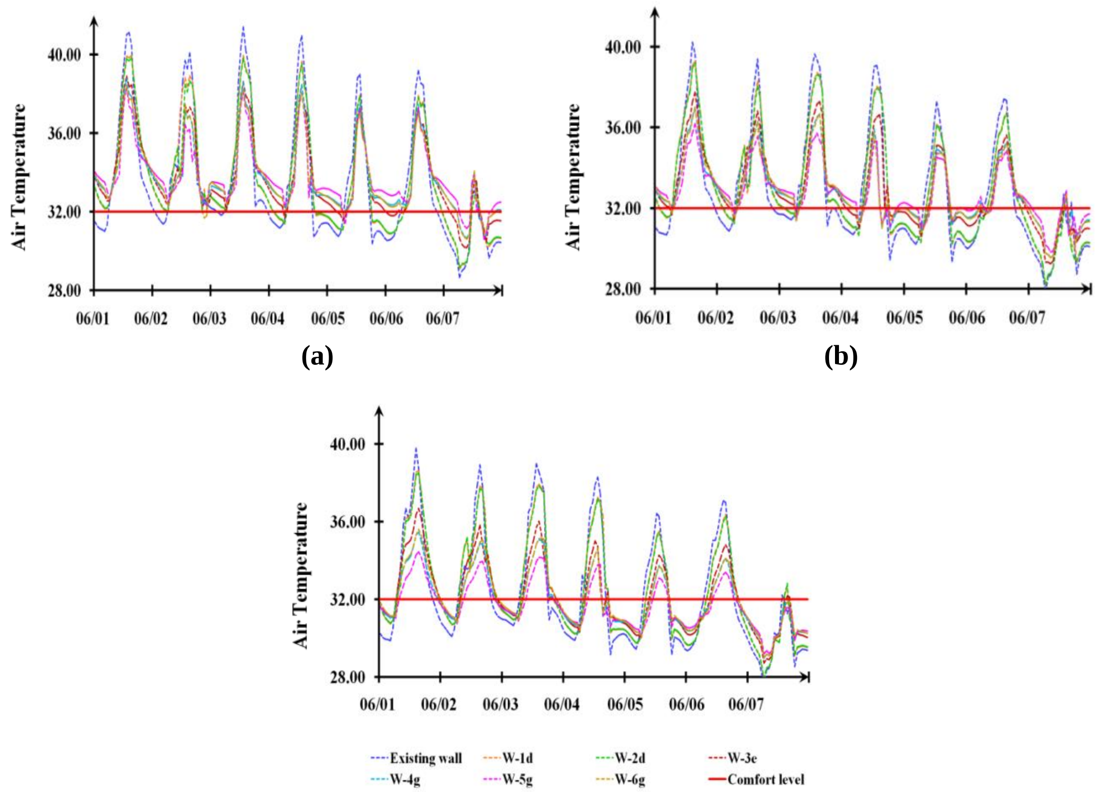


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Figure 6.49 Comparison of changes in AT(ºC) for different wall Constructions: (a) Zone-1 (Z-1), (b) Zone-2 (Z-2) and (c) Zone-3 (Z-3).

Table 6.25 Standard deviation of relatively best performed walls for considered Constructions.

Wall Type	Outdoor Temp.	Air Temp.			MRT Temp.			OT Temp.		
		Z-1	Z-2	Z-3	Z-1	Z-2	Z-3	Z-1	Z-2	Z-3
W-1d	2.03	2.47	2.22	2.3	2.33	2.38	2.48	2.38	2.28	2.38
W-2d	2.03	2.42	2.19	2.27	2.29	2.35	2.45	2.34	2.25	2.35
W-3e	2.03	1.9	1.67	1.71	1.76	1.8	1.87	1.81	1.72	1.78
W-4g	2.03	1.72	1.43	1.43	1.53	1.54	1.56	1.59	1.47	1.49
W-5g	2.03	1.52	1.25	1.17	1.29	1.3	1.27	1.36	1.25	1.21
W-6g	2.03	1.63	1.39	1.38	1.46	1.49	1.5	1.52	1.42	1.44

*Color gradient shows comparative changes in standard deviation

Table 6.93 shows that lowest standard deviation is observed for wall type W-5g compared to other walls which means fluctuation of temperature level is less for this wall type throughout the simulation period. Wall types W-6g and W-4g have slightly higher standard deviation compared to W-

5g. Wall types W-3e, W-4g, W-5g and W-6g have standard deviation below 2 whereas for W-1d and W-2d it is above 2. Standard deviation for W-1d has the highest value. Standard deviation values were relatively less at front zone (Z-2) than those of the middle (Z-1) and rear zone (Z-3) which mean temperature fluctuate less in the front zone. From correlation matrix, it is observed that resulted temperature gradients for Z-2 are less scattered compared to other two zones in all the cases considered for parametric simulation studies. Table 6.25 illustrates standard deviation of relatively best performed walls for considered walls. From the analysis it is seen that AT(ºC), MRT(ºC) and OT(ºC) for the configurations varies slightly from each other whereas is relatively high for cavity and insulated cavity walls compared to the others in question.

6.6 Simulation Study Result for Roof Construction

6.6.1. Roof with Attic Space: R-1

Three-dimensional model for parametric study of roof type R-1 is similar to that of the model considered for wall simulation. The model has three zones: Z-1 (front zone), Z-2 (middle zone) and back zone (Z-3) having total area of 43.64 sqm. Considered model has 12.5mm thick wooden wall envelope while floor is earthen attached with ground. Fenestrations are considered same as the existing window pattern: swing having two wooden shutters of 18.75mm (¾") thickness. Both internal and external doors have two swing wooden panels of 25mm (1") thickness. Under roof Construction of R-1, two roof types are considered: R-1a and R-1b. Both roof types have similar Construction but the only exception is roof covering material. For R-1a C.I. sheet whereas for R-1b roof tile is considered as roofing materials. Cross-sectional view of R-1 is shown in Fig. 6.50. Thermal properties of all envelope materials considered for roof Construction of R-1 are presented in Table 6.26.

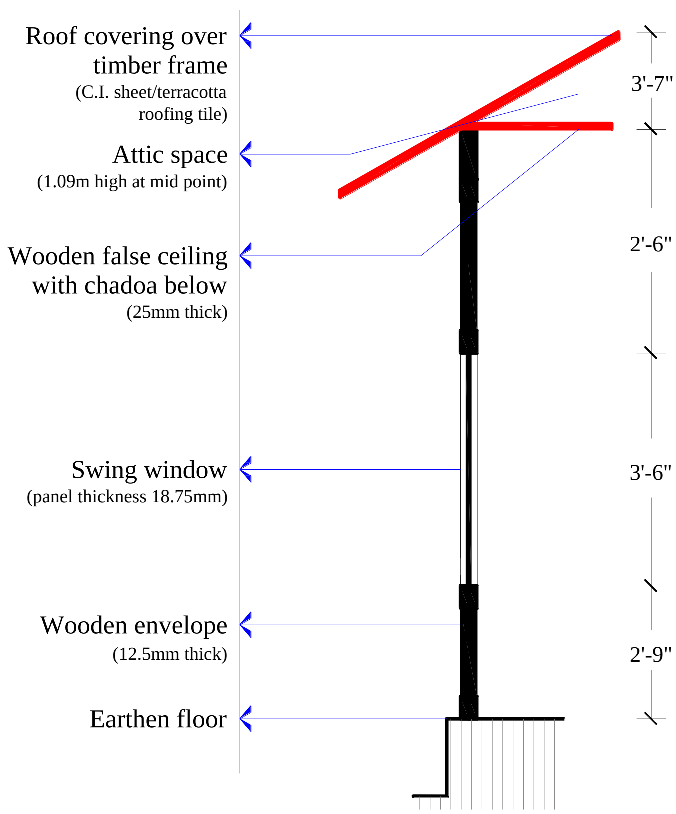


Figure 6.50 Cross sectional view of roof type R-1.

Table 6.26 Thermal properties of envelopes considered for roof type R-1.

Envelope	Material	Thickness	Conductivity	Density	Specific-Heat
Roof covering	C.I. sheet	0.5mm	65	7300	235
	Terracotta roof tile				
Ceiling	Raintree	25mm	0.74	480	1880
Chadoa	Cotton fabric	0.01	0.04	225	1380.72
Wall	Teak	12.5mm	1.28	710	1880
Floor	Earthen	-	1.4	1460	879
Window	Sal	18.75mm	0.96	660	1880
Door	Sal	25mm	0.96	660	1880

a) Roof type R-1a

Roof type R-1a, considered for simulation study, is similar to that of the existing model. It has C.I. sheet covering with an attic space of 1.09m high provided with 25mm thick wooden false-ceiling. ‘Chadoa’ (a cotton/polyester fabric) is also considered under the false ceiling. Statistical summary of the parametric study is similar for existing condition presented in Table 6.1. Appendix D illustrates linear regression analysis for roof type R-1a. With respect to outdoor temperature, linear regression analysis of resulted temperature gradients shows variability of about 77-80.5 percent. MRT(ºC), with the value of 80.5 percent, has the maximum variation around its mean. AT(ºC) variation with respect to outdoor AT(ºC) is 77.1 percent whereas variation of MRT is 79.8 percent around its’ mean.

Temperature gradients have a positive correlation with outdoor temperature. Correlation among outdoor temperature and resulted temperature gradients occurs when AT(ºC), MRT(ºC) and OT(ºC) are 0.88, 0.90 and 0.89 respectively, whereas, standard correlation with AT(ºC) exists between MRT(ºC) and OT(ºC) when the value of these two temperature gradients are 0.97 and 0.99 respectively.

b) Roof Type R-1b

Roof type R-1b has terracotta roof tiles over the timber frame with an attic space of 1.09m high. Wooden false-ceiling is 25mm thick which is provided with a ‘Chadoa’ extended under the ceiling. Table 6.96 illustrates the descriptive statistics summary of the parametric study for roof type R-1b and Fig. 6.51 presents the AT(ºC) variation within different zones during the study period. Descriptive statistics of roof type R-1b shows that among all temperature gradients AT(ºC) has the higher value for all the three zones (Appendix D). Z-1 has highest (41.55ºC) and Z-3 has the lowest (40.25ºC) AT(ºC). Mean AT(ºC) of Z-1 is 0.48ºC higher than comfort temperature while MRT(ºC) and OT(ºC) remain within comfort level. Z-2 and Z-3 mean temperature gradients are lower than upper level of comfort. Maximum and minimum AT difference within a zone is nearly 13.5ºC-14ºC and difference between zones mean AT(ºC) and MRT(ºC) ranges between 0.3ºC-0.7ºC. In all cases standard deviations remain above 2.5.

AT(ºC) of all zones remains above upper range of comfort most of the time when outdoor AT(ºC) is higher than 28ºC. However, temperature gradients remain within comfort level during late-night to early-morning. Z-3 shows lower temperature compared to Z-1 but still temperature remains above the comfort level most of the time. Fig. 6.51 presents the comparative variation in zone AT(ºC) while temperature gradient for first seven days of the study period for roof type R-1b are shown in Appendix D.

Linear regression analysis of resulted temperature gradients and outdoor AT(ºC) shows 77-80.5 percent variability. Maximum variation is 80.5 percent which occurs for MRT(ºC). Minimum variation resulted for AT(ºC) which is 77.1 percent. Variation of OT is 79.7 percent around its' mean. Linear regression analysis for roof type R-1b is studied and presented in Appendix D.Positive correlation remains between temperature gradients and outdoor temperature. Best fitted correlation occurs among outdoor temperature and resulted temperature gradients when AT(ºC), MRT(ºC) and OT(ºC) are 0.88, 0.90 and 0.89 respectively. Standard correlation with AT(ºC) exists between MRT(ºC) and OT(ºC) when the values of these two temperature gradients are 0.97 and 0.99 respectively (Appendix D).

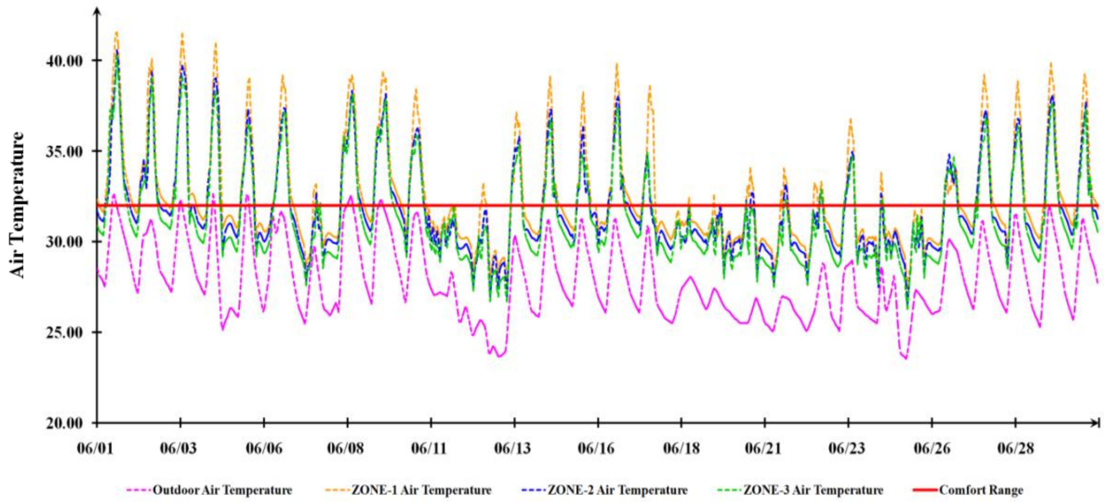


Figure 6.51 Comparison of AT(ºC) of different zones for roof type R-1b.

6.6.2. Roof without Attic Space: R-2

Parametric studies conducted for roof Construction R-2 has similar model Construction to that of the model considered for R-1. But Roof Construction R-2 has no attic space below roof covering. Under roof Construction of R-2, four roof types are considered: R-2a, R-2b, R-2c and R-2d. R-2a and R-2b have C.I. sheet while R-2c and R-2d have terracotta tiles as roof covering material. Material used under roof covering is different which is either wooden shingles or bamboo knitted mat. Cross-sectional view of R-2 is shown in Fig. 6.52. Thermal properties of all envelope materials (roof, floor, wall) considered for roof Construction of R-2 are presented in Table 6.27.

Table 6.27 Thermal properties of envelopes considered for roof type R-2.

Envelope	Material	Thickness (mm)	Conductivity	Density	Specific-Heat
Roof covering	C.I. sheet	0.5	65	7300	235
	Terracotta roof tile	15	0.84	1900	800
Material below covering	Wooden shingle	12.5	0.115	512	1256
	Bamboo knitted mat	5	0.55	900	1800
Ceiling	Raintree	25	0.74	480	1880
Chadoa	Cotton fabric	0.01	0.04	225	1380.72
Wall	Teak	12.5	1.28	710	1880
Floor	Earthen	-	1.4	1460	879
Window	Sal	18.75	0.96	660	1880
Door	Sal	25	0.96	660	1880

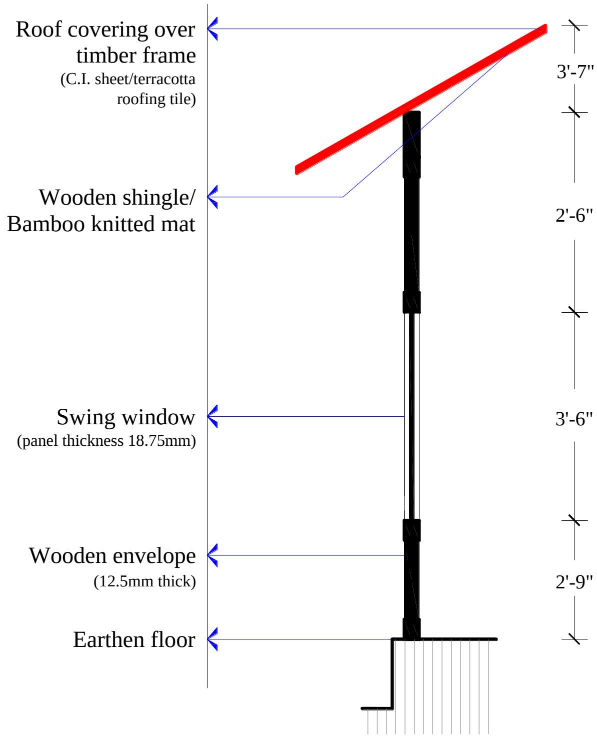


Figure 6.52 Cross sectional view of roof type R-2.

a) Roof type R-2a

Roof type R-2a has C.I. sheet over the timber frame without any attic space. 12.5mm wooden shingle under the C.I. sheet is considered. Summary of the descriptive statistics of parametric study shows that temperature gradients resulted for all the three zones show much higher value compared to comfort temperature. Z-1 air and OTs have nearly similar and higher value compared to MRT(ºC). Difference between MRT and other two (AT(ºC) and OT(ºC)) is about 1.5ºC at Z-1; whereas, Z-2 and Z-3 temperature gradients have almost similar values. Mean temperature gradients of Z-1 is 0.5ºC-1ºC higher whereas Z-2 and Z-3 remain around the value of upper level of comfort (32ºC). In all cases standard deviations are high (around 5).

Z-1 has higher and Z-3 has lower temperature value. AT of all zones remains far above the upper limit of comfort most of the time but remains within comfort level during late-night to early-morning when outdoor AT(ºC) is above 28ºC. Maximum zone AT(ºC) is 15.5C-18.27C higher than comfort temperature. Mean AT(ºC) of Z-1 is 0.92C higher but at rest of the zone it remains around the comfort temperature. Fig. 6.53 presents the comparative variation in zone AT(ºC) during study period and temperature gradient for first seven days of study period for roof type R-2a is provided in Appendix D.

Linear regression analysis of resulted temperature gradients has been studied. linear regression analysis for roof type R-1b is provided in Appendix D. From the figure a variability of 68.6-71.8 percent is observed for different temperature gradients where maximum variation resulted for MRT(ºC). Variation of MRT(ºC) is 80.5 percent around its' mean. Minimum variation resulted for AT(ºC) which is 77.1 percent whereas variation of OT is 79.7 percent around its' mean. Positive correlation remains between temperature gradients and outdoor temperature. Best fitted correlation results among outdoor temperature and resulted temperature gradients when AT(ºC), MRT(ºC) and OT(ºC) are 0.83, 0.85 and

0.85 respectively. Standard correlation with AT(ºC) exists between MRT(ºC) and OT(ºC) when the value of these two temperature gradients are 0.97 and 0.99 respectively (Appendix D).

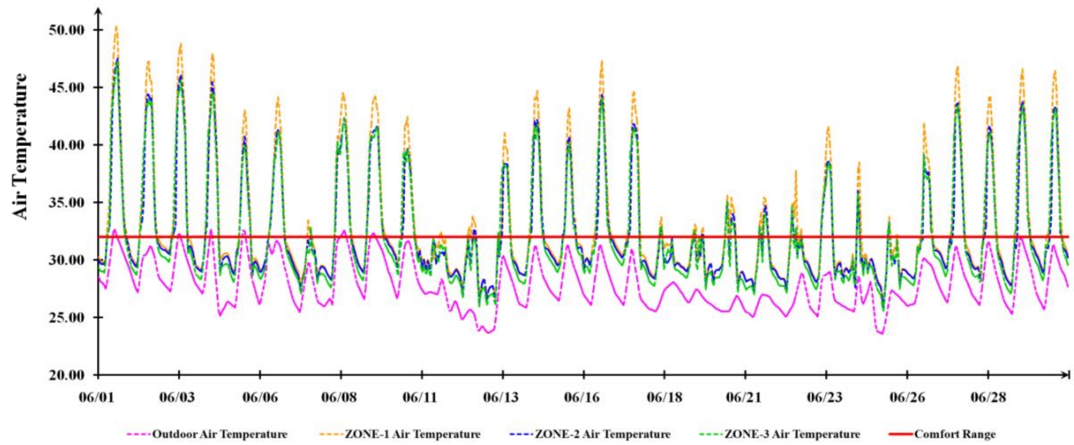


Figure 6.53 Comparison of AT(ºC) of different zones for roof type R-2a.

b) Roof type R-2b

Roof type R-2b is similar to the roof combination of R-2a but the only difference is that below C.I. sheet instead of wooden shingle, 5mm thick bamboo knitted mat is considered. Table 6.101 presents the summary of descriptive statistics of obtained parametric study results for roof type R-2b. From the table it is observed that maximum AT(ºC) is above 50ºC while minimum AT(ºC) is around 25ºC for all the three zones. For all temperature gradients Z-1 has higher value. Difference between maximum and minimum temperature within a zone is nearly 24.5ºC-28ºC. Zone mean temperature is 0.26ºC-1.13ºC higher than upper range of comfort. Standard deviations range between nearly 5.5-6 where Z-1 has a higher and Z-2 has a lower standard deviation. Variation in zone AT(ºC) during study period is presented in Fig. 6.54. When outdoor AT(ºC) is higher than 28ºC, zone AT(ºC) remains above upper range of comfort most of the time; however, they remain within comfort level during late-night to early-morning. Z-3 shows comparatively lower temperature than other two zones though it remains above the comfort level. Temperature gradient for first seven days of study period for roof type R-2b is provided in Appendix D.

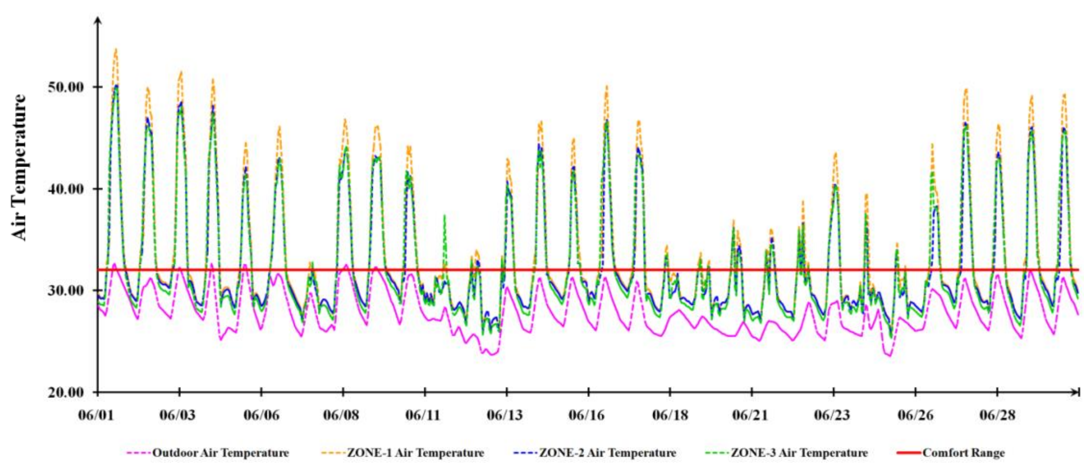


Figure 6.54 Comparison of AT(ºC) of different zones for roof type R-2b.

Linear regression analysis shows 67-70 percent variability of resulted temperature gradients. Maximum variation occurs for both MRT(ºC) and OT(ºC) which is 69.5 percent whereas minimum variation resulted for AT(ºC) which is 67.1 percent. Linear regression analysis for roof type R-2b is presented in Appendix D. Positive correlation remains between outdoor and resulted temperature gradients. Best fitted correlation occurs among them when AT(ºC), MRT(ºC) and OT(ºC) are 0.82, 0.83 and 0.83 respectively. Best correlation of MRT(ºC) and OT(ºC) with AT(ºC) occurs when values of the former two temperature gradients are 0.97 and 0.99 respectively.

c) Roof type R-2c

Roof type R-2c has similar composition as R-2a except that, instead of C.I. sheet, terracotta roof tile is considered as roof covering material. Summary of the descriptive statistics shows that Z-2 and Z-3 mean temperature gradients remain around comfort temperature while Z-1 temperature gradients are 0.5ºC-0.8ºC higher than upper level of comfort (Appendix D). Maximum temperature gradients are 15.11ºC-17.75ºC higher and minimum temperature gradients are 5.85ºC-7ºC lower than upper level of comfort. Standard deviations are below 5. Z-1 has higher and Z-3 has lower while Z-2 has slightly higher temperature gradients. Temperature gradients of all three zones remain within comfort level during late-night to early-morning. Fig. 6.55 presents the variation in zone AT(ºC) during study period while temperaturegradient for first seven days is shown in Appendix D.

Linear regression analysis of resulted temperature gradients and outdoor AT(ºC) show 68.5-73 percent variability. Maximum variation is 73.1 percent which occurs for MRT. Minimum variation resulted for AT(ºC) which is 68.6 percent. Linear regression analysis for roof type R-2c is provided in Appendix D.Correlation matrix of temperature gradients is presented in Appendix D. Positive correlation remains between outdoor and resulted temperature gradients while best fitted correlation occurs among outdoor temperature and resulted temperature gradients when AT(ºC), MRT(ºC) and OT(ºC) are 0.83, 0.86 and 0.85 respectively. However, best correlation of MRT(ºC) and OT with AT(ºC) occurs when value of former two temperature gradients is 0.97 and 0.99 respectively.

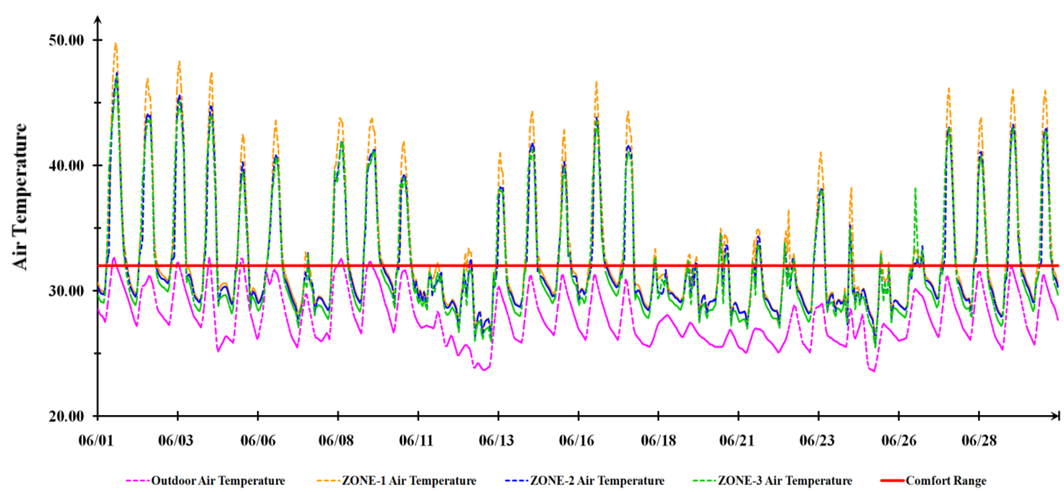


Figure 6.55 Comparison of AT(ºC) of different zones for roof type R-2c.

d) Roof type R-2d

Roof type R-2d has terracotta roof tile over the timber frame. 5mm bamboo knitted mat under the terracotta roof covering is considered. R-2d has no false ceiling or attic space below the roof. Table

6.105 illustrates the summary of parametric study for roof type R-2d. From the descriptive statistics it is observed that temperature gradients resulted for all the three zones shows much higher value compared to comfort temperature range which ranges between 49.5ºC-50.5ºC (Appendix D). Z-1 has a higher temperature compared to other two zones while Z-2 and Z-3 have nearly similar temperature gradients. Difference between maximum and minimum temperature within a zone varies between 24.5ºC-27ºC where minimum difference resulted in Z-3. Among all temperature gradients MRT(ºC) has the lowest value. Mean temperature of all zones remains above the upper level of comfort whereas for Z-2 and Z-3 it is 0.1ºC-0.3ºC and for Z-1 it is 0.75ºC-1ºC higher than the upper level of comfort. Standard deviations are high and remain nearly 5-5.5. Zone AT(ºC) reach as high as 50ºC-52ºC when maximum outdoor AT reaches the upper level of comfort (32ºC) during mid-day. Zone temperature gradients remain above upper range of comfort most of the time when outdoor AT(ºC) is higher than 28ºC; however, temperature gradients remain within comfort level during late-night to early-morning. Variation in temperature is higher at Z-1 and lower at Z-2 and Z-3. Fig. 6.56 presents the zone AT(ºC) variation during study period while first seven days' temperature gradients resulted for roof type R-2d is shown in Appendix D.

Linear regression analysis for roof type R-1d and from the figure it is observed that resulted temperature gradients have a variability of about 68.8-72 percent around its' mean. Maximum variation resulted for MRT(ºC) which is 71.7 percent. Minimum variation resulted for AT(ºC) which is 68.8 percent whereas variation of OT(ºC) is 71.2 percent around its' mean. Positive correlation remains between temperature gradients where best fitted correlation occurs among outdoor temperature and resulted temperature gradients when AT(ºC), MRT(ºC) and OT(ºC) are 0.83, 0.85 and 0.84 respectively. Standard correlation with AT(ºC) exists between MRT(ºC) and OT(ºC) when the value of these two temperature gradients are 0.97 and 0.99 respectively.

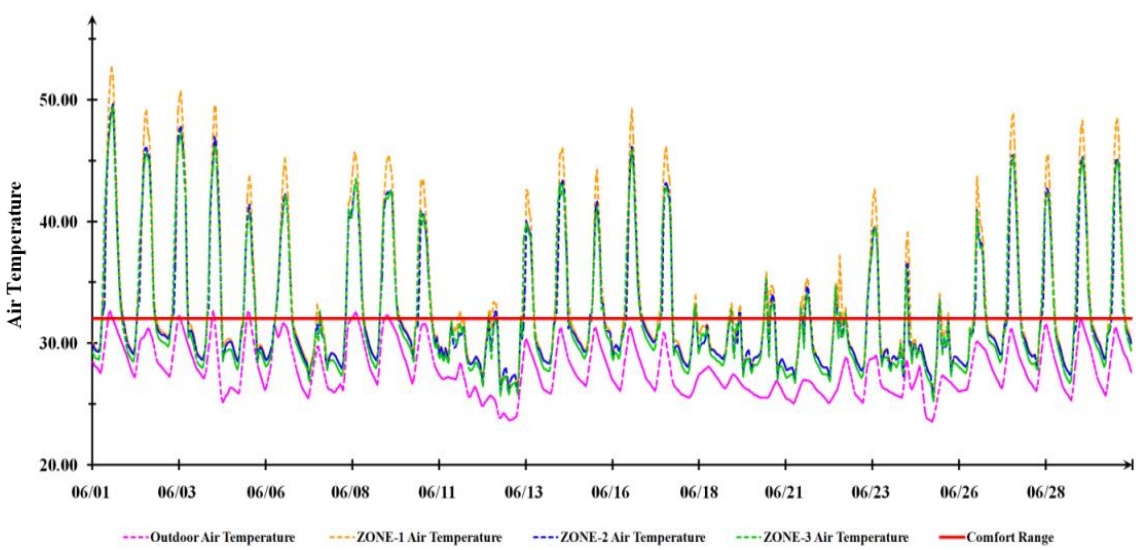


Figure 6.56 Comparison of AT(ºC) of different zones for roof type R-2d.

6.7 Comparative Performance Analysis of Different Roof Constructions

For parametric study, six roof types: R-1a, R-1b, R-2a, R-2b, R-2c and R-2d have been considered. R-1a and R-1b has attic space and wooden false ceiling below roof covering. Two different roof covering have been considered: C.I. sheet and terracotta roof tiles. Roof types R-2a to R-2d have wooden shingle/bamboo knitted mat below the covering material instead of attic and false ceiling. In this section different roof types have been analyzed to figure out best possible roof construction to improve indoor thermal environment of traditional timber house. For all parametric study outdoor condition is kept constant. Maximum, mean and minimum outdoor AT(ºC) is 32.63ºC, 27.83ºC and 23.54ºC respectively with standard deviation of 2.03. Table 6.28 illustrates maximum, mean and minimum temperature gradients.

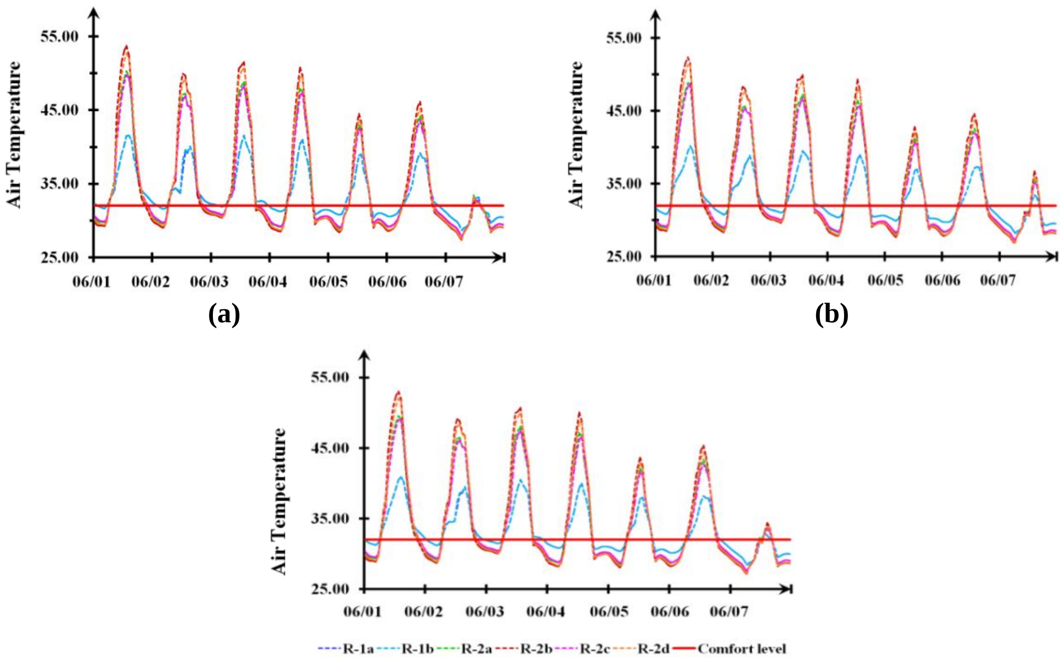
From the table it is observed that all roofs have maximum temperature gradients higher than comfort level. R-1a and R-1b have relatively lower temperatures compared to other roof Constructions in question. This result reflects that roof with attic space having wooden ceiling below shows higher resistant against outdoor temperature compared to non-attic one. Again both C.I. sheet and terracotta roof tiles exhibit relatively same thermal performance. Temperature gradient (maximum) resulted for R-1b is slightly higher (≤ 0.5ºC) compared to R-1a while mean and minimum temperature gradients are nearly the same as temperature gradients resulted for R-1a. Maximum temperature gradients of Z-2 and Z-3 resulted for R-1a is 7ºC-8ºC higher whereas at Z-1 it is 7.5ºC-9.5ºC higher than upper level of comfort.

Temperature gradient for MRT(ºC) is lower compared to OT(ºC) whereas AT(ºC) has the highest temperature values within a zone. This situation is similar for all roof types. Fig. 6.57-6.59 show zone-wise AT(ºC), MRT(ºC) and OT(ºC) variation resulted for different roof constructions. Z-1 (middle space of the house) has relatively higher temperature gradients and Z-3 (rear/north room) has the lowest temperature whereas Z-2 (south and front room) has a slightly higher temperature compared to Z-3. Temperature increases from Z-2 to Z-1 and decreases from Z-1 to Z-3. Therefore, it is clear that even with temperature higher than comfort level, Z-3 is comparatively comfortable compared to other two. Correlation matrix characterizes positive correlation among different temperatures.

Table 6.28 Maximum, mean and minimum temperature gradients resulted for different roofs.

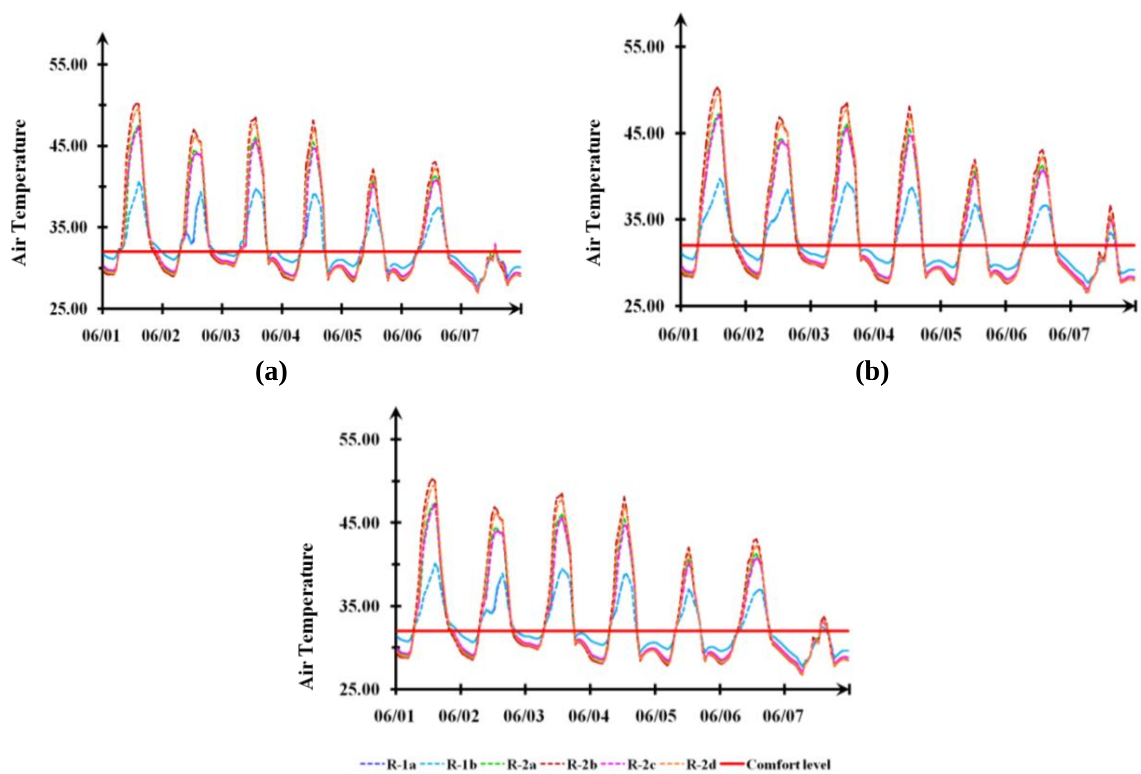
Name	Roof Type	Maximum			Mean			Minimum		
		Z-1	Z-2	Z-3	Z-1	Z-2	Z-3	Z-1	Z-2	Z-3
Air Temp (ºC)	R-1a	41.39	40.23	39.78	32.46	31.8	31.36	27.38	26.5	26.26
	R-1b	41.55	40.57	40.25	32.48	31.78	31.39	27.38	26.5	26.26
	R-2a	50.27	47.49	47.21	32.92	32.15	31.98	26.21	25.66	25.56
	R-2b	53.74	50.19	49.94	33.13	32.37	32.26	25.75	25.32	25.35
	R-2c	49.74	47.36	47.11	32.81	32.08	31.88	26.15	25.59	25.45
	R-2d	52.7	49.66	49.44	33.07	32.31	32.18	25.73	25.31	25.22
MRT Temp. (ºC)	R-1a	39.73	39.33	39.05	31.73	31.37	31.04	26.97	26.3	26.01
	R-1b	40.19	39.7	39.55	31.76	31.38	31.07	26.97	26.3	26.01
	R-2a	48.83	47.25	47.2	32.59	32.11	31.92	25.74	25.31	25.16
	R-2b	52.37	50.33	50.14	32.93	32.42	32.27	25.43	25.06	24.78
	R-2c	48.6	47.15	47.11	32.45	31.98	31.79	25.62	25.21	25.05
	R-2d	51.35	49.52	49.5	32.75	32.26	32.1	25.26	24.94	24.8
OT Temp. (ºC)	R-1a	40.42	39.78	39.42	32.1	31.58	31.2	27.18	26.4	26.14
	R-1b	40.87	40.13	39.9	32.12	31.58	31.23	27.18	26.4	26.14
	R-2a	49.55	47.37	47.2	32.76	32.13	31.95	25.97	25.49	25.36
	R-2b	53.06	50.26	50.04	33.03	32.39	32.26	25.59	25.21	25.16
	R-2c	49.03	47.26	47.11	32.63	32.03	31.84	25.89	25.4	25.25
	R-2d	52.02	49.59	49.47	32.91	32.29	32.14	25.49	25.12	25.01

*Temperature gradients above comfort temperature is highlighted with color



(c)

Figure 6.57 Comparison of changes in Z-1 temperature gradients for different roofs: (a) AT(ºC), (b) MRT(ºC) and (c) OT(ºC)



(c)

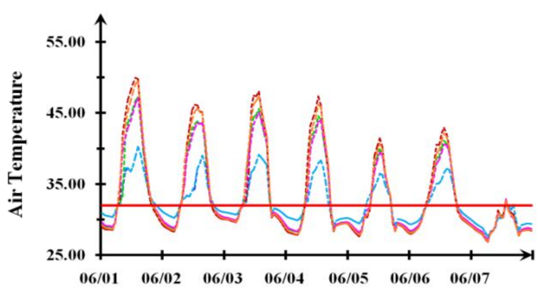
Figure 6.58 Comparison of changes in Z-2 temperature gradients for different roofs: (a) AT(ºC), (b) MRT(ºC) and (c) OT(ºC)

Table 6.29 Standard deviation of different roofs considered for parametric study.

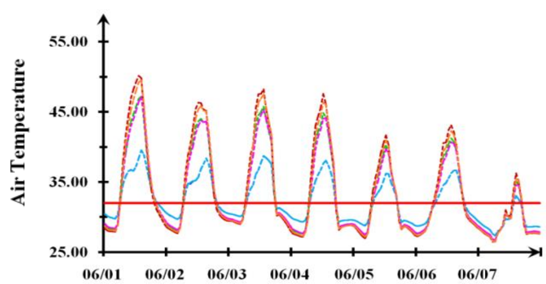
Wall Type	Outdoor Temp.	Air Temp.			MRT Temp.			OT Temp.		
		Z-1	Z-2	Z-3	Z-1	Z-2	Z-3	Z-1	Z-2	Z-3
R-1a	2.03	2.77	2.52	2.54	2.61	2.66	2.76	2.67	2.57	2.63
R-1b	2.03	2.79	2.51	2.57	2.62	2.67	2.78	2.69	2.56	2.66
R-2a	2.03	5.03	4.38	4.58	5.05	4.79	4.95	5	4.53	4.73
R-2b	2.03	5.91	5.19	5.4	5.97	5.62	5.77	5.89	5.35	5.55
R-2c	2.03	4.84	4.23	4.41	4.87	4.64	4.79	4.82	4.39	4.57
R-2d	2.03	5.66	4.97	5.17	5.69	5.36	5.51	5.63	5.12	5.31

*Color gradient shows comparative changes in standard deviation

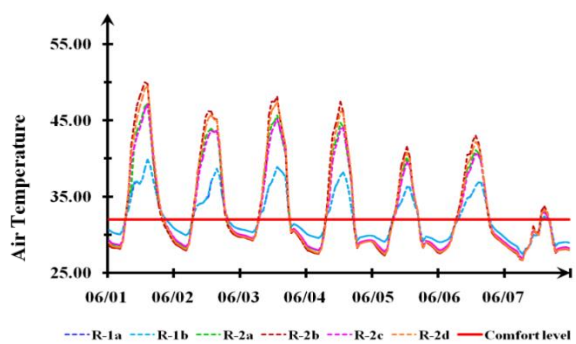
Lowest standard deviation is observed for roof with attic compared non-attic roof types which means that fluctuation of temperature level is less for this roof throughout the simulation period. Standard deviation of roof with attic remained around 2.5 whereas for non-attic roof it is as high as 4.5-5.5. Standard deviation for R-2b (C.I. sheet with bamboo knitted mat) has the highest value (5.5-6) among all roof types. Table 6.29 shows standard deviations of different roof constructions considered. Standard deviation values are relatively less at front zone (Z-2) compared to middle (Z-1) and rear zone (Z-3) which means temperature fluctuates less at the front zone. From correlation matrix, it is observed that resulted temperature gradients for Z-2 are less scattered compared to other two zones in all the cases considered for parametric studies.



(a)



(b)



(c)

Figure 6.59 Comparison of changes in Z-3 temperature gradients for different roofs: (a) AT (ºC), (b) MRT (ºC) and (c) OT (ºC)

6.8 Floor Constructions

During the field investigation two types of floor constructions have been found: one is attached to ground (F-1) and another is elevated from the ground (F-2). Floor finish material of F-1 is earth and

F-2 is wood. To analyze the impact of floor Construction on indoor thermal environment parametric study has been conducted and three-dimensional model considered for parametric study is similar to the model considered for existing traditional house study. Thermal properties of the materials are illustrated in Table 6.30. Cross-sectional view of R-1 is shown in Fig. 6.60.

Table 6.30 Thermal properties of envelopes considered for roof type F-1.

Envelope	Material	Thickness	Conductivity	Density	Specific-Heat
Floor	Earthen	-	1.4	1460	879
	Timber flooring	25mm	0.14	650	1200
Roof covering	C.I. sheet	0.5mm	65	7300	235
Ceiling	Raintree	25mm	0.74	480	1880
Chadoa	Cotton fabric	0.01	0.04	225	1380.72
Wall	Teak	12.5mm	1.28	710	1880
Window	Sal	18.75mm	0.96	660	1880
Door	Sal	25mm	0.96	660	1880

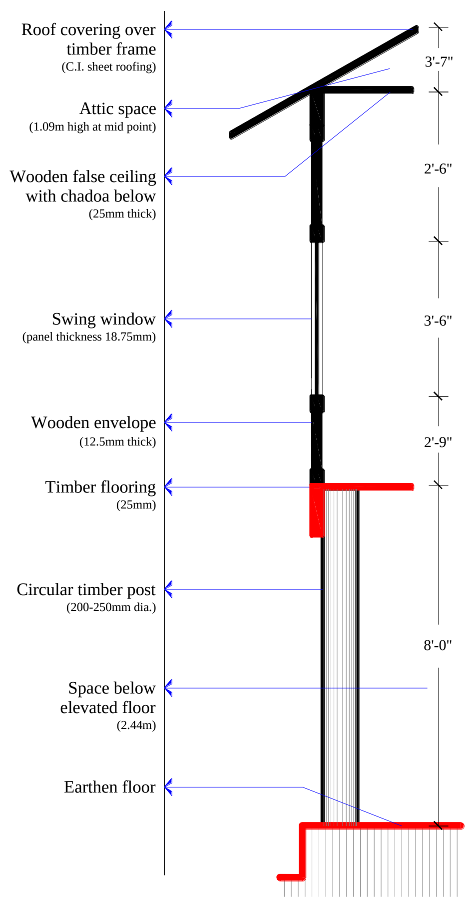


Figure 6.60 Cross sectional view of floor type F-1.

a) Floor Attached to the Ground: F-1

Floor type F-1, considered for parametric study, has earthen floor finish and is attached to ground. Three-dimensional model considered for simulation study is similar to that of the existing model/model considered for roof Construction R-1a. Descriptive statistics of obtained result is presented in Table 6.1.

b) Floor Elevated from the Ground: F-2

Floor type F-2 is elevated from the ground at a height of 2.44m (8ft.). Floor has timber framing finished with 25mm (1") thick wooden panels. Descriptive statistics shows that maximum AT(ºC) is nearly 39.5ºC -40ºC while minimum AT(ºC) is around 25ºC for all the three zones (Appendix D). For all temperature gradients Z-1 has higher value. Difference between zone maximum and minimum temperature remains between 13.5ºC-14.5ºC whereas zone mean temperature remains within comfortable range. Standard deviation is 2.5-3 where Z-1 has a comparatively higher standard deviation. Fig. 6.61 shows the variation in zone AT(ºC). During the first few days when outdoor AT(ºC) is comparatively high, zone AT(ºC) remains within comfort level from evening to early-morning (19:00pm-8:00am). Z-3 shows comparatively lower temperature than other two zones though its temperature remains above the comfort level during day. MRT(ºC) is lower than zone air and OT(ºC) by 0.75ºC-1.86ºC and 0.3ºC-0.5ºC respectively.

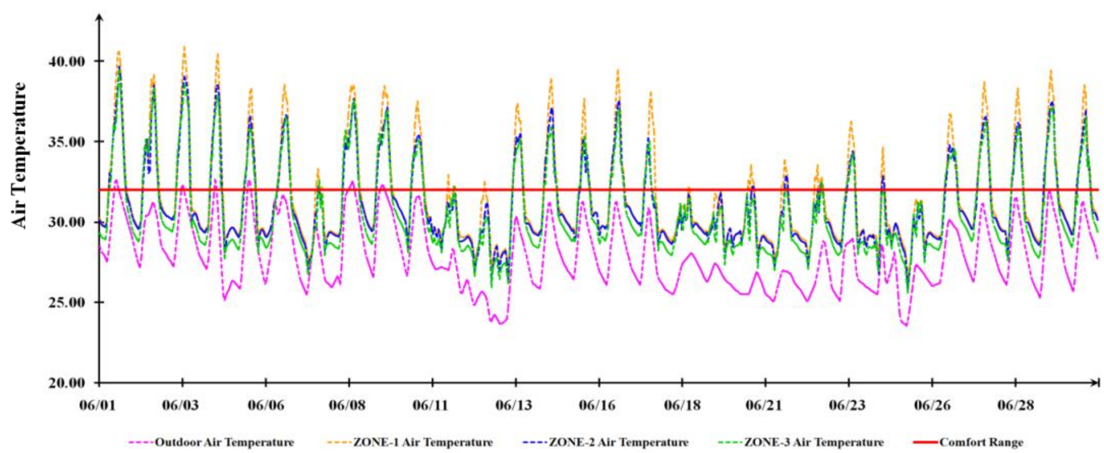


Figure 6.61 Comparison of AT(ºC) of different zones for floor type F-2.

Temperature gradient for first seven days of study period for floor type F-2 is provided in Appendix D. Variation of 75-76 percent is observed from the linear regression analysis of resulted temperature gradients with respect to outdoor AT(ºC). Maximum variation occurs for both MRT(ºC) and OT(ºC) which is 76 percent whereas minimum variation resulted for AT(ºC) which is 75 percent.

Correlation matrix shows positive relationship between outdoor and resulted temperature gradients. Best fitted correlation occurs among outdoor and resulted temperatures when all temperature gradients has the same value which is 0.87 whereas AT(ºC) shows best correlation with MRT(ºC) and OT(ºC) when value of these two temperature gradients is 0.99 and 1 respectively (Appendix D).

6.9 Comparative Performance Analysis of Floor Constructions

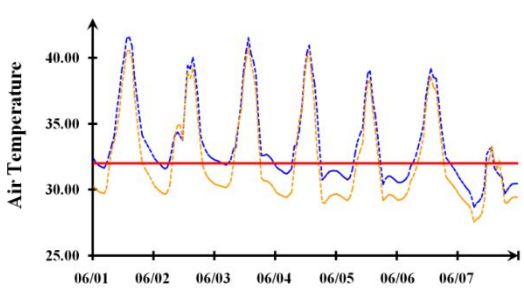
For parametric study, two floor Constructions: one attached (F-1) and another elevated (F-2) from the ground are considered. Statistical summary of different floor types has been analyzed to find out impact of floor Construction on indoor thermal environment towards enhanced thermal comfort of traditional timber house. For all parametric study outdoor condition has been kept constant where maximum, mean and minimum outdoor temperatures are 32.63ºC, 27.83ºC and 23.54ºC respectively with standard deviation of 2.03. Maximum, mean and minimum temperatures are presented in Table 6.31 and standard deviation in Table 6.32.

From the table it is observed that F-2 resulted in lower temperature gradients compared to F-1 though maximum temperature gradients are higher than comfort level. Zone AT(ºC) of F-2 is 0.5ºC-0.9ºC lower than F-1 where Z-3 has the lowest temperature value. Mean and minimum temperature gradients of both F-1 and F-2 remain within comfortable range. Compared to OT(ºC), MRT(ºC) has a lower value whereas AT(ºC) has the highest temperature value within a zone. Z-1 has relatively higher temperature and Z-3 has lowest temperature. Temperature of Z-2 is slightly higher than that of the Z-3. Temperature increases from Z-2 to Z-1 by about 0.8ºC-1.2ºC, 0.4ºC-0.6ºC and 0.6ºC-0.7ºC for air, MRT(ºC) and OT respectively. However, temperature decreases from Z-1 to Z-3 by about a range of 1ºC-1.5ºC, 0.7ºC-0.9ºC and 0.8ºC-1ºC for AT(ºC), MRT(ºC) and OT(ºC) respectively. Therefore, it is clear that even with temperature higher than comfort level, Z-3 is comparatively comfortable compared to other two zones (Z-1 and Z-2).

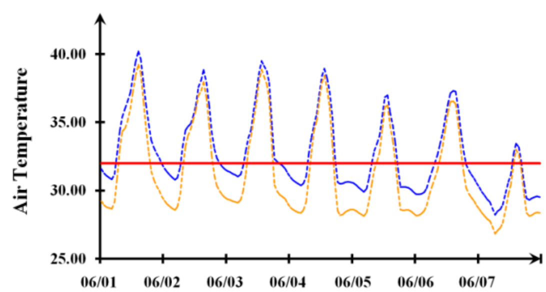
Table 6.31 Maximum, mean and minimum temperature gradients resulted for different floors.

Name	Roof Type	Maximum			Mean			Minimum		
		Z-1	Z-2	Z-3	Z-1	Z-2	Z-3	Z-1	Z-2	Z-3
AT (ºC)	F-1	41.39	40.23	39.78	32.46	31.8	31.36	27.38	26.5	26.26
	F-2	40.89	39.67	39.46	31.52	31.03	30.66	26.54	25.81	25.59
MRT (ºC)	F-1	39.73	39.33	39.05	31.73	31.37	31.04	26.97	26.3	26.01
	F-2	39.21	38.81	38.72	30.58	30.41	30.11	25.9	25.47	25.19
OT (ºC)	F-1	40.42	39.78	39.42	32.1	31.58	31.2	27.18	26.4	26.14
	F-2	39.9	39.24	39.09	31.05	30.72	30.39	26.22	25.64	25.39

*Color gradient shows comparative changes in standard deviation



(a)



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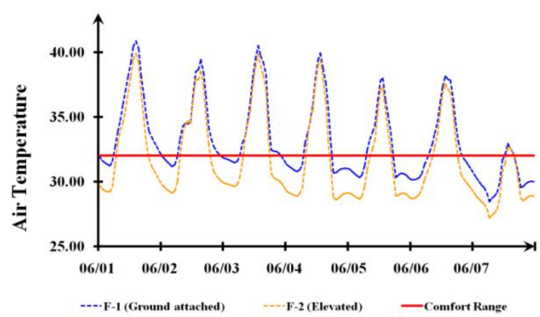

(c)

Figure 6.62 Comparison of changes in Z-1 temperature gradients for different floors: (a) AT(ºC), (b) MRT(ºC) and (c) OT(ºC).

Fig. 6.62 shows that zone AT(ºC) variation resulted for different floor Constructions during first week of the study period when outdoor temperature was comparatively high. From this figure it is clear that temperature gradients resulted for F-2 are considerably lower than those of F-1. Temperature gradients of F-2 remain below upper comfort level during evening to early morning while for F-1 these remain above comfortable range all the day when outdoor temperature remain high. This result reflects that elevated wooden floor types shows higher resistant against outdoor temperature and can easily release heat into the environment compared to ground-attached earthen one. Conductivity of earth is higher while specific heat is lower compared to wood (Table 6.116). But as thickness of timber floor is small therefore during evening when outdoor temperature starts decreasing timber flooring release heat through convection and radiation more easily compared to ground-attached earthen one.

Lowest standard deviation is observed for both floor Constructions which are around 2.5; however, F-1 has marginally lower standard deviation than F-2. Table 6.120 shows standard deviations of F-1 and F-2. Temperature gradients fluctuate less within southern zone, hence, standard deviation values are relatively less at Z-2. Correlation matrix shows that resulted temperature gradients are less at Z-2 compared to others. Correlation matrix characterizes positive correlation among different temperature gradients. Table 6.32 illustrates standard deviation of F-1 and F-2.

Table 6.32 Standard deviation of different floors considered for parametric study.

Wall Type	Outdoor Temp.	Air Temp.			MRT Temp.			OT Temp.		
		Z-1	Z-2	Z-3	Z-1	Z-2	Z-3	Z-1	Z-2	Z-3
F-1	2.03	2.77	2.52	2.54	2.61	2.66	2.76	2.67	2.57	2.63
F-2	2.03	2.95	2.58	2.68	2.83	2.81	2.95	2.88	2.68	2.81

*Color gradient shows comparative changes in standard deviation

6.10 Conclusion

In this chapter discussion has been presented on the obtained results of parametric study conducted for different envelope Constructions (wall, roof and floor) is discussed. Thirty-eight wall, six roof and two floor Constructions have been considered for parametric study. Performance of envelope has been analyzed based on previously established indoor thermal comfort range for rural areas of Bangladesh. From the simulation studies it is observed that wall having cavity insulated with local insulation materials (straw/jute fiber/coconut fiber) performs better compared to the simple wooden/glued/cavity wall types. Cavity thickness of 25mm insulated with coconut fiber/coir has showed enhanced indoor thermal performance among the entire considered wall Constructions. Among all roof Constructions roof with attic space performed comparatively well. Attic space acts as buffer zone and impact of thermal performance of roof covering is very little on indoor thermal environment. In terms of floor Construction elevated timber flooring has far better thermal performance compared to ground-attached earthen flooring. Elevated timber flooring being high from the ground is less impacted by the radiant heat emitted from the soil. Again flow of air helps convective heat loss from elevated floor construction. Different envelope constructions have been explored according to the findings from detailed field study. Therefore, conducted parametric studies may help providing future guideline towards enhanced indoor thermal environment of traditional timber houses in Bangladesh.

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CHAPTER SEVEN: CONCLUSION AND RECOMMENDATIONS

Introduction

Summary of the Study

Observation and Findings

Scope of Future Research

Conclusion

References

7.1 Introduction

The research detailed in this thesis is summarized in this chapter, which also includes final findings. It contains the results of the parametric studies conducted as well as the results of the field investigation regarding thermal performance of traditional timber house. The results are summarized in this chapter to provide guidelines regarding effective design for reducing indoor heat gain in these houses. Finally, it discusses future research work on the aspects that are needed to be explored in regarding traditional timber houses of Bangladesh.

7.2 Summary of the Study

The aim of this study is to investigate envelopes' thermal performance of the traditional timber houses of Bangladesh regarding indoor thermal comfort. With the changing global thermal condition selection of building envelope design and their thermal performance should be given appropriate attention since building envelope is one of the crucial part of building's indoor thermal comfort (Mridha 2002). Again, thermal comfort range varies from urban to rural subjects and studies reveals that rural people are more tolerant towards high temperature then urban subjects (Xu, Li et al. 2018; Xiong, Liu et al. 2019). Therefore, before investigating the thermal performance of envelope, literature study has been carried out to determine the thermal comfort range for rural areas of Bangladesh. Besides that, literature survey reveals that research on traditional timber houses of Bangladesh is marginal. Therefore, prior to the research a reconnaissance survey has been conducted to identify the typology of the house and specific location of the houses.

Following the literature and reconnaissance survey a detailed field exploration of qualitative and quantitative parameters regarding thermal performance of the existing envelope with respect to indoor thermal comfort have been performed. From this field investigation an interpretational graph has been developed relating indoor thermal environment with the occupants' thermal experience and behavior of using indoor space within the house. This graph help assessing the thermal efficiency among several envelope design strategies by determining the number of thermally comfortable hours to total occupancy hours in a specific period. To develop the graph and achieve its aim the current study worked on the following objectives:

i) Studying and analyzing construction methods, architectural details and thermal parameters (i.e. air Temp/AT, relative humidity/RH, surface temp etc.) as well related to indoor thermal performance of timber house.

ii) Exploring the occupants' comfort perception, experience and related lifestyle adaptation within the existing condition of traditional timber house.

iii) To develop envelope construction database for designing timber house envelope regarding thermal performance in the context of Bangladesh

Parametric studies using Energy-Plus and Open-Studio Plug-in software have been performed to identify the most uncomfortable period within the existing envelope condition. Then different envelope design strategies have been explored for this identified uncomfortable period. Observation and comparison of the design alternatives have been made based on local thermal comfort standard. The aim of this comparison is that it allows recognition of design strategies that contribute towards effective reduction of heat gain in the indoor environment of a traditional timber house in the future. Therefore, from these insights, strategies for development of timber house envelope were proposed.

7.3 Observations and Findings

It has been emphasized in the very first chapter that in the Bangladesh National Building Code (BNBC) or in other published guideline there is no standard specification about thermal performance of local envelopes typically used for construction in rural areas of Bangladesh. This study particularly deals with the thermal performance of traditional timber house envelope. Again study concerning traditional timber houses and occupants' perception of indoor thermal comfort in naturally ventilated houses is marginal. Therefore, in this study meticulous field monitoring has been conducted for better understanding of the occupants' perception, experience and lifestyle adaptation regarding indoor thermal comfort which is followed by parametric simulation studies for accessing design options and improving thermal performance that can be an effectual technique towards achieving indoor thermal comfort within traditional timber house of rural Bangladesh in the future.

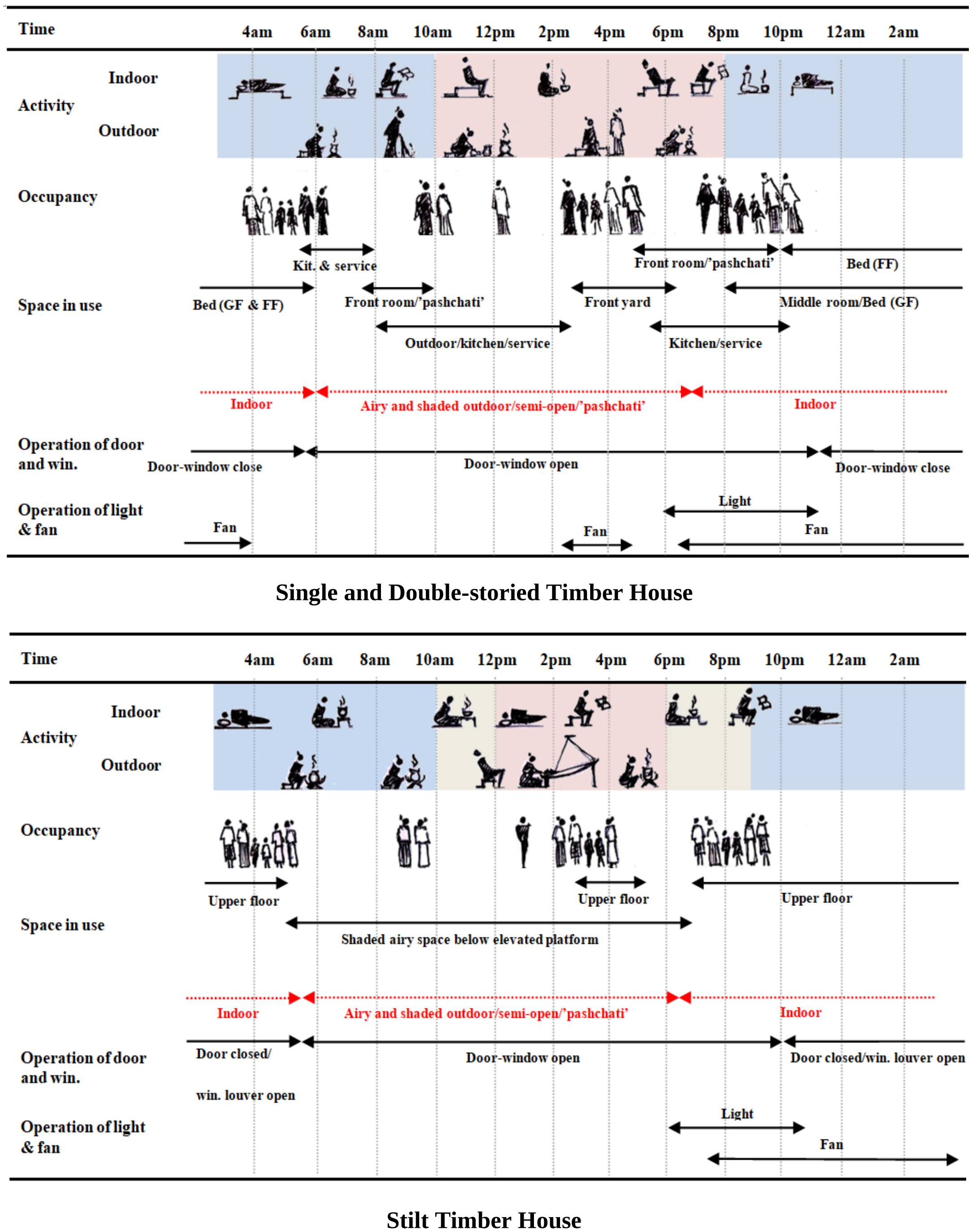
Comparative analysis of thermal performance of different types of traditional timber houses with respect to indoor thermal comfort level for rural subjects are studied. Indoor temperature rises penetratingly during day and reach their pick in the afternoon because of house envelopes' low thermal mass. During night even with very light winds, indoor cools down quickly by natural ventilation. Because of natural ventilation, indoor AT(°C) remains same as outdoor AT(°C) during day. Indoor temperature remains 1°C-4°C higher than comfort level during mid-day. Besides that an interpretational graph has been developed summarizing the findings from field survey relating indoor thermal environment with occupant's living pattern. The interpretational graph has been presented in Fig. 7.1. There remains a relationship among indoor thermal environment and lifestyle of the occupants living within the traditional timber house. Experience and perception of occupants' indoor thermal environment impacts their frequency of using indoor spaces.

Most of the occupants find the indoor environment very uncomfortable during the period 12:00pm-3:00pm while they find it comfortable during evening to till morning. Discomfort hours are compensated by staying at the airy semi-open spaces (veranda, balcony, shaded areas etc.) or shaded outdoor areas. Therefore, in traditional timber houses veranda plays a vital role in their lifestyle and becomes a way to cope with the discomfort hours of the day.

For simulation studies five different wall categories have been considered. Table 7.1 and 7.2 shows the design matrix of wall envelopes varying in thickness and layer respectively considered for simulation studies and their comparative thermal performance in the existing condition of the traditional timber house. Thickness is taken as only variable for the first four wall types W-1a to W-1d. It has been observed that though increasing wall thickness results in decrease in maximum temperature but mean temperature slightly increases than existing condition. This is because insulation property of timber affects heat loss from indoor spaces during night. At the same time closed window and doors traps heat inside the house and hampers effective convective heat release from inside through natural ventilation. All these impact the overall indoor thermal environment of the traditional timber house.

For the wall type W-2a to W-2f glued layer of timber and low/high density polythene have been considered. Wall thickness ranges between 25mm-37.5mm. Similar to the first group these walls results in low max. but slightly high mean MRT(°C) compared to existing one. Insulating property of timber and low/high density polythene decreases heat transfer rate during night resulting in overall increase in indoor temperature.

Table 7.2 shows the design matrix of cavity and insulated cavity wall envelopes considered for simulation studies and their comparative thermal performance. From simulation studies for cavity construction it is found that with the increasing cavity air gap thermal performance of the envelope deteriorates though cavity has high thermal resistance.



Note: Responses nearly 50% or above (−3 to −1) (0) (+1 to +3).

Figure 7.1 Relationship between thermal experience and occupant's living pattern in traditional timber houses

In case of insulated cavity though maximum MRT(°C) decreases by 1.5°C-4.9°C but at the same time minimum MRT(°C) increases by 1°C-2.5°C through temperature remains nearly 3°C-4°C below the upper limit of comfort. This is because cavity decreases heat transfer rate between two timber wall panels resulting in high indoor temperature. But in all cases increases in mean MRT(°C) remains between 0.1°C-0.5°C. Therefore, for cavity wall small air gap whereas for cavity insulation moderate cavity insulation with comparatively thick inner wall panel is preferable. But outer wall panel should be always thin in thickness for better heat transfer with outdoor environment.

For roof deign strategies, it is found that roof with attic space performs better compared to non-attic one. Because attic space acts as a barrier for the radiant heat radiated from the roof covering materials. Again in terms of materials, both C.I. sheet and terracotta has little thermal impacts on indoor thermal environment if attic space is provided below the roof. Similarly, elevated ground floor performs well compared to ground attached one as elevating from the ground floor keeps the house off from the radiant heat gain from the hotter ground. Table 7.3-7.4 illustrates the design matrix of floor and roof envelopes respectively.

Table 7.1 Design matrix of wall envelope indices varying in thickness and layer

Wall Type		Comparative performance		
		Good	Moderate	Poor
18.75mm wooden envelope	W-1a			■
25mm wooden envelope	W-1b			■
31.25mm wooden envelope	W-1c		■	
37.5mm wooden envelope	W-1d		■	
Two 12.5mm layers glued together	W-2a			■
Three 12.5mm layers glued together	W-2b		■	
Two 12.5mm layers having one low density polythene in between	W-2c			■
Three 12.5mm layers having two low density polythene in between	W-2d		■	
Two 12.5mm layers having one high density polythene in between	W-2e			■
Three 12.5mm layers having two high density polythene in between	W-2f		■	

Relationship between other temperature gradients and standard deviation show the similar characteristics. Total forty-six wall, roof and floor combination has been considered for simulation studies. Three temperature gradients for each three zones (Z-1, Z-2 and Z-3) have been calculated for a whole week of June. Therefore, a total of 69552 hourly data have been obtained. Relationship between temperature gradients and standard deviation has been developed based on these obtained data. From the relationship it is observed that standard deviation remains within 2.0 if temperature gradients remain below 37.5°C-38°C but it is become 2.5-3.0 when temperature increases above 39°C. In other words, fluctuation is high with higher temperatures.

The thermal qualities of envelopes have been researched in relation to local thermal comfort standards (Sharma and Ali 1986; Mallick 1996; Ahmed and Rashid 2010) and environment, which may contribute towards future design advancements for traditional timber houses. Statistical summary shows that all walls have maximum temperature gradients higher than comfort level. Among all, W-5g has comparatively lowest temperature gradients. Maximum temperature gradients of W-5g is 3ºC-3.3ºC lower than existing and 0.5ºC-2.32ºC lower than other wall types considered. This result reflects that wall types having only wooden panels are relatively less resistant against outdoor temperature compared to cavity/insulated one. Again among all considered insulation materials, coconut fiber shows better insulation quality. For this reason, minimum temperature gradients are 1.5ºC (maximum) higher than other walls considered, though these remain below upper level comfort. Similarly, though mean temperature is slightly higher for W-5g compared to other walls but it remains within upper level of comfort.

Table 7.2 Design matrix of cavity and insulated cavity wall envelope indices

Wall Type		Comparative performance		
		Good	Moderate	Poor
12.5mm and 18.75mm walls leaving 6.25mm cavity air gap in between	W-3a		■	
Two 12.5mm walls leaving 12.5mm cavity air gap in between	W-3b			■
12.5mm and 18.75mm walls leaving 12.5mm cavity air gap in between	W-3c		■	
Two 12.5mm walls leaving 18.75mm cavity air gap in between	W-3d			■
12.5mm and 25mm walls leaving 12.5mm cavity air gap in between	W-3e	■		
12.5mm and 18.75mm walls leaving 18.75mm cavity air gap in between	W-3f		■	
Two 12.5mm walls leaving 25mm cavity air gap in between	W-3g		■	
12.5mm and 18.75mm walls with 6.25mm cavity insulated with straw	W-4a		■	
Two 12.5mm walls with 12.5mm cavity insulated with straw	W-4b		■	
12.5mm and 18.75mm walls with 12.5mm cavity insulated with straw	W-4c		■	
Two 12.5mm walls with 18.75mm cavity insulated with straw	W-4d		■	
12.5mm and 25mm walls with 12.5mm cavity insulated with straw	W-4e	■		
12.5mm and 18.75mm walls with 18.75mm cavity insulated with straw	W-4f	■		
Two 12.5mm walls with 25mm cavity insulated with straw	W-4g	■		
12.5mm and 18.75mm walls with 6.25mm cavity insulated with coir	W-5a		■	
Two 12.5mm walls with 12.5mm cavity insulated with coir	W-5b		■	
12.5mm and 18.75mm walls with 12.5mm cavity insulated with coir	W-5c	■		
Two 12.5mm walls with 18.75mm cavity insulated with coir	W-5d		■	
12.5mm and 25mm walls with 12.5mm cavity insulated with coir	W-5e	■		
12.5mm and 18.75mm walls with 18.75mm cavity insulated with coir	W-5f	■		
Two 12.5mm walls with 25mm cavity insulated with coir	W-5g	■		
12.5mm and 18.75mm walls with 6.25mm cavity insulated with jute fiber	W-6a			■
Two 12.5mm walls with 12.5mm cavity insulated with jute fiber	W-6b		■	
12.5mm and 18.75mm walls with 12.5mm cavity insulated with jute fiber	W-6c		■	
Two 12.5mm walls with 18.75mm cavity insulated with jute fiber	W-6d		■	
12.5mm and 25mm walls with 12.5mm cavity insulated with jute fiber	W-6e		■	
12.5mm and 18.75mm walls with 18.75mm cavity insulated with jute fiber	W-6f	■		
Two 12.5mm walls with 25mm cavity insulated with jute fiber	W-6g	■		

Table 7.3 Design matrix of floor envelope indices.

Floor Type		Comparative performance		
		Good	Moderate	Poor
Floor attached with ground	F-1		■	
Floor elevated 2.44m (8ft.) from the ground	F-2	■		

Table 7.4 Design matrix of roof envelope indices.

Roof Type		Comparative performance		
		Good	**Moderate**	**Poor**
C.I. sheet on timber frame with attic and wooden false ceiling below	R-1a	■		
Terracotta tile on timber frame with attic and wooden false ceiling below	R-1b	■		
C.I. sheet and wooden panel (12.5mm) on timber frame (No attic)	R-2a		■	
C.I. sheet and bamboo knitted mat (5mm) on timber frame (No attic)	R-2b			■
Terracotta tile and wooden panel (12.5mm) on timber frame (No attic)	R-2c		■	
Terracotta tile and bamboo knitted mat (5mm) on timber frame (No attic)	R-2d			■

Fig. 7.2 illustrates the temperature variations of different zones within traditional timber house both double storied and stilt. From parametric studies it is observed that in double-storied traditional timber houses mean value of both MRT(°C) and OT(°C) for the Z-3 (service/back zone) remains below comfort level whereas AT(°C) remains slightly higher than comfort temperature level.

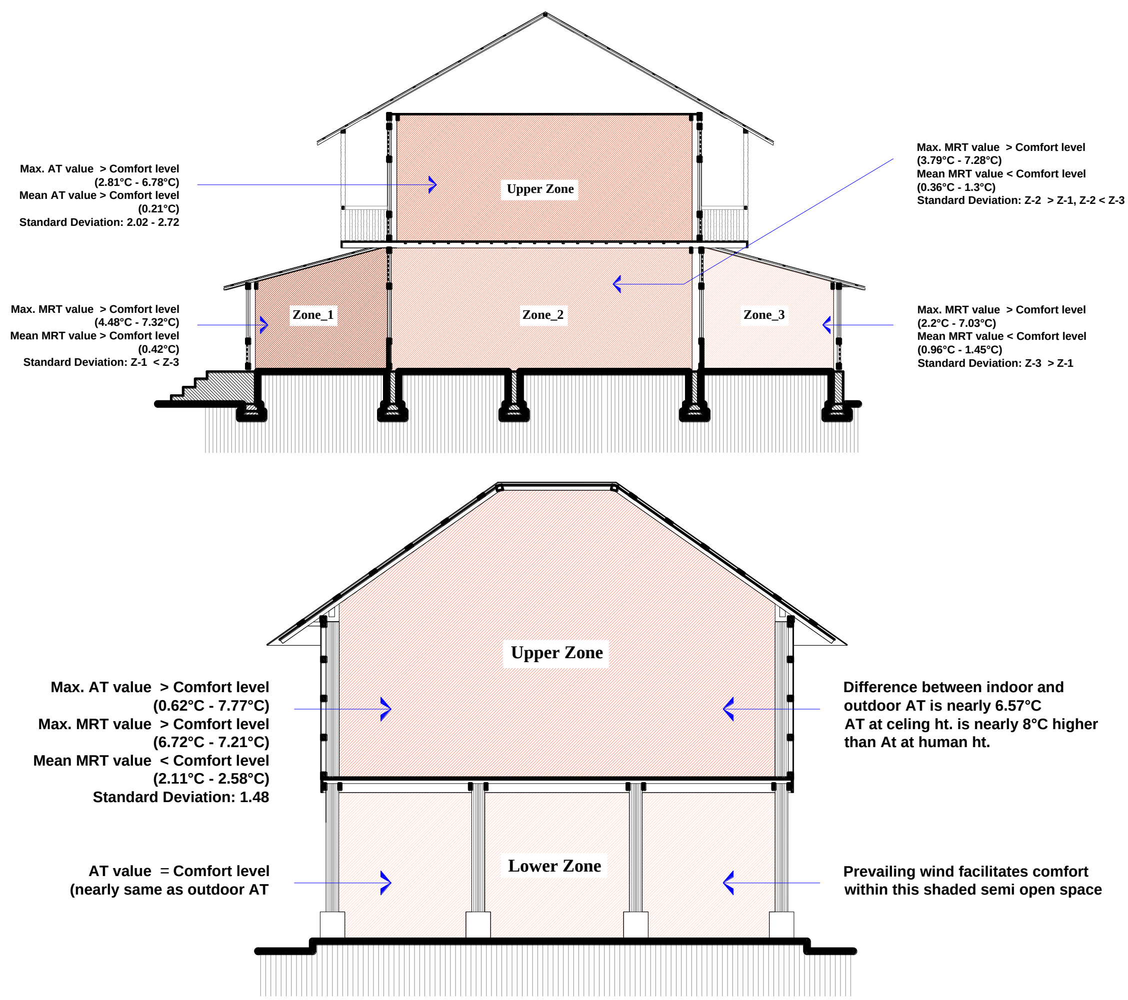


Figure 7.2 Temperature variations of different zones within traditional timber house: Double-storied (top) and Stilt (bottom)

Z-2 (rest/middle zone) mean MRT remains 0.36°C-1.3°C below whereas Z-1 has highest MRT(°C) and remains slightly higher (0.42°C) than comfort temperature. But from the field survey it is observed that upper floor temperature remains higher (max. MRT(°C) 2.81°C-6.78°C higher than comfort level) than lower zones and never occupied by residents during day. The upper zones are used during night when indoor temperature falls below comfort temperature level. Because of low floor height and radiant heat from the roof covering of the upper floor, temperature remains relatively high compared to lower floors. But Z-1 temperature is highest among all the zones because this zone has no false ceiling below C.I. sheet covering.

In case of stilt timber houses from field monitoring it is found that AT(°C) at ceiling height level is higher than human height level. As this type house has no attic space therefore radiation from the roof covering directly enters inside the house. But because of huge roof height AT(°C) near human height is lower than ceiling level. Again, operable louver in the window helps night-time ventilation resulting in lower night-time indoor AT(°C). From the parametric studies it is observed that stilt houses resulted in lower indoor MRT(°C)/AT(°C) compared to single and double-storied houses. This is because the stilt posts keep the main house form off from the radiant grain from the ground.

7.4 Scope of Future Research

As this research has limitations therefore some critical features are needed to be investigated in future regarding thermal performance of traditional timber house. Some are listed below:

- Field survey for different seasons to understand real-life performance of traditional timber houses.
- Investigation of thermal performance of traditional timber houses considering the air-leakage of the houses for more precise results.
- Study on thermal properties (U-value, R-value etc.) of local construction materials is needed for more authentications of simulation results.
- Impacts of architectural features i.e. height, depth of the house, window design, shadings, shade from balcony/nearby structure etc. on ultimate indoor thermal environment of the house is needed to be explored.

7.5 Conclusion

This research deals with thermal performance of traditional timber houses in rural Bangladesh. Detailed field investigation has been performed followed by parametric studies to assess limited design strategies. Field survey has been conducted during hot-humid period of the year. Then for parametric studies limited design strategies have been explored for the extreme seasonal condition towards improvement of rural traditional timber houses of Bangladesh in future. But due to lack of database of thermal properties of local envelope and construction materials of Bangladesh these properties were taken from different published documents. Therefore, research on this aspect will contribute towards better understanding and achieving an improved indoor thermal performance of these traditional houses. However, a more thorough examination of crucial design and subjective elements will result in a more suitable interpretation. The findings of this study will help professionals and design concerns towards future sustainable development in the rural environment of the tropics, as well as the well-being of the occupants.

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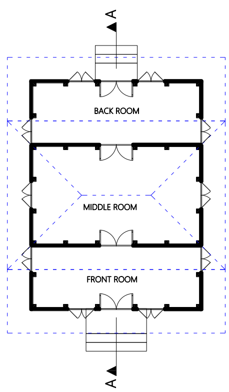
Appendix: A

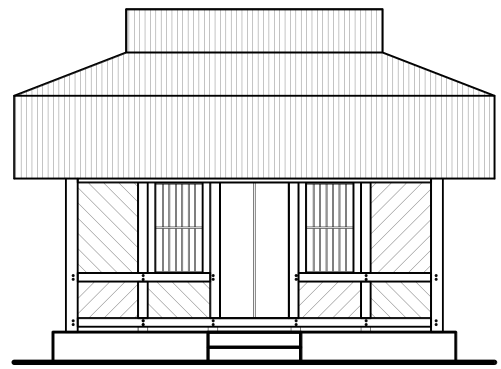
(Traditional timber house case studies in detail: plan/ elevation/ sections/ details: window/wall/roof)

Case Example 1

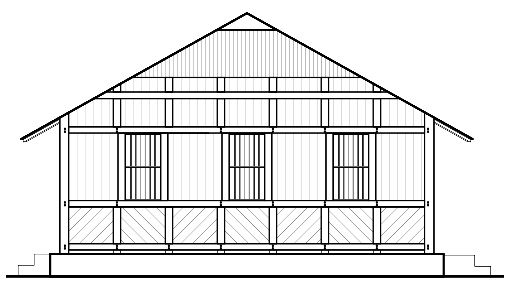
Type: One-storied



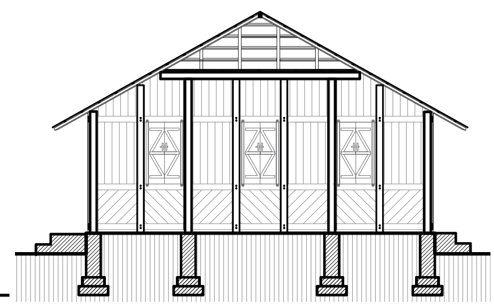
GROUND FLOOR PLAN



SOUTH/FRONT ELEVATION



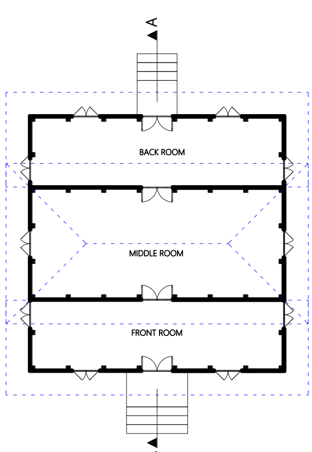
WEST ELEVATION



SECTION AA

Case Example 2

Type: One-storied



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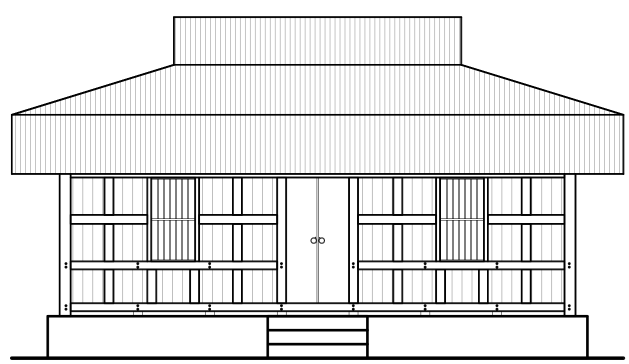
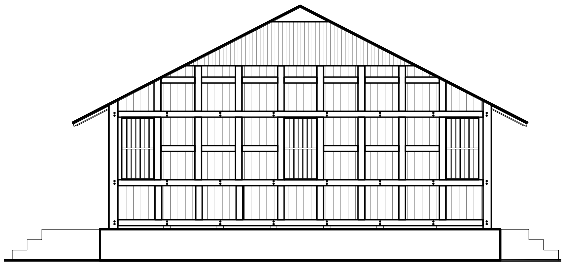


SOUTH/FRONT ELEVATION



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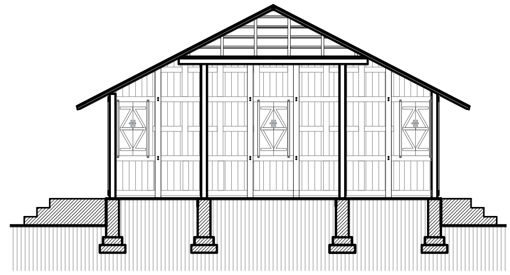
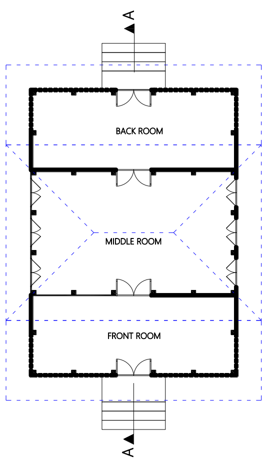


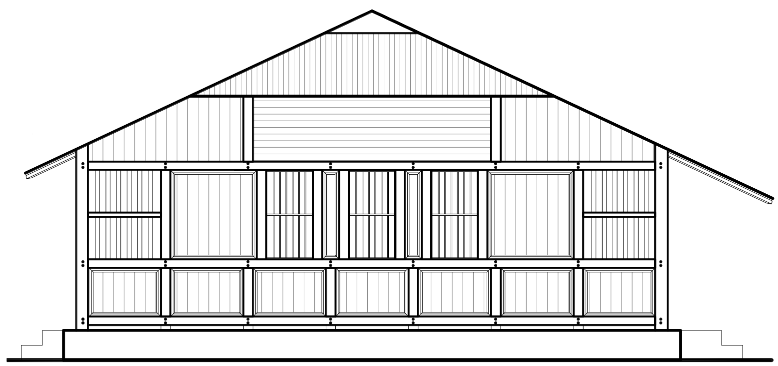
SECTION AA

Case Example3

Type: One-storied



GROUND FLOOR PLAN



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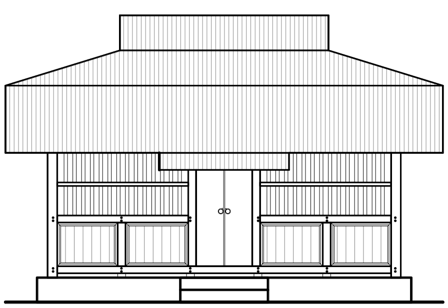
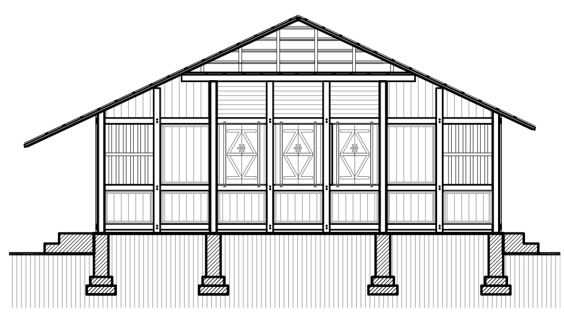


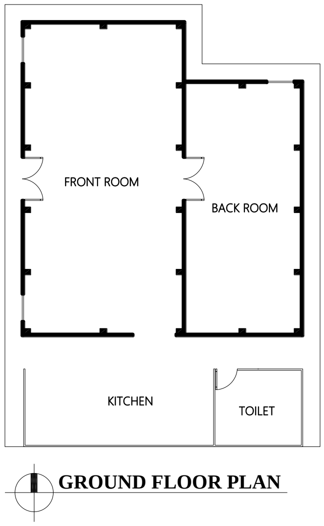
SOUTH/FRONT ELEVATION



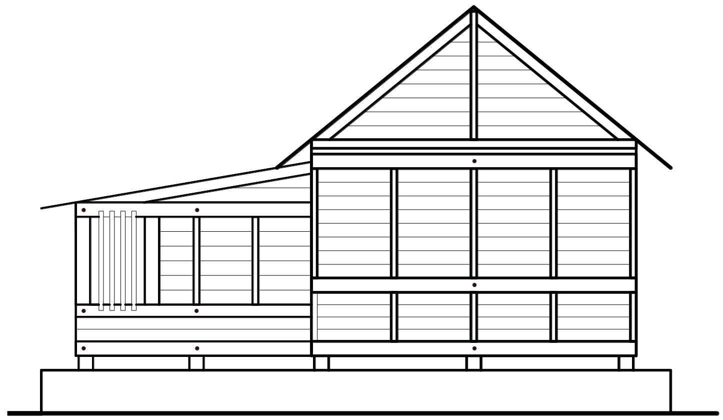
SECTION AA

Case Example 4

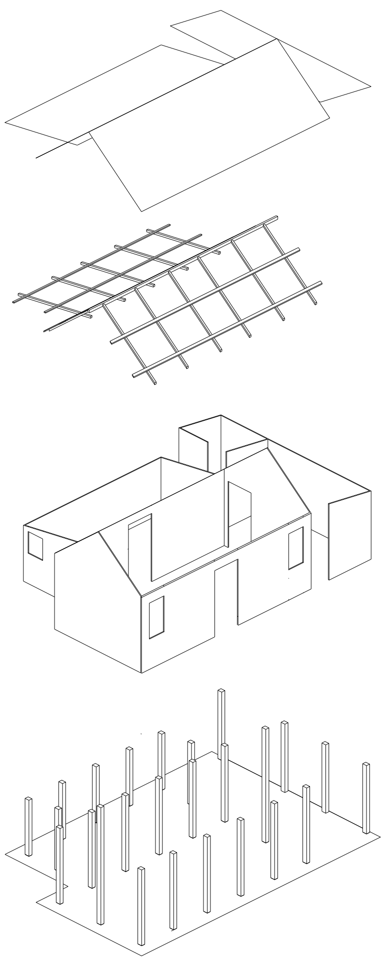
Type: One-storied

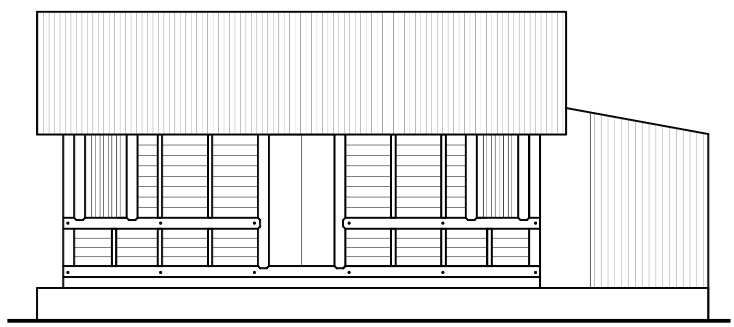


GROUND FLOOR PLAN

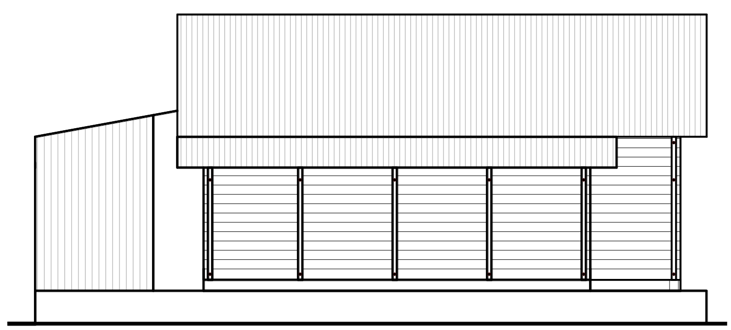


NORTH ELEVATION





WEST ELEVATION

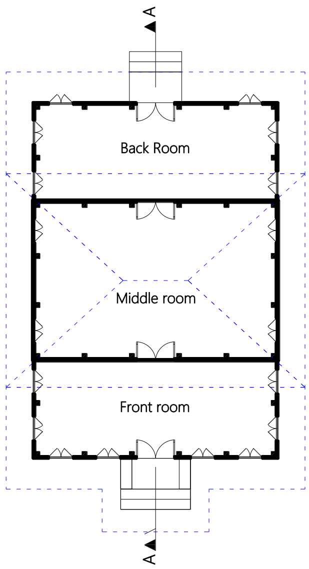


EXPLODED DRAWING

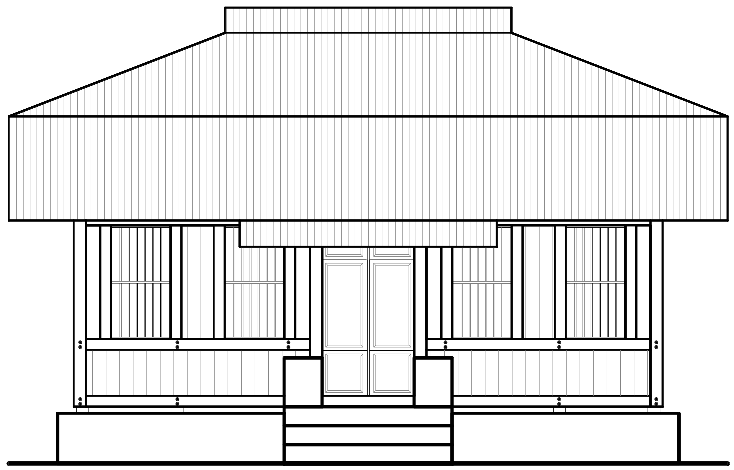
EAST ELEVATION

Case Example 5

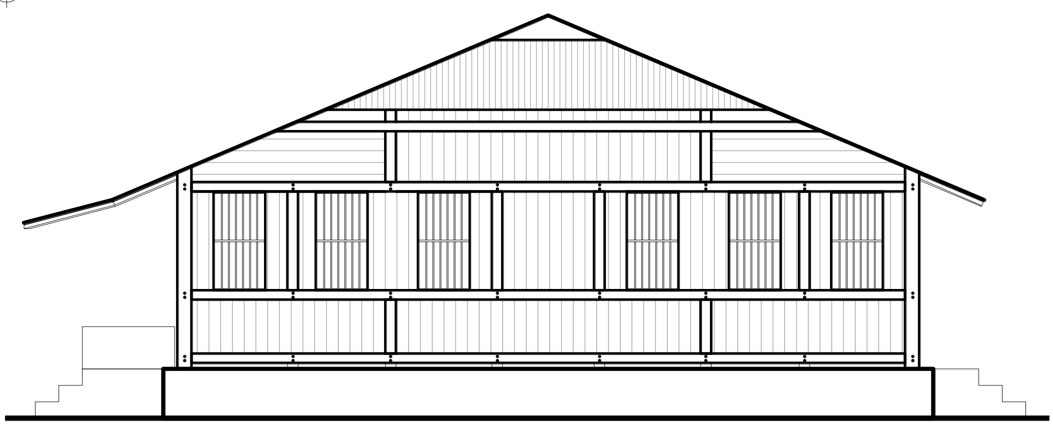
Type: One-storied



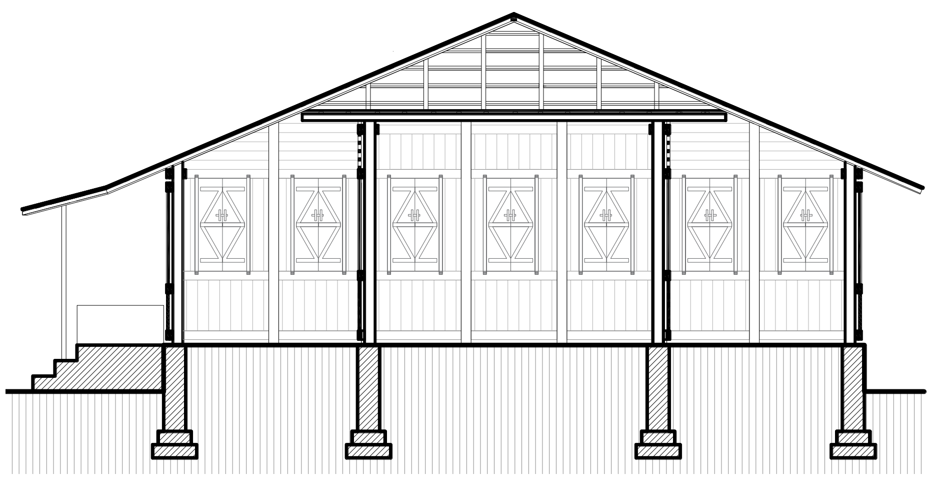
GROUND FLOOR PLAN



SOUTH/FRONT ELEVATION



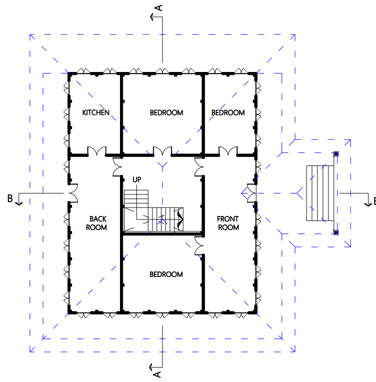
WEST ELEVATION



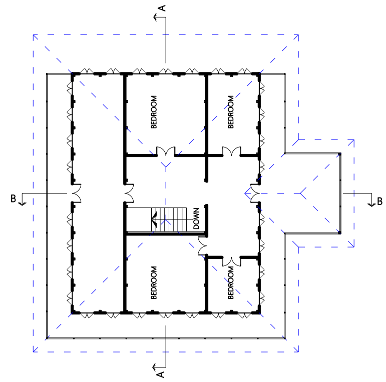
SECTION AA

Case Example 6

Name: Shikder Bari

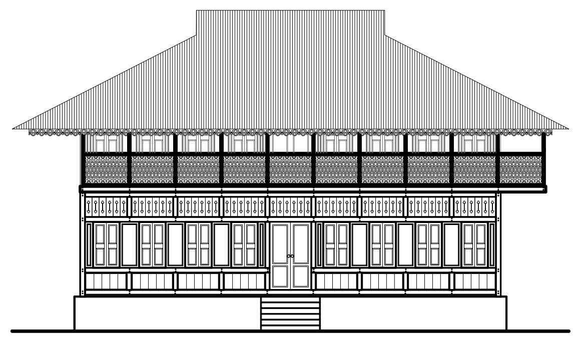


GROUND FLOOR PLAN



UPPER FLOOR PLAN

FRONT/EAST ELEVATION



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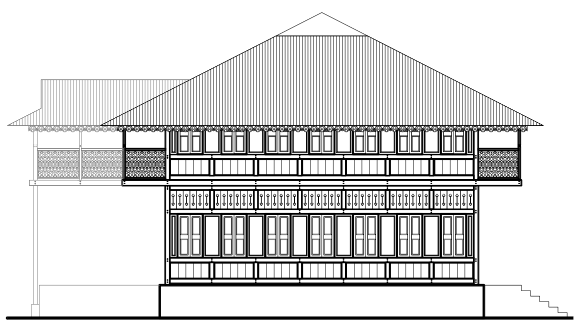
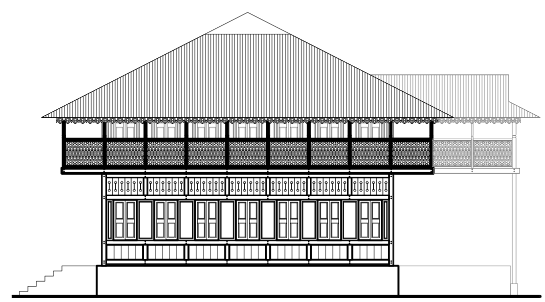
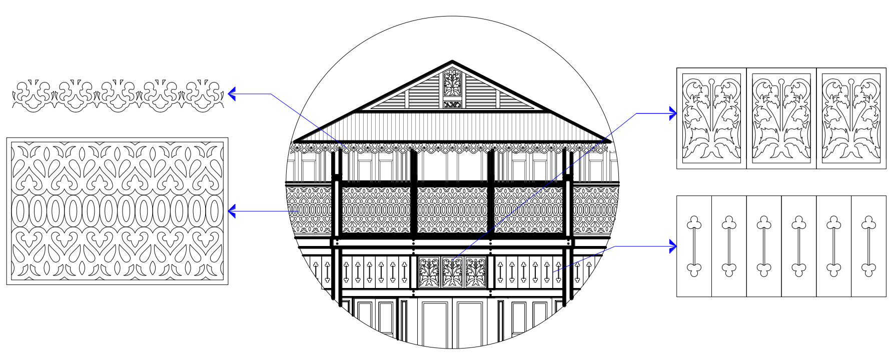


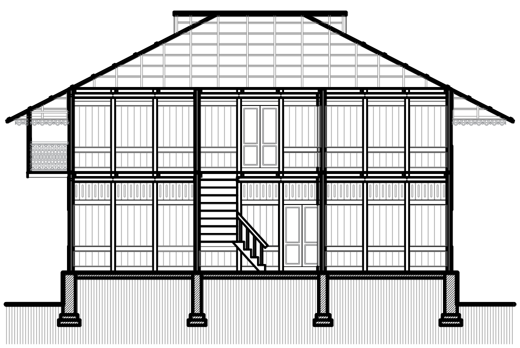
NORTH ELEVATION



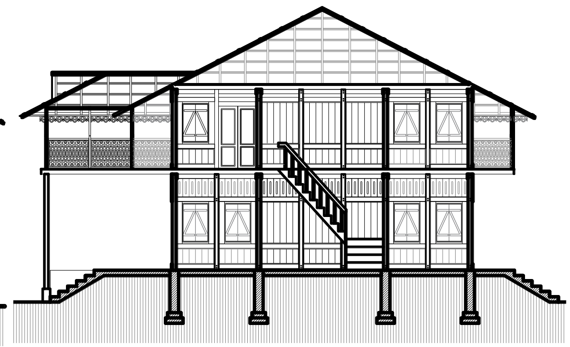
SOUTH ELEVATION



SCREENING DETAILS



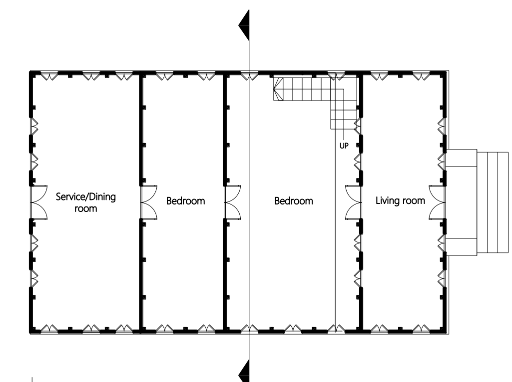
SECTION_AA



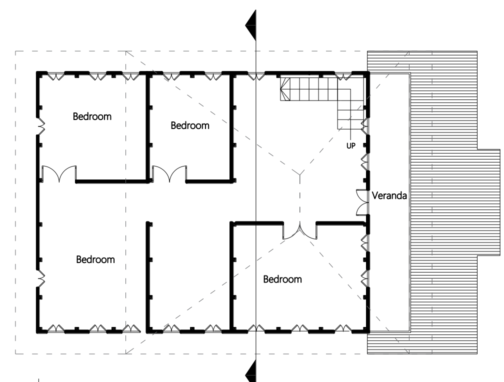
SECTION_BB

Case Example 7

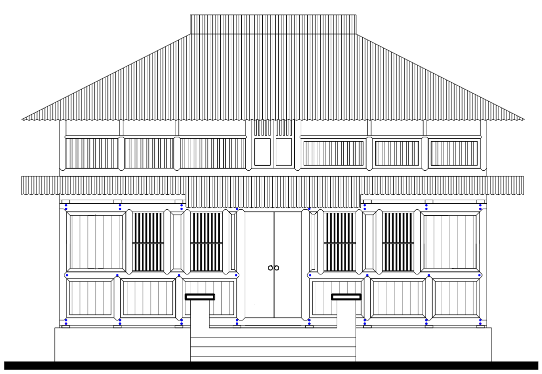
Name: Akber Residence



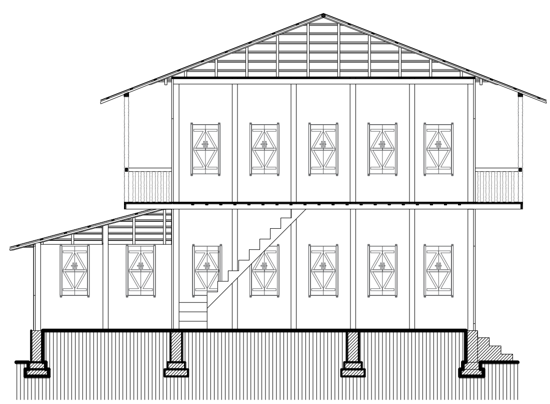
GROUND FLOOR PLAN



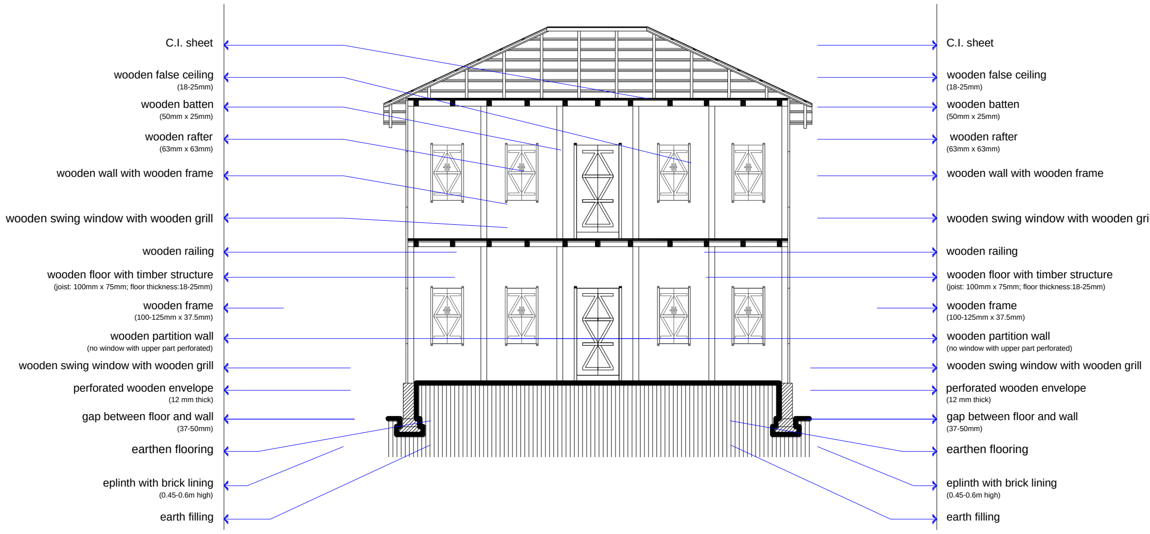
FIRST FLOOR PLAN



FRONT ELEVATION



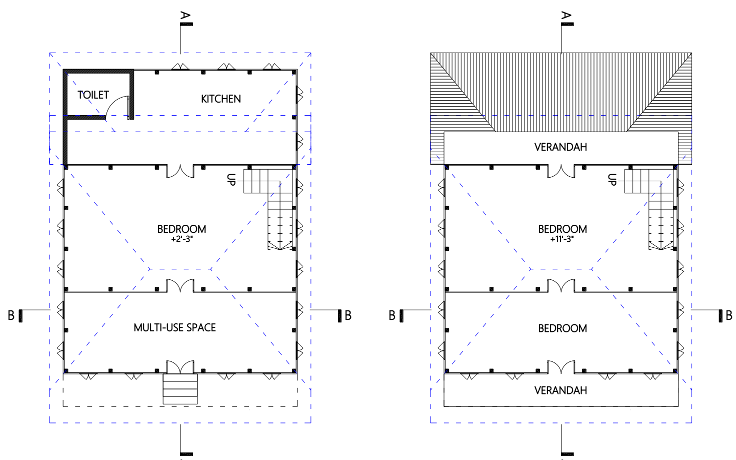
TRANSVERS SECTION



LONGITUDINAL SECTION

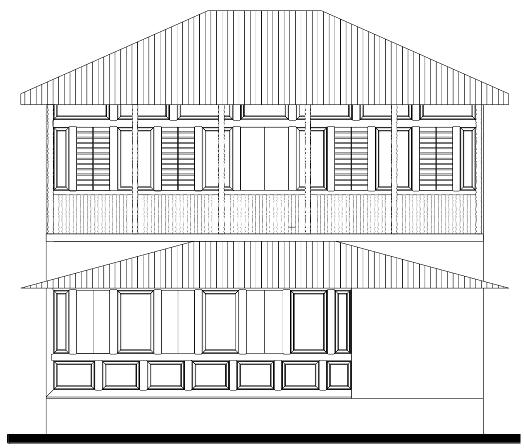
Case Example 8

Name: Sardar Bari

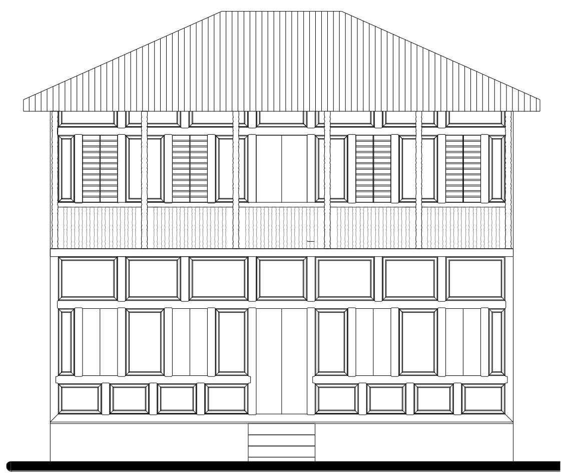


GROUND FLOOR PLAN **UPPER FLOOR PLAN**

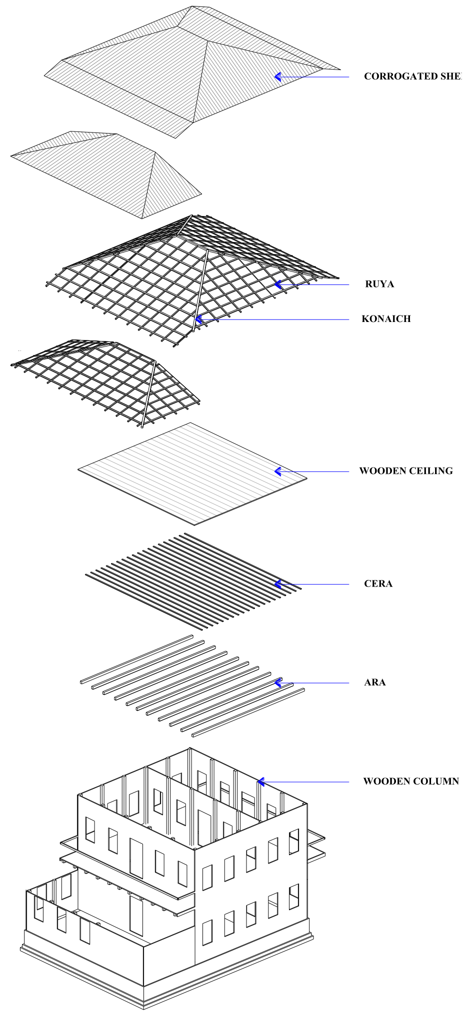
WEST ELEVATION **EAST ELEVATION**



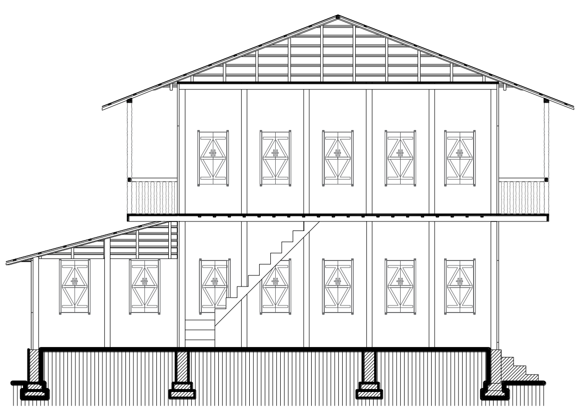
NORTH ELEVATION



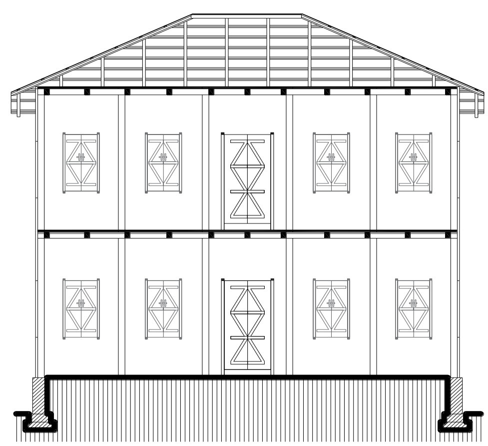
SOUTH ELEVATION



EXPLODED DRAWING



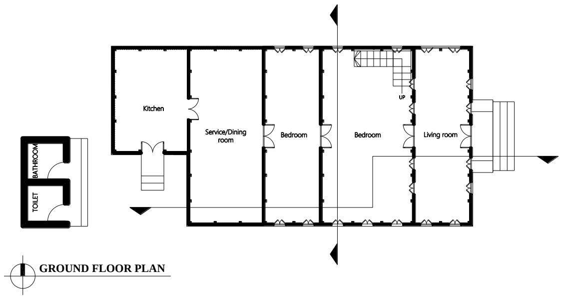
SECTION_AA

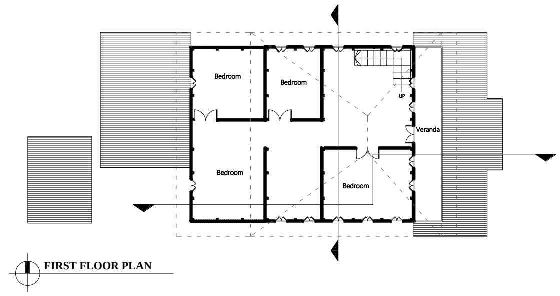


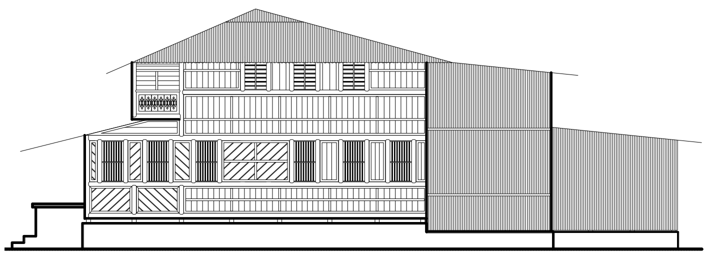
SECTION_BB

Case Example 9

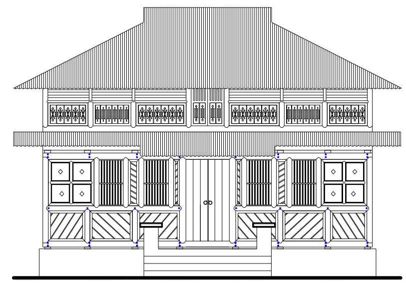
Name: Hannan-Mannan Bari



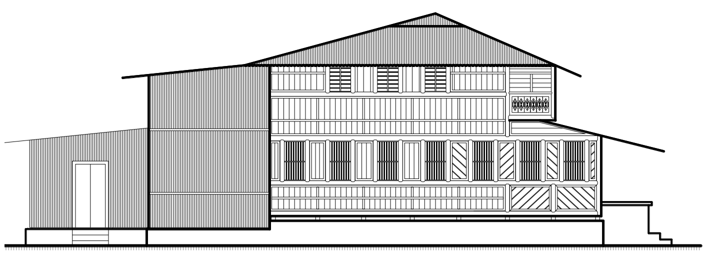




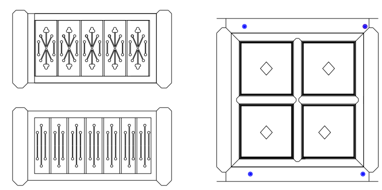
NORTH ELEVATION



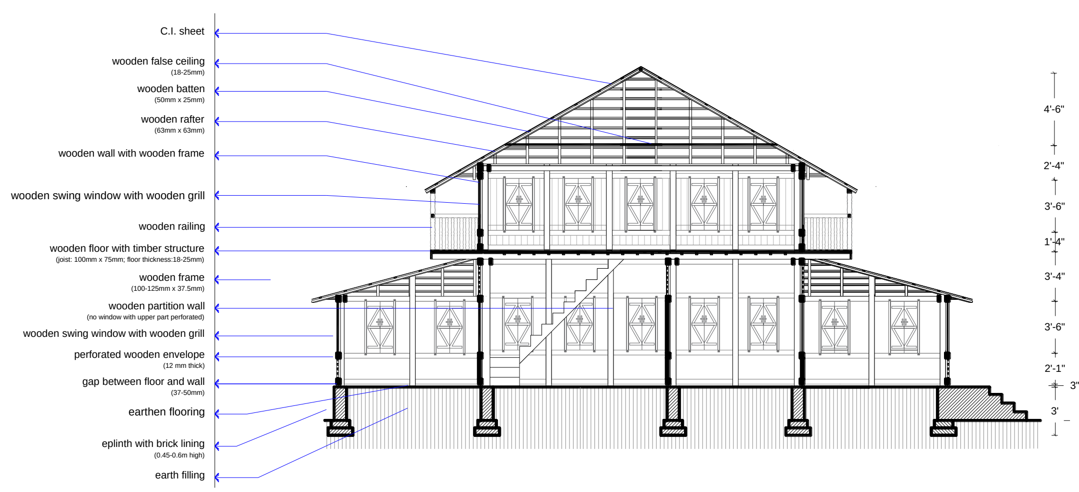
EAST ELEVATION



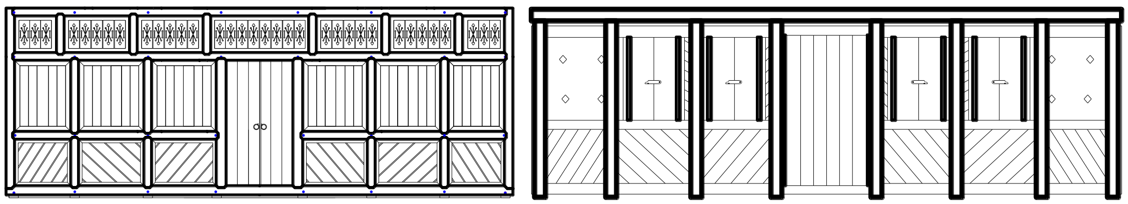
SOUTH ELEVATION



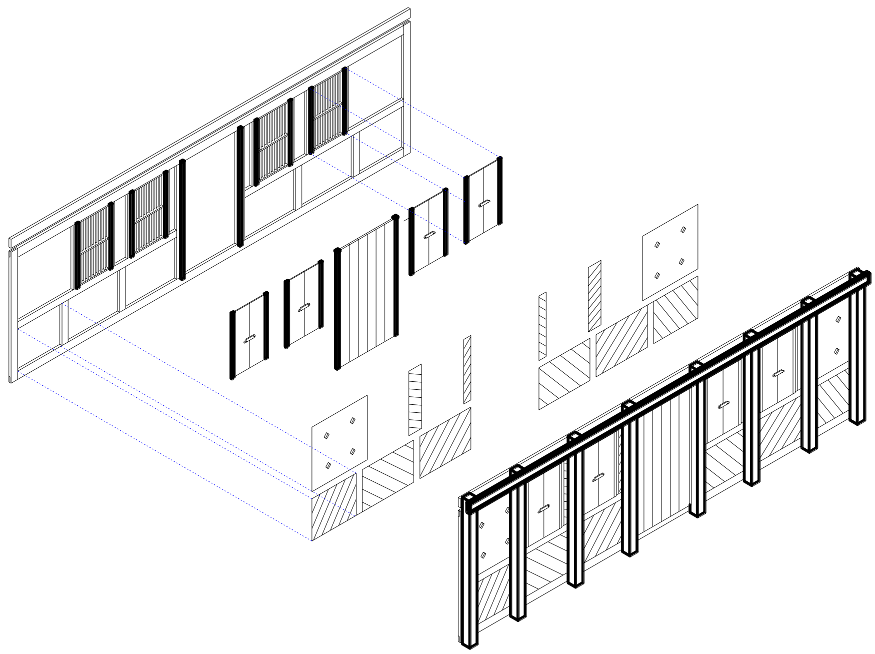
JALI/SCREENING



LONGITUDINAL SECTION



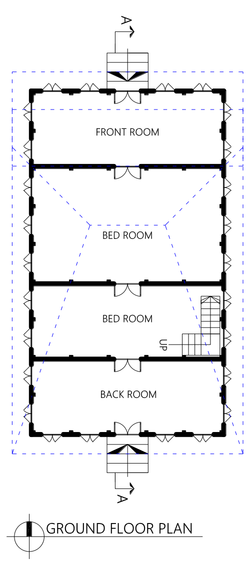
WALL ENVELOPE DETAILS

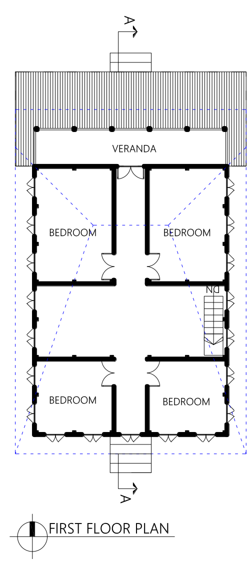


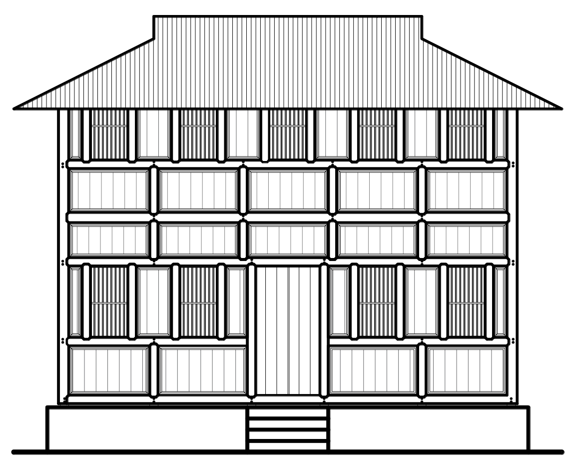
WALL EXPLODED DRAWING

Case Example 10

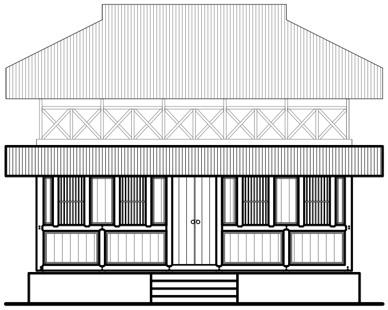
Name: Reaz's Bari



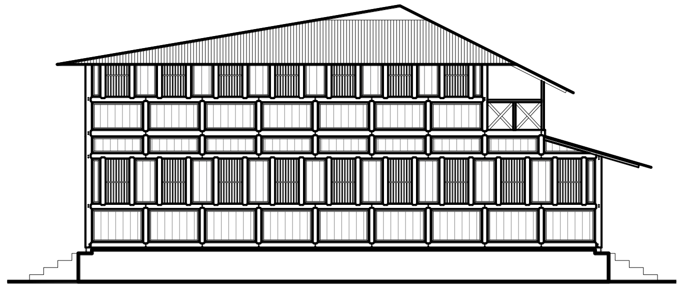




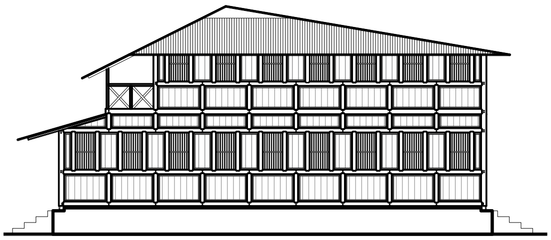
SOUTH ELEVATION



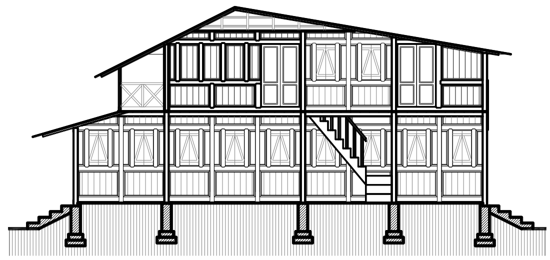
NORTH ELEVATION



WEST ELEVATION



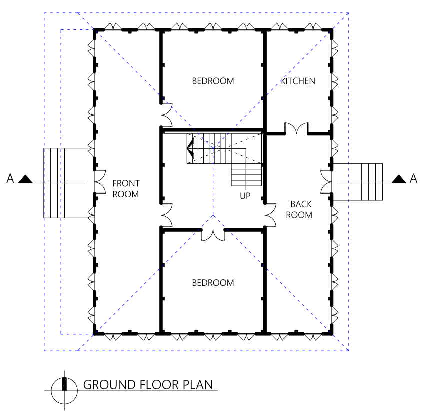
EAST ELEVATION

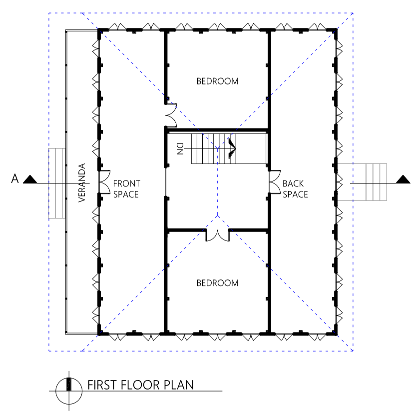


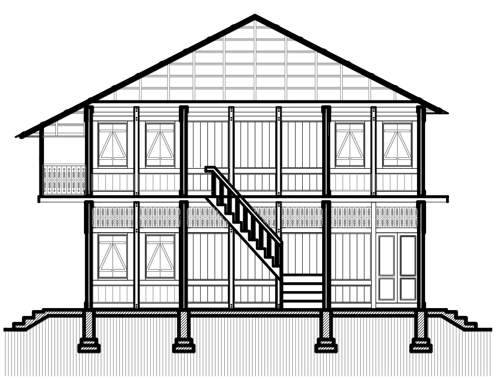
SECTION AA

Case Example: 11

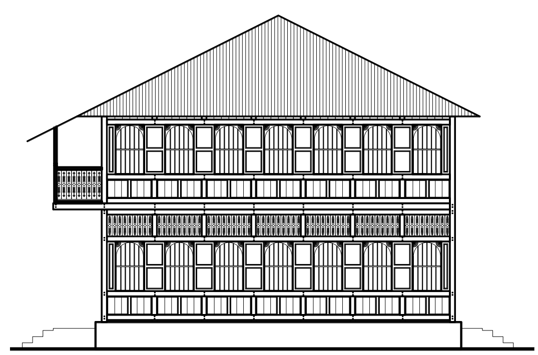
Name: Rafiq's Bari



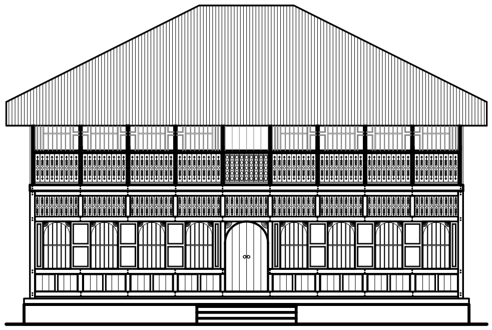




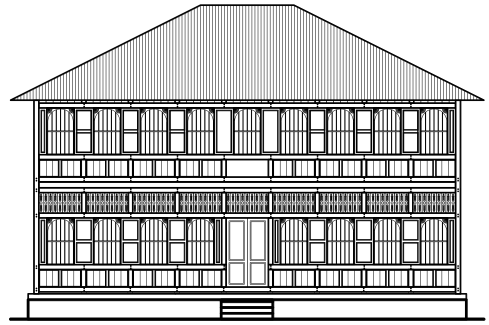
SECTION AA



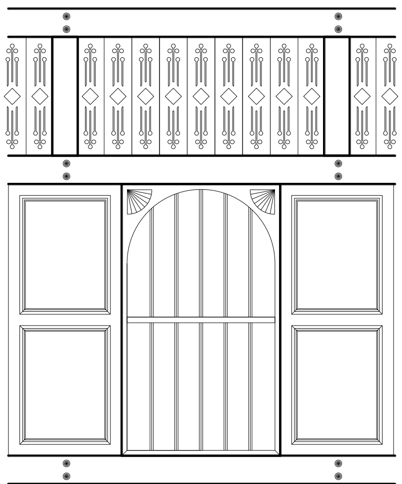
SOUTH ELEVATION



WEST/FRONT ELEVATION



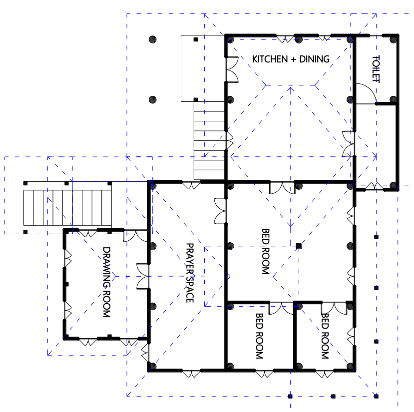
EAST ELEVATION



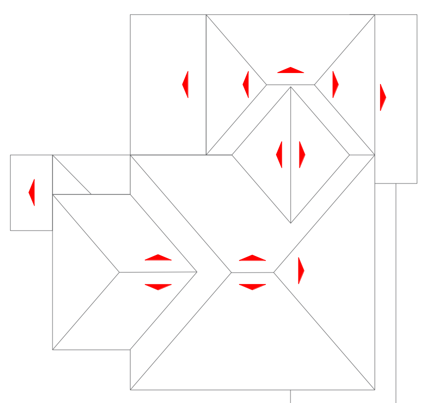
WINDOW AND SCREEN DETAIL

Case Example 12

Type: MongKyjy Residence



GROUND FLOOR PLAN



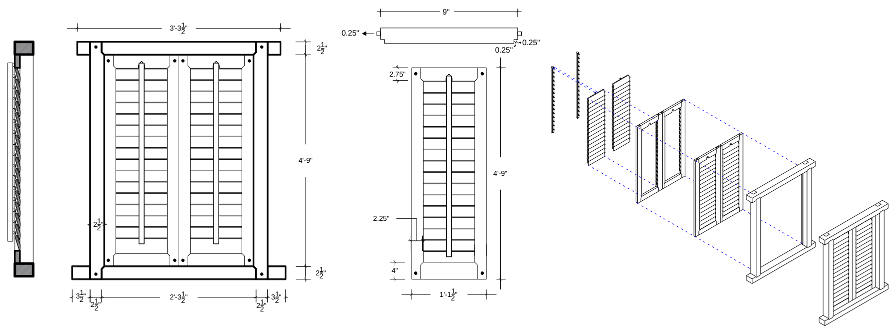
ROOF PLAN

NORTH ELEVATION

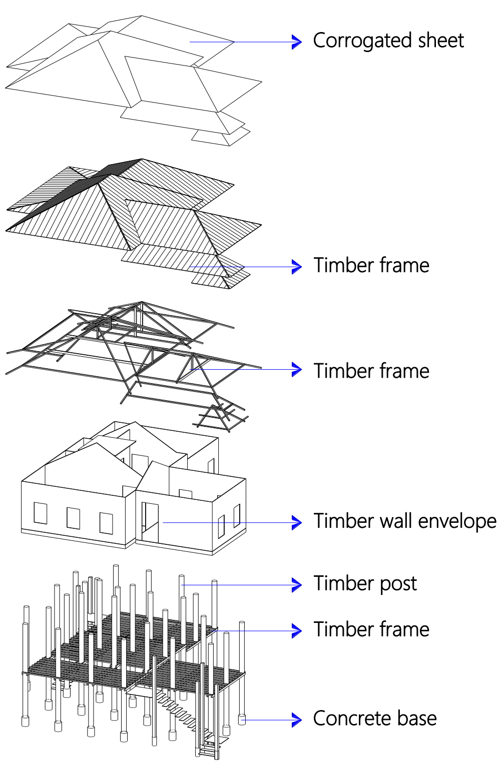
SOUTH ELEVATION

EAST ELEVATION

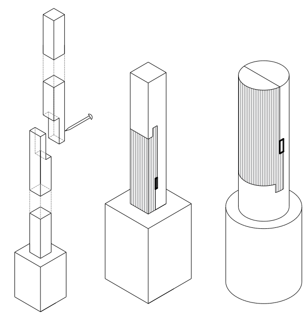
WEST ELEVATION



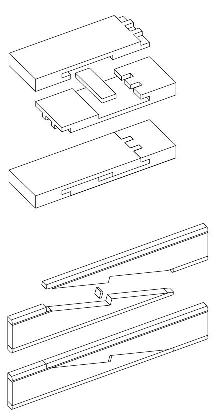
WINDOW DETAILS



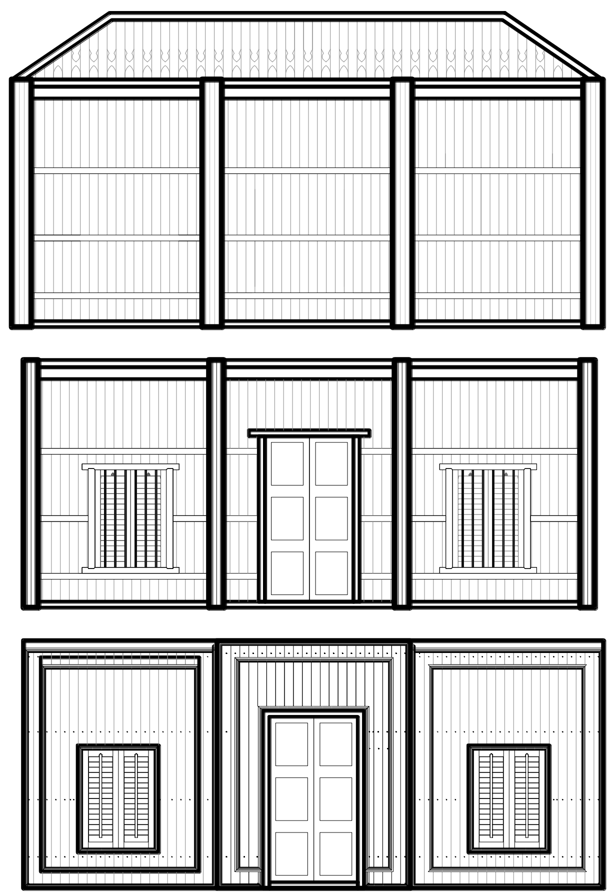
EXPLODED DRAWING



COLUMN JOINT DETAILS



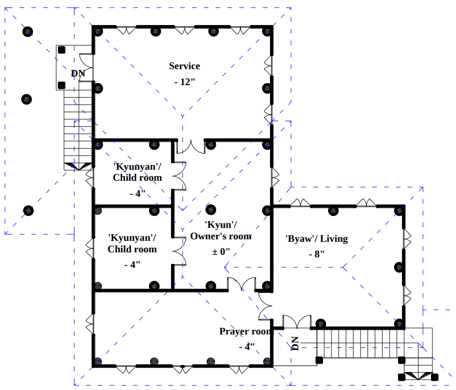
BEAM JOINT DETAILS



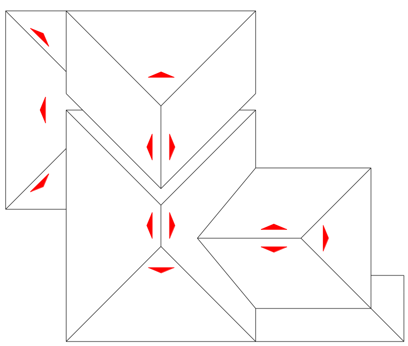
WALL DETAILS

Case Example 13

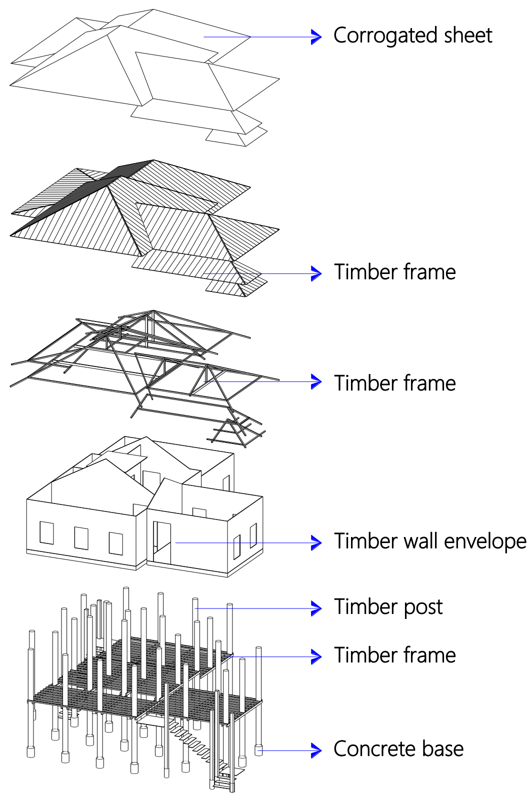
Type: UayeTun Residence



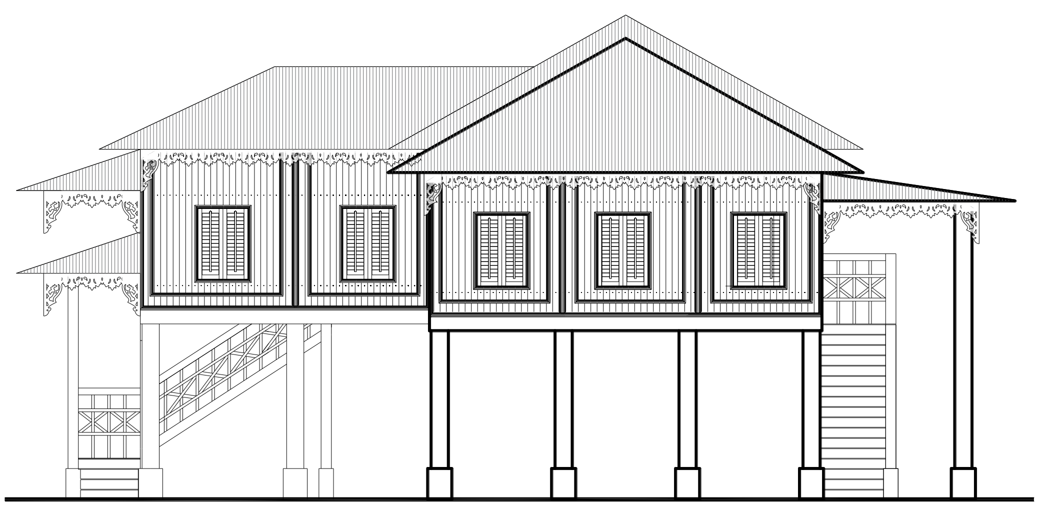
UPPER FLOOR PLAN



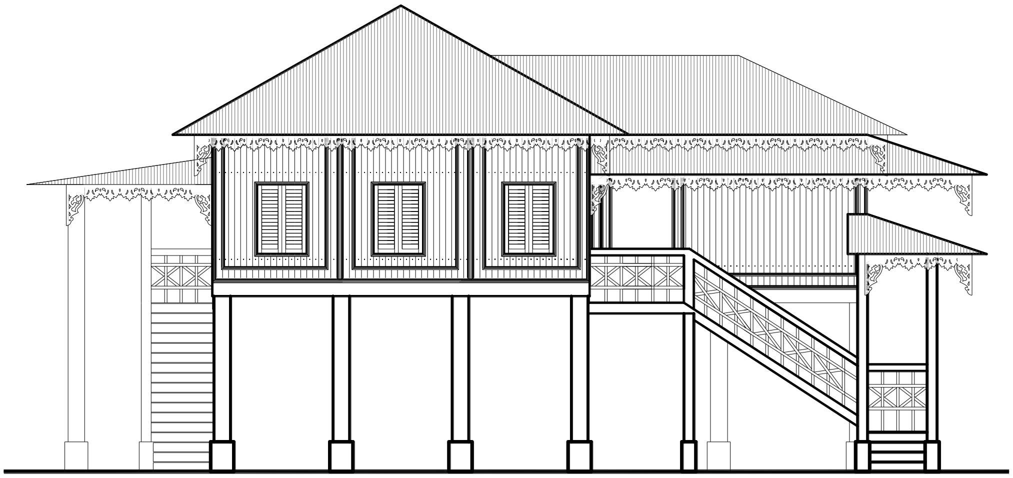
ROOF PLAN



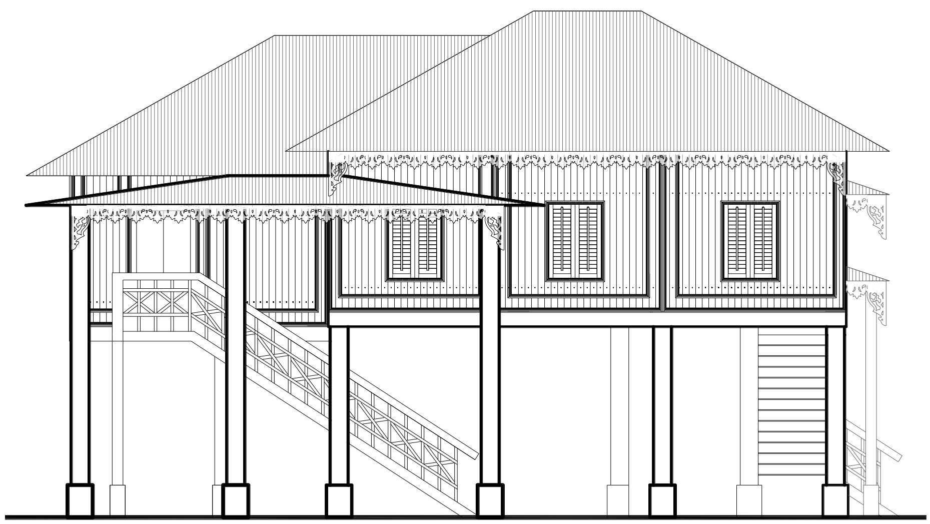
EXPLODED DRAWING



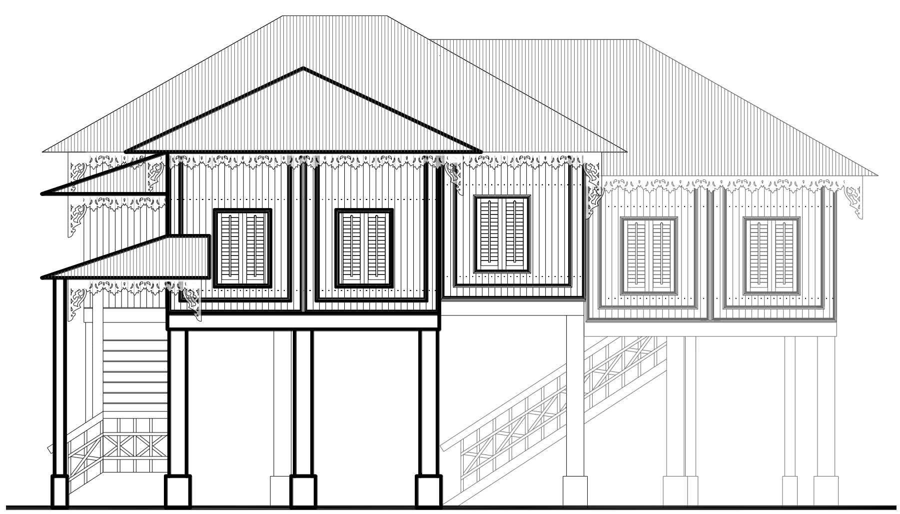
NORTH ELEVATION



SOUTH ELEVATION



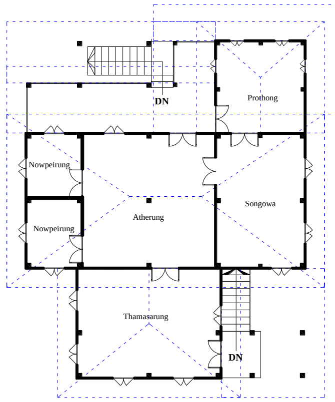
EAST ELEVATION



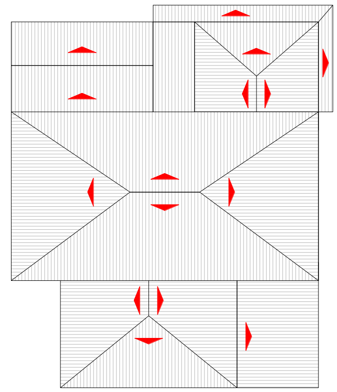
WEST ELEVATION

Case Example 14

Type: Monsing Residence



UPPER FLOOR PLAN

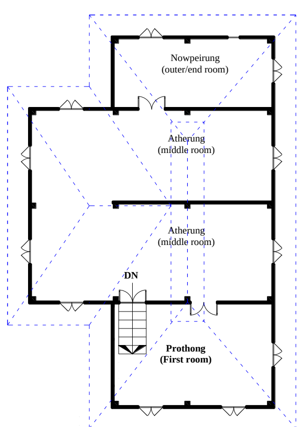


ROOF PLAN

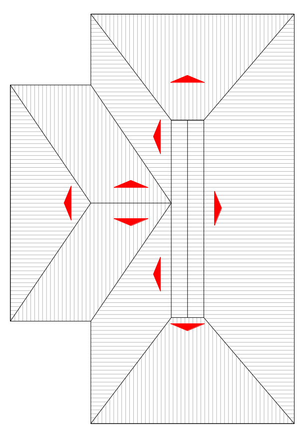
WEST/FRONT ELEVATION

Case Example 15

Name: Atun Residence

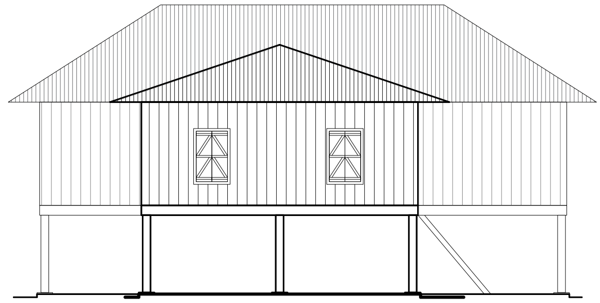


GROUND FLOOR PLAN



ROOF PLAN

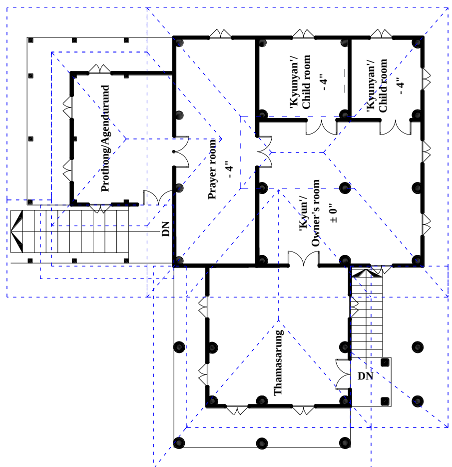
SOUTH/FRONT ELEVATION



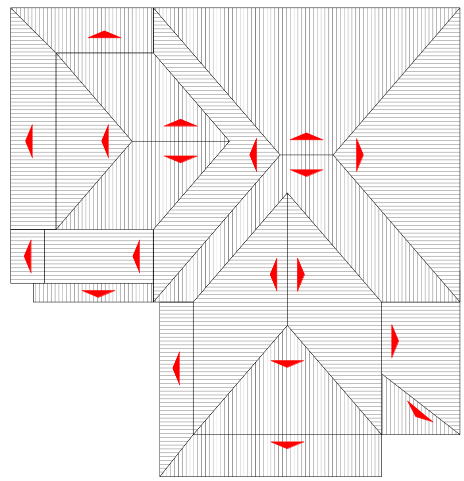
WEST ELEVATION

Case Example 16

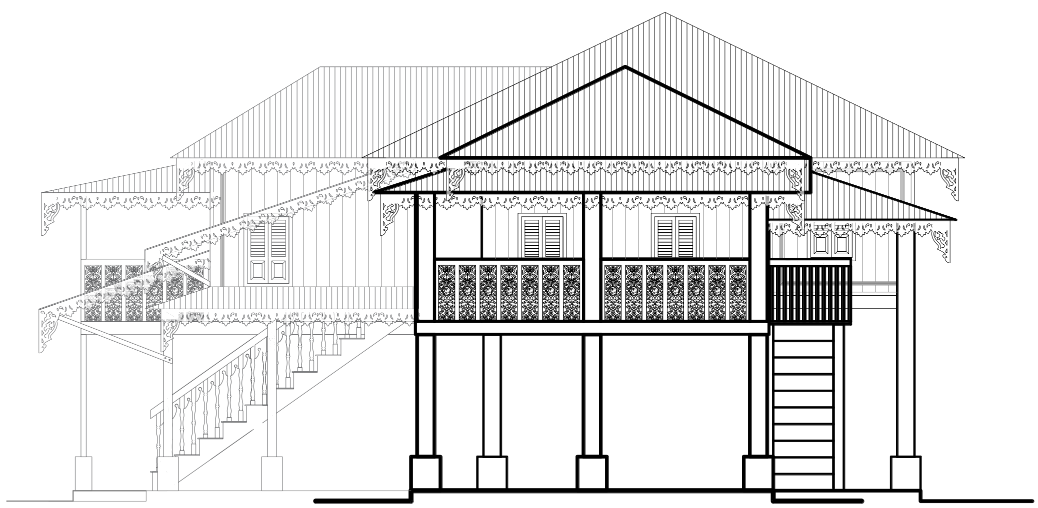
Name: District judge (Lajong) Residence



UPPER FLOOR PLAN



ROOF PLAN



SOUTH ELEVATION

Appendix: B

Table B.1 Construction element and the typical dimension of the traditional timber house

House	Element		Local name	Shape/ Dimension	Remarks
Single/ Double storied	Plinth			Rectangular L:W = 2:1/3:1	The earthen plinth is usually stepped, while the plinth with peripheral brick lining has no steps.
	Post		Khuti	Square 100mm x 100mm/ 112.5mm x 112.5mm Placing @ 1.2-1.5m c/c	Posts are provided with clay plate/brick (Katla) for protecting the post from ground moisture. Short separated posts are joined together by easily replaceable scarf joints.
	Beam		Kolpair/Kolda (interior) Kachpair (exterior)	Rectangular 100-125mm x 37.5mm	Holds the post in position
	Wall	Top/Bottom plate	Choukath	100-125mm x 25mm	Non-load bearing wall nailed ('gojal') with mainframe structure and provides structural stiffness. Prefabricated member.
		Trimmer	Ubi	75mm x 25mm	
		Sill/ wall nailer	Peti	100mm x 25mm	
		Wall envelope	Bera	75-100mm wide and 12-19mm thick	
		King stud	Batta	100-125mm x 25mm	
	Floor	Joist	Aara	88-100mm x 63-75mm Placing @600-750mm c/c	The floor structure is the load-bearing structure.
		Purlin	Chera	50mm x 25mm Placing @ 300mm c/c	
		Deck board	Pataton	300mm wide, 18-25mm thick	
	Roof	Ridge board	Tuli	63mm x 63mm	Thumb rule for the height of the roof is H=x/3, where, H = roof height and x = width of the house. The roof is provided with wooden false ceiling underneath.
		Hip rafter	Konaich	63mm x 63mm	
		Jack rafter	Rua	50mm x 50mm	
		Roof batten	Chera/Batam	50mm x 25mm	
Stilt timber	Plinth		-	-	Usually no plinth, earthen ground. The ground is sometimes provided with brick paving/CC
	Post		In-ache	Circular Dia. 200-250mm	Traditionally posts are pounding into the ground but nowadays bolted with an iron angle with 30mm high concrete base
	Wall (In-Tharen)	Top/Bottom wall plate	Baam	75mm x 63mm	Non-load bearing wall nailed ('gojal') with mainframe structure and provides structural stiffness. Prefabricated member.
		Nogging	Dhaam	75mm x 37.5mm	
		Sill trimmer		75mm x 37.5mm	
		Head trimmer		75mm x 37.5mm	
		Wall envelope		100mm wide and 12mm thick	
	Floor/ Elevated platform (In-gao)	Joist		94-100mm x 37.5mm	Different levels in floor height for religious reasons and functional separations
		Purlin		62.5mm x 37.5mm Placed @250-300mm c/c	
		Edge joist		200mm x 37.5mm	
		Deck board		150-200mm wide, 25mm thick	
	Roof (In-Akhang)	Ridge		100mm x 62.5mm	The roof is provided with a wooden shingle just underneath the coverings. Two types of roof structure: Hip & valley and Truss roof
		Hip rafter		100mm x 62.5mm	
		Purlin		75mm x 37.5mm	
		Jack rafter		75mm x 62.5mm	
		Wall-plate		75mm x 62.5mm	

Appendix: C

- **Residence Name:** **Date: . .20**
- **Location:**

Physical Survey

Building Plan (Conceptual with dimensions):
Building Elevation (Conceptual):
Building Zoning:
Construction Materials

Roof Detail	Floor Detail
Surface Wall Detail	**Other Details**

Socio-Demographic Survey

- **Family Member:**
- **Construction Period:**
- **Comfort Issue:**

Sensation	Morning	Noon	Evening	Night
Hot (+3)				
Warm (+2)				
Slightly Warm (+1)				
Neutral (0)				
Slightly Cool (-1)				
Cool (-2)				
Cold (-3)				

- **Flood Affected:** ☐ Yes ☐ No
- **Condition during rainy season:**

Approximately 1.5' during tide and flow. In rainy season slightly cool and comfortable as compared to rainy season

- **Mold Growth:** ☐ Yes ☐ No
- **Wetness:** ☐ Yes ☐ No
- **Dampness:** ☐ Yes ☐ No

Field Data Monitoring

Condition	Reading 1		Reading 2		Reading 3		Reading 4		Reading 5		Reading 6		Reading 7	
	Temp (°C)	RH %	Temp (°C)	RH %	Temp (°C)	RH %	Temp (°C)	RH %	Temp (°C)	RH %	Temp (°C)	RH %	Temp (°C)	RH %
Indoor														
Outdoor														

Part 03: Thermal Condition

Date: / /20……

Time: ………….. Indoor: Temp. [°C] **; RH** [%] **Ondoor: Temp.** [°C] **; RH** [%]

Part 03: Personal Data

Age: ………….. **Sex:** ☐**M** ☐**F** **Height: …………..** **Weight: ……………**

- **Education and occupation?**……………………………………
- **House type?** ☐ Mud ☐ Wood ☐ Bamboo fence ☐ C.I. sheet ☐ Exposed Brick ☐ Brick with one side plastered ☐ Brick with two side plastered ☐ Composite ☐ Other
- **Orientation of the house?** ☐ North-South ☐ East-West ☐ Other (specify)……………
- **How old is your house?**……………………………………
- **How long do you live in the house?**……………………………………
- **Family Member?**……………………………………

Part 04: Thermal Comfort Survey

1. **How do you describe the indoor conditions of your house right now?**
   ☐ Cold ☐ Cool ☐ Slightly Cool ☐ Neutral ☐ Slightly warm ☐ Warm ☐ Hot
2. **How do you find it?**
   ☐ Very comfortable ☐ Comfortable ☐ Slightly comfortable ☐ Neutral ☐ Slightly uncomfortable ☐ Uncomfortable ☐ Very uncomfortable
3. **How would you like to feel?**
   ☐ Cool ☐ A little bit cool ☐ No change ☐ A little bit warm ☐ Warm
4. **How do you find your house at different time of the day?**

Time/ Comfort Level	Very comfortable	Comfortable	Slightly comfort-able	Neutral	Slightly uncomfort -able	Uncomfort -able	Very uncomfort -able
12:00-02:00am							
03:00-05:00 am							
06:00-08:00 am							
09:00-11:00 am							
12:00-02:00 pm							
03:00-5:00 pm							
06:00-08:00 pm							
09:00-11:00 pm							

5. **Condition of air movement in the house?**
   ☐ Very still ☐ Moderately still ☐ Slightly still ☐ Neutral ☐ Slightly draughty ☐ Moderately draughty ☐ Very draughty
6. **Would you like to alter air movement?**
   ☐ Smaller than now ☐ No change ☐ Greater than now
7. **What was your activity during the last hour?**

Activity	15 min.	30 min.	45 min.	60 min.	Activity	15 min.	30 min.	45 min.	60 min.
Resting/sleeping					Swimming				
Seating					Taking a bath				
Reading					Washing				
Running					Cooking				
Eating					Driving				
Walking					Other				

8. **Are you sweating?** ☐ Yes ☐ No
9. **How do you find it?**
   ☐ Very wet ☐ Moderately wet ☐ A little bit wet ☐ Neutral ☐ A little bit dry ☐ Moderately dry ☐ Very dry
10. **How would you like to feel?**
    ☐ Wet ☐ A little bit wet ☐ No change ☐ A little bit dry ☐ Dry
11. **Occupant's clothing**

Saree (Cotton)		Blouse/ Top		Shirt/T-shirt (Cotton)		Shorts		Shoes	
Saree (Polyester)		Salwar-Kameez (Cotton)		Shirt/T-shirt (Polyester)		Pant/ Trousers		Sandals	
Petikot/ long skirt		Salwar-Kameez (Polyester)		Sleeveless T-shirt		Lungi			

Part 04: Personal Micro-climatic Control

12. **Can you open/close the window?** ☐ Yes ☐ No
13. **Can you open/close the external doors?** ☐ Yes ☐ No
14. **Which action you take when you feel hot?**

Use ceiling fan		Clothing change		Do light job		Taking shower		Other (specify)	
Use hand blowing fan		Change posture		Stay in airy place		Going out-side			

15. **How do you find it?** ☐ Satisfied ☐ Neutral ☐ Not satisfied
16. **Specify if you feel any special health symptoms right now** (site specific thermal sensation)?

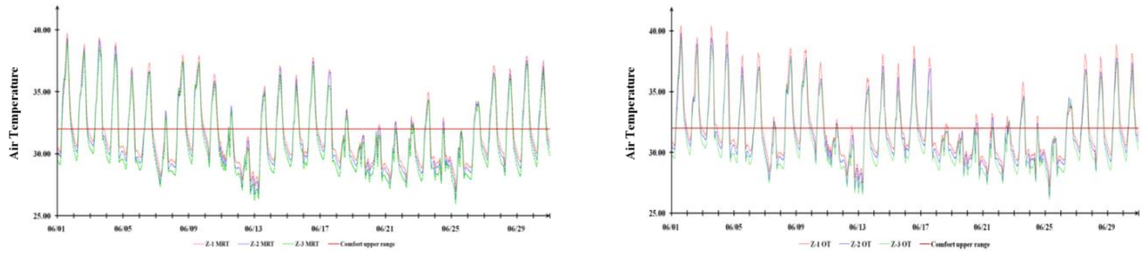
……………………………………………………………………

……………………………………………………………………

Thank you

Figure C.1 Questionnaire for survey

APPENDIX D

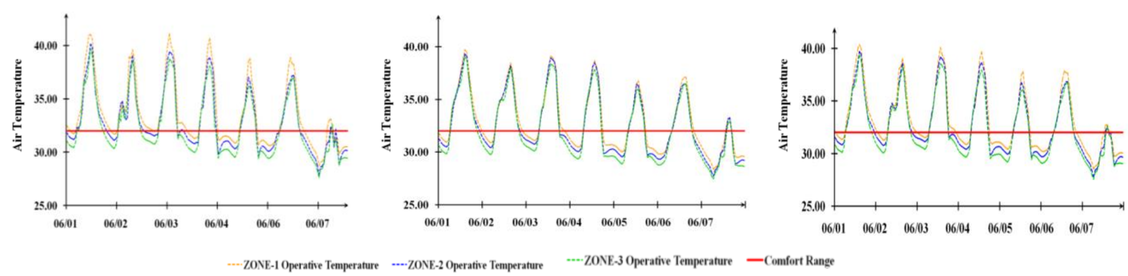


(a) **(b)**

Figure D.1 Hourly temperature gradient for Z-1, Z-2 and Z-3 during study period: (a) MRT (ºC) and (b) OT (ºC)

Table D.1 Simulation result summary for wall type W-1a.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	**MRT**(ºC)	**OT**(ºC)	**AT**(ºC)	**MRT**(ºC)	**OT**(ºC)	**AT**(ºC)	**MRT**(ºC)	**OT**(ºC)
Maximum	32.63	41.10	39.10	40.37	40.14	39.28	39.71	39.72	39.03	39.38
Minimum	23.54	27.52	27.12	27.32	26.58	26.39	26.49	26.29	26.08	26.19
Mean	27.83	32.50	31.75	32.12	31.81	31.37	31.59	31.38	31.04	31.21
Median	27.41	31.72	31.05	31.43	31.10	30.68	30.92	30.68	30.24	30.49
Mode	26.58	32.16	31.42	31.79	31.50	30.89	31.20	30.74	30.25	30.49
Kurtosis	-0.6	0.58	0.00	0.32	0.58	-0.08	0.27	0.19	-0.37	-0.10
Skewness	0.42	1.13	0.88	1.01	1.03	0.84	0.94	0.92	0.75	0.83
Std. Dev.	2.03	2.71	2.55	2.61	2.45	2.60	2.51	2.49	2.70	2.58
Sample Var.	2.11	7.34	6.52	6.83	6.00	6.78	6.29	6.22	7.29	6.67
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

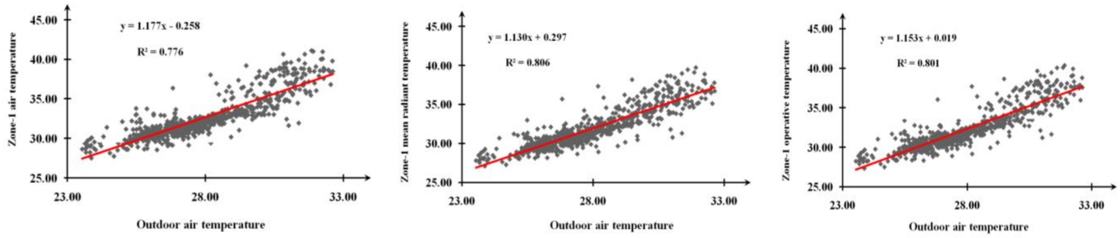


(a) **(b)** **(c)**

Figure D.2 Comparison of temperature gradient of different zones for wall type W-1a: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.2 Correlation matrix among different temperature index for wall type W-1a.

	Outdoor AT(ºC)	**AT** (ºC)	**MRT**(ºC)	**OT**(ºC)
Outdoor AT(°C)	1			
AT(°C)	0.88	1		
MRT(°C)	0.90	0.97	1	
OT(°C)	0.90	0.99	0.99	1

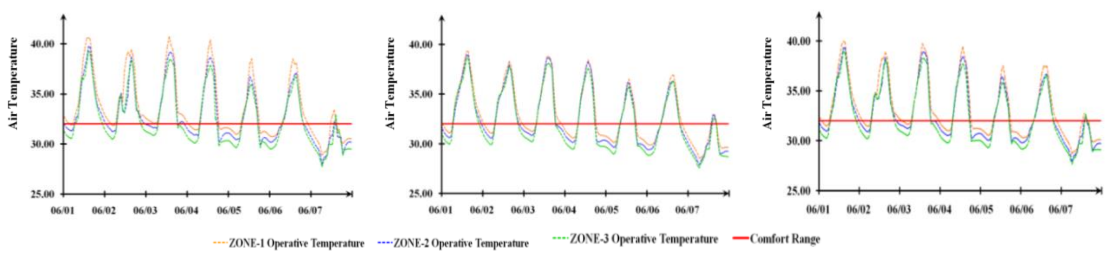


(a) **(b)** **(c)**

Figure D.3 Linear regression analysis for wall type W-1a: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.3 Simulation result summary for wall type W-1b.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	**MRT**(ºC)	**OT**(ºC)	**AT**(ºC)	**MRT**(ºC)	**OT**(ºC)	**AT**(ºC)	**MRT**(ºC)	**OT**(ºC)
Maximum	32.63	40.72	39.32	39.96	39.72	38.92	39.31	39.30	38.63	38.96
Minimum	23.54	27.68	27.32	27.50	26.71	26.54	26.63	26.38	26.19	26.29
Mean	27.83	32.52	31.77	32.15	31.84	31.38	31.61	31.41	31.04	31.22
Median	27.41	31.75	31.12	31.46	31.16	30.69	30.96	30.76	30.27	30.54
Mode	26.58	32.39	31.66	32.02	31.69	31.10	31.39	30.93	30.46	30.69
Kurtosis	-0.6	0.45	-0.03	0.23	0.41	-0.09	0.17	0.08	-0.39	-0.17
Skewness	0.42	1.08	0.86	0.98	0.97	0.83	0.90	0.87	0.74	0.79
Std. Dev.	2.03	2.65	2.49	2.55	2.41	2.54	2.46	2.44	2.64	2.53
Sample Var.	2.11	7.03	6.19	6.52	5.82	6.45	6.06	5.97	6.95	6.39
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

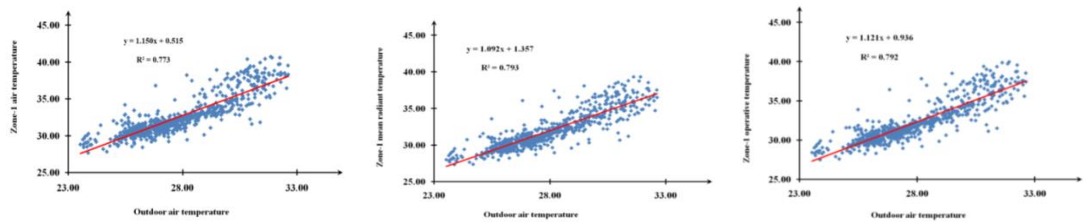


(a) **(b)** **(c)**

Figure D.4 Comparison of temperature gradient of different zones for wall type W-1b: (a) Zone AT °(b) Zone MRT (°C) and (c) Zone OT (°C

Table D.4 Correlation matrix among different temperature index for wall type W-1b.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.88	1		
MRT(°C)	0.89	0.98	1	
OT(°C)	0.89	0.99	0.99	1

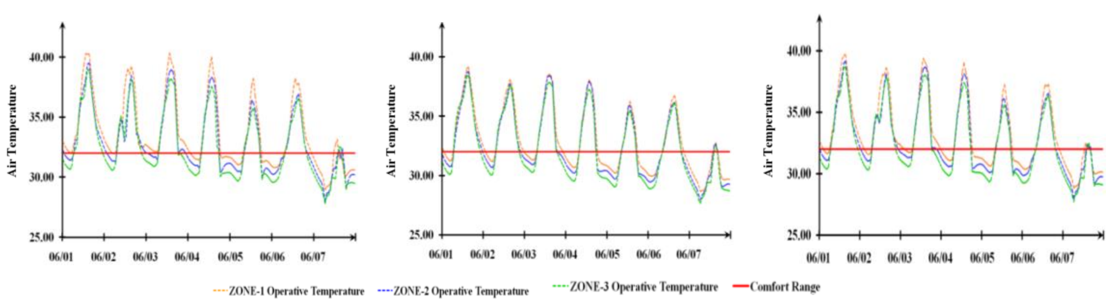


(a) (b) (c)

Figure D.5 Linear regression analysis for wall type W-1b: a) AT(ºC) and outdoor temperature(ºC), b) MRT(ºC) and outdoor temperature(ºC) and c) OT(ºC) and outdoor temperature(ºC)

Table D.5 Simulation result summary for wall type W-1c.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	40.36	39.12	39.69	39.52	38.78	39.15	38.98	38.43	38.67
Minimum	23.54	27.83	27.44	27.65	26.83	26.65	26.74	26.46	26.28	26.37
Mean	27.83	32.51	31.75	32.13	31.81	31.35	31.58	31.41	31.02	31.21
Median	27.41	31.79	31.16	31.48	31.23	30.75	31.03	30.76	30.26	30.51
Mode	26.58	32.60	31.88	32.24	31.87	31.30	31.58	31.11	30.65	30.88
Kurtosis	-0.6	0.40	-0.04	0.19	0.48	-0.08	0.20	0.01	-0.38	-0.21
Skewness	0.42	1.05	0.84	0.95	0.95	0.81	0.88	0.82	0.73	0.76
Std. Dev.	2.03	2.57	2.41	2.47	2.32	2.46	2.37	2.39	2.57	2.47
Sample Var.	2.11	6.59	5.82	6.12	5.37	6.04	5.62	5.70	6.60	6.09
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

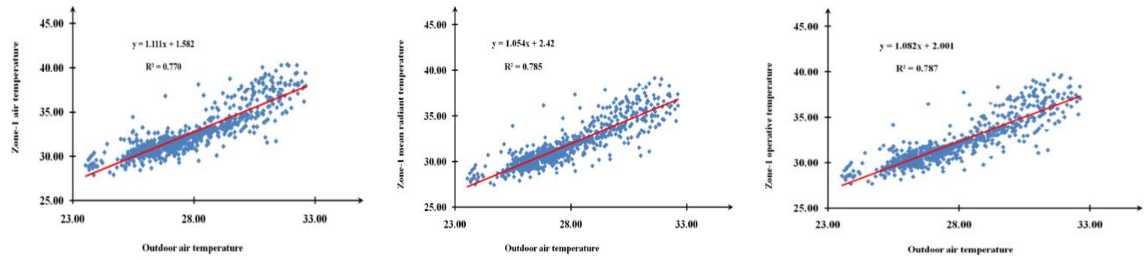


(a) (b) (c)

Figure D.6 Comparison of temperature gradient of different zones for wall type W-1c: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.6 Correlation matrix among different temperature index for wall type W-1c.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.88	1		
MRT(°C)	0.89	0.98	1	
OT(°C)	0.89	0.99	0.99	1

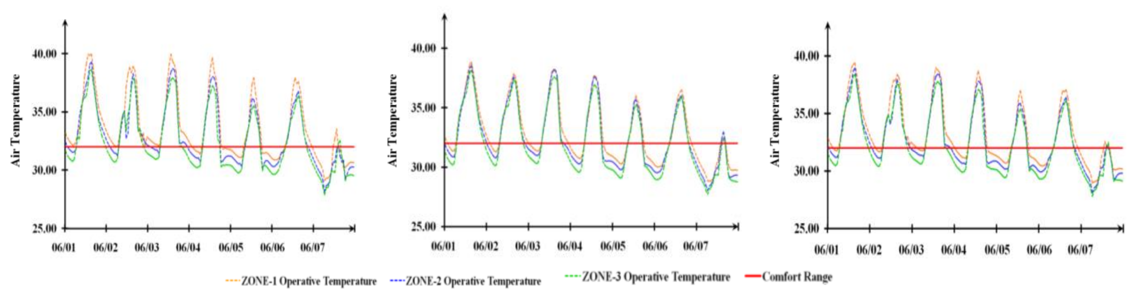


(a) (b) (c)

Figure D.7 Linear regression analysis for wall type W-1c: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.7 Simulation result summary for wall type W-1d.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	39.97	38.84	39.40	39.31	38.57	38.94	38.63	38.16	38.39
Minimum	23.54	27.97	27.51	27.75	26.94	26.76	26.85	26.54	26.38	26.46
Mean	27.83	32.50	31.74	32.12	31.78	31.34	31.56	31.38	30.99	31.19
Median	27.41	31.85	31.20	31.52	31.23	30.77	31.05	30.82	30.34	30.60
Mode	26.58	32.79	32.07	32.43	32.04	31.48	31.76	31.27	30.82	31.04
Kurtosis	-0.6	0.36	-0.07	0.16	0.54	-0.09	0.21	-0.02	-0.39	-0.23
Skewness	0.42	1.01	0.81	0.91	0.92	0.79	0.84	0.78	0.70	0.73
Std. Dev.	2.03	2.47	2.33	2.38	2.22	2.38	2.28	2.30	2.48	2.38
Sample Var.	2.11	6.10	5.41	5.67	4.92	5.66	5.19	5.31	6.17	5.68
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

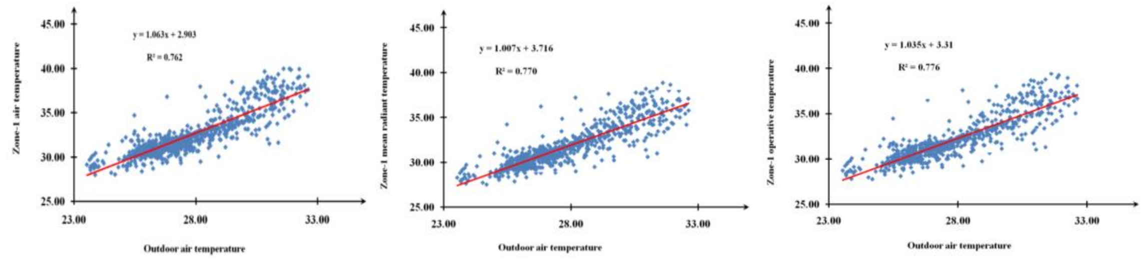


(a) (b) (c)

Figure D.8 Comparison of temperature gradient of different zones for wall type W-1d: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.8 Correlation matrix among different temperature index for wall type W-1d.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.87	1		
MRT(°C)	0.88	0.97	1	
OT(°C)	0.88	0.99	0.99	1

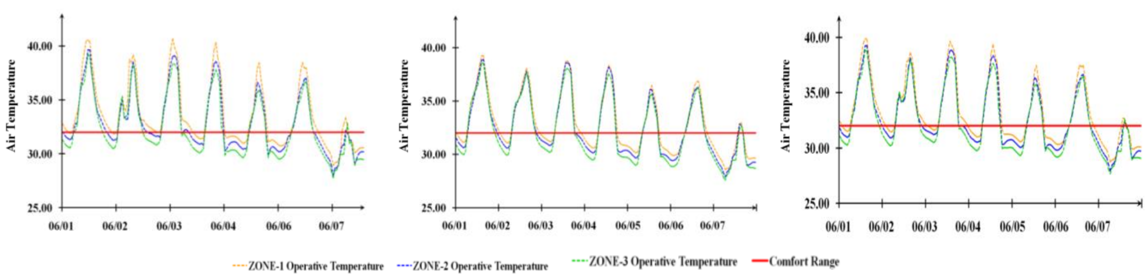


(a) **(b)** **(c)**

Figure D.9 Linear regression analysis for wall type W-1d: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.9 Simulation result summary for wall type W-2c.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	40.67	39.24	39.88	39.65	38.89	39.25	39.21	38.55	38.88
Minimum	23.54	27.70	27.35	27.53	26.73	26.56	26.65	26.39	26.21	26.30
Mean	27.83	32.52	31.76	32.14	31.82	31.37	31.59	31.41	31.04	31.22
Median	27.41	31.77	31.10	31.49	31.15	30.70	30.99	30.74	30.26	30.53
Mode	26.58	32.42	31.69	32.06	31.72	31.14	31.43	30.95	30.49	30.72
Kurtosis	-0.6	0.45	-0.04	0.22	0.47	-0.09	0.20	0.06	-0.40	-0.19
Skewness	0.42	1.07	0.85	0.97	0.97	0.83	0.90	0.86	0.74	0.79
Std. Dev.	2.03	2.62	2.47	2.53	2.38	2.51	2.43	2.43	2.62	2.52
Sample Var.	2.11	6.86	6.08	6.39	5.65	6.32	5.90	5.93	6.88	6.33
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

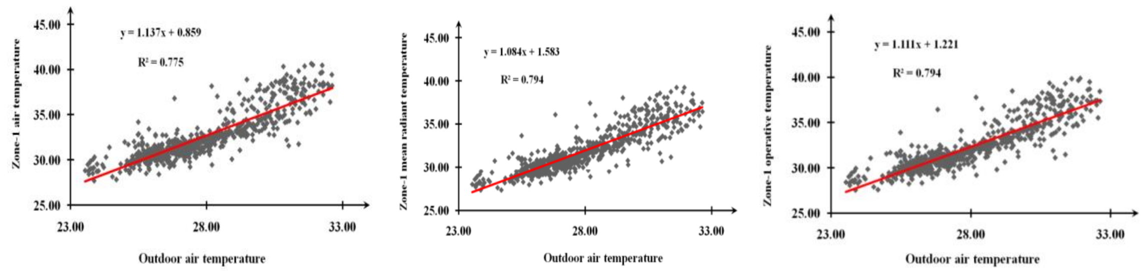


(a) **(b)** **(c)**

Figure D.10 Comparison of temperature gradient of different zones for wall type W-2c: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.10 Correlation matrix among different temperature index for wall type W-2c.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.88	1		
MRT(°C)	0.89	0.98	1	
OT(°C)	0.89	0.99	0.99	1

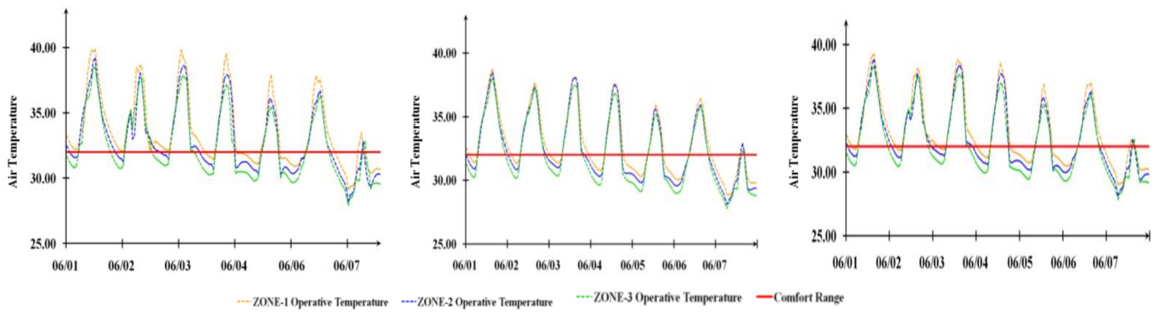


(a) **(b)** **(c)**

Figure D.11 Linear regression analysis for wall type W-2c: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.11 Simulation result summary for wall type W-2d.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	**MRT**(ºC)	**OT**(ºC)	**AT**(ºC)	**MRT**(ºC)	**OT**(ºC)	**AT**(ºC)	**MRT**(ºC)	**OT**(ºC)
Maximum	32.63	39.85	38.72	39.28	39.20	38.47	38.84	38.52	38.04	38.28
Minimum	23.54	28.04	27.56	27.80	26.99	26.81	26.90	26.58	26.42	26.50
Mean	27.83	32.49	31.75	32.12	31.78	31.34	31.56	31.38	30.98	31.18
Median	27.41	31.86	31.19	31.50	31.25	30.78	31.04	30.85	30.36	30.59
Mode	26.58	32.85	32.14	32.49	32.09	31.54	31.81	31.31	30.87	31.09
Kurtosis	-0.6	0.36	-0.10	0.14	0.50	-0.12	0.17	-0.05	-0.40	-0.25
Skewness	0.42	1.00	0.79	0.90	0.89	0.77	0.82	0.77	0.69	0.72
Std. Dev.	2.03	2.42	2.29	2.34	2.19	2.35	2.25	2.27	2.45	2.35
Sample Var.	2.11	5.87	5.24	5.47	4.79	5.51	5.05	5.17	5.99	5.52
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

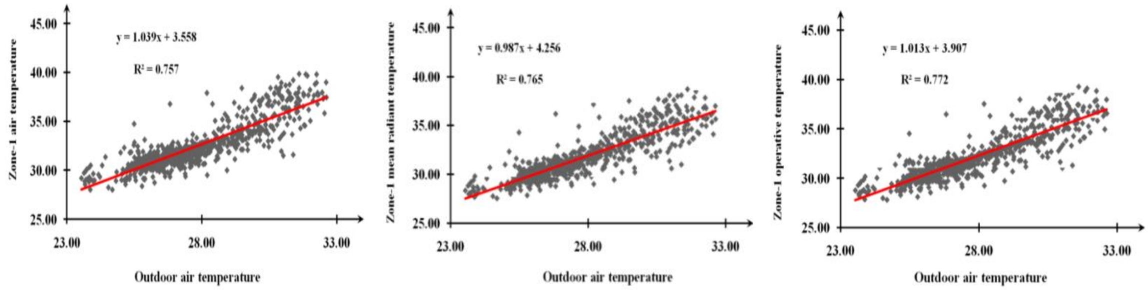


(a) **(b)** **(c)**

Figure D.12 Comparison of temperature gradient of different zones for wall type W-2d: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.12 Correlation matrix among different temperature index for wall type W-2d.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.87	1		
MRT(°C)	0.87	0.97	1	
OT(°C)	0.88	0.99	0.99	1

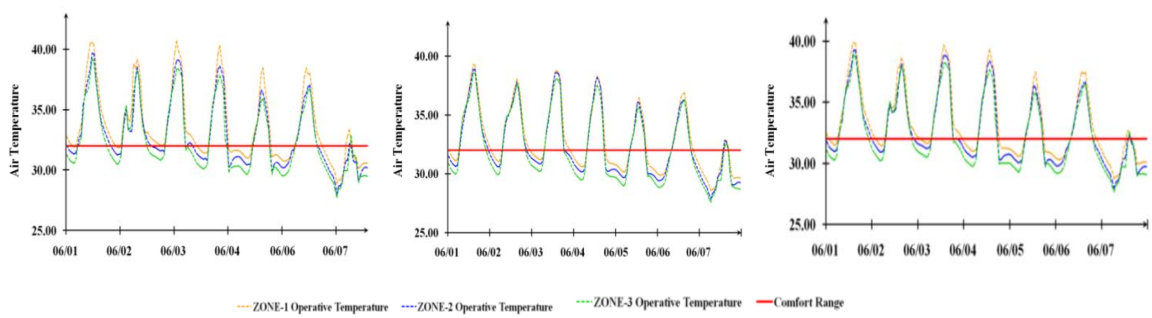


(a) **(b)** **(c)**

Figure D.13 Linear regression analysis for wall type W-2d: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.13 Simulation result summary for wall type W-2e.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	40.68	39.26	39.90	39.67	38.90	39.27	39.23	38.57	38.90
Minimum	23.54	27.70	27.34	27.52	26.73	26.56	26.64	26.39	26.21	26.30
Mean	27.83	32.52	31.76	32.14	31.82	30.70	31.59	31.41	31.04	31.22
Median	27.41	31.77	31.10	31.48	31.15	31.13	30.99	30.74	30.26	30.53
Mode	26.58	32.42	31.69	32.05	31.71	31.37	31.42	30.95	30.48	30.72
Kurtosis	-0.6	0.45	-0.04	0.22	0.47	-0.09	0.20	0.06	-0.39	-0.18
Skewness	0.42	1.07	0.85	0.97	0.97	0.83	0.90	0.86	0.74	0.79
Std. Dev.	2.03	2.62	2.47	2.53	2.38	2.52	2.43	2.44	2.63	2.52
Sample Var.	2.11	6.88	6.10	6.40	5.67	6.34	5.91	5.95	6.90	6.35
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

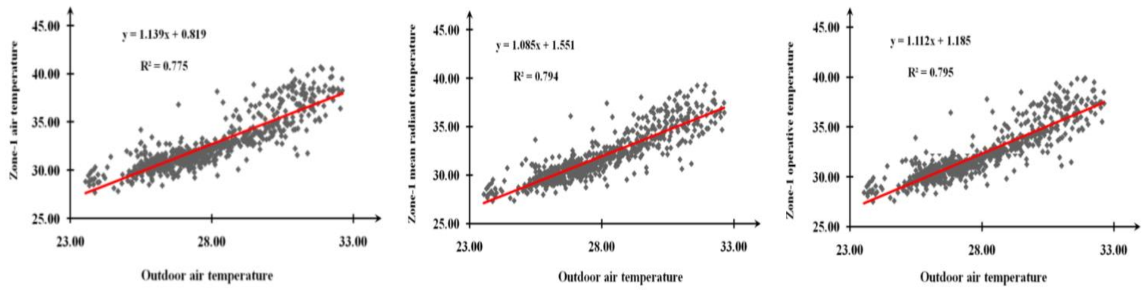


(a) **(b)** **(c)**

Figure D.14 Comparison of temperature gradient of different zones for wall type W-2e: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C).

Table D.14 Correlation matrix among different temperature index for wall type W-2e.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.88	1		
MRT(°C)	0.89	0.97	1	
OT(°C)	0.89	0.99	0.99	1

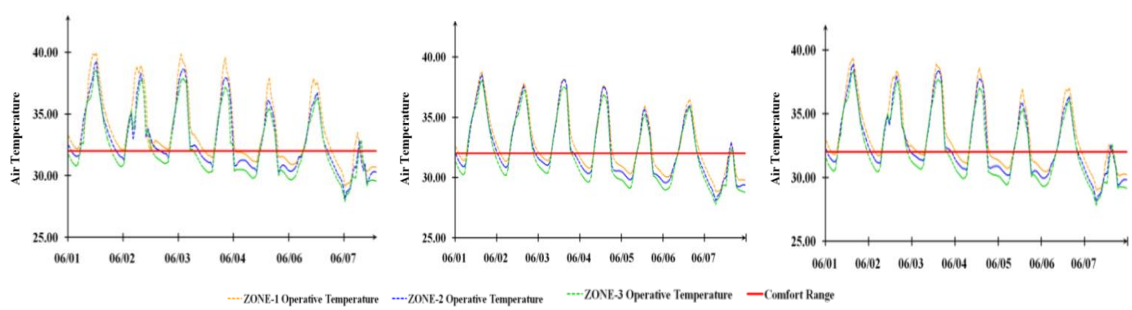


(a) (b) (c)

Figure D.15 Linear regression analysis for wall type W-2e: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.15 Simulation result summary for wall type W-2f.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	39.89	38.76	38.31	39.24	38.50	38.87	38.55	38.07	38.31
Minimum	23.54	28.02	27.54	26.49	26.98	26.80	26.89	26.57	26.41	26.49
Mean	27.83	32.50	31.74	31.18	31.78	31.34	31.56	31.38	30.98	31.18
Median	27.41	31.87	31.19	30.59	31.25	30.78	31.04	30.85	30.35	30.59
Mode	26.58	32.85	32.13	31.09	32.09	31.53	31.81	31.31	30.86	31.09
Kurtosis	-0.6	0.35	-0.08	-0.24	0.51	-0.10	0.19	-0.03	-0.39	-0.24
Skewness	0.42	1.00	0.80	0.73	0.90	0.78	0.83	0.77	0.70	0.73
Std. Dev.	2.03	2.44	2.30	2.36	2.20	2.36	2.26	2.28	2.45	2.36
Sample Var.	2.11	5.96	5.29	5.57	4.86	5.57	5.12	5.22	6.02	5.57
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439



(a) (b) (c)

Figure D.16 Comparison of temperature gradient of different zones for wall type W-2f: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.16 Correlation matrix among different temperature index for wall type W-2f.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.87	1		
MRT(°C)	0.87	0.97	1	
OT(°C)	0.88	0.99	0.99	1

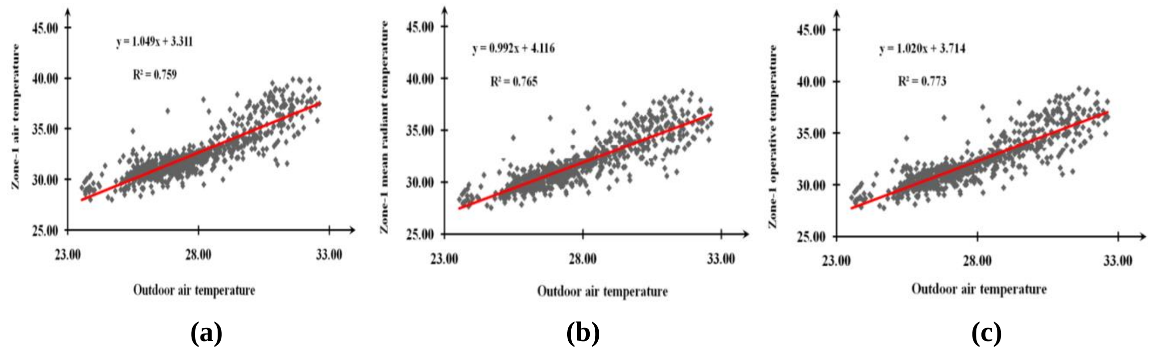


Figure D.17 Linear regression analysis for wall type W-2f: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.17 Simulation result summary for wall type W-3a.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	39.47	38.08	38.57	38.36	37.78	38.07	37.37	37.03	37.20
Minimum	23.54	29.01	28.47	28.74	27.83	27.61	27.72	27.22	27.04	27.13
Mean	27.83	32.69	31.96	32.33	31.91	31.47	31.69	31.38	30.94	31.16
Median	27.41	32.10	31.49	31.81	31.50	31.03	31.27	30.94	30.44	30.68
Mode	26.58	33.13	32.36	32.75	32.31	31.70	32.01	31.36	30.85	31.10
Kurtosis	-0.6	0.56	0.07	0.34	0.62	0.04	0.32	-0.15	-0.37	-0.28
Skewness	0.42	1.08	0.85	0.98	0.86	0.81	0.83	0.71	0.69	0.70
Std. Dev.	2.03	2.11	1.96	2.02	1.83	1.99	1.89	1.91	2.08	1.99
Sample Var.	2.11	4.45	3.86	4.07	3.36	3.98	3.59	3.66	4.32	3.95
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

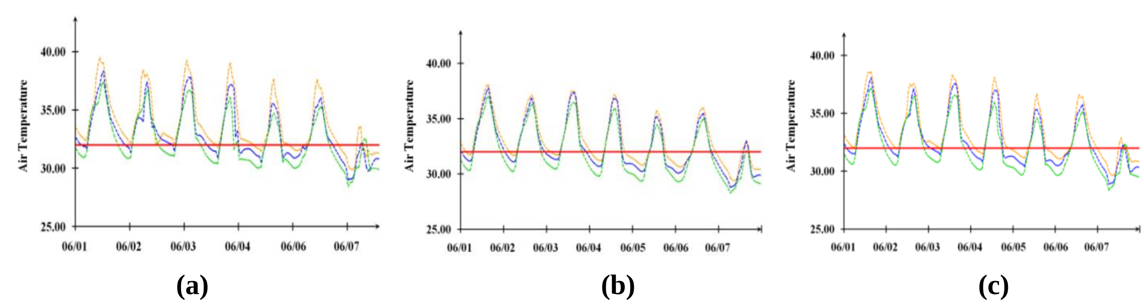
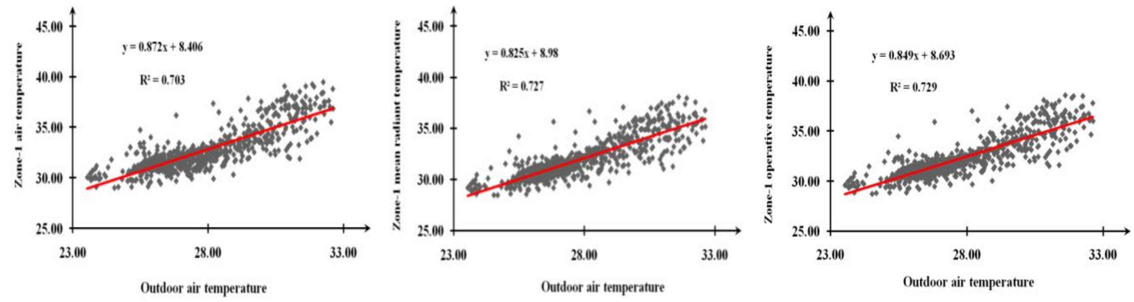


Figure D.18 Comparison of temperature gradient of different zones for wall type W-3a: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.18 Correlation matrix among different temperature index for wall type W-3a.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.84	1		
MRT(°C)	0.85	0.96	1	
OT(°C)	0.85	0.99	0.99	1

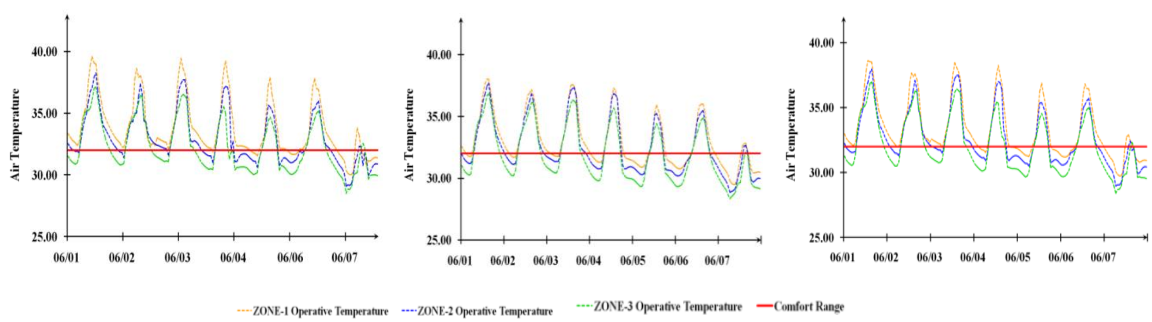


(a) **(b)** **(c)**

Figure D.19 Linear regression analysis for wall type W-3a: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.19 Simulation result summary for wall type W-3b.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	40.72	39.32	39.96	39.72	38.92	39.31	39.30	38.63	38.96
Minimum	23.54	27.68	27.32	27.50	26.71	26.54	26.63	26.38	26.19	26.29
Mean	27.83	32.52	31.77	32.15	31.84	31.38	31.61	31.41	31.04	31.22
Median	27.41	31.75	31.12	31.46	31.16	30.69	30.96	30.76	30.27	30.54
Mode	26.58	32.39	31.66	32.02	31.69	31.10	31.39	30.93	30.46	30.69
Kurtosis	-0.6	0.45	-0.03	0.23	0.41	-0.09	0.17	0.08	-0.39	-0.17
Skewness	0.42	1.08	0.86	0.98	0.97	0.83	0.90	0.87	0.74	0.79
Std. Dev.	2.03	2.65	2.49	2.55	2.41	2.54	2.46	2.44	2.64	2.53
Sample Var.	2.11	7.03	6.19	6.52	5.82	6.45	6.06	5.97	6.95	6.39
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

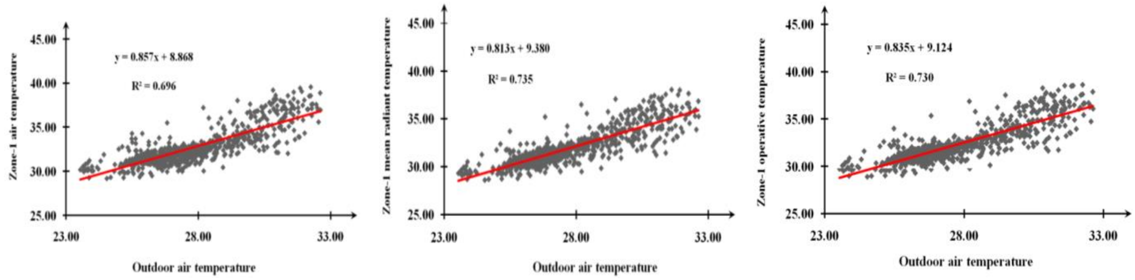


(a) **(b)** **(c)**

Figure D.20 Comparison of temperature gradient of different zones for wall type W-3b: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.20 Correlation matrix among different temperature index for wall type W-3b.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.83	1		
MRT(°C)	0.86	0.96	1	
OT(°C)	0.85	0.99	0.99	1

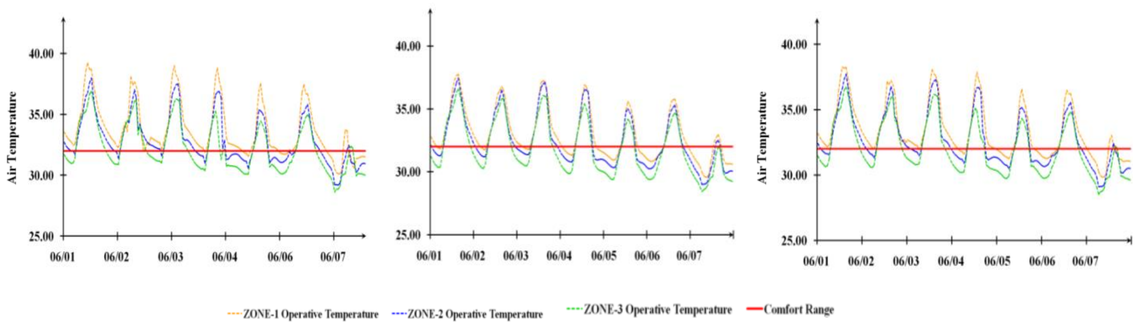


(a) **(b)** **(c)**

Figure D.21 Linear regression analysis for wall type W-3b: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.21 Simulation result summary for wall type W-3c.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	39.22	37.77	38.25	38.00	37.45	37.72	36.90	36.59	36.74
Minimum	23.54	29.28	28.72	29.00	28.08	27.87	27.98	27.42	27.23	27.32
Mean	27.83	32.73	32.01	32.37	31.95	31.49	31.72	31.35	30.90	31.12
Median	27.41	32.16	31.59	31.89	31.57	31.07	31.33	30.95	30.46	30.70
Mode	26.58	33.26	32.47	32.86	32.41	31.79	32.10	31.40	30.87	31.14
Kurtosis	-0.6	0.57	0.10	0.37	0.57	0.06	0.32	-0.18	-0.38	-0.31
Skewness	0.42	1.09	0.85	0.99	0.82	0.80	0.81	0.68	0.68	0.67
Std. Dev.	2.03	2.00	1.84	1.90	1.73	1.87	1.78	1.78	1.94	1.85
Sample Var.	2.11	3.99	3.39	3.59	2.98	3.50	3.17	3.18	3.76	3.43
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

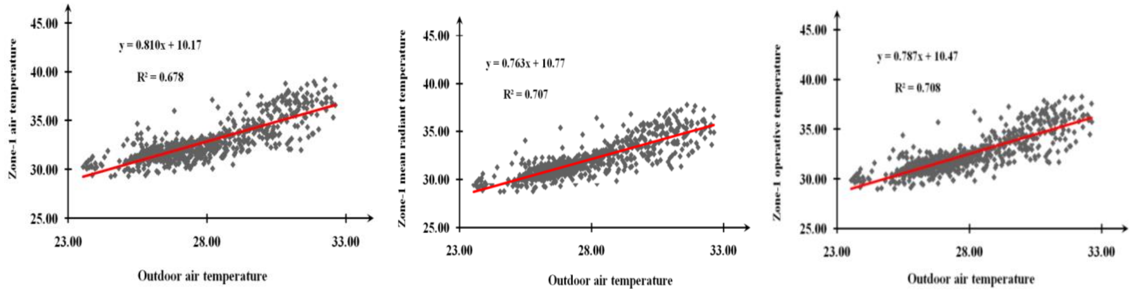


(a) **(b)** **(c)**

Figure D.22 Comparison of temperature gradient of different zones for wall type W-3c: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.22 Correlation matrix among different temperature index for wall type W-3c.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.82	1		
MRT(°C)	0.84	0.95	1	
OT(°C)	0.84	0.99	0.99	1

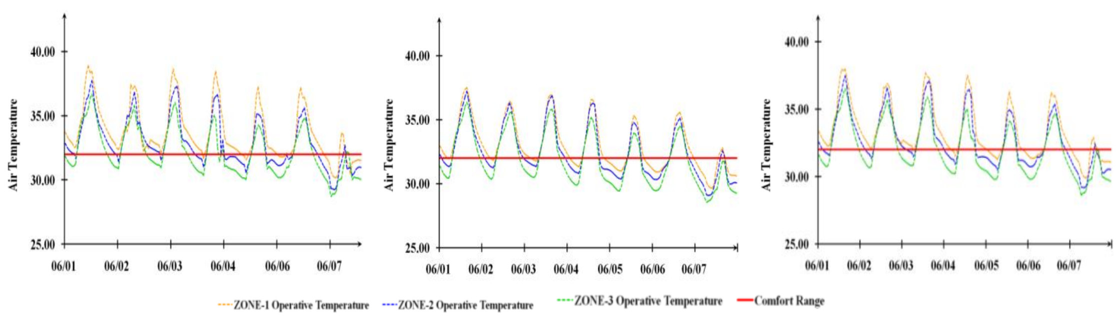


(a) **(b)** **(c)**

Figure D.23 Linear regression analysis for wall type W-3c: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.23 Simulation result summary for wall type W-3e.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	**MRT**(ºC)	**OT**(ºC)	**AT**(ºC)	**MRT**(ºC)	**OT**(ºC)	**AT**(ºC)	**MRT**(ºC)	**OT**(ºC)
Maximum	32.63	38.91	37.51	37.98	37.75	37.21	37.48	36.68	36.35	36.51
Minimum	23.54	29.39	28.84	29.11	28.22	28.01	28.12	27.53	27.35	27.44
Mean	27.83	32.72	32.02	32.37	31.96	31.50	31.73	31.34	30.89	31.12
Median	27.41	32.21	31.63	31.90	31.59	31.13	31.37	30.98	30.46	30.75
Mode	26.58	33.42	32.64	33.03	32.55	31.94	32.25	31.55	31.03	31.29
Kurtosis	-0.6	0.51	0.01	0.29	0.42	0.00	0.22	-0.30	-0.42	-0.39
Skewness	0.42	1.04	0.79	0.93	0.74	0.76	0.75	0.61	0.64	0.62
Std. Dev.	2.03	1.90	1.76	1.81	1.67	1.80	1.72	1.71	1.87	1.78
Sample Var.	2.11	3.62	3.10	3.26	2.79	3.24	2.95	2.94	3.49	3.18
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

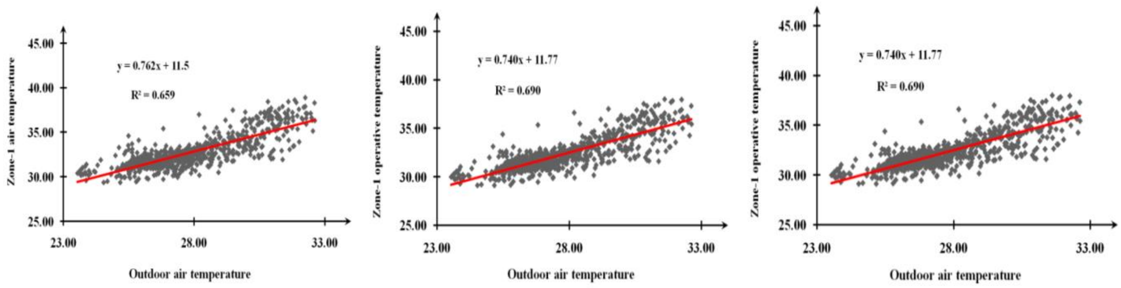


(a) **(b)** **(c)**

Figure D.24 Comparison of temperature gradient of different zones for wall type W-3e: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.24 Correlation matrix among different temperature index for wall type W-3e

	Outdoor AT(°C)	**AT(°C)**	**MRT(°C)**	**OT(°C)**
Outdoor AT(°C)	1			
AT(°C)	0.81	1		
MRT(°C)	0.83	0.94	1	
OT(°C)	0.83	0.99	0.98	1

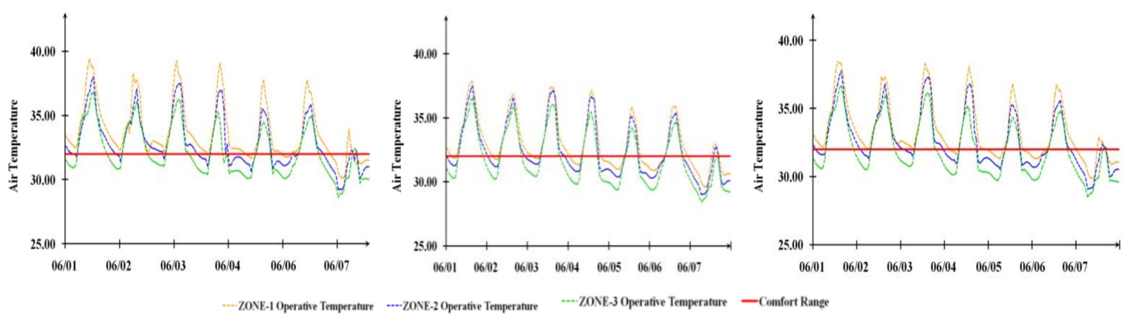


(a) (b) (c)

Figure D.25 Linear regression analysis for wall type W-3e: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.25 Simulation result summary for wall type W-3g.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	39.42	37.83	38.45	38.02	37.50	37.76	36.81	36.55	36.68
Minimum	23.54	29.34	28.78	29.06	28.09	27.86	27.97	27.41	27.21	27.31
Mean	27.83	32.77	32.06	32.42	31.97	31.51	31.74	31.34	30.88	31.11
Median	27.41	32.21	31.65	31.91	31.62	31.10	31.35	30.93	30.38	30.65
Mode	26.58	33.16	32.36	32.76	32.33	31.69	32.01	31.28	30.72	31.00
Kurtosis	-0.6	0.76	0.19	0.51	0.66	0.14	0.39	-0.21	-0.38	-0.31
Skewness	0.42	1.16	0.90	1.05	0.85	0.84	0.85	0.69	0.70	0.69
Std. Dev.	2.03	2.01	1.85	1.90	1.71	1.87	1.77	1.76	1.93	1.84
Sample Var.	2.11	4.04	3.41	3.63	2.93	3.49	3.14	3.11	3.72	3.38
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

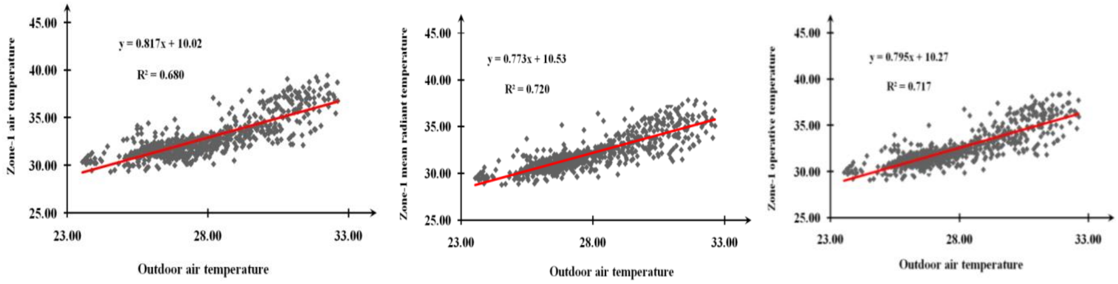


(a) (b) (c)

Figure D.26 Comparison of temperature gradient of different zones for wall type W-3g: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.26 Correlation matrix among different temperature index for wall type W-3g.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.82	1		
MRT(°C)	0.85	0.95	1	
OT(°C)	0.85	0.99	0.99	1

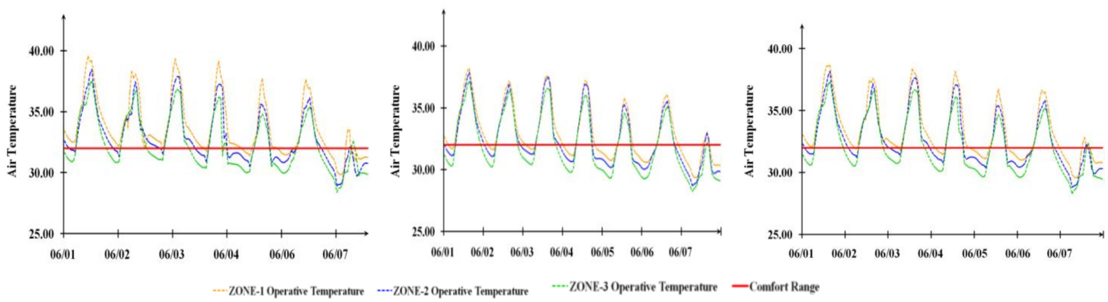


(a) **(b)** **(c)**

Figure D.27 Linear regression analysis for wall type W-3g: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.27 Simulation result summary for wall type W-4a.

Parameter	**Outdoor AT**(ºC)	**Zone-1**			**Zone-2**			**Zone-3**		
		AT(ºC)	**MRT**(ºC)	**OT**(ºC)	**AT**(ºC)	**MRT**(ºC)	**OT**(ºC)	**AT**(ºC)	**MRT**(ºC)	**OT**(ºC)
Maximum	32.63	39.54	38.17	38.67	38.47	37.87	38.17	37.51	37.16	37.34
Minimum	23.54	28.94	28.40	28.67	27.75	27.54	27.64	27.17	26.98	27.08
Mean	27.83	32.67	31.94	32.31	31.90	31.46	31.68	31.38	30.95	31.16
Median	27.41	32.06	31.47	31.77	31.49	31.01	31.24	30.93	30.42	30.67
Mode	26.58	33.10	32.33	32.72	32.28	31.68	31.98	31.35	30.84	31.09
Kurtosis	-0.6	0.55	0.06	0.33	0.63	0.03	0.32	-0.11	-0.37	-0.26
Skewness	0.42	1.08	0.84	0.97	0.87	0.81	0.83	0.72	0.70	0.70
Std. Dev.	2.03	2.14	1.99	2.04	1.86	2.03	1.93	1.94	2.11	2.02
Sample Var.	2.11	4.56	3.97	4.17	3.48	4.12	3.71	3.78	4.46	4.08
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

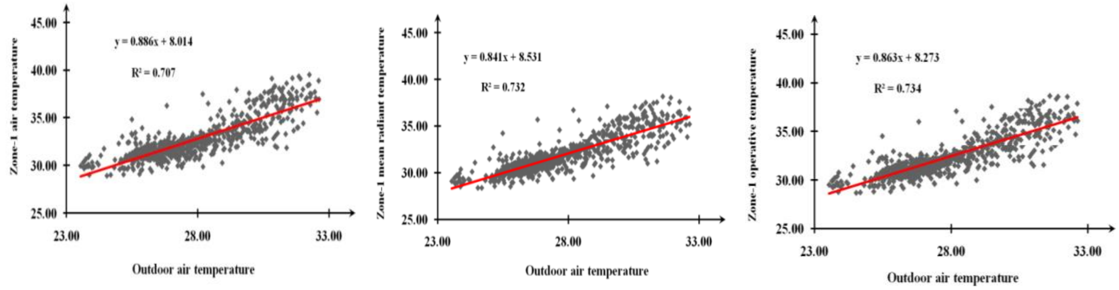


(a) **(b)** **(c)**

Figure D.28 Comparison of temperature gradient of different zones for wall type W-4a: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.28 Correlation matrix among different temperature index for wall type W-4a.

	Outdoor AT(°C)	**AT(°C)**	**MRT(°C)**	**OT(°C)**
Outdoor AT(°C)	1			
AT(°C)	0.84	1		
MRT(°C)	0.86	0.96	1	
OT(°C)	0.86	0.99	0.99	1

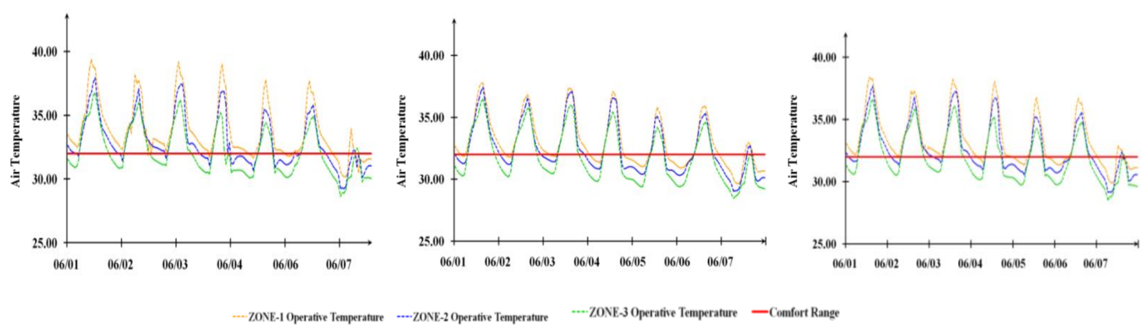


(a) (b) (c)

Figure D.29 Linear regression analysis for wall type W-4a: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.29 Simulation result summary for wall type W-4b.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	39.36	37.77	38.39	37.95	37.43	37.69	36.72	36.46	36.59
Minimum	23.54	29.39	28.82	29.11	28.13	27.91	28.02	27.45	27.25	27.35
Mean	27.83	32.79	32.07	32.43	31.98	31.52	31.75	31.33	30.88	31.10
Median	27.41	32.24	31.65	31.95	31.63	31.12	31.36	30.93	30.40	30.66
Mode	26.58	33.19	32.39	32.79	32.35	31.71	32.03	31.29	30.73	31.01
Kurtosis	-0.6	0.73	0.21	0.51	0.63	0.14	0.40	-0.23	-0.38	-0.32
Skewness	0.42	1.15	0.90	1.05	0.85	0.84	0.85	0.68	0.70	0.68
Std. Dev.	2.03	1.99	1.82	1.88	1.70	1.84	1.75	1.74	1.90	1.81
Sample Var.	2.11	3.96	3.32	3.55	2.90	3.40	3.08	3.02	3.63	3.29
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

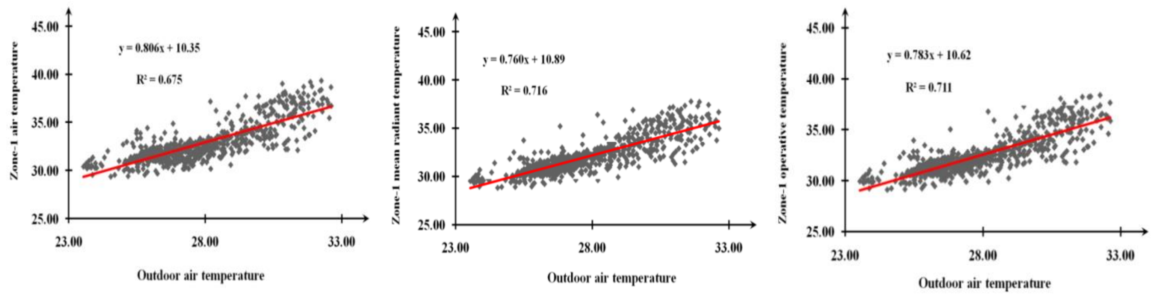


(a) (b) (c)

Figure D.30 Comparison of temperature gradient of different zones for wall type W-4b: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.30 Correlation matrix among different temperature index for wall type W-4b.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.82	1		
MRT(°C)	0.85	0.95	1	
OT(°C)	0.84	0.99	0.99	1

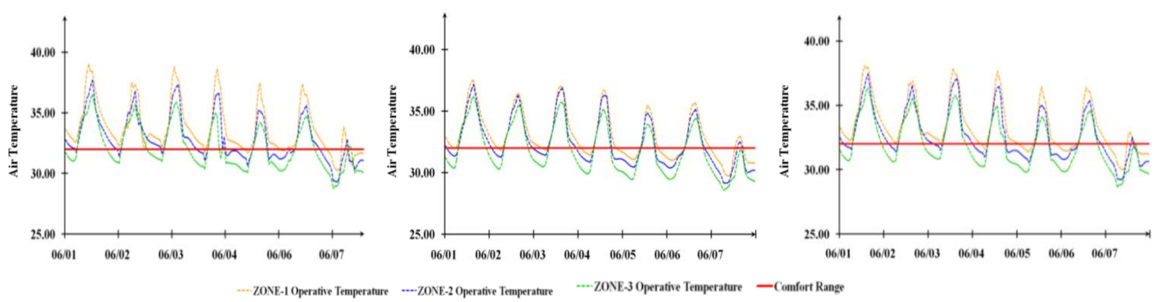


(a) (b) (c)

Figure D.31 Linear regression analysis for wall type W-4b: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.31 Simulation result summary for wall type W-4c.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	39.00	37.51	38.04	37.69	37.17	37.43	36.50	36.21	36.35
Minimum	23.54	29.49	28.93	29.22	28.29	28.08	28.19	27.57	27.38	27.47
Mean	27.83	32.77	32.07	32.42	31.98	31.52	31.75	31.32	30.87	31.09
Median	27.41	32.22	31.69	31.93	31.63	31.12	31.37	30.96	30.45	30.72
Mode	26.58	33.36	32.57	32.97	32.50	31.87	32.19	31.44	30.90	31.17
Kurtosis	-0.6	0.61	0.10	0.39	0.50	0.08	0.29	-0.27	-0.40	-0.35
Skewness	0.42	1.08	0.84	0.98	0.77	0.79	0.78	0.63	0.66	0.65
Std. Dev.	2.03	1.90	1.74	1.79	1.64	1.77	1.69	1.68	1.83	1.75
Sample Var.	2.11	3.59	3.02	3.21	2.68	3.14	2.85	2.81	3.35	3.05
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439



(a) (b) (c)

Figure D.32 Comparison of temperature gradient of different zones for wall type W-4c: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.32 Correlation matrix among different temperature index for wall type W-4c.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.81	1		
MRT(°C)	0.83	0.94	1	
OT(°C)	0.83	0.99	0.98	1

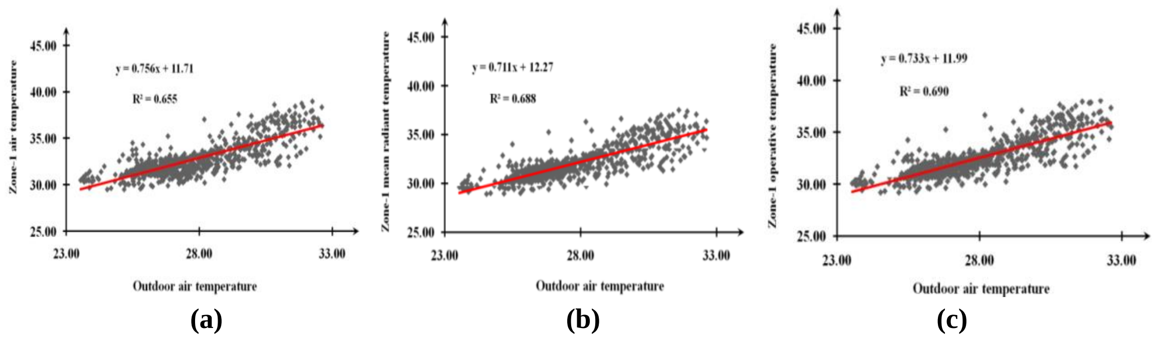


Figure D.32 Linear regression analysis for wall type W-4c: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.33 Simulation result summary for wall type W-4d.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	39.02	37.34	38.05	37.41	36.94	37.17	36.00	35.78	35.89
Minimum	23.54	29.76	29.22	29.49	28.51	28.29	28.40	27.71	27.51	27.61
Mean	27.83	32.85	32.16	32.50	32.02	31.55	31.79	31.27	30.80	31.03
Median	27.41	32.35	31.78	32.04	31.71	31.17	31.45	30.94	30.40	30.67
Mode	26.58	33.39	32.58	32.98	32.51	31.86	32.19	31.35	30.76	31.06
Kurtosis	-0.6	0.83	0.27	0.60	0.55	0.18	0.38	-0.19	-0.37	-0.30
Skewness	0.42	1.16	0.92	1.07	0.76	0.83	0.81	0.65	0.68	0.66
Std. Dev.	2.03	1.83	1.65	1.72	1.55	1.67	1.59	1.56	1.71	1.63
Sample Var.	2.11	3.36	2.74	2.94	2.40	2.79	2.54	2.44	2.92	2.65
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

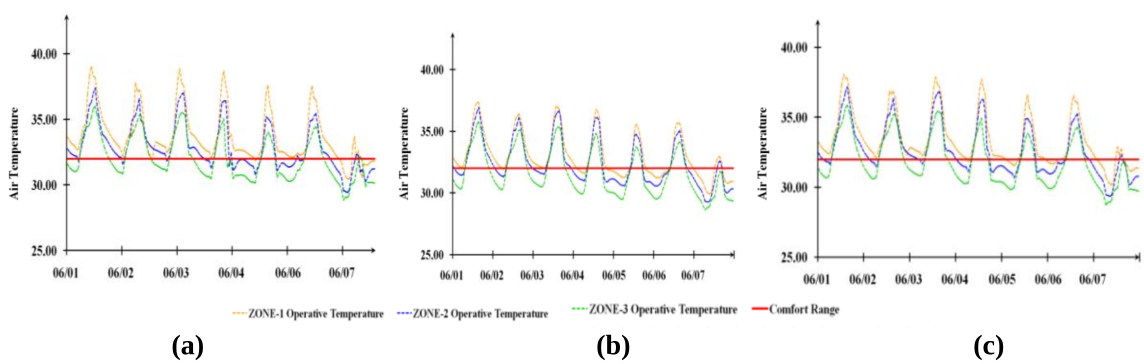
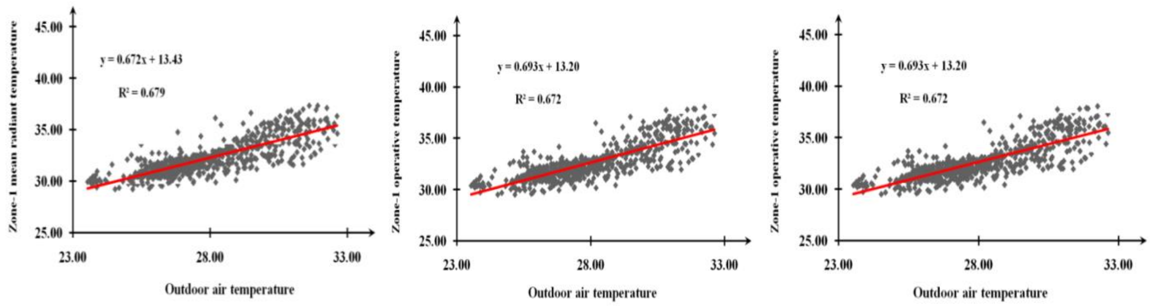


Figure D.33 Comparison of temperature gradient of different zones for wall type W-4d: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.33 Correlation matrix among different temperature index for wall type W-4d.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.79	1		
MRT(°C)	0.82	0.94	1	
OT(°C)	0.82	0.99	0.98	1

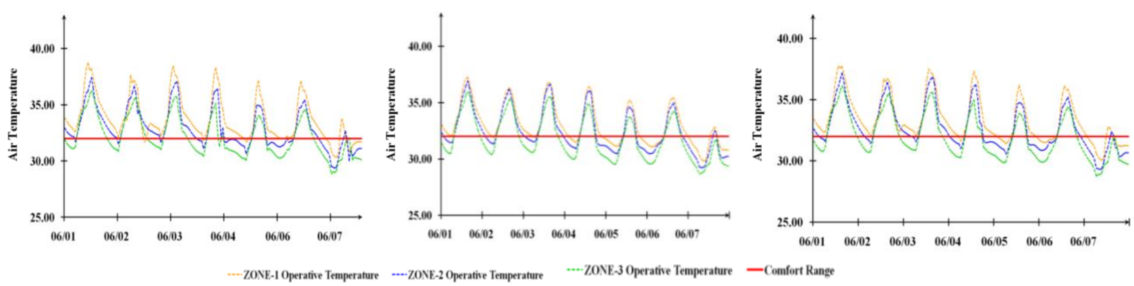


(a) **(b)** **(c)**

Figure D.34 Linear regression analysis for wall type W-4d: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.34 Simulation result summary for wall type W-4e.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	38.71	37.26	37.75	37.44	36.93	37.18	36.28	35.98	36.13
Minimum	23.54	29.55	29.01	29.28	28.42	28.20	28.31	27.68	27.48	27.58
Mean	27.83	32.75	32.07	32.41	31.99	31.52	31.76	31.32	30.85	31.09
Median	27.41	32.27	31.70	31.99	31.68	31.17	31.40	30.98	30.46	30.72
Mode	26.58	33.52	32.73	33.13	32.63	32.02	32.32	31.58	31.05	31.32
Kurtosis	-0.6	0.53	0.02	0.30	0.35	-0.01	0.18	-0.26	-0.41	-0.35
Skewness	0.42	1.03	0.78	0.93	0.69	0.74	0.72	0.61	0.63	0.62
Std. Dev.	2.03	1.82	1.67	1.71	1.59	1.71	1.64	1.63	1.76	1.69
Sample Var.	2.11	3.30	2.79	2.94	2.54	2.94	2.68	2.65	3.11	2.85
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

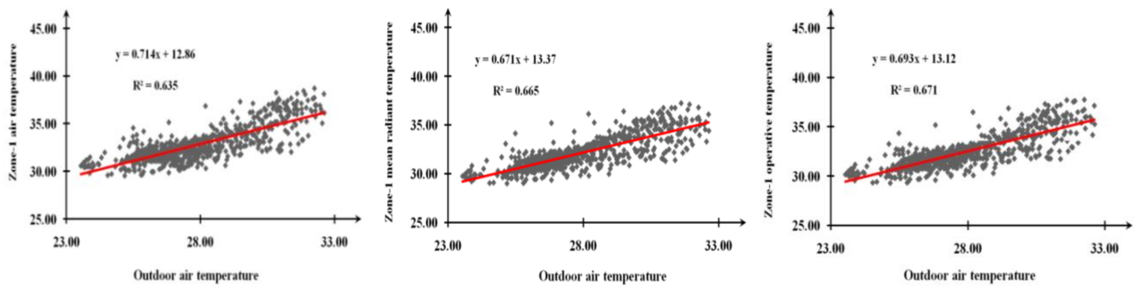


(a) **(b)** **(c)**

Figure D.35 Comparison of temperature gradient of different zones for wall type W-4e: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.35 Correlation matrix among different temperature index for wall type W-4e.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.80	1		
MRT(°C)	0.82	0.93	1	
OT(°C)	0.82	0.98	0.98	1

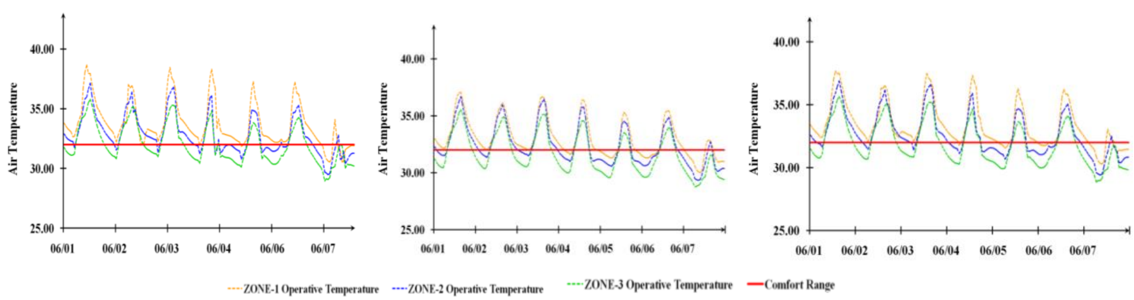


(a) (b) (c)

Figure D.36 Linear regression analysis for wall type W-4e: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.36 Simulation result summary for wall type W-4f.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	38.66	37.08	37.71	37.14	36.67	36.90	35.78	35.54	35.66
Minimum	23.54	29.82	29.28	29.55	28.65	28.44	28.55	27.83	27.62	27.73
Mean	27.83	32.83	32.16	32.50	32.02	31.55	31.79	31.26	30.79	31.03
Median	27.41	32.38	31.83	32.08	31.73	31.19	31.45	30.96	30.43	30.69
Mode	26.58	33.54	32.74	33.14	32.65	32.01	32.33	31.49	30.92	31.21
Kurtosis	-0.6	0.68	0.13	0.44	0.37	0.07	0.23	-0.24	-0.40	-0.34
Skewness	0.42	1.07	0.84	0.99	0.67	0.76	0.73	0.60	0.64	0.62
Std. Dev.	2.03	1.74	1.58	1.63	1.49	1.60	1.53	1.50	1.64	1.57
Sample Var.	2.11	3.02	2.48	2.64	2.21	2.56	2.33	2.26	2.69	2.45
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

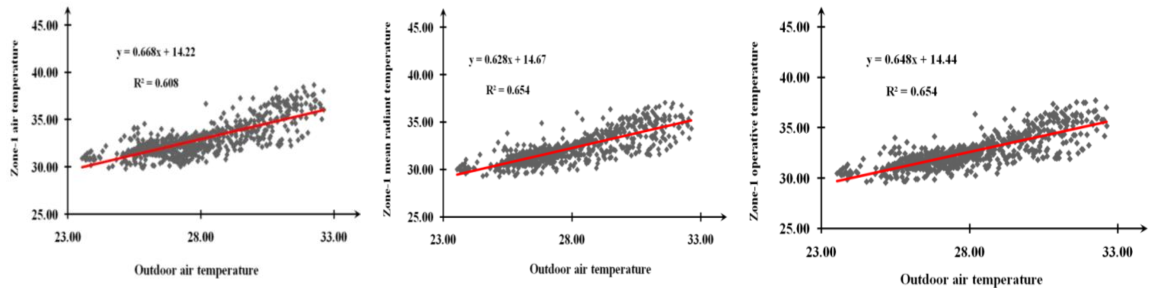


(a) (b) (c)

Figure D.37 Comparison of temperature gradient of different zones for wall type W-4f: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.37 Correlation matrix among different temperature index for wall type W-4f.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.78	1		
MRT(°C)	0.81	0.93	1	
OT(°C)	0.81	0.98	0.98	1

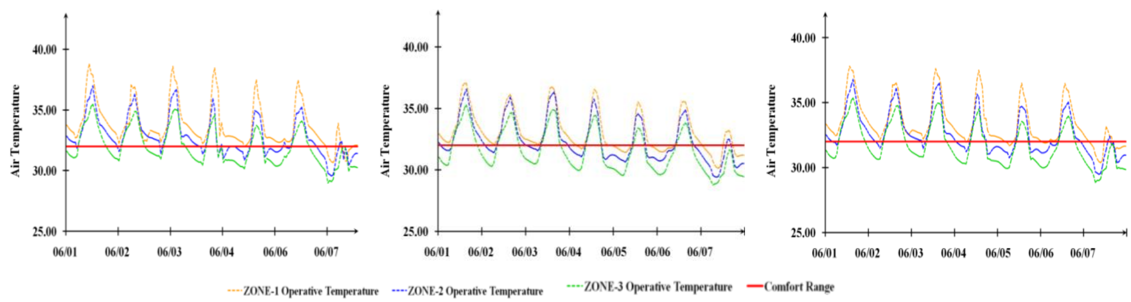


(a) **(b)** **(c)**

Figure D.38 Linear regression analysis for wall type W-4f: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.38 Simulation result summary for wall type W-4g.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	38.78	37.04	37.82	37.00	36.57	36.79	35.46	35.26	35.36
Minimum	23.54	30.00	29.46	29.73	28.75	28.54	28.65	27.88	27.67	27.78
Mean	27.83	32.90	32.24	32.57	32.04	31.58	31.81	31.21	30.73	30.97
Median	27.41	32.46	31.89	32.14	31.79	31.23	31.49	30.90	30.38	30.65
Mode	26.58	33.53	32.72	33.13	32.63	31.97	32.30	31.39	30.77	31.08
Kurtosis	-0.6	0.91	0.30	0.65	0.47	0.18	0.35	-0.21	-0.37	-0.30
Skewness	0.42	1.15	0.92	1.08	0.68	0.81	0.76	0.60	0.66	0.64
Std. Dev.	2.03	1.72	1.53	1.59	1.43	1.54	1.47	1.43	1.56	1.49
Sample Var.	2.11	2.95	2.35	2.54	2.06	2.38	2.16	2.04	2.45	2.22
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439



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

Figure D.39 Comparison of temperature gradient of different zones for wall type W-4g: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.39 Correlation matrix among different temperature index for wall type W-4g.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.77	1		
MRT(°C)	0.81	0.92	1	
OT(°C)	0.80	0.98	0.98	1

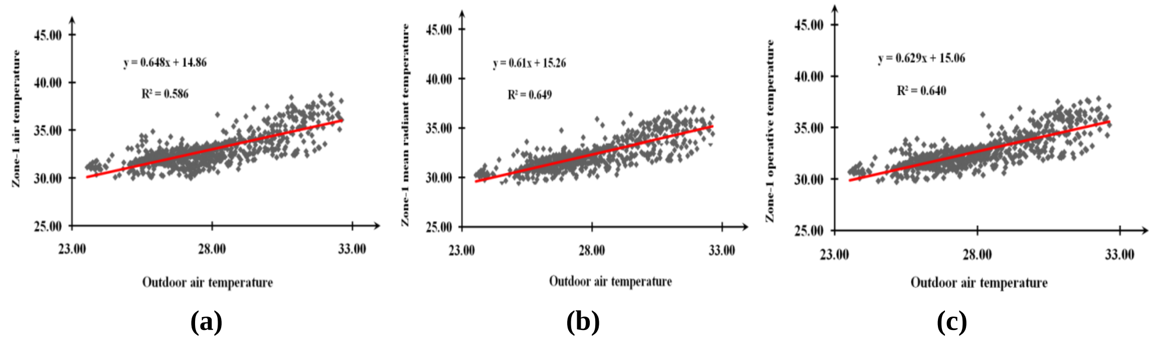


Figure D.40 Linear regression analysis for wall type W-4g: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.40 Simulation result summary for wall type W-5a.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	39.07	37.59	38.11	37.79	37.26	37.53	36.63	36.34	36.49
Minimum	23.54	29.42	28.86	29.14	28.22	28.01	28.12	27.52	27.33	27.42
Mean	27.83	32.75	32.05	32.40	31.97	31.51	31.74	31.33	30.88	31.11
Median	27.41	32.21	31.65	31.92	31.61	31.11	31.36	30.96	30.46	30.71
Mode	26.58	33.33	32.54	32.94	32.47	31.85	32.16	31.43	30.89	31.16
Kurtosis	-0.6	0.61	0.09	0.39	0.49	0.06	0.29	-0.28	-0.41	-0.37
Skewness	0.42	1.09	0.84	0.98	0.78	0.79	0.79	0.63	0.66	0.64
Std. Dev.	2.03	1.92	1.77	1.82	1.67	1.80	1.72	1.71	1.86	1.78
Sample Var.	2.11	3.71	3.13	3.32	2.79	3.25	2.95	2.91	3.48	3.16
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

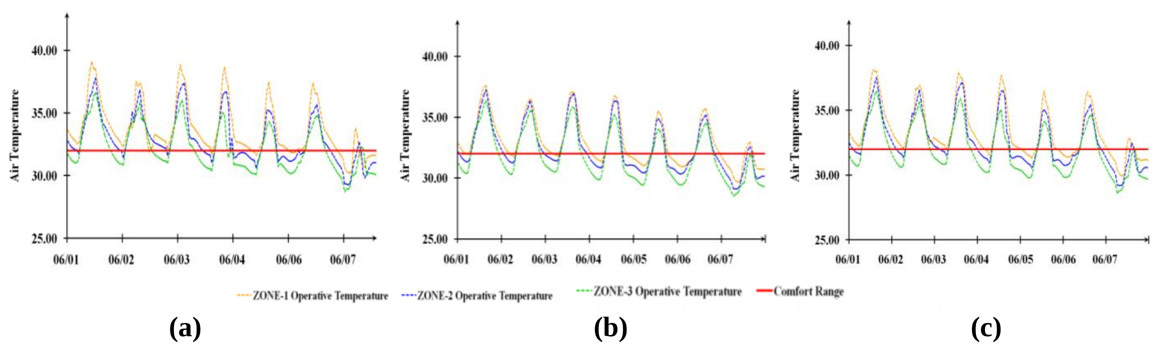
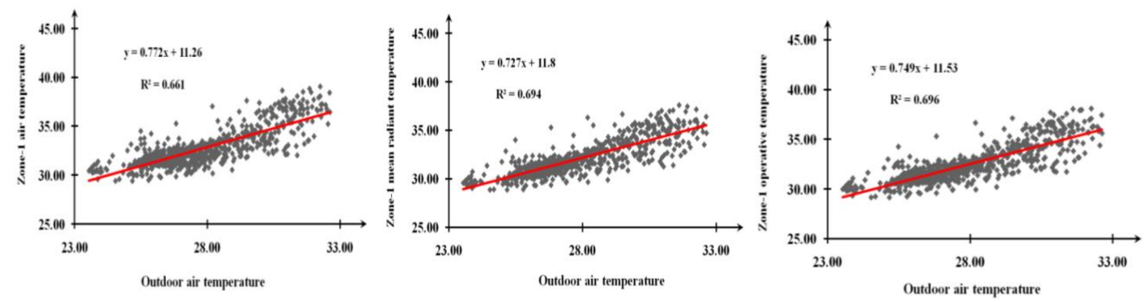


Figure D.41 Comparison of temperature gradient of different zones for wall type W-5a: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.41 Correlation matrix among different temperature index for wall type W-5a.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.81	1		
MRT(°C)	0.83	0.94	1	
OT(°C)	0.83	0.99	0.98	1

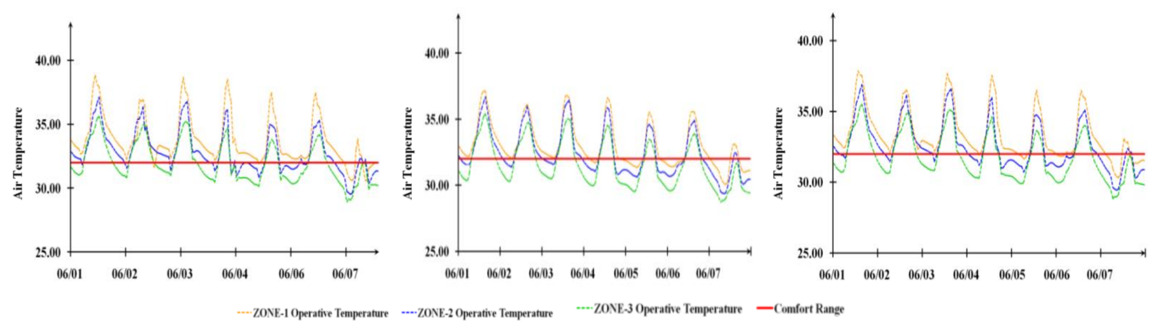


(a) (b) (c)

Figure D.42 Linear regression analysis for wall type W-5a: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.42 Simulation result summary for wall type W-5b.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	38.84	37.12	37.87	37.11	36.67	36.89	35.61	35.41	35.51
Minimum	23.54	29.93	29.39	29.66	28.69	28.47	28.58	27.83	27.62	27.73
Mean	27.83	32.89	32.22	32.55	32.04	31.57	31.80	31.23	30.74	30.99
Median	27.41	32.45	31.85	32.12	31.77	31.23	31.48	30.91	30.39	30.65
Mode	26.58	33.49	32.68	33.09	32.60	31.94	32.27	31.38	30.77	31.08
Kurtosis	-0.6	0.85	0.27	0.61	0.50	0.17	0.35	-0.21	-0.38	-0.30
Skewness	0.42	1.14	0.91	1.06	0.70	0.81	0.77	0.61	0.66	0.64
Std. Dev.	2.03	1.75	1.57	1.63	1.46	1.58	1.50	1.47	1.60	1.53
Sample Var.	2.11	3.07	2.46	2.66	2.14	2.49	2.26	2.15	2.57	2.33
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

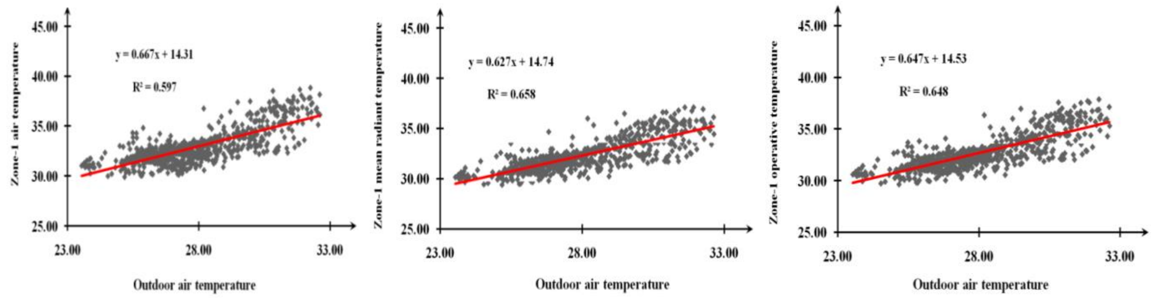


(a) (b) (c)

Figure D.43 Comparison of temperature gradient of different zones for wall type W-5b: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.43 Correlation matrix among different temperature index for wall type W-5b.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.77	1		
MRT(°C)	0.81	0.93	1	
OT(°C)	0.81	0.98	0.98	1

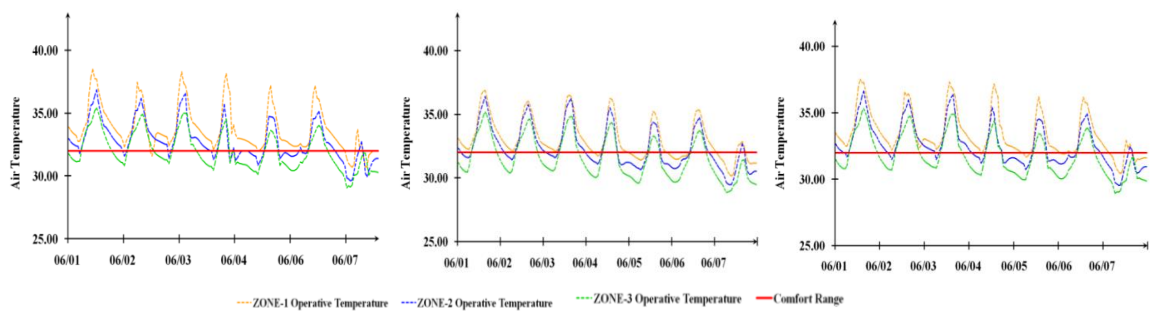


(a) (b) (c)

Figure D.44 Linear regression analysis for wall type W-5b: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table 6. E.44 Simulation result summary for wall type W-5c.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	38.49	36.87	37.53	36.84	36.40	36.62	35.41	35.18	35.29
Minimum	23.54	30.02	29.48	29.75	28.83	28.61	28.74	27.96	27.75	27.85
Mean	27.83	32.87	32.21	32.54	32.03	31.58	31.81	31.22	30.74	30.98
Median	27.41	32.43	31.88	32.14	31.78	31.27	31.51	30.95	30.40	30.68
Mode	26.58	33.64	32.84	33.24	32.72	32.08	32.40	31.52	30.93	31.22
Kurtosis	-0.6	0.85	0.18	0.55	0.32	0.06	0.22	-0.25	-0.40	-0.33
Skewness	0.42	1.10	0.85	1.00	0.63	0.75	0.70	0.56	0.63	0.60
Std. Dev.	2.03	1.65	1.48	1.53	1.41	1.51	1.44	1.41	1.54	1.47
Sample Var.	2.11	2.71	2.20	2.34	2.00	2.29	2.08	1.99	2.37	2.16
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

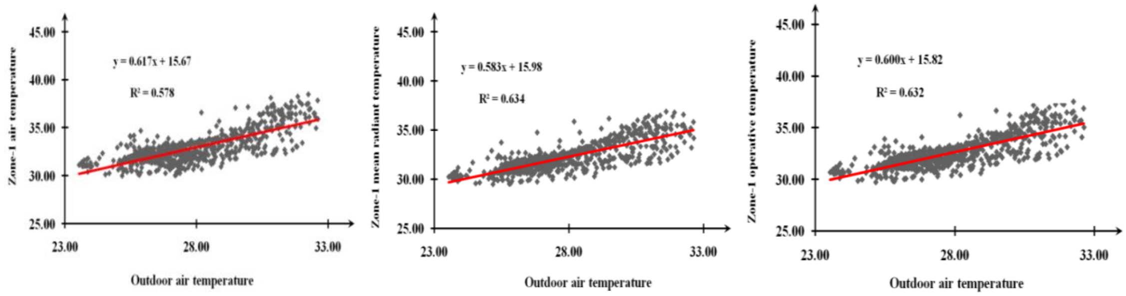


(a) (b) (c)

Figure D.45 Comparison of temperature gradient of different zones for wall type W-5c: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.45 Correlation matrix among different temperature index for wall type W-5c.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.76	1		
MRT(°C)	0.80	0.91	1	
OT(°C)	0.80	0.98	0.98	1

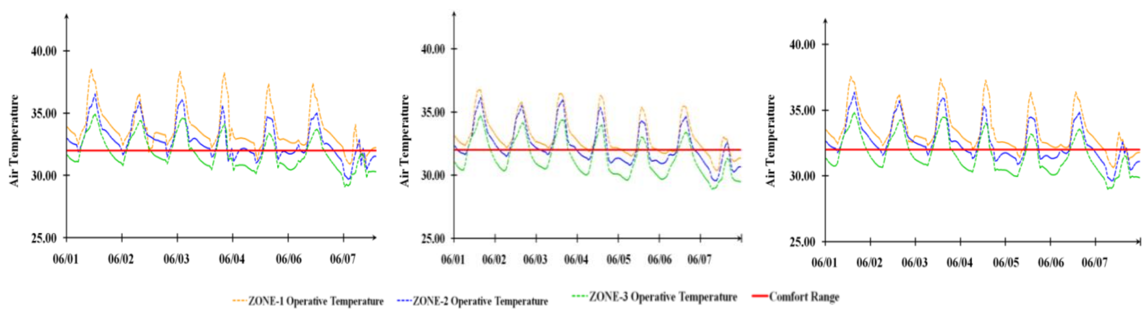


(a) **(b)** **(c)**

Figure D.46 Linear regression analysis for wall type W-5c: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.46 Simulation result summary for wall type W-5d.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	38.52	36.74	37.56	36.55	36.14	36.34	34.92	34.69	34.81
Minimum	23.54	30.10	29.76	30.03	28.92	28.79	28.92	28.06	27.85	27.96
Mean	27.83	32.96	32.32	32.64	32.07	31.61	31.84	31.14	30.63	30.88
Median	27.41	32.60	32.00	32.28	31.84	31.32	31.56	30.90	30.32	30.60
Mode	26.58	33.70	32.88	33.29	32.75	32.09	32.42	31.42	30.78	31.10
Kurtosis	-0.6	1.03	0.36	0.74	0.34	0.16	0.29	-0.21	-0.36	-0.29
Skewness	0.42	1.14	0.93	1.09	0.60	0.77	0.70	0.54	0.64	0.60
Std. Dev.	2.03	1.59	1.40	1.46	1.32	1.41	1.35	1.28	1.40	1.33
Sample Var.	2.11	2.54	1.95	2.14	1.75	1.98	1.81	1.64	1.96	1.78
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

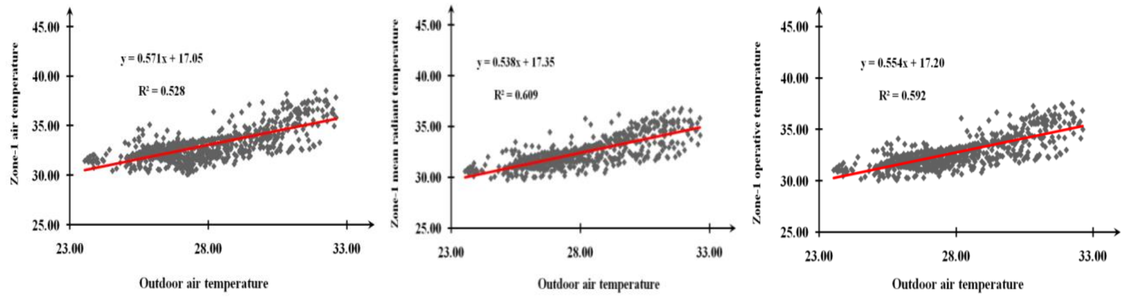


(a) **(b)** **(c)**

Figure D.47 Comparison of temperature gradient of different zones for wall type W-5d: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.47 Correlation matrix among different temperature index for wall type W-5d.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.73	1		
MRT(°C)	0.78	0.91	1	
OT(°C)	0.77	0.98	0.97	1

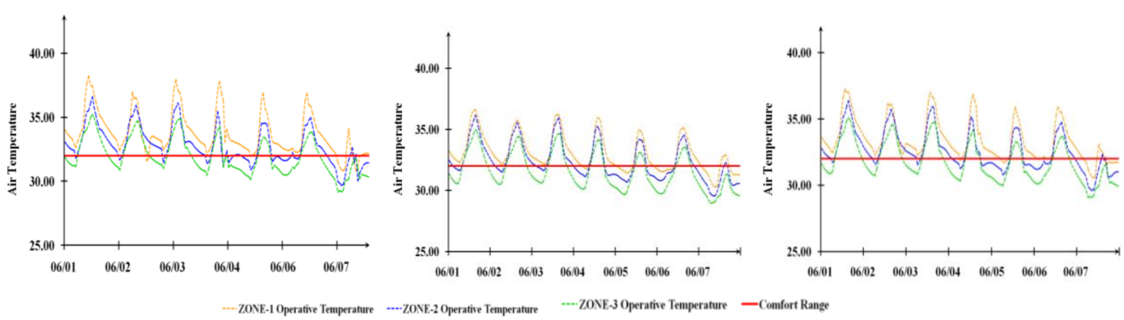


(a) (b) (c)

Figure D.48 Linear regression analysis for wall type W-5d: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.48 Simulation result summary for wall type W-5e.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	38.22	36.63	37.26	36.60	36.16	36.38	35.23	34.97	35.10
Minimum	23.54	30.07	29.55	29.82	28.88	28.70	28.82	28.05	27.82	27.94
Mean	27.83	32.85	32.22	32.54	32.04	31.59	31.82	31.22	30.74	30.98
Median	27.41	32.50	31.93	32.19	31.82	31.29	31.54	30.97	30.42	30.71
Mode	26.58	33.77	32.97	33.37	32.83	32.21	32.52	31.64	31.07	31.35
Kurtosis	-0.6	0.71	0.03	0.39	0.12	-0.06	0.04	-0.29	-0.43	-0.37
Skewness	0.42	1.01	0.76	0.92	0.53	0.68	0.62	0.51	0.58	0.55
Std. Dev.	2.03	1.57	1.42	1.45	1.37	1.46	1.39	1.36	1.48	1.42
Sample Var.	2.11	2.47	2.01	2.12	1.87	2.12	1.94	1.86	2.19	2.01
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

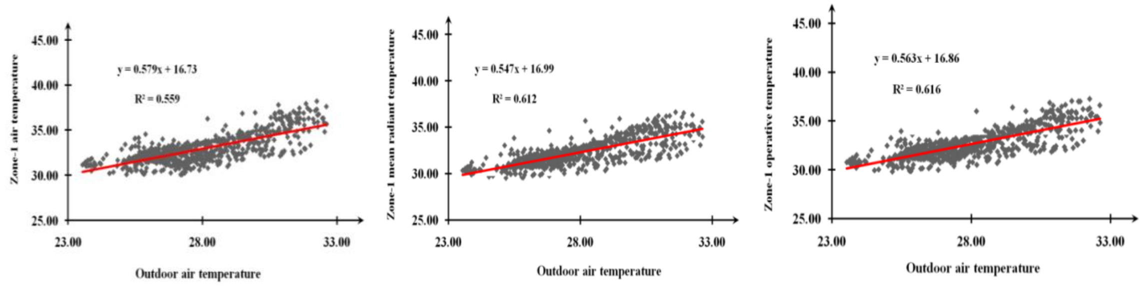


(a) (b) (c)

Figure D.49 Comparison of temperature gradient of different zones for wall type W-5e: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.49 Correlation matrix among different temperature index for wall type W-5e.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.75	1		
MRT(°C)	0.78	0.90	1	
OT(°C)	0.78	0.98	0.97	1

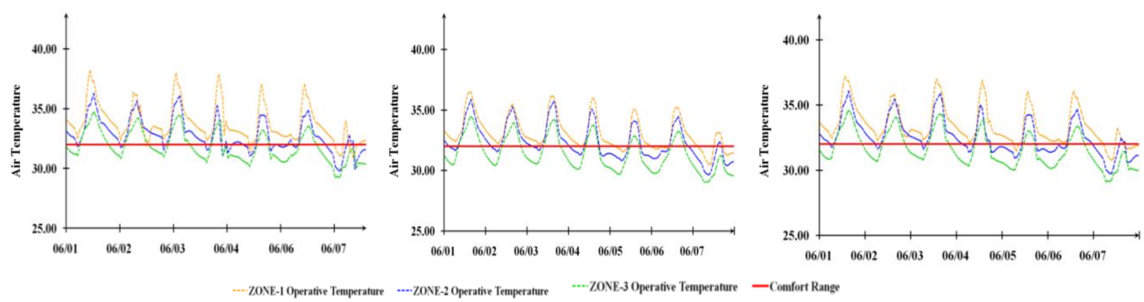


(a) **(b)** **(c)**

Figure D.50 Linear regression analysis for wall type W-5e: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.50 Simulation result summary for wall type W-5f.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	38.19	36.48	37.23	36.28	35.88	36.08	34.73	34.48	34.61
Minimum	23.54	30.08	29.86	30.13	29.05	28.92	29.00	28.17	27.96	28.07
Mean	27.83	32.95	32.34	32.64	32.08	31.62	31.85	31.14	30.63	30.89
Median	27.41	32.63	32.02	32.31	31.88	31.35	31.61	30.92	30.35	30.65
Mode	26.58	33.82	33.02	33.42	32.86	32.21	32.54	31.54	30.92	31.23
Kurtosis	-0.6	0.86	0.15	0.54	0.16	0.03	0.13	-0.27	-0.42	-0.36
Skewness	0.42	1.03	0.82	0.98	0.51	0.70	0.63	0.47	0.58	0.54
Std. Dev.	2.03	1.51	1.32	1.37	1.29	1.35	1.30	1.24	1.34	1.28
Sample Var.	2.11	2.29	1.75	1.89	1.66	1.81	1.68	1.53	1.80	1.65
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439



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

Figure D.51 Comparison of temperature gradient of different zones for wall type W-5f: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.51 Correlation matrix among different temperature index for wall type W-4f.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.71	1		
MRT(°C)	0.77	0.88	1	
OT(°C)	0.76	0.97	0.96	1

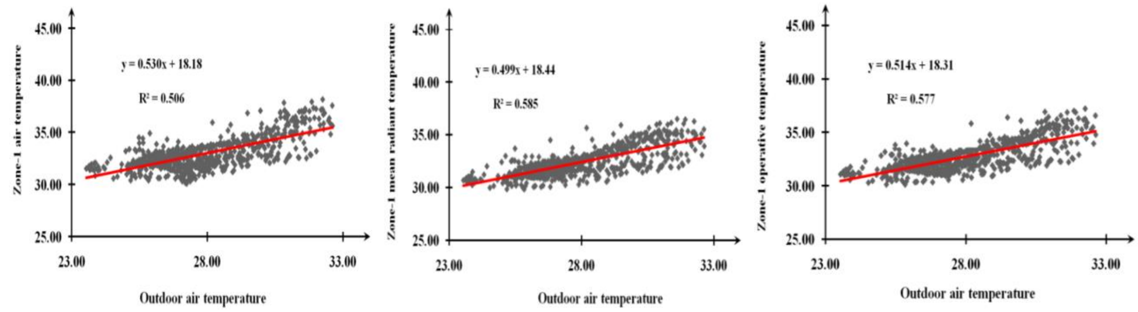


Figure D.52 Linear regression analysis for wall type W-5f: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.52 Simulation result summary for wall type W-5g.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	38.34	36.52	37.37	36.18	35.79	35.99	34.45	34.20	34.33
Minimum	23.54	29.87	30.01	30.27	29.04	28.99	29.05	28.19	27.98	28.08
Mean	27.83	33.02	32.42	32.72	32.10	31.64	31.87	31.07	30.55	30.81
Median	27.41	32.70	32.11	32.39	31.92	31.38	31.66	30.87	30.27	30.59
Mode	26.58	33.84	33.03	33.44	32.86	32.19	32.53	31.43	30.77	31.10
Kurtosis	-0.6	1.07	0.36	0.77	0.21	0.13	0.23	-0.23	-0.39	-0.32
Skewness	0.42	1.09	0.92	1.07	0.50	0.73	0.64	0.47	0.60	0.55
Std. Dev.	2.03	1.52	1.29	1.36	1.25	1.30	1.25	1.17	1.27	1.21
Sample Var.	2.11	2.30	1.68	1.86	1.56	1.69	1.58	1.36	1.61	1.47
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

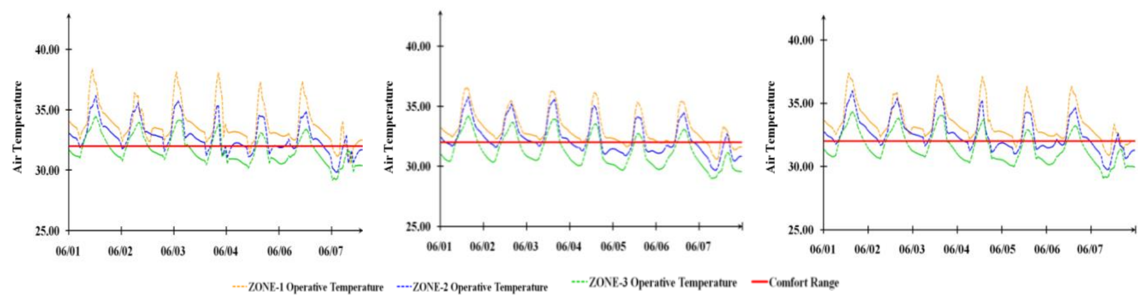
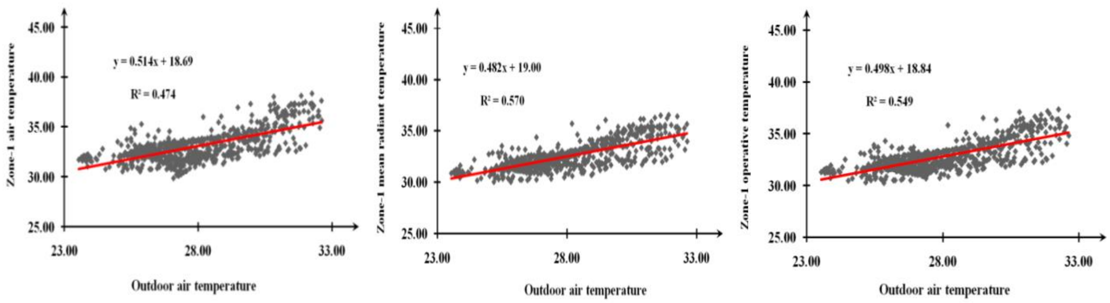


Figure D.53 Comparison of temperature gradient of different zones for wall type W-5g: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.53 Correlation matrix among different temperature index for wall type W-4g.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.79	1		
MRT(°C)	0.76	0.88	1	
OT(°C)	0.74	0.97	0.96	1

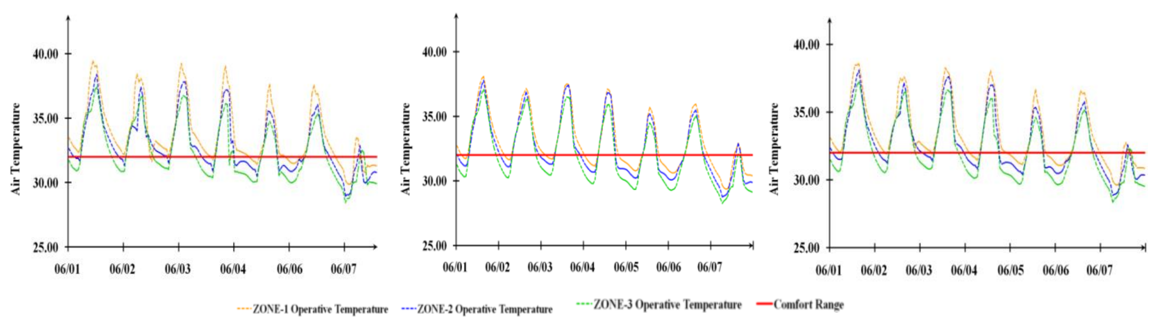


(a) **(b)** **(c)**

Figure D.54 Linear regression analysis for wall type W-5g: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.54 Simulation result summary for wall type W-6a.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	**MRT**(ºC)	**OT**(ºC)	**AT**(ºC)	**MRT**(ºC)	**OT**(ºC)	**AT**(ºC)	**MRT**(ºC)	**OT**(ºC)
Maximum	32.63	39.44	38.08	38.58	38.39	37.80	38.09	37.43	37.07	37.25
Minimum	23.54	28.98	28.44	28.71	27.80	27.59	27.69	27.21	27.02	27.11
Mean	27.83	32.67	31.94	32.31	31.91	31.46	31.68	31.38	30.94	31.16
Median	27.41	32.10	31.49	31.79	31.50	31.00	31.26	30.94	30.44	30.69
Mode	26.58	33.15	32.38	32.77	32.33	31.73	32.03	31.39	30.88	31.13
Kurtosis	-0.6	0.54	0.07	0.33	0.61	0.04	0.31	-0.13	-0.37	-0.27
Skewness	0.42	1.07	0.84	0.97	0.85	0.80	0.82	0.72	0.69	0.70
Std. Dev.	2.03	2.12	1.97	2.02	1.84	2.00	1.90	1.93	2.09	2.00
Sample Var.	2.11	4.48	3.87	4.09	3.39	4.00	3.62	3.71	4.36	4.00
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

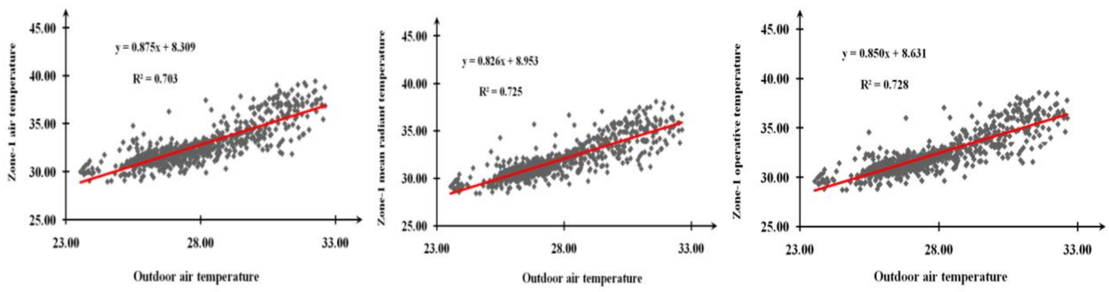


(a) **(b)** **(c)**

Figure D.55 Comparison of temperature gradient of different zones for wall type W-6a: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.55 Correlation matrix among different temperature index for wall type W-6a.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.84	1		
MRT(°C)	0.85	0.96	1	
OT(°C)	0.85	0.99	0.99	1

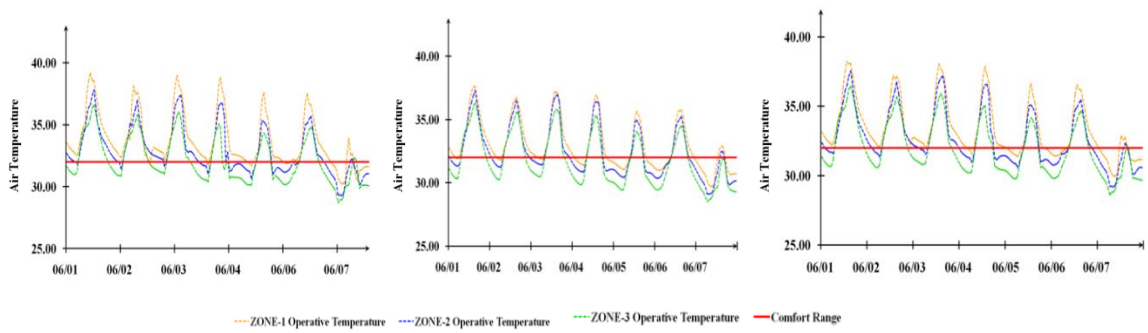


(a) **(b)** **(c)**

Figure D.56 Linear regression analysis for wall type W-6a: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.56 Simulation result summary for wall type W-6b.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	**MRT**(ºC)	**OT**(ºC)	**AT**(ºC)	**MRT**(ºC)	**OT**(ºC)	**AT**(ºC)	**MRT**(ºC)	**OT**(ºC)
Maximum	32.63	39.18	37.64	38.22	37.82	37.30	37.56	36.60	36.32	36.46
Minimum	23.54	29.45	28.88	29.17	28.21	27.99	28.10	27.51	27.31	27.41
Mean	27.83	32.79	32.08	32.43	31.98	31.52	31.75	31.32	30.87	31.09
Median	27.41	32.27	31.66	31.94	31.62	31.13	31.36	30.94	30.44	30.68
Mode	26.58	33.28	32.48	32.88	32.42	31.79	32.11	31.36	30.80	31.08
Kurtosis	-0.6	0.67	0.17	0.46	0.58	0.13	0.37	-0.24	-0.38	-0.34
Skewness	0.42	1.11	0.88	1.02	0.81	0.83	0.82	0.66	0.68	0.66
Std. Dev.	2.03	1.95	1.78	1.84	1.67	1.80	1.72	1.70	1.86	1.78
Sample Var.	2.11	3.80	3.17	3.39	2.79	3.25	2.95	2.90	3.47	3.15
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

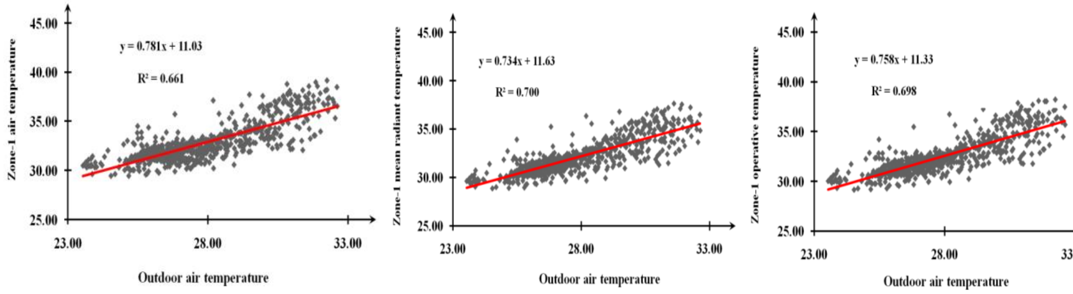


(a) **(b)** **(c)**

Figure D.57 Comparison of temperature gradient of different zones for wall type W-6b: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.57 Correlation matrix among different temperature index for wall type W-6b.

	Outdoor AT(°C)	**AT(°C)**	**MRT(°C)**	**OT(°C)**
Outdoor AT(°C)	1			
AT(°C)	0.81	1		
MRT(°C)	0.84	0.95	1	
OT(°C)	0.84	0.99	0.99	1

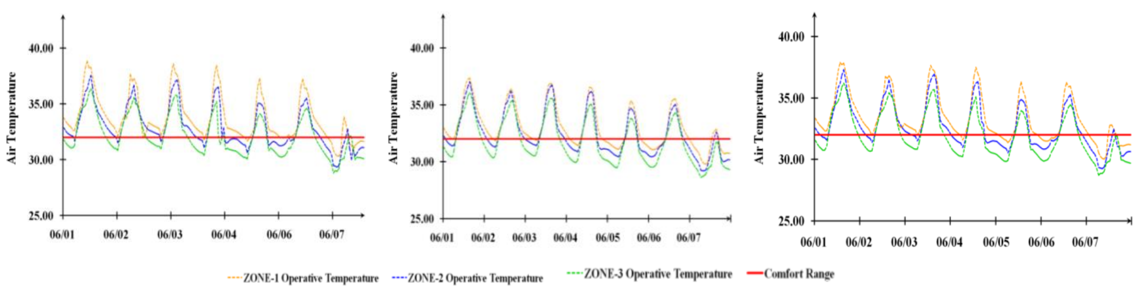


(a) (b) (c)

Figure D.58 Linear regression analysis for wall type W-6b: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.58 Simulation result summary for wall type W-6c.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	38.84	37.37	37.88	37.55	37.04	37.30	36.36	36.07	36.22
Minimum	23.54	29.53	28.99	29.26	28.37	28.15	28.26	27.63	27.43	27.53
Mean	27.83	32.77	32.07	32.42	31.99	31.52	31.76	31.31	30.85	31.08
Median	27.41	32.25	31.69	31.96	31.66	31.14	31.40	30.97	30.43	30.71
Mode	26.58	33.45	32.66	33.06	32.57	31.95	32.26	31.51	30.97	31.24
Kurtosis	-0.6	0.57	0.06	0.35	0.40	0.03	0.22	-0.27	-0.40	-0.36
Skewness	0.42	1.06	0.82	0.96	0.72	0.77	0.75	0.62	0.65	0.63
Std. Dev.	2.03	1.85	1.70	1.75	1.61	1.74	1.66	1.65	1.79	1.71
Sample Var.	2.11	3.43	2.89	3.06	2.59	3.02	2.75	2.71	3.21	2.93
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

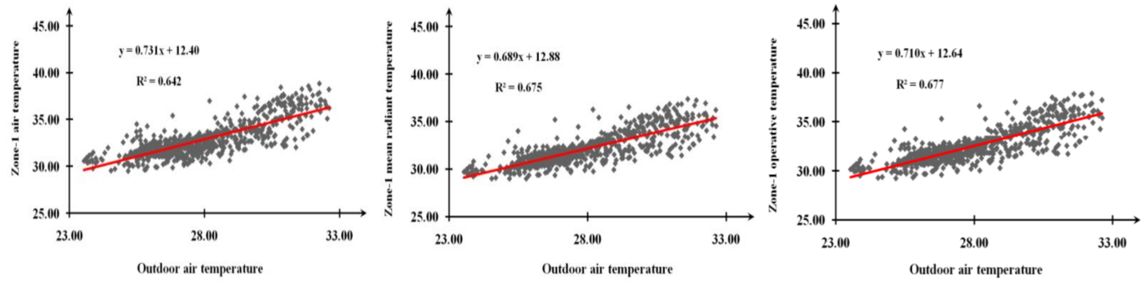


(a) (b) (c)

Figure D.59 Comparison of temperature gradient of different zones for wall type W-6c: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.59 Correlation matrix among different temperature index for wall type W-6c.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.80	1		
MRT(°C)	0.82	0.94	1	
OT(°C)	0.82	0.99	0.98	1

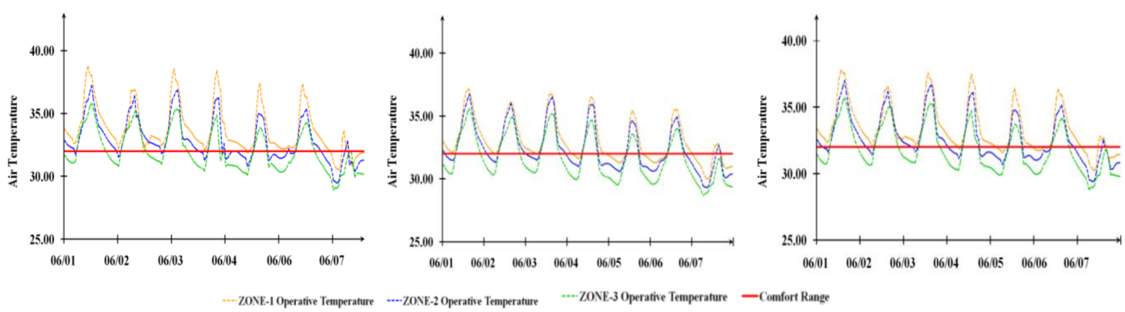


(a) **(b)** **(c)**

Figure D.60 Linear regression analysis for wall type W-6c: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.60 Simulation result summary for wall type W-6d.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	38.77	37.16	37.81	37.23	36.76	37.00	35.84	35.60	35.72
Minimum	23.54	29.80	29.26	29.53	28.60	28.39	28.49	27.78	27.58	27.68
Mean	27.83	32.84	32.17	32.50	32.03	31.55	31.79	31.26	30.78	31.02
Median	27.41	32.39	31.80	32.07	31.75	31.21	31.48	30.95	30.41	30.69
Mode	26.58	33.50	32.70	33.10	32.61	31.97	32.29	31.44	30.86	31.15
Kurtosis	-0.6	0.73	0.17	0.48	0.43	0.12	0.28	-0.23	-0.39	-0.33
Skewness	0.42	1.09	0.86	1.01	0.70	0.79	0.76	0.61	0.65	0.63
Std. Dev.	2.03	1.77	1.60	1.65	1.51	1.63	1.55	1.52	1.66	1.58
Sample Var.	2.11	3.12	2.55	2.73	2.29	2.64	2.42	2.31	2.75	2.50
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439



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

Figure D.61 Comparison of temperature gradient of different zones for wall type W-6d: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.61 Correlation matrix among different temperature index for wall type W-6d.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.78	1		
MRT(°C)	0.81	0.93	1	
OT(°C)	0.81	0.98	0.98	1

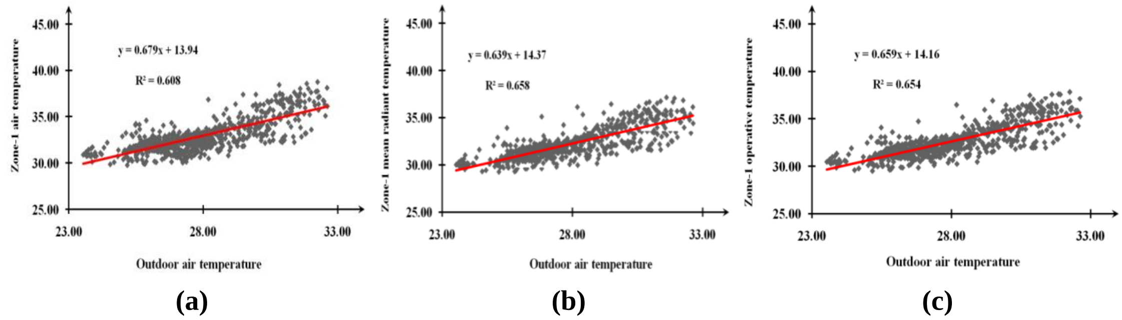


Figure D.62 Linear regression analysis for wall type W-6d: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.62 Simulation result summary for wall type W-6e.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	38.56	37.12	37.61	37.30	36.79	37.05	36.14	35.84	35.99
Minimum	23.54	29.61	29.07	29.35	28.50	28.27	28.39	27.74	27.52	27.65
Mean	27.83	32.74	32.07	32.41	31.99	31.53	31.76	31.31	30.85	31.08
Median	27.41	32.31	31.75	32.05	31.71	31.19	31.44	31.00	30.44	30.74
Mode	26.58	33.60	32.82	33.21	32.70	32.09	32.40	31.65	31.12	31.38
Kurtosis	-0.6	0.57	-0.01	0.30	0.28	-0.03	0.13	-0.28	-0.42	-0.37
Skewness	0.42	1.01	0.75	0.89	0.64	0.72	0.69	0.58	0.62	0.60
Std. Dev.	2.03	1.75	1.62	1.65	1.56	1.67	1.60	1.59	1.72	1.65
Sample Var.	2.11	3.05	2.61	2.72	2.42	2.79	2.55	2.54	2.97	2.73
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

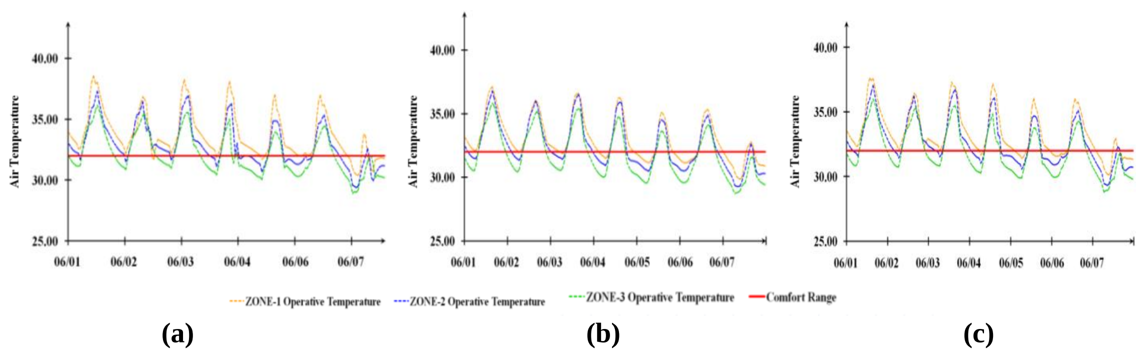


Figure D.63 Comparison of temperature gradient of different zones for wall type W-6e: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.63 Correlation matrix among different temperature index for wall type W-6e.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.79	1		
MRT(°C)	0.81	0.91	1	
OT(°C)	0.81	0.98	0.98	1

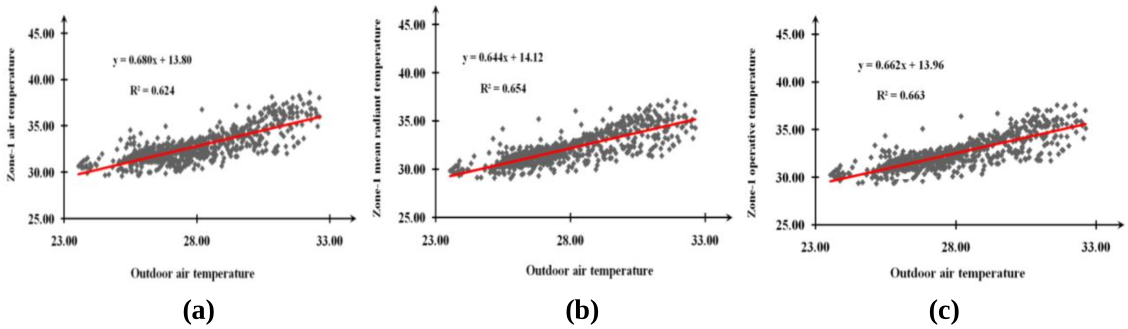


Figure D.64 Linear regression analysis for wall type W-6e: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.64 Simulation result summary for wall type W-6f.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	38.45	36.90	37.49	36.96	36.49	36.72	35.61	35.36	35.48
Minimum	23.54	29.88	29.34	29.61	28.74	28.50	28.63	27.90	27.69	27.80
Mean	27.83	32.82	32.16	32.49	32.02	31.56	31.79	31.25	30.77	31.01
Median	27.41	32.41	31.85	32.11	31.75	31.24	31.47	30.95	30.40	30.70
Mode	26.58	33.66	32.86	33.26	32.74	32.11	32.42	31.58	31.02	31.30
Kurtosis	-0.6	0.70	0.08	0.42	0.25	0.01	0.14	-0.26	-0.41	-0.35
Skewness	0.42	1.05	0.80	0.95	0.61	0.73	0.68	0.57	0.62	0.60
Std. Dev.	2.03	1.67	1.52	1.56	1.45	1.55	1.48	1.47	1.59	1.52
Sample Var.	2.11	2.79	2.31	2.43	2.10	2.41	2.19	2.15	2.53	2.32
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

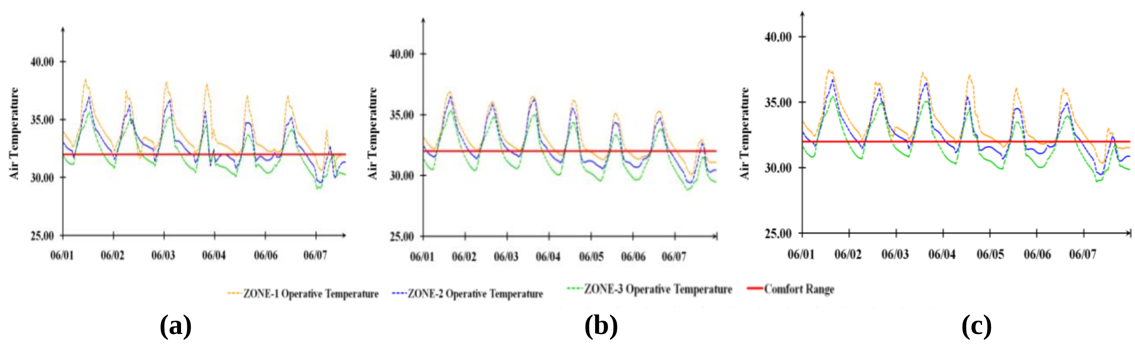
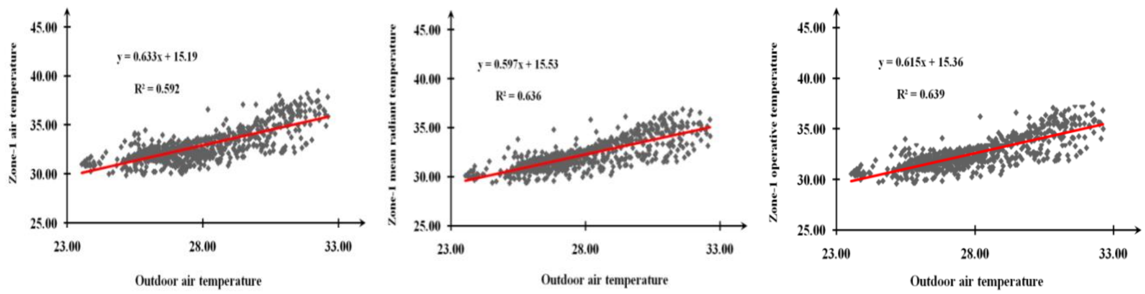


Figure 6.111 Comparison of temperature gradient of different zones for wall type W-6f: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.65 Correlation matrix among different temperature index for wall type W-6f.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.77	1		
MRT(°C)	0.80	0.92	1	
OT(°C)	0.80	0.98	0.98	1

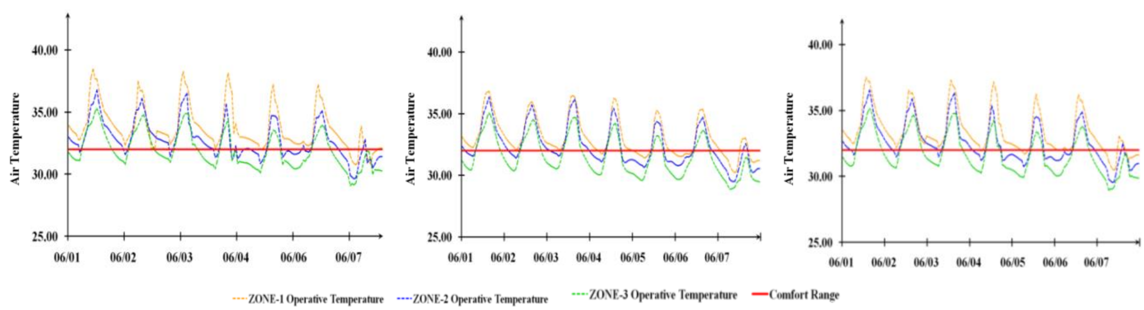


(a) **(b)** **(c)**

Figure 6.112 Linear regression analysis for wall type W-6f: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.66 Simulation result summary for wall type W-6g.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	**MRT**(ºC)	**OT**(ºC)	**AT**(ºC)	**MRT**(ºC)	**OT**(ºC)	**AT**(ºC)	**MRT**(ºC)	**OT**(ºC)
Maximum	32.63	38.48	36.82	37.52	36.78	36.34	36.56	35.29	35.05	35.17
Minimum	23.54	30.02	29.53	29.80	28.83	28.62	28.75	27.97	27.77	27.87
Mean	27.83	32.89	32.24	32.56	32.04	31.58	31.81	31.19	30.70	30.95
Median	27.41	32.50	31.91	32.17	31.80	31.27	31.53	30.93	30.35	30.64
Mode	26.58	33.68	32.87	33.27	32.74	32.10	32.42	31.50	30.90	31.20
Kurtosis	-0.6	0.87	0.19	0.56	0.31	0.08	0.22	-0.24	-0.39	-0.33
Skewness	0.42	1.10	0.85	1.01	0.61	0.75	0.69	0.56	0.63	0.60
Std. Dev.	2.03	1.63	1.46	1.52	1.39	1.49	1.42	1.38	1.50	1.44
Sample Var.	2.11	2.67	2.14	2.30	1.95	2.21	2.02	1.91	2.26	2.06
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

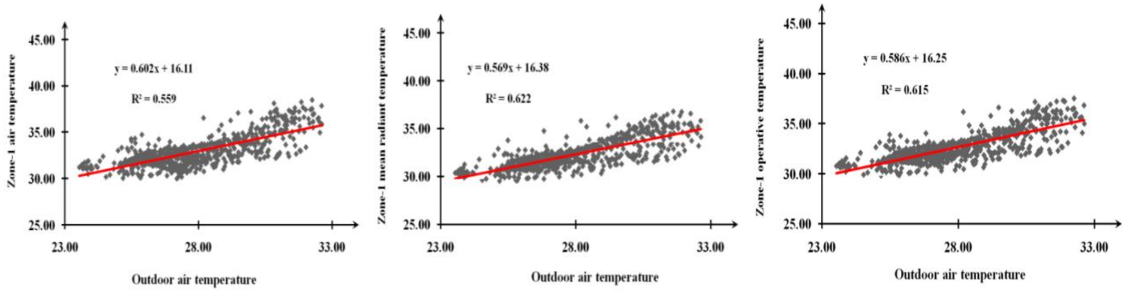


(a) **(b)** **(c)**

Figure 6.114 Comparison of temperature gradient of different zones for wall type W-6g: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.67 Correlation matrix among different temperature index for wall type W-6g.

	Outdoor AT(°C)	**AT(°C)**	**MRT(°C)**	**OT(°C)**
Outdoor AT(°C)	1			
AT(°C)	0.75	1		
MRT(°C)	0.79	0.91	1	
OT(°C)	0.78	0.98	0.98	1

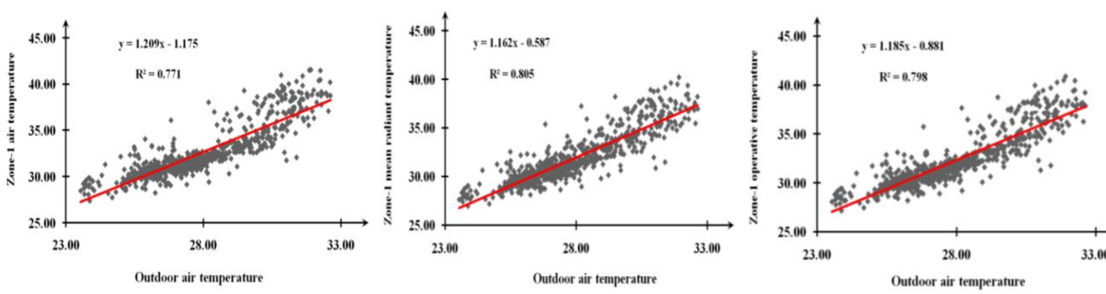


(a) **(b)** **(c)**

Figure 6.115 Linear regression analysis for wall type W-6g: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.68 Correlation matrix among different temperature index for roof type R-1a.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.88	1		
MRT(°C)	0.90	0.97	1	
OT(°C)	0.89	0.99	0.99	1

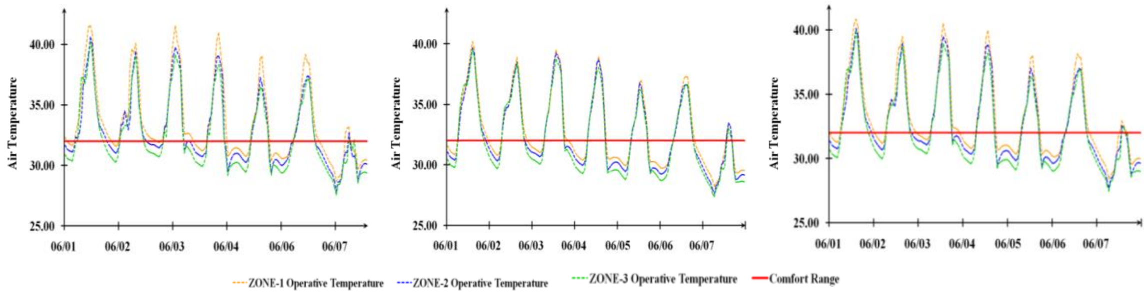


(a) **(b)** **(c)**

Figure 6.119 Linear regression analysis for roof type R-1a: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.69 Simulation result summary for roof type R-1b.

Parameter	**Outdoor** AT(ºC)	**Zone-1**			**Zone-2**			**Zone-3**		
		AT(ºC)	**MRT**(ºC)	**OT**(ºC)	**AT**(ºC)	**MRT**(ºC)	**OT**(ºC)	**AT**(ºC)	**MRT**(ºC)	**OT**(ºC)
Maximum	32.63	41.55	40.19	40.87	40.57	39.70	40.13	40.25	39.55	39.90
Minimum	23.54	27.38	26.97	27.18	26.50	26.30	26.40	26.26	26.01	26.14
Mean	27.83	32.48	31.76	32.12	31.78	31.38	31.58	31.39	31.07	31.23
Median	27.41	31.67	31.04	31.35	31.04	30.60	30.89	30.65	30.20	30.46
Mode	26.58	32.00	31.26	31.63	31.36	30.75	31.06	30.62	30.13	30.37
Kurtosis	-0.6	0.72	0.07	0.43	0.72	-0.04	0.37	0.34	-0.33	-0.01
Skewness	0.42	1.19	0.91	1.06	1.09	0.86	0.98	0.99	0.78	0.88
Std. Dev.	2.03	2.79	2.62	2.69	2.51	2.67	2.56	2.57	2.78	2.66
Sample Var.	2.11	7.80	6.89	7.24	6.29	7.11	6.58	6.58	7.74	7.06
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

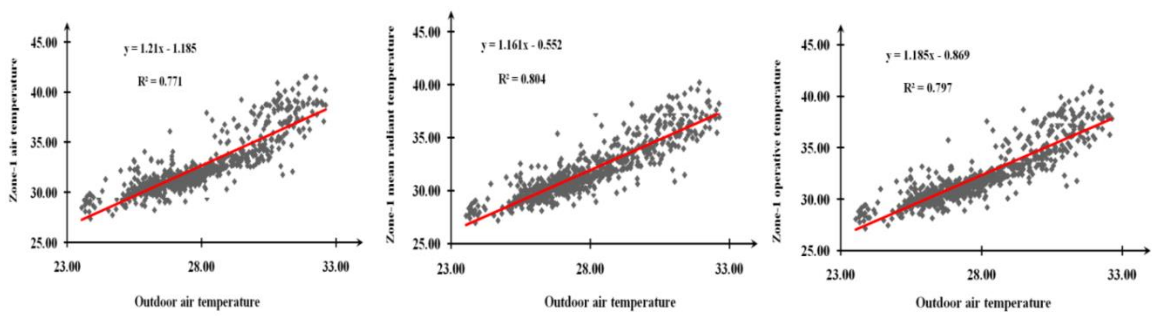


(a) **(b)** **(c)**

Figure 6.121 Comparison of temperature gradient of different zones for roof type R-1b: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.70 Correlation matrix among different temperature index for roof type R-1b.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.88	1		
MRT(°C)	0.90	0.97	1	
OT(°C)	0.89	0.99	0.99	1

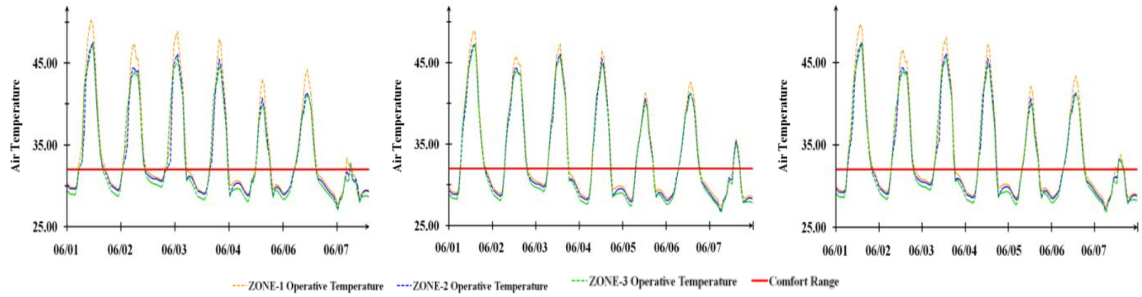


(a) **(b)** **(c)**

Figure 6.122 Linear regression analysis for roof type R-1b: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.71 Simulation result summary for roof type R-2a.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	50.27	48.83	49.55	47.49	47.25	47.37	47.21	47.20	47.20
Minimum	23.54	26.21	25.74	25.97	25.66	25.31	25.49	25.56	25.16	25.36
Mean	27.83	32.92	32.59	32.76	32.15	32.11	32.13	31.98	31.92	31.95
Median	27.41	31.07	30.59	30.88	30.57	30.26	30.46	30.30	29.95	30.14
Mode	26.58	29.92	29.23	29.58	29.69	28.93	29.31	29.03	28.42	28.73
Kurtosis	-0.6	1.12	0.20	0.71	1.26	0.13	0.75	0.54	-0.12	0.24
Skewness	0.42	1.45	1.10	1.28	1.48	1.07	1.28	1.27	0.99	1.13
Std. Dev.	2.03	5.03	5.05	5.00	4.38	4.79	4.53	4.58	4.95	4.73
Sample Var.	2.11	25.32	25.51	24.99	19.15	22.96	20.54	20.93	24.51	22.42
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

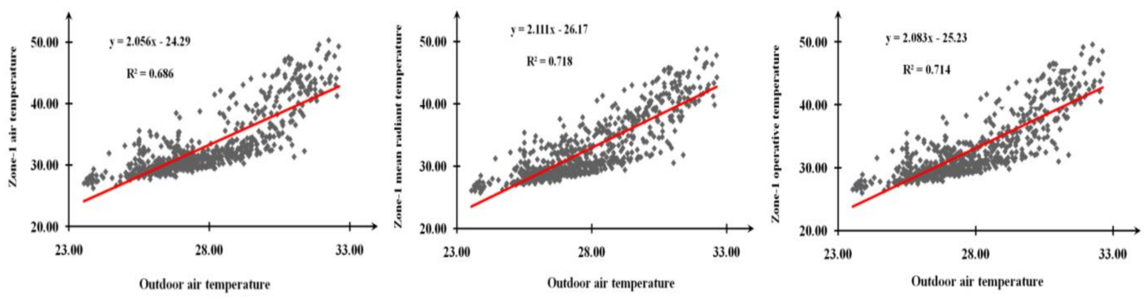


(a) **(b)** **(c)**

Figure 6.125 Comparison of temperature gradient of different zones for roof type R-2a: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.72 Correlation matrix among different temperature index for roof type R-2a.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.83	1		
MRT(°C)	0.85	0.97	1	
OT(°C)	0.85	0.99	0.99	1

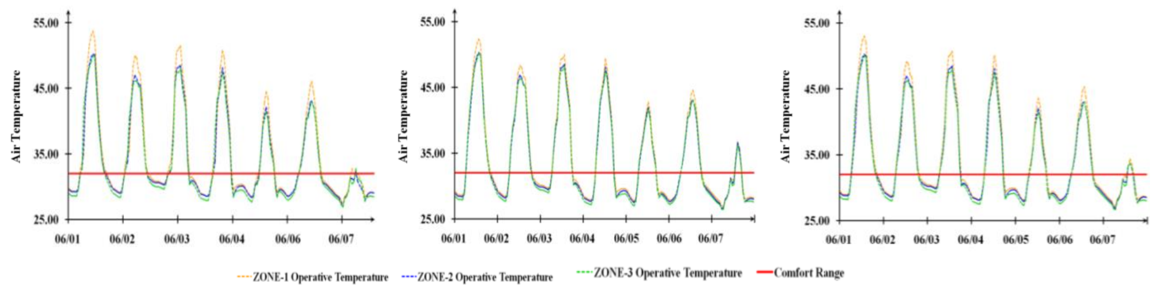


(a) **(b)** **(c)**

Figure 6.126 Linear regression analysis for roof type R-2a: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.73 Simulation result summary for roof type R-2b.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	53.74	52.37	53.06	50.19	50.33	50.26	49.94	50.14	50.04
Minimum	23.54	25.75	25.43	25.59	25.32	25.06	25.21	25.35	24.78	25.16
Mean	27.83	33.13	32.93	33.03	32.37	32.42	32.39	32.26	32.27	32.26
Median	27.41	30.93	30.41	30.72	30.43	30.06	30.32	30.14	29.83	29.99
Mode	26.58	29.37	28.74	29.06	29.24	28.50	28.87	28.62	28.02	28.32
Kurtosis	-0.6	1.19	0.25	0.77	1.25	0.19	0.79	0.63	-0.02	0.34
Skewness	0.42	1.47	1.13	1.31	1.50	1.10	1.31	1.32	1.04	1.18
Std. Dev.	2.03	5.91	5.97	5.89	5.19	5.62	5.35	5.40	5.77	5.55
Sample Var.	2.11	34.94	35.63	34.69	26.97	31.57	28.58	29.11	33.28	30.78
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

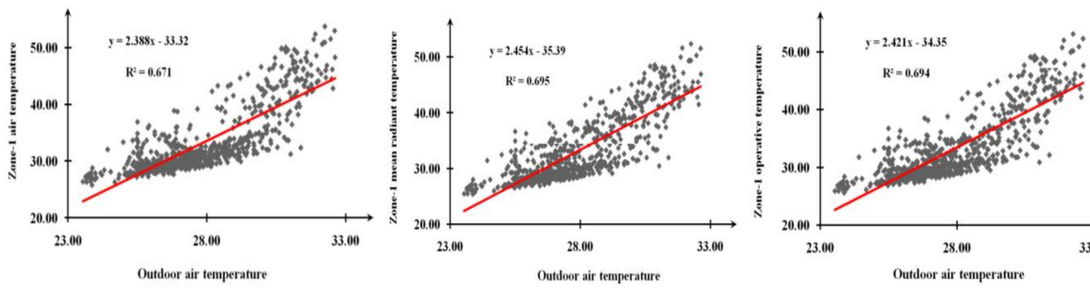


(a) **(b)** **(c)**

Figure 6.128 Comparison of temperature gradient of different zones for roof type R-2b: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.74 Correlation matrix among different temperature index for roof type R-2b.

	Outdoor AT(°C)	**AT(°C)**	**MRT(°C)**	**OT(°C)**
Outdoor AT(°C)	1			
AT(°C)	0.82	1		
MRT(°C)	0.83	0.97	1	
OT(°C)	0.83	0.99	0.99	1

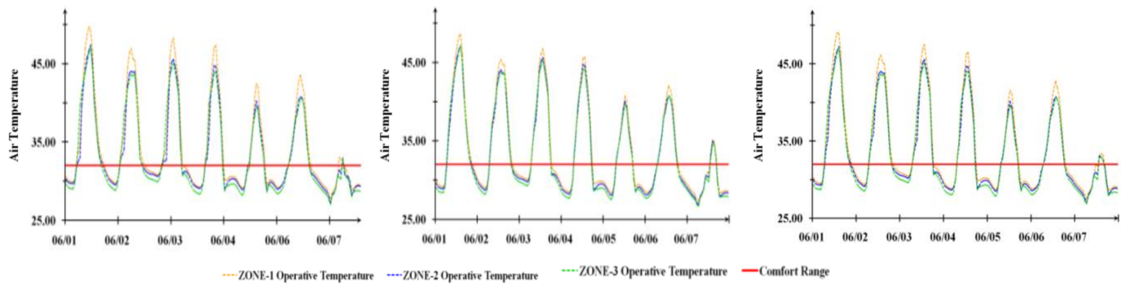


(a) **(b)** **(c)**

Figure 6.129 Linear regression analysis for roof type R-2b: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.75 Simulation result summary for roof type R-2c.

Parameter	**Outdoor AT(ºC)**	**Zone-1**			**Zone-2**			**Zone-3**		
		AT(ºC)	**MRT**(ºC)	**OT**(ºC)	**AT**(ºC)	**MRT**(ºC)	**OT**(ºC)	**AT**(ºC)	**MRT**(ºC)	**OT**(ºC)
Maximum	32.63	49.74	48.60	49.03	47.36	47.15	47.26	47.11	47.11	47.11
Minimum	23.54	26.15	25.62	25.89	25.59	25.21	25.40	25.45	25.05	25.25
Mean	27.83	32.81	32.45	32.63	32.08	31.98	32.03	31.88	31.79	31.84
Median	27.41	31.04	30.51	30.84	30.61	30.17	30.42	30.27	29.89	30.12
Mode	26.58	30.18	29.49	29.83	29.90	29.16	29.53	29.24	28.65	28.94
Kurtosis	-0.6	1.25	0.30	0.84	1.34	0.24	0.85	0.64	-0.03	0.34
Skewness	0.42	1.48	1.12	1.31	1.49	1.09	1.30	1.29	1.01	1.16
Std. Dev.	2.03	4.84	4.87	4.82	4.23	4.64	4.39	4.41	4.79	4.57
Sample Var.	2.11	23.43	23.75	23.20	17.93	21.49	19.27	19.47	22.91	20.92
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

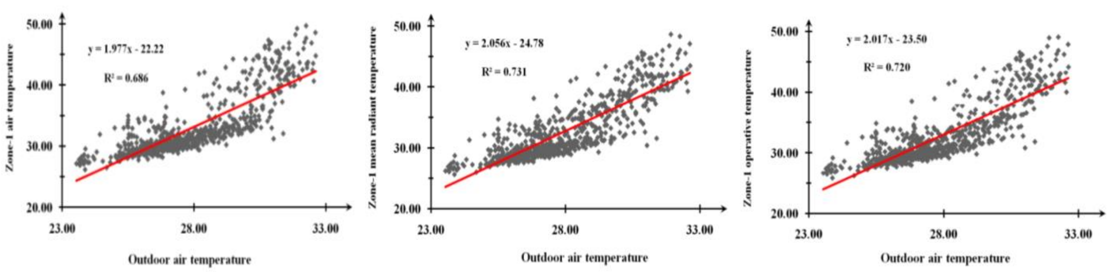


(a) **(b)** **(c)**

Figure 6.131 Comparison of temperature gradient of different zones for roof type R-2c: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.76 Correlation matrix among different temperature index for roof type R-2c.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.83	1		
MRT(°C)	0.86	0.97	1	
OT(°C)	0.85	0.99	0.99	1



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

Figure 6.132 Linear regression analysis for roof type R-2c: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.77 Simulation result summary for roof type R-2d.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	52.70	51.35	52.02	49.66	49.52	49.59	49.44	49.50	49.47
Minimum	23.54	25.73	25.26	25.49	25.31	24.94	25.12	25.22	24.80	25.01
Mean	27.83	33.07	32.75	32.91	32.31	32.26	32.29	32.18	32.10	32.14
Median	27.41	30.91	30.40	30.69	30.48	30.06	30.31	30.22	29.79	30.04
Mode	26.58	29.67	29.02	29.35	29.47	28.74	29.11	28.85	28.27	28.56
Kurtosis	-0.6	1.10	0.28	0.74	1.18	0.23	0.76	0.54	0.00	0.30
Skewness	0.42	1.44	1.14	1.30	1.47	1.11	1.30	1.28	1.04	1.17
Std. Dev.	2.03	5.66	5.69	5.63	4.97	5.36	5.12	5.17	5.51	5.31
Sample Var.	2.11	32.04	32.34	31.74	24.65	28.76	26.18	26.70	30.39	28.25
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

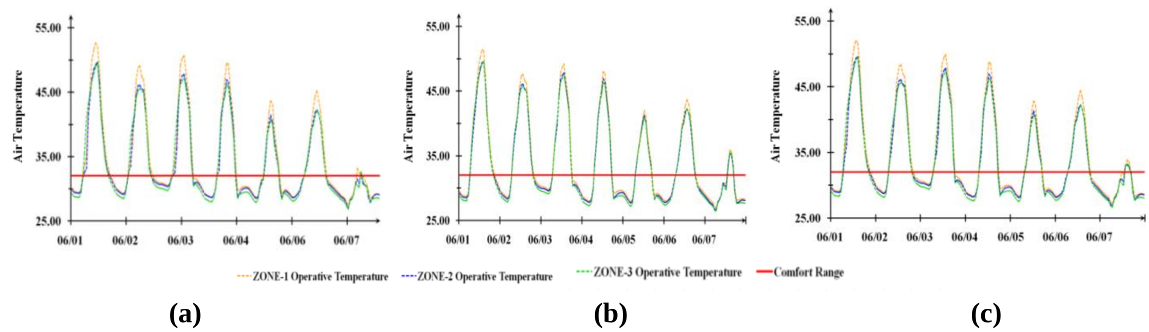


Figure 6.134 Comparison of temperature gradient of different zones for roof type R-2d: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.78 Correlation matrix among different temperature index for roof type R-2d.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.83	1		
MRT(°C)	0.85	0.97	1	
OT(°C)	0.84	0.99	0.99	1

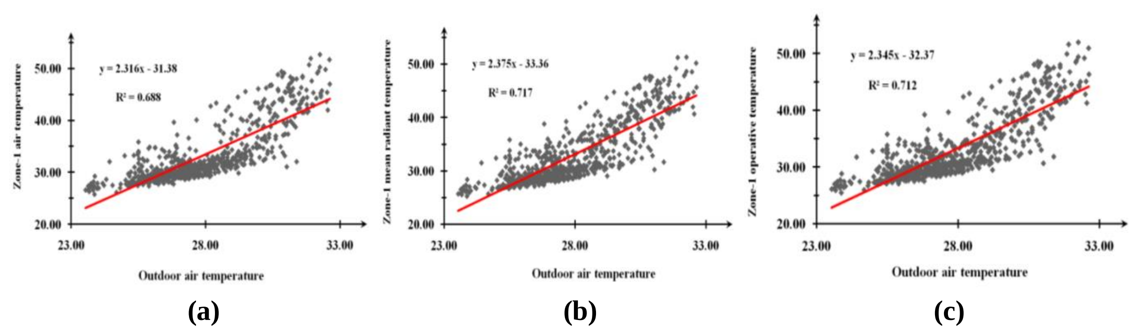
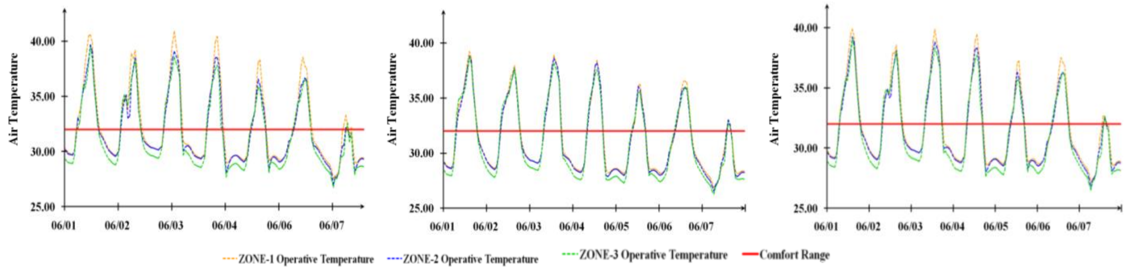


Figure 6.135 Linear regression analysis for roof type R-2d: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature

Table D.79 Simulation result summary for floor type F-2.

Parameter	Outdoor AT(ºC)	Zone-1			Zone-2			Zone-3		
		AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)	AT(ºC)	MRT(ºC)	OT(ºC)
Maximum	32.63	40.89	39.21	39.90	39.67	38.81	39.24	39.46	38.72	39.09
Minimum	23.54	26.54	25.90	26.22	25.81	25.47	25.64	25.59	25.19	25.39
Mean	27.83	31.52	30.58	31.05	31.03	30.41	30.72	30.66	30.11	30.39
Median	27.41	30.46	29.52	30.02	30.20	29.36	29.79	29.68	28.99	29.32
Mode	26.58	30.25	29.21	29.73	30.10	29.10	29.60	29.30	28.40	28.85
Kurtosis	-0.6	0.45	-0.07	0.19	0.43	-0.13	0.14	-0.01	-0.47	-0.26
Skewness	0.42	1.16	0.98	1.07	1.06	0.94	1.00	0.95	0.83	0.88
Std. Dev.	2.03	2.95	2.83	2.88	2.58	2.81	2.68	2.68	2.95	2.81
Sample Var.	2.11	8.68	8.02	8.29	6.68	7.88	7.19	7.20	8.72	7.89
Total sample	1439	1439	1439	1439	1439	1439	1439	1439	1439	1439

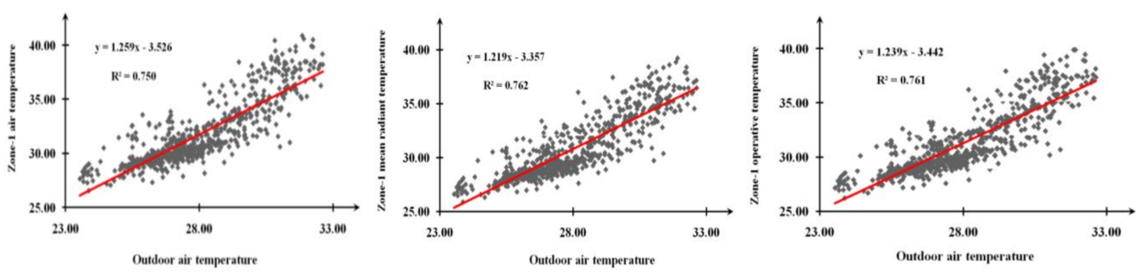


(a) **(b)** **(c)**

Figure 6.141 Comparison of temperature gradient of different zones for floor type F-2: (a) Zone AT (°C), (b) Zone MRT (°C) and (c) Zone OT (°C)

Table D.80 Correlation matrix among different temperature index for floor type F-2.

	Outdoor AT(°C)	AT(°C)	MRT(°C)	OT(°C)
Outdoor AT(°C)	1			
AT(°C)	0.87	1		
MRT(°C)	0.87	0.99	1	
OT(°C)	0.87	1	1	1



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

Figure 6.142 Linear regression analysis for floor type F-2: a) AT (ºC) and outdoor temperature, b) MRT (ºC) and outdoor temperature and c) OT (ºC) and outdoor temperature